PHOTOMETRIC EXOPLANET CHARACTERIZATION

AND

MULTIMEDIA ASTRONOMY COMMUNICATION

A Dissertation in
Astronomy & Astrophysics
by
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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

August 2017
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Abstract

The transit method of detecting exoplanets has dominated the search for distant worlds since the success of the *Kepler* space telescope and will continue to lead the field after the launch of the Transiting Exoplanet Survey Satellite in 2018. But detections are just the beginning. Transit light curves can only reveal a limited amount of information about a planet, and that information is almost entirely dependent on the properties of the host star or stars. This dissertation discusses follow-up techniques to more precisely characterize transiting planets using photometric observations.

A high-resolution follow-up imaging program using the *Hubble* Space Telescope (*HST*) searched for previously unknown stars nearby the hosts of small and cool *Kepler* exoplanets and observed a higher-than-expected occurrence rate of stellar multiplicity. The rate of previously unknown stellar multiples has strong implications for the size and habitability of the orbiting planets. Three systems with newly discovered stellar multiplicity, *Kepler*-296 (2 stars, 5 planets), KOI-2626 (3 stars, 1 planet), and KOI-3049 (2 stars, 1 planet), were characterized in more detail. In the cases of *Kepler*-296 and KOI-2626, some of the planets lost their previous habitable zone status because of host star ambiguity.

Next, the ultra-short period, ultra-hot Jupiter WASP-103b was used as a case-study to test for the presence of a stratospheric temperature inversion through dayside emission spectroscopy using *HST*. WASP-103b’s near-infrared emission spectrum is consistent with an isothermal or thermally-inverted atmosphere and shows no significant broadband water absorption feature. Detection of an anomalously strong “super-Rayleigh” slope in its optical transmission spectrum prompted follow-up transmission spectroscopy of WASP-103b’s atmosphere using the MINiature Radial Velocity Array (MINERVA), which tentatively verified the unexplained “super-Rayleigh” spectral slope.

The final follow-up technique for transiting planets presented in this work quantifies the information contained in a sequence of transit depths using a normalized information content metric. The normalized information content metric can distinguish between naturally occurring, regular transits of real exoplanets detected via *Kepler* (low information content) and simulated artificial beacons whose depth
and timing vary in a prime number sequence (high information content). Highly variable transit sequences with natural explanations—as seen with KIC 12557548, for example—can only be distinguished from artificial beacons when observed at a high signal-to-noise ratio (moderate information content) and may otherwise be confused with a more information-rich sequence.

This dissertation also presents a review of effective methods for communicating science to various audiences, with specific applications to astronomy. That chapter highlights the necessity of integrating formal communications training into the early stages of a career in astronomy, explains why and how to apply story telling techniques to astronomy communication, and details specific strategies to apply when using common communication media. Examples are given for effectively communicating astronomy through academic research papers, slides for an oral presentation, and academic research posters, as well as examples of popular science blogs, feature articles, and news stories.
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List of Symbols

Telescopes and Surveys

KIC  *Kepler* Input Catalog
KOI  *Kepler* Object of Interest
HST  *Hubble* Space Telescope
Spitzer  *Spitzer* Space Telescope
WFC3  Wide Field Camera 3 on *HST*
UVIS  The ultraviolet-visible range of WFC3
CFOP  Community Follow-up Observing Program for *Kepler*
WASP  Wide-Angle Search for Planets
MINERVA  MINiature Exoplanet Radial Velocity Array
HATnet  Hungarian-made Automated Telescope Network
HATSouth  Hungarian-made Automated Telescope Network-South
KELT  Kilodegree Extremely Little Telescope (North and South)
CoRoT  Convection Rotation et Transits planétaires (French) or Convection Rotation and planetary Transits (English)
TReS  Trans-atlantic Exoplanet Survey
TRAPPIST  Transiting Planets and Planetesimals Small Telescope
XO  The XO Project
TESS  Transiting Exoplanet Survey Satellite
QES  Qatar Exoplanet Survey
ŚG  G-HAT, Glimpsing Heat from Alien Technology
SETI  Search for Extra-Terrestrial Intelligence
ETI  Extra-Terrestrial Intelligence

Astronomical Observing

RA  Right ascension
Dec  Declination
CCD  Charge coupled device
AO  Adaptive optics
PSF  Point-spread function
S/N and SNR  The signal-to-noise ratio of an observation
   LC  Photometric light curve
   RV  Radial Velocity
   TTV  Transit Timing Variation
   TDV  Transit Duration Variation
   DTS  Depth Time Series (Transit or Eclipse)
   IR  Infrared
   NIR  Near-infrared
   UV  Ultraviolet
   KP  Photometric magnitude in the *Kepler* bandpass
   PA  Position angle between two objects, measured north through east
   E(B − V)  Photometric reddening due to interstellar material
   A_{band}  extinction in a desired bandpass
   T_C  Time of transit center
   T_S  Time of secondary eclipse center
   T_{14}  Duration of a transit or eclipse, calculated as time from first to last
   contact of the planet and star
   \( \tau \)  Ingress and/or egress time of a transit or eclipse
   \( \lambda \)  Wavelength of observation
   FoV  Field of view

### Stars

   R_S  and R_*  Stellar radius
   M_*  Stellar mass
   T_{eff}  and T_*  Stellar effective temperature
   \log g  Base-10 logarithm of stellar surface gravity measured in cgs units
   [Fe/H]  Stellar metallicity relative to Solar in logarithmic units
   [\alpha/Fe ]  Ratio of \( \alpha \) elements to iron in a star
   F_S  Stellar flux
   SED  Spectral energy distribution

### Planets

   HZ  Circumstellar habitable zone
   R_p  Planetary radius
   M_P  Planetary mass
   a_p  Planetary orbital semi-major axis
   T_{eq}  Planetary equilibrium temperature without atmospheric warming
   e  Orbital eccentricity
$P_P$ Planetary orbital period
$\omega$ Argument of periasteron
$i$ Orbital inclination
$F_P$ Planetary flux
$S_{\text{eff}}$ Effective stellar irradiation received at a planet
$\rho_P$ Bulk planetary density
$A$ Planetary albedo
$C/O$ Ratio of carbon to oxygen in a medium
$P$ Atmospheric pressure
$\text{TiO}$ Titanium oxide
$\text{VO}$ Vanadium oxide

Calculations

FWHM The full width at half maximum of a distribution
RMS The square root of the mean of the square of a value
CMD Color-magnitude diagram for apparent brightness
HR Hertzsprung-Russel diagram for absolute brightness
GP Gaussian process
A-D Anderson-Darling test for normality
$A^2$ Adjusted A-D statistic
EDF Empirical Distribution Function
$\Phi$ Set of hyperparameters of a GP regression
$\Sigma$ Covariance matrix of a GP regression
$r$ Vector of residuals to a model specified in a GP regression
$X$ Vector of data locations for a GP regression
$\chi^2$ Result of a $\chi^2$ goodness of fit test
BIC Bayesian Information Criterion
d.o.f Degrees of freedom of a regression
KDE Kernel Density Estimation
PDF Probability Density Function
DFT Discrete Fourier Transform

Units of Measure

AU Astronomical Unit
pc Parsec
Gyr Gigayear, $1 \times 10^9$ years
Myr Megayear, $1 \times 10^6$ years
$M_\odot$ Mass of the Sun
$R_\odot$ Radius of the Sun
$L⊕$ Luminosity of the Sun
$T⊕$ Effective temperature of the Sun
$M⊕$ Mass of the Earth
$R⊕$ Radius of the Earth
$ρ⊕$ Bulk density of the Earth
$M_J$ and $M_{\text{J\#}}$ Mass of Jupiter
$R_J$ and $R_{\text{J\#}}$ Radius of Jupiter
$S_0$ Solar irradiation received at Earth at present
JD Julian date
BJD$_{\text{TDB}}$ Barycentric Julian Date in Barycentric Dynamical Time, as defined in Eastman et al. (2010)
BJD$_{\text{UTC}}$ Barycentric Julian Date in Coordinated Universal Time
ppm Parts per million, $1 \times 10^{-6}$
mmag Millimagnitudes, $1 \times 10^{-3}$ magnitudes
nm Nanometers, $1 \times 10^{-9}$ meters, typically used for ultraviolet and optical measurements
μm Micrometers, $1 \times 10^{-6}$ meters, typically used for infrared measurements
Acknowledgments

I would like to thank my advisor, Jason Wright, for constantly supporting and mentoring me through my graduate education, for always being my advocate and ally, and for teaching me how to be a scientist.

To Ron Gilliland, Kevin Luhman, Katherine Freeman, Jenn Macalady, Steinn Sigurðsson, Thomas Beatty, and Ming Zhao for being excellent research advisors and mentors, teaching me good research practices, asking the tough questions, and helping me with the research contained in this dissertation.

To the Penn State Astronomy Department, for being supportive, friendly, and inclusive, and offering opportunities for growth and change.

To Chris, Leah, Sean, Anne, Alex, and Charles, for forming the best team of sassy, sarcastic, sword-wielding, magic-slinging, punchy-stabby...err...wereflamingos ever seen this side of imaginary Cleveland. This insanity kept me sane.

To my parents, Diane and Greg; my sisters Pam and Staci; my oldest and best friends Rachel and Deb; my aunts and uncles; the expanded Suite of Sweets and Joy and Joyness; all of my friends and family over the years; for their unwavering support, for being my first fans, for their fierce belief in my strength and abilities, for providing me with the tools to grow and learn, and giving unending opportunities to make the best life for myself.

And to Charles Antoine Cartier, the best husband I could ever wish for, for being my strength when I had none, for making me laugh in difficult times, for understanding and sharing my burdens, and for never letting me give up. I love you.
Dedication

This dissertation is dedicated to Beverly Chercasky, Morris Chercasky, and Sylvia Star, for their boundless, endless love and who would have been endlessly proud of where I am today.
Chapter 1  Introduction and Literature Review

The transit method of detecting exoplanets has dominated the search for distant worlds since the launch of the Kepler Space Telescope in 2009. Due in large part to the success of Kepler (Borucki et al. 2010b; Koch et al. 2010a), a total of 2,734 of the 3,475 confirmed exoplanets were discovered using the transit method.\(^1\) Aside from the overwhelming contribution from the primary Kepler mission, the cumulative contribution from other dedicated transit surveys begins to approach the total detections from the stalwart radial velocity method.

When added to the detections made by Kepler prime, the results from Kepler’s secondary K2 mission (Howell et al. 2014; Vanderburg & Johnson 2014), citizen science follow-up programs (Fischer et al. 2012; Schwamb et al. 2012), WASP (Butters et al. 2010; Pollacco et al. 2006), HATNet and HATSouth (Bakos et al. 2004, 2013, respectively), CoRoT (Auvergne et al. 2009), KELT and KELT-South (Pepper et al. 2007, 2012, respectively), and a few scattered others (e.g. TReS, Alonso et al. 2004; XO, McCullough et al. 2005; TRAPPIST, Gillon et al. 2017 and QES, Alsubai et al. 2011) collectively account for 78.8% of all planet detections to date. Transit detections will continue to lead the field in detections after the launch of the Transiting Exoplanet Survey Satellite (TESS) in 2018 (Ricker et al. 2014, 2015).

Yet photometric light curves of transits can only reveal a limited subset of information about the underlying planet, and most of that is entirely dependent on a prior understanding of the star around which it orbits. Calculations of planetary radius, temperature, orbital distance, and density, among other parameters, depend first and foremost on an accurate assessment of the planet hosting star(s). Significant effort has been made to improve measurements of the intrinsic properties of these

\(^1\)Numbers retrieved from the NASA Exoplanet Archive (http://exoplanetarchive.ipac.caltech.edu/) on April 13, 2017.
stars, reaching a precision of 60 K in effective temperature, 0.07 dex in surface
gravity, 0.04 dex in [Fe/H], and 1.0 km/s in projected rotational velocity (from the
California-Kepler Survey; Petigura et al. 2017), and improved uncertainties of ~ 27%
in radius, ~ 17% in mass, and ~ 51% in density (Mathur et al. 2017) for typical cases
with photometric and spectroscopic inputs. In the relatively infrequent, but quite
important, cases where asteroseismology of the host star is possible, precisions for
stellar mass and radius can improve by a full order of magnitude (e.g. Huber et al.
2013).

This dissertation covers three methods of characterizing extrasolar planets that
have been discovered via the transit method: high-resolution imaging (Chapter 2),
measurements of emission and transmission spectra of exo-atmospheres (Chapters
3 and 4 respectively), and information content analysis of transit depth sequences
(Chapter 5). Given the rapidly evolving nature of our understanding of exoplanets, the
remainder of this chapter reviews relevant literature for each of these characterization
methods and overviews the state of each subfield at the time of this dissertation.

The main subject of Chapter 5, namely, an information content analysis of
transit depth sequences, has not been significantly updated since the original date
of publication (Wright et al. 2016). KMSC is the second author of that publication,
and so Chapter 5 includes sections of that paper written by KMSC and summaries of
sections written by other co-authors. However, one of the anomalous targets discussed
therein, KIC 8462852 aka Boyajian’s Star, has received significant attention due to the
publication of Wright et al. (2016) and the continued lack of plausible explanation for
the phenomenon. Appendix 5.2.2 reviews advances in our understanding of Boyajian’s
Star subsequent to completion of the work in Chapter 5.

An introduction and literature review for Chapter 6, which discusses effective
strategies for communicating astronomy to various audiences, is found within that
chapter rather than in this introduction.

1.1 High Resolution Follow-ups of Kepler Targets

This dissertation presents in Chapter 2 the results from one high-resolution imaging
follow-up program using the Hubble Space Telescope, first published as Gilliland
et al. (2015) and Cartier et al. (2015), and shows how improved characterization of
exoplanet host stars may change current estimates of the occurrence rate of habitable
zone planets. KMSC was the second author of \cite{Gilliland:2015}, and so the Chapter 2 summarizes the results and conclusions of that publication.

Despite evidence that an appreciable fraction of field stars reside in multi-star systems, the initial production of the list of \textit{Kepler} Objects of Interest (KOIs) assumed a single star for each KOI. Not accounting for stellar multiplicity statistically biases the planets toward smaller radii due to dilution of the transit signal from nearby stars. If the stellar multiplicity rates are not accounted for correctly, then occurrence rate calculations for Earth-sized planets may overestimate the frequency of small planets by as much as $15\%-20\%$ \cite{Ciardi:2015}.

Follow-up observations of \textit{Kepler} planet candidates have focused on either high-resolution imaging or spectroscopic follow-ups, each of which probes different parameter spaces for potential companion stars. High-resolution imaging, which is focused on in Chapter 2 of this dissertation, is generally used to detect chance background stars and wider bound companion stars that would not produce a measurable radial velocity signal for a spectroscopic follow-up \cite{Teske:2015}.

Before the end of the primary \textit{Kepler} mission, \cite{Adams:2012} reported a nearby star detection rate of 60\% within 6", 20\% within 2", and 7\% within 0\'.5. Subsequent follow-up companion searches have adjusted these estimates to 32.8\% within 6" \cite{Lillo-Box:2014} and between 17.2\% – 30\% within 3" – 4" using larger sample populations \cite{Adams:2013,Lillo-Box:2014}.

More recently, \cite{Ziegler:2017} measured an overall nearby-star probability for \textit{Kepler} planet candidates of $12.6\%\pm0.9\%$ at separations between 0\'.15 and 4\'.0, and \cite{Baranec:2016} report a $10.6\%\pm1.1\%$ nearby star probability at angular separations up to 2\'.5. \cite{Hirsch:2017} reported 176 companions within 2" of 170 KOI hosts, which suggests a not-insignificant rate of higher order multi-star systems with 3 or more stars.

\cite{Wang:2015} discuss the implications of the occurrence rate of stellar multiplicity on the formation of planetary systems with multiple transiting planets (MTPSs). They report that for stellar separations wider than 200AU, the occurrence rate of stellar multiples is the same for systems with and without planets. For stellar separations between 20 and 200AU, they report a 34\% multiplicity rate for planet hosting systems compared to the 12\% for planet-free systems. And for stellar separations between 1 to 100AU they find a multiplicity rate of $5.2\pm5\%$ for MTPSs, significantly lower than for field stars in the Solar neighborhood.
Wang et al. (2015a,b) suggests that close stellar companions either suppress planet formation in those systems or disrupt orbital co-planarity of one or more planets. Results from Kraus et al. (2016) suggest that perhaps a fifth of all solar-type stars in the Milky Way are disallowed from hosting planetary systems due to the influence of a binary companion.

Furlan et al. (2017) compiled a catalog of previously published *Kepler* planet hosts with companion stars from high-resolution imaging, and finds that \( \sim 10\% \) of the observed stars have at least one companion detected within 1\" and \( \sim 30\% \) have at least one companion star within 4\". Their multi-star occurrence rates decrease the number of KOI planets with radii smaller than 2\( R_\oplus \) by \( \sim 2\% – 23\% \), which will influence the predicted yield of small, cool, rocky planets from TESS.

### 1.2 Exoplanet Atmosphere Characterization

This dissertation discusses the topics of exoplanet atmospheres (exo-atmospheres) and Gaussian process regression in Chapters 3 and 4 through a case study of the ultra-short period hot Jupiter WASP-103b. This section discusses the overall necessity for characterizing exo-atmospheres, important exo-atmosphere detections, and questions that must still be answered.

The future of exoplanetary science lies with characterizing the atmospheres of these worlds, which can tell us how and where these planets formed and what their surface conditions might be like (Deming & Seager 2017; Madhusudhan et al. 2016). Spectroscopic measurements of exo-atmospheres have been taken of the day-sides of planets (emission spectra), the day-night terminators (transmission spectra), wavelength-dependent albedo (reflection spectra), and of the full day-to-night transition (phase curves). The full suite of exo-atmosphere measurements is essential for a full characterization of exoplanet composition, atmospheric dynamics, temperature, and, eventually, habitability.

Currently, the best telescopes for observing exo-atmospheres are space telescopes like *Hubble* Space Telescope (*HST*) and *Spitzer* Space Telescope. Both telescopes can observe the near-infrared wavelengths\(^2\) (NIR) in which the hottest exo-atmospheres (i.e. planets with the largest masses or smallest orbital distances) are brightest and

\(^2\)Both HST and Spitzer observe a wider wavelength than just the NIR. However, researchers have primarily utilized the NIR capabilities of these two telescopes to study exo-atmospheres.
typically have the highest flux contrast ratio to their host stars. *Spitzer* can also observe in the mid-IR using its Infrared Spectrograph, which may reach planets cooler than 1000K. However, few cooler exo-atmospheres have been studied in either emission or transmission due to temperature-dependencies on the signal-to-noise ratio (S/N) of those observing methods, either from orbiting cooler (and fainter) stars or by having larger orbital separations.

Given the limitations of *HST*, *Spitzer*’s Infrared Array Camera, and NIR ground-based telescopes, transiting hot Jupiters are the best candidates for both transmission and emission spectroscopy because of their large radii, extended atmospheres, and hot equilibrium temperatures (Charbonneau et al. 2002; Deming et al. 2013; Kataria et al. 2016; Knutson et al. 2007; Sing et al. 2016; Snellen et al. 2008). Consequently, the study of exo-atmospheres has been largely limited to hot Jupiters, with super-Earths 55 Cancri e (Demory et al. 2016), HD 97658 (Knutson et al. 2014b), and GJ1214b (Bean et al. 2010; Berta et al. 2012; Desert et al. 2011; Kreidberg et al. 2014a) as notable exceptions.

The first detection of an exoplanet atmosphere (HD 209458b by Charbonneau et al. 2002) utilized transmission spectroscopy to detect absorption from sodium. Sodium and potassium absorption features should be prominent in optical transmission spectra for atmospheric temperatures $\lesssim 1500$ K. Since the detection of sodium in HD 209458b, sodium has been detected in the atmospheres of a handful of planets (e.g. HD 198733b, HAT-P-1b, WASP-49b, WASP-17b, XO-1b, and XO-2b; Deming et al. 2013; Nikolov et al. 2014; Redfield et al. 2008; Sing et al. 2012; Wood et al. 2011; Wyttenbach et al. 2017, respectively). Potassium has been detected in only a small subset of planets that also have sodium absorption (e.g. WASP-17b and XO-2b; Sedaghati et al. 2016; Sing et al. 2011, respectively), leading to speculation that clouds may be masking the signal of potassium in planets with sodium absorption. Focus has expanded to detecting broad absorption features (e.g. H$_2$O), spectral slopes (e.g. Rayleigh scattering), and absorption features due to carbon-based molecules (e.g. CO, CO$_2$, and CH$_4$) and heavy-metal oxides like titanium oxide (TiO) and vanadium oxide (VO).

Exo-atmospheres, hot Jupiter or otherwise, likely all contain H$_2$O (e.g. Birkby et al. 2017; Kreidberg et al. 2014b) regardless of the presence or lack of an absorption feature at 1.4µm, and Sing et al. (2016) suggest that the diversity of water absorption feature strength seen in exo-atmosphere spectra is due to a continuum of cloud and
haze density rather than depletion of H$_2$O during formation. Clouds and hazes are nearly ubiquitous in exo-atmospheres (Gao et al. 2017; Heng 2016; Kirk et al. 2016), and Rayleigh scattering due to upper-atmosphere hazes is prevalent (e.g. Dragomir et al. 2015; Gibson et al. 2017; Lecavelier Des Etangs et al. 2008; Sing et al. 2013; Stevenson et al. 2014a).

With the development of more sophisticated atmospheric retrieval methods (e.g. Line et al. 2013a, 2016; Parmentier & Guillot 2014), researchers have also begun to profile the thermal structure of atmospheres from the top down, which has raised the question of stratospheric thermal inversions. Thermal inversions involve the presence of additional heating in the upper layers of an atmosphere, inverting a “standard” monotonically decreasing atmospheric profile (one where temperature decreases monotonically with atmospheric height) to one that has increasing temperature with decreasing pressure in one atmospheric layer. One such inversion is seen in Earth’s atmosphere due to the ozone layer. Due to the temperature constraints of hot Jupiters, TiO and VO are prime suspects as the instigators of thermal inversions in hot exo-atmospheres (Fortney et al. 2008; Mollière et al. 2015) and initial theories suggested that all hot Jupiters with temperatures $\gtrsim 1800$ K should display thermal inversions (Charbonneau et al. 2008; Fortney et al. 2008).

However, only a few of the hottest of hot Jupiters exhibit atmospheric profiles consistent with a stratospheric thermal inversion: WASP-33b (Haynes et al. 2015; von Essen et al. 2015), WASP-12b (Stevenson et al. 2014b), and possibly WASP-103b (Cartier et al. 2017). To date, no exo-atmospheres with daysides cooler than 2500 K are consistent with the presence of a thermal inversion (for example, Line et al. 2016; Madhusudhan & Seager 2010). One theory suggests that strong stellar UV radiation might photodissociate TiO and VO in the planets’ atmospheres (Knutson et al. 2010), though the UV-strong host of WASP-33b challenges this theory. Another explanation suggests that TiO and VO may be condensing out of the upper atmospheres of the slightly more temperate planets and being trapped in the colder interiors (“cold traps,” e.g. Beatty et al. 2016c; Spiegel et al. 2009). No consensus currently exists to explain the lack of strong inversion for all but the hottest of planets.

Beatty et al. (2016a,c) explores the theory that both atmospheric temperature and surface gravity influence the formation of a stratospheric temperature inversion in hot Jupiter atmospheres. Beatty et al. (2016c) reports a monotonically decreasing atmosphere for the hot Jupiter Kepler-13Ab despite its 3000 K temperature, and
Beatty et al. (2016a) reports the same for the transiting brown dwarf KELT-1b at 3200 K. If cold trap processes are in fact the inhibiting factor in the formation of stratospheric thermal inversions, then the higher surface gravity of even the hottest planets must cause TiO and VO to settle out at faster timescales than for low-gravity planets and inhibit the formation of an inversion (see Fig. 7 of Beatty et al. (2016c) for more detail).

We need to master atmospheric characterization in the time before the James Webb Space Telescope launches in order to select the best targets for exo-atmosphere spectroscopy in the early release science and first round of proposals (Batalha & Line 2017; Stevenson et al. 2016). Yet we can only tune atmospheric models as precisely as data can support, and we are currently pushing HST and Spitzer to their technological limits when measuring the relative handful of observable planets. Doing so introduces previously unseen systematics into transit and eclipse light curves that must be dealt with in a more robust and flexible way than previously seen (e.g. Gibson et al. 2012a; Knutson et al. 2014a,b; Wilkins et al. 2014).

Gaussian process (GP) regression of exo-atmosphere spectra has gained popularity in recent years (e.g. Beatty et al. 2016a,b; Gibson et al. 2011, 2012b) specifically for its ability to model time correlated noise and unknown systematics, freedom from pre-specifying a parametric model for systematics, more conservative error estimation, and robustness against precise but inaccurate solutions (Cartier et al. 2017; Gibson et al. 2012b; Ingalls et al. 2016). GP regression requires $N^2$ computing time for a dataset of $N$ points due to the inversion of an $N \times N$ matrix at every step in a chosen optimization algorithm, which significantly slows down GP regression for $N \gtrsim 1000$ datasets. Some recent advances have been made to speed up the required matrix inversions by exploiting matrix properties to approximate some steps of the inversions (e.g. Ambikasaran et al. 2014; Foreman-Mackey et al. 2017; Moore et al. 2016).

Chen & Wang (2016) has suggested that GP regression may be sensitive to selection of prior probability distributions of the parameters that define the covariance kernel (hyperparameters) depending on the chosen kernel. This issue can be mitigated by using less-sensitive kernels and randomizing initialization values to assess the locations of global versus local maxima of the posterior probabilities. Overall, GP regression will be a powerful tool for future exo-atmosphere characterization using new telescopes with untested detectors, like JWST and the MINiature Exoplanet Radial Velocity Array (MINERVA).
Chapter 2
High-resolution imaging of Kepler planet hosts using the Hubble Space Telescope

This chapter details the results of a Hubble Space Telescope Guest Observing Program (GO-12893) that proposed observations of 158 stellar hosts of Kepler Objects of Interest having planetary radii $R_p < 2.5R_\oplus$ and equilibrium temperatures $T_{\text{eq}} < 500$ K. As of May 2014, GO-12893 observed 22 of those host stars, and Gilliland et al. (2015) and Cartier et al. (2015) published analyses of those systems. HST observed 12 additional systems after May 2014, and those systems were analyzed in the same way presented here and delivered to the Kepler Community Follow-up Observing Program. This chapter first describes the design, goals, and results of the overall observing program (Sec. 2.1; Gilliland et al. 2015) and then presents a more in-depth analysis of three systems of interest observed by GO-12893 (Sec. 2.2; Cartier et al. 2015).

The work within this chapter is based on research published as multi-author publications. Sec. 2.1 summarizes work first published in the Astronomical Journal (AJ) as Gilliland et al. (2015), and is summarized here with permission by the authors of that paper. KMSC was the second author on that paper and performed image reduction and data analysis for each observing target and contributed text related to those analyses. A more detailed breakdown of the author contributions and acknowledgments can be found in Gilliland et al. (2015). Sec. 2.2 was published in its entirety as Cartier et al. (2015) and contains a full and comprehensive breakdown of the contributions of each author of that publication. The analysis presented in Sec. 2.1 and in more detail in Gilliland et al. (2015), serves as a staging ground for the
remainder of the chapter. This chapter is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

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### 2.1 Overview of **Hubble Space Telescope** Observing Program GO-12893

Prior to the start of GO-12893 in early 2014, NASA’s *Kepler* Mission (Borucki et al. 2010b; Jenkins et al. 2010; Koch et al. 2010a) presented its largest catalog to date of transit light curves, which contained over 2000 stars with over 2700 planet-like transit signatures (Batalha et al. 2013; Borucki et al. 2011; Burke et al. 2014). The large quantity of validated planets presented by Lissauer et al. (2014) and Rowe et al. (2014) raised the number of confirmed planets to nearly 1000 by the time this HST observing campaign concluded in early 2015. Many of the confirmed planets in the *Kepler* catalog represented discoveries of new planetary phenomena (e.g. circumbinary planets, transit timing variations, and improvements from asteroseismology; Doyle et al. 2011; Holman et al. 2010; Huber et al. 2013, respectively).

However, the low photometric resolution of the *Kepler* CCDs leaves the data vulnerable to false positives from blended background eclipsing binaries (BEBs) despite the great care taken when rejecting the false positive scenarios that arise from BEBs. Whether the stars are physically associated with the *Kepler* target or a chance superposition, close-separated stars can dilute transit signals and affect extraction of planetary parameters from the light curves (Morton & Johnson 2011).
High-resolution follow-up imaging is therefore a critical step in recognizing false positives, for validating planets, and for refining parameters of detected exoplanets.

2.1.1 Observing Program, Target Selection, and Basic Image Analysis

GO-12893 was proposed in early 2012, at a time when *Kepler* high-resolution follow-up programs were relying on ground-based 3-6m telescopes, adaptive optics (AO), or speckle imaging. The faint magnitudes ($V \approx 16$), shallow transit depths (few hundred parts-per-million; ppm), and deep imaging (to $\Delta \text{mag} \gtrsim 8$) required to rule out false positive scenarios for the most interesting of planet candidates challenged the ground-based resources available at the time. [Gilliland & Rajan (2011)] showed that *HST* imaging for half an orbit could provide superior results to a full night of ground-based observing at the time for the most challenging targets. Advances in the Keck-AO imaging system (in particular, the switch from their Natural Guide Star AO system to the Laser Guide Star AO system on the OH-Suppressing Infrared Imaging Spectrograph (OSIRIS) on Keck I) have since leveled the playing field and allowed for both ground- and space-based high-resolution follow-up imaging in well-calibrated bandpasses that are useful for establishing dilution corrections.

Our *HST* program proposed observations of 158 stellar hosts of *Kepler* Objects of Interest (KOIs), concentrating on planets with estimated radii $R_P \lesssim 2.5R_\oplus$, estimated equilibrium temperatures $T_{eq} \lesssim 500$ K, and with shallow transit depths that would be difficult for the ground-based follow-up of the time to observe. With these constraints, GO-12893 focused on the KOIs most likely to be rocky planets in or near Habitable Zones (HZ; [Kasting, Whitmire & Reynolds 1993, Kopparapu et al. 2013]). At the time of publication of [Gilliland et al. (2015)], *HST* observed 22 out of 158 targets spanning UT 2012 October 27 to 2014 January 7, and these observations are listed in Table 1 of [Gilliland et al. (2015)].

*HST* acquired all observations with a set of five dithered exposures in each of the Wide Field Camera 3 (WFC3) filters F555W and F775W, chosen to span the *Kepler* bandpass. We chose exposure times so that four of the five exposures reached 90% of saturation and set the fifth exposure to six times the exposure of the others to raise the signal-to-noise (S/N) of the wings of the point spread function (PSF). Table 1 of [Gilliland et al. (2015)] also includes observations of KIC 12557548 added
from GO-12987 (PI Rappaport, Croll et al. 2014) for which nearly identical exposures were available. Further details of the observing program and WFC3 are found in Gilliland & Rajan (2011); Gilliland et al. (2015), and Dressel (2014).

We first aligned each set of five exposures per target per filter, combined them together using astrodrizzle from STScI DrizzlePac (Gonzaga et al. 2012), and scaled them to $0''.03333$ per pixel. We then shifted the post-drizzle image to center the target star on a single pixel. This post-drizzle centering helped during the creation of our empirical PSF. Additional details about this image processing is found in Sec. 2.2.2.2.

2.1.2 Empirically Defined PSF and Subtraction

Gilliland et al. (2015) state, “The primary product to be obtained from these HST observations is a list of all stars within the field of view, pushing as close to the bright target as allowed by the data and PSF, and providing accurate photometry and positions.” To that end, we defined an empirical PSF using 20 of the 23 images (including KIC 12557548), excluding three systems for which an additional star or stars were found within $0''.5$ of the target star and with small $\Delta$mag. These three systems (KIC-6263593, KIC-11497958, and KIC-11768142) are the focus of Sec. 2.2.

We stacked the remaining 20 post-drizzle images and developed the PSF model for each pixel relative to the target center. The PSF was a function of F555W-F775W color, telescope focus, and sub-pixel $\Delta X$ and $\Delta Y$ target centering shifts. Additional details regarding the development of the PSF can be found in Gilliland et al. (2015).

Our empirical PSF sufficiently deals with diffraction spikes, filter artifacts, and the wings of the target PSFs, but leaves residuals that do not approach the Poisson limit in the inner $\sim 0''.2$. This is likely due to the precision limits when aligning the pre-drizzle images. We defined an individualized PSF for each target star and calculated the color of each target. We then searched for any stellar sources in the WFC3 aperture by subtracting the PSF from the target and searching the difference image using the DAOFIND task in the Image Reduction and Analysis Facility (IRAF; based on Stetson 1987).

The source detection procedure detailed in Gilliland et al. (2015) resulted in nearly 100% completeness for detecting any stellar companions that could result in a false positive for the shallow transits of the targeted KOIs. This completeness
rate is true outside of an inner working radius of \( \sim 0.4 \) (due to the PSF centroiding issue mentioned above) and reaches \( \Delta \text{mags} \) sufficient to detect BEBs of equal mass stars, a worst case false positive scenario. The PSF subtraction and source search yielded a table of detected sources for each target star that we delivered to the Kepler Community Follow-up Observing Program (CFOP)\[^2\] We also delivered the post-drizzle images in F775W for each target to CFOP.

2.1.3 Detected Companions, Odds of Physical Association, and Implications for Transit Hosts

Our imaging program detected many spatially close companion stars near and within 1" of the target star. As our goal was a more accurate interpretation of planetary parameters from the transit light curves, we sought a method to determine whether these close companions were physically bound to the target stars or merely chance superpositions. Astrometry, radial velocities, and common proper motion searches were unavailable for this set of targets, so we made due with the angular separation and photometry extracted from this HST program to determine the likelihood of physical association. Simply correcting for diluting flux from a spatially close companion star does not rely on determining physical association, but rather, physical association affects the interpretation of planetary parameters from the transit light curve and may introduce ambiguity regarding the transit host.

We matched closely separated companion stars to stellar isochrones of a single metallicity to determine the likelihood of physical association. Many of our target stars are K and M dwarfs, and their possible companions are all fainter than the targets and, therefore, mostly M-type stars. If the closely separated stars are of the same luminosity class (i.e. dwarfs versus giants), then regression to a common isochrone would indicate that the stars are at the same distance from us, share a common age and metallicity, and are, therefore, likely physically associated.

There is some degree of uncertainty that two (or more) stars that match to the same isochrone are truly the same age, as many isochrones coincide on the main sequence. There is also some degeneracy between age and metallicity when fitting to isochrones. To supplement the isochrone fitting, we also quantified the odds of a random superposition producing an isochrone match of the same quality as a bound

\[^2\]https://cfop.ipac.caltech.edu
companion through a “Bayesian argument providing odds ratios in individual cases for the [closely separated stars] being a physical companion versus chance alignment” (Gilliland et al. 2015).

Both Gilliland et al. (2015) and Sec. 2.2.3.3 discuss some of the challenges with testing M dwarfs against isochrones, particularly when relying mostly on optical bandpass photometry. The key issues arise from incomplete molecular line lists for cool stellar atmospheres and a discrepancy in the shape of the low-mass main sequence tail for isochrones versus Solar neighborhood stars. So, for a dataset containing mostly late-type stars, results depending solely on isochrone matching may vary depending on the details of the isochrone and stellar atmosphere models.

We determined the odds ratio of companion versus chance alignment using the full set of GO-12893 images to establish the frequency at which two physically-unrelated stars match to a given $\chi^2$ level. The isochrone $\chi^2$ was calculated using the F555W-F775W colors of the two stars and the $\Delta F775W$ magnitude between them. We tested each target star against every other detected source in its image to determine the probability that those two stars would fit a single isochrone with the same goodness-of-fit as a physically-bound companion. Since the 23 targets are separated on the sky by $>0.75$ deg ($\gtrsim 10$ pc), it is highly unlikely that sources at the edge of one target image are physically related to sources at the edge of a different target image, so we did not calculate odds ratios between stars in different images.

We found with this approach that random pairings of stars occasionally have good matches to a single isochrone, with 5% of 11,000 random matches having $\chi^2 \lesssim 1.0$. So, a close match to a single isochrone is not sufficient to argue for physical association. The isochrone matching detected 481 cases of possible physical association, and we calculated odds ratios for each of these to guard against the 5% isochrone failure rate.

The odds ratio of physical association was calculated as

$$\text{Odds Ratio} = \frac{N_{\text{expected bound}}}{N_{\text{random alignments}}}$$

where prior expectation of bound systems, $N_{\text{expected bound}}$, was determined based on the frequency of bound systems as a function of stellar spectral type and semi-major axis from Duchêne & Kraus (2013). The prior expectation of random superpositions, $N_{\text{random alignments}}$, was determined based on the number density per unit solid angle of test matches up to the $\chi^2$ level of the star in question, the galactic latitude of the
target, and cumulative fraction of detected stars as a function of Kp brightness.

We determined that two stars were likely physically associated if they had both an odds ratio of physical association > 1 and an isochrone $\chi^2 < 10$. Only 8 of the 481 potential matches indicated by isochrone matching alone met both criteria. These 8 matches are listed in Table 2.1.

The close companions listed in Table 2.1 complicate the consideration of the true transit host either by introducing ambiguity about which star truly hosts the planet(s) or by remaining as a potential false positive scenario. We determined cases for which the transit host is uncertain by whether the companion star offset is within the $3\sigma$ centroiding error from the Kepler Data Validation reports (Bryson et al. 2013) and whether the companion brightness can support the observed transit depths when diluted by the target star (see Table 2.1). We found 5 of our 23 KOIs with physically-associated companions that could be the true transit host: KIC 5358241, KIC 6263593, KIC 11497958, KIC 11768142, and KIC 12256520.

We used these results to calculate the rate of stellar multiplicity for our sample, ignoring KIC 6149553 and KIC 11306996 which were shown in the interim to be false positive detections. Though our calculations suffered from low-number statistics (7, 8, and 6 stars at G, K, and M spectral types, respectively), we detected $2.8\times$ as many stellar multiples across G, K, and M spectral types compared to the number expected from Duchêne & Kraus (2013), with $>98\%$ significance. For our sub-sample of M-dwarfs, the over-abundance is $9.7\times$ expected, with $99.6\%$ ($3\sigma$) significance. When we include observations taken after May 2014, this HST observing program measured a stellar multiplicity rate of 17% within $3''$, higher than both the 10% rate within $1''$ from Furlan et al. (2017) and the 12% rate within $4''$ from Ziegler et al. (2017).

This over-abundance of stellar multiples in our sample leads to questions about the role of stellar multiplicity in planet formation. While our higher-than-expected rate of stellar multiplicity might suggest that wide binaries favor the formation of small planets, an interferometric survey by Kraus et al. (2014) suggested that closely separated stellar multiples ($5 - 50$ AU) suppresses planet formation. An alternate view suggests that having two stars in the Kepler aperture simply doubles the probability of transits existing at a particular RA and Dec (or triples for the case of three stars, etc.), and so stellar multiples should be over-represented in the KOI list.

More recent studies on the effects of stellar multiples (published after Gilliland et al. (2015), and discussed in Ch. 1) revealed that the rate of stellar multiplicity...
Table 2.1: Companions with Likely Physical Association

<table>
<thead>
<tr>
<th>KIC</th>
<th>KOI</th>
<th>Sep. arsec</th>
<th>Pos. Angle deg E of N</th>
<th>Δmag F555W-F775W</th>
<th>χ²</th>
<th>odds ratio</th>
<th>3σ error arsec</th>
<th>Depth if host</th>
<th>Bound?</th>
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</thead>
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<tr>
<td>5358241</td>
<td>829</td>
<td>0.107</td>
<td>239.9</td>
<td>2.39</td>
<td>1.034</td>
<td>1.123</td>
<td>3703.9</td>
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<td>3813</td>
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<td>5358241</td>
<td>829</td>
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<td>335.4</td>
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<td>0.032</td>
<td>1.3</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>6263593</td>
<td>3049</td>
<td>0.478</td>
<td>196.9</td>
<td>0.54</td>
<td>1.362</td>
<td>0.011</td>
<td>1923.7</td>
<td>1.39</td>
<td>888</td>
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<td>65.9</td>
<td>7.36</td>
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<td>6.3</td>
<td>—</td>
<td>—</td>
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<td>0.217</td>
<td>217.3</td>
<td>1.56</td>
<td>2.478</td>
<td>0.008</td>
<td>4101.6</td>
<td>1.03</td>
<td>3311</td>
</tr>
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<td>11768142</td>
<td>2626</td>
<td>0.161</td>
<td>181.6</td>
<td>1.44</td>
<td>2.389</td>
<td>1.019</td>
<td>928.1</td>
<td>2.07</td>
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<td>0.61</td>
<td>2.299</td>
<td>0.107</td>
<td>2832.9</td>
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</tbody>
</table>

Note—Data in this table taken from Gilliland et al. (2015).
for separations wider than 200AU is the same for stars with and without multiple
transiting planets (Wang et al. 2015a,b). At separations between 20 and 200AU,
Wang et al. (2015a,b) report an occurrence rate of 34% multiplicity for planet-hosting
systems compared to 12% for planet-free systems, and only 5.2% for systems with
separations between 1 and 100AU. This may suggest that close stellar companions
suppress planet formation or disrupt orbital co-planarity of one or more planets in
those systems.

However, our sample size (23 stars before May 2014 and an additional 12 after May
2014) is still too small to determine whether this overabundance of stellar multiples
hosting transiting planets is truly significant compared to more extensive surveys
containing ~ 100 or more stars.

2.2 Revision of Earth-sized *Kepler* Planet Candidate
Properties with High Resolution Imaging by *Hubble*

*Space Telescope*

We present the results of our *Hubble Space Telescope* program and describe how
our analysis methods were used to re-evaluate the habitability of some of the most
interesting *Kepler* planet candidates. Our program observed 22 *Kepler* Object of
Interest (KOI) host stars, several of which were found to be multiple star systems
unresolved by *Kepler*. We use our high-resolution imaging to spatially resolve the
stellar multiplicity of *Kepler*-296, KOI-2626, and KOI-3049\(^3\) and develop a conversion
to the *Kepler* photometry (Kp) from the F555W and F775W filters on WFC3/UVIS.
The binary system *Kepler*-296 (5 planets) has a projected separation of 0\('\).217 (80 AU);
KOI-2626 (1 planet candidate) is a triple star system with a projected separation of
0\('\).201 (70 AU) between the primary and secondary components and 0\('\).161 (55 AU) be-
tween the primary and tertiary; and the binary system KOI-3049 (1 planet candidate)
has a projected separation of 0\('\).464 (225 AU). We use our measured photometry to fit
the separated stellar components to the latest Victoria-Regina Stellar Models with
synthetic photometry to conclude that the systems are coeval. The components of the
three systems range from mid-K dwarf to mid-M dwarf spectral types. We solved for
the planetary properties of each system analytically and via an MCMC algorithm us-

\(^3\)KOI-3049b has since been confirmed and is known as *Kepler*-1418b.
ing our independent stellar parameters. The planets range from $\sim 1.6 \, R_\oplus$ to $\sim 4.2 \, R_\oplus$, mostly Super Earths and mini-Neptunes. As a result of the stellar multiplicity, some planets previously in the Habitable Zone are, in fact, not, and other planets may be habitable depending on their assumed stellar host.

This section includes contributions from Kimberly M. S. Cartier\textsuperscript{4,5}, Ronald L. Gilliland\textsuperscript{4,5}, Jason T. Wright\textsuperscript{4,5}, and David R. Ciardi\textsuperscript{6}. KMSC wrote the text contained herein and performed analyses and discussions found in Sec. 2.2.2, Sec. 2.2.3, Sec. 2.2.4, Sec. 2.2.1, Sec. 2.2.5, and Sec. 2.2.6. RLG contributed analysis to Sec. 2.2.3.1 and Sec. 2.2.3.4 as well as overall guidance and direction for this work and the companion paper Gilliland et al. (2015). JTW contributed to Sec. 2.2.1, Sec. 2.2.6, and valuable discussion and advice regarding isochrone use. DRC contributed Keck AO K-band data to Sec. 2.2.3.6 and provided discussion on KOI-2626. This work is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

### 2.2.1 Introduction

Since its advent, the Kepler mission has increased the number of candidate exoplanets by thousands, confirmed hundreds of planets, and has pushed the boundaries of transiting exoplanets to smaller radii and longer orbital periods than previously detected \cite{Batalha2013, Borucki2010b, Borucki2011, Burke2014, Fressin2013, Howard2012, Lissauer2014}. The 2013 release of the first 16 quarters of Kepler data has increased the number of known transiting exoplanet candidates of all radii, but has been especially fruitful for the smallest candidates (with a fractional increase of 201\% known planets smaller than $2 \, R_\oplus$) and for the longest orbital periods (with a fractional increase of 124\% for orbits longer than 50 days; \cite{Batalha2013, Borucki2011}. More recently, Rowe et al. (2014) has nearly doubled the total number of validated exoplanets through careful elimination of false-positive detections in multi-planet systems. Nearly 40\% of Kepler planet candidates have been found to reside in multiple planet systems \cite{Batalha2013}.

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Rowe et al. (2014) and recent surveys show that the vast majority of multiple transiting system detections are true multiple planet systems (Lissauer et al. 2014; Rowe et al. 2014). Howard et al. (2012) showed that the planet occurrence rate increases from F to K dwarfs, and followup studies by Dressing & Charbonneau (2013) and Kopparapu (2013) showed that this trend continues increasing towards M dwarfs. New estimates of $\eta_\oplus$ have made use of these more robust data, arriving at a conservative prediction that between 6-15% of Sun-like stars have an Earth-size planet in the Habitable Zone (HZ; Kasting et al. 1993; Petigura et al. 2013; Silburt et al. 2015), though utilization of state-of-the-art Habitable Zone calculations will likely reduce this number (Kopparapu et al. 2013).

While the majority (> 2000) of the *Kepler* planet candidates reside in apparently single-star systems, this percentage is likely due to a selection effect that avoids binary targets (Kratter & Perets 2012). Accounting for the frequency of binary stars, the occurrence of planets in multiple star systems could be as high as 50% (Kaib et al. 2013). Nearly all of the *Kepler* targets have been imaged by the United Kingdom Infrared Telescope (UKIRT) or other ground based telescopes that provide $\sim 1''$ seeing, but only 30.5% of planet candidate hosts have been followed up with speckle interferometry, adaptive optics imaging, or other high-resolution imaging capable of resolving tightly bound systems. This implies that a significant fraction of *Kepler* targets may in fact be close-in binary or higher multiple star systems that remain unresolved. Recent advancements in ground-based adaptive optics (AO), particularly at the Keck Observatory, have accelerated high-resolution imaging of *Kepler* Objects of Interest (KOIs), especially those with the smallest planets at the coolest temperatures. The identification of any diluting sources in the aperture allows for improved precision when determining planet habitability and can also reveal previously unresolved stellar companions. Gilliland & Rajan (2011) and Gilliland et al. (2015) have shown that the sharp and stable point spread function (PSF) of the WFC3 camera on *Hubble Space Telescope* is ideal for detailed photometric study of *Kepler* targets and for the identification of field stars in the *HST* photometric aperture down to about $\Delta mag = 10$. The F555W and F775W filters on WFC3/UVIS

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<http://cfop.ipac.caltech.edu/home/>

Keck II received its first AO system in 1999, and Keck I received its own AO system in 2001. Keck II upgraded to a Laser Guide Star (LGS) AO system in 2003, and Keck I upgraded to an LGS-AO system on OSIRIS in 2012. GO-12893 was proposed in early 2012 before the OSIRIS LGS-AO system obtained first light and gained widespread use, so the comparison between ground- and space-based capabilities is based on pre-2012 instrument performance.
are ideally suited to observe the majority of *Kepler* targets.

Our *HST* Guest Observing Snapshot Program GO-12893 observed 22 targets before May 1, 2014, six of which were found to be multiple star systems unresolved by *Kepler*. Gilliland *et al.* (2015) discusses the overarching scientific goals and conclusions of the observing program, including program parameters and basic image analysis, stellar companion detections and detection completeness, comparison to other high-resolution imaging, and tests for physical association of detected stellar companions. Gilliland *et al.* (2015) presents analysis that directly supports the methods in this paper, and serves as a companion paper to this work. Here, we perform multiple-star isochrone fitting using the latest release of the Victoria-Regina Stellar Models (Casagrande & VandenBerg 2014; VandenBerg *et al.* 2014b) for three *Kepler* targets of particular interest: KIC 11497958 (KOI-1422, hereafter *Kepler*-296), KIC 11768142 (hereafter KOI-2626), and KIC 6263593 (hereafter KOI-3049). We discuss the parameters of GO-12893 and our image analysis in Sec. 2.2.2 including our use of the DrizzlePac software and our conversion of our *HST* photometry to the *Kepler* photometric bandpass. In Sec. 2.2.3 we discuss the importance of our three targets and detail our characterization of the stellar components in each multi-star system, including the use of our empirically derived PSF to calculate the photometry of our systems, fitting to the Victoria-Regina isochrones, and examination of their suitability for our targets. Sec. 2.2.4 presents our re-evaluation of the planetary habitability. For the purposes of this paper, we define a “habitable planet” to be a planet that falls between the moist greenhouse limit and the maximum greenhouse limit as defined by Kopparapu *et al.* (2013). Finally, we discuss our results in context of previous and future work in Sec. 2.2.5 and summarize our findings in Sec. 2.2.6.

### 2.2.2 Observations and Image Analysis

The 158 targets proposed for observation were selected from the 2013 data release of *Kepler* planet candidates by Batalha *et al.* (2013), prioritized by smaller candidate radius and cooler equilibrium temperature. The remaining ranked targets were then sorted between ground-based AO and *HST* observations based on the quality of observations for the fainter targets, where *HST* would provide comparable or better data in half an orbit than a full night of ground-based AO observation on Lick or Palomar systems. This resulted in the selected *HST* targets having the shallowest
transit signatures, which thus require the deepest imaging. The targets have a nominal upper limit of $R_p < 2.5R_\oplus$ (Batalha et al. 2013), though our revision of the stellar parameters indicates that some of the planets are actually larger than this limit. Of the 158 proposed targets, 22 were observed before May 2014 and are included in our analysis. Any observations collected after May 2014 will be analyzed using the techniques presented in this section, but are not included in this paper. Our image analysis utilized the latest image registration and drizzling software from STScI DrizzlePac (Gonzaga et al. 2012) and our own PSF definition and subtraction.

2.2.2.1 HST High Resolution Imaging

Our HST program provided high resolution imaging in the F555W ($\lambda \sim 0.531\mu m$) and F775W ($\lambda \sim 0.765\mu m$) filters of the WFC3/UVIS camera to support the analysis of faint KOIs. In particular, the parameters of our observations allowed us to examine the properties of faint stellar hosts of small and cool planet candidates. At the faint magnitudes of typical Kepler stars, our WFC3 imaging provides resolution that is competitive with current ground-based AO and has the advantage of using two well calibrated optical filters well matched to the Kepler bandpass.

The observations made by HST closely resemble those made by Gilliland & Rajan (2011), though we only used observations in F555W and F775W since the faintest Kepler targets could still be probed in these bandpasses. Observations planned for each of the 158 SNAP targets were identical in form. In each filter, we took 5 observations of each target: 4 observations with exposure times to reach 90% of full well depth in the brightest pixel, and an additional observation at an exposure time equal to 50% more than the sum of the unsaturated exposures to bring up the wings of the PSF. The saturated exposure yielded a $\Delta$-mag of $\sim 9$ outside 2″ and helped with the signal-to-noise anywhere outside the inner 0′′.1.

2.2.2.2 AstroDrizzle

The “drizzle” process, formally known as variable-pixel linear reconstruction, was developed to align and combine multiple under-sampled dithered images from HST into a single image with improved resolution, reduction in correlated noise, and superior cosmic ray removal when compared to images combined using a lower quality shift-and-add method (Gonzaga et al. 2012). AstroDrizzle replaced MultiDrizzle in
the *HST* data pipeline in June 2012 and is a significant improvement over the previous MultiDrizzle software as it directly utilizes the FITS headers for the instrument, exposure time, etc. instead of through user input. AstroDrizzle also provides more freedom in regard to the parameters for the image combination, leading to faster, more compact, and target specific drizzled products ([Fruchter et al., 2010](#)). Using AstroDrizzle, we were able to adjust the parameters used in creating the median image, the shape of the kernel used in the final drizzled image, and the linear drop in pixel size when creating the final drizzled image, all of which allowed us to create products with sharper and smoother PSFs than previous MultiDrizzle or STScI pipeline products.

We processed each target in our sample in the same manner in order to best compare the final products. The 5 images in each filter were first registered using the *tweakreg* task in DrizzlePac, which performed fine-alignment of the images via additional sources found using a *daofind*-like algorithm. This fine-alignment was necessary to fully realize the high resolution of our observations to create accurate PSFs out of the drizzled products. After registering the images, they were combined through *astrodrrizzle*, which first drizzled each separate image, created a median image, and split the median image back into the separate exposures to convolve

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9Original text said units are *unscaled* $\log_{10} e^{-}/s$, which is incorrect.
each exposure with the instrumental PSF and reconstruct it after the instrumental effects were removed. These reconstructed images were then corrected for cosmic ray contamination and finally drizzled together, with the final astrodrizzle product scaled to $0''.03333$ /pixel. Lastly, we centered the target on a pixel to within ±0.01 pix by utilizing the astrodrizzle output world coordinate system rotation matrix to transform the desired shift of the centroid of the star in pixel-space to a shift in RA/DEC-space. The drizzling and centering process was iterated as often as necessary to center the target on a pixel to the desired accuracy, which aided in constructing an accurate PSF.

Fig. 2.1 shows the final drizzled product in the F775W band for KIC 4139816, a typical single star from our sample. The HST pipeline product for this target showed a rough PSF near the center of the target, and further examination showed that the pipeline had incorrectly classified pixels in the saturated exposure. Manual adjustment of the data quality flags allowed us to correct the issue in our AstroDrizzled product, leading to a smoother and sharper PSF than the pipeline product.

### 2.2.2.3 Kp–HST Photometric Conversion

Converting the Kepler photometric system to the HST system served two purposes: the first to provide a check on the quality of our images and analysis, and the second to calculate the dilution of the transit depths due to additional stars in the Kepler photometric aperture. We calculated photometry from the AstroDrizzle products by summing the flux within a square aperture equivalent in area to a $2.0''$ radius aperture centered on the target. We then used the published encircled energy of 99% relative to an infinite aperture along with published zero points\(^\text{10}\) to obtain F555W and F775W magnitudes for the targets. Errors on the magnitudes are estimated to be 0.03 in both filters.

We then compared the published values for Kp from the Kepler Input Catalogue to F555W and F775W for the 22 observed targets and one from Croll et al. (2014) that had identical observations (Table 2.2). Based on a plot of (Kp–F555W) vs. (F555W–F775W), we observed that the transformation between Kp, F555W, and F775W would follow a linear relation. Fitting of a linear model to the data produced

\(^{10}\text{www.stsci.edu/hst/wfc3/phot_zp_lbn}\)
Table 2.2: Derived WFC3 photometry and Kp magnitudes from the Kepler Input Catalog, used to derive Eq. 2.2

<table>
<thead>
<tr>
<th>KIC ID</th>
<th>Obs. Date</th>
<th>Kp</th>
<th>F555W</th>
<th>F775W</th>
</tr>
</thead>
<tbody>
<tr>
<td>2853029</td>
<td>2013-08-12</td>
<td>15.679</td>
<td>16.017</td>
<td>15.006</td>
</tr>
<tr>
<td>4129816</td>
<td>2013-04-12</td>
<td>15.584</td>
<td>16.004</td>
<td>15.814</td>
</tr>
<tr>
<td>5358241</td>
<td>2013-02-02</td>
<td>15.386</td>
<td>15.656</td>
<td>14.902</td>
</tr>
<tr>
<td>5942949</td>
<td>2012-10-29</td>
<td>15.699</td>
<td>16.154</td>
<td>14.990</td>
</tr>
<tr>
<td>6149553</td>
<td>2013-06-12</td>
<td>15.886</td>
<td>17.004</td>
<td>14.812</td>
</tr>
<tr>
<td>6263593</td>
<td>2013-02-14</td>
<td>15.037</td>
<td>15.524</td>
<td>14.275</td>
</tr>
<tr>
<td>6435936</td>
<td>2013-08-18</td>
<td>15.849</td>
<td>16.846</td>
<td>14.796</td>
</tr>
<tr>
<td>8150320</td>
<td>2013-09-02</td>
<td>15.791</td>
<td>16.303</td>
<td>14.985</td>
</tr>
<tr>
<td>8890150</td>
<td>2013-08-16</td>
<td>15.987</td>
<td>16.853</td>
<td>14.969</td>
</tr>
<tr>
<td>8973129</td>
<td>2013-07-07</td>
<td>15.056</td>
<td>15.329</td>
<td>14.455</td>
</tr>
<tr>
<td>10118816</td>
<td>2012-10-27</td>
<td>15.233</td>
<td>16.000</td>
<td>14.226</td>
</tr>
<tr>
<td>10606955</td>
<td>2013-02-10</td>
<td>14.872</td>
<td>15.135</td>
<td>14.253</td>
</tr>
<tr>
<td>11305996</td>
<td>2013-03-31</td>
<td>14.807</td>
<td>15.519</td>
<td>13.850</td>
</tr>
<tr>
<td>11497958</td>
<td>2013-04-06</td>
<td>15.921</td>
<td>16.807</td>
<td>14.805</td>
</tr>
<tr>
<td>11768142</td>
<td>2013-07-31</td>
<td>15.931</td>
<td>17.056</td>
<td>14.895</td>
</tr>
<tr>
<td>12470844</td>
<td>2013-03-19</td>
<td>15.339</td>
<td>15.636</td>
<td>14.695</td>
</tr>
<tr>
<td>12557548</td>
<td>2013-02-06</td>
<td>15.692</td>
<td>16.349</td>
<td>14.936</td>
</tr>
</tbody>
</table>

Note—HST photometry is for blended stellar components in KIC 6263593, 11497958, and 11768142 systems. KIC 12557548 data are from Croll et al. (2014). Observation Date is the same for all exposures of the same target.

The correlation shown in Fig. 2.2 whose form follows

\[ Kp = 0.236 + 0.406 \times F555W + 0.594 \times F775W \]  \hspace{1cm} (2.2)

The fitted errors for this relation are 0.019 mag for the F555W and F775W coefficients and 0.027 mag for the intercept, with an RMS scatter about the fit of 0.042, showing that our simple linear modeling works well for this sample. The error on the derived Kp magnitude depends on the F555W – F775W color as

\[ \sigma_{Kp} = \sqrt{0.019^2 (F555W - F775W)^2 + 0.027^2} \]  \hspace{1cm} (2.3)

leading to slightly higher errors in Kp for redder targets in HST.
2.2.3 Evaluation of *Kepler*-296, KOI-2626, and KOI-3049 Stellar Parameters

Our program observed three systems of particular interest: *Kepler*-296, KOI-2626, and KOI-3049. *Kepler*-296 was first published as a multiple planet system by [Borucki et al.](2011) and it has since been confirmed as a five planet system. The stellar properties for this system were significantly updated by [Muirhead et al.](2012), [Dressing & Charbonneau](2013), and [Mann et al.](2013), and as a result of these studies it was found that *Kepler*-296 contained at least three potentially habitable planets. However, [Lissauer et al.](2014) showed using Keck AO and these HST images that *Kepler*-296 is actually a tight binary star system that appeared blended in the *Kepler* CCDs. KOI-2626 was first published in [Batalha et al.](2013), and examination by [Dressing & Charbonneau](2013) showed that the single planet candidate in the system was potentially habitable, though [Mann et al.](2013) disputed this finding. Later Keck AO observations[^1] revealed KOI-2626 to be a tight triple star system, and this realization challenged all previous arguments about habitability. It was

[^1]: https://cfop.ipac.caltech.edu/edit_obsnotes.php?id=2626;‘‘ciardi’’
Figure 2.3: Drizzled image of Kepler-296 in the F775W filter showing a 1″ scale bar and orientation. The fainter component, B, is to the left. Scale and units as in Fig. 2.1. The FWHM of the PSF is 0″1719 for blended system.

noted in July 2013 on the Kepler Community Follow-up Observing Program (CFOP) that Lick AO detected a secondary star in their image 0″5 away from KOI-3049[12] (1 planet candidate), but no confirmation of association has been published to date. The stellar multiplicity of each system has profound impacts on the habitability of their planets, which we re-evaluated in this study.

Figures 2.3, 2.4, and 2.5 show the AstroDrizzle combined images of Kepler-296, KOI-2626, and KOI-3049, respectively, and display the tight, apparent multiplicity of the systems. We performed PSF fitting for each system as described in Gilliland et al. (2015) to photometrically separate the components in the HST filters.

To ensure that the multiple components are not random superpositions of stars at different distances, we then attempted to fit the components of each system to a single isochrone to prove that the systems’ are most likely bound and, therefore, that the stars are the same age (coeval). We then determined the probability that a random star in the field would produce a false isochrone match to the same precision while not being physically associated with the target star. This determines the probability of the isochrone fits for our target systems indicating bound systems over randomly superimposed stars on the CCD. The PSF definition and the false association probability are outlined here and described in detail

[12]https://cfop.ipac.caltech.edu/edit_obsnotes.php?id=3049;‘‘hirsch’’
Component B is lowest in the image, with component C to the left. Scale and units as in Fig. 2.1. The FWHM of the PSF is $0'.3870$ for blended system.

in Gilliland et al. (2015).

2.2.3.1 PSF Definition and Photometry Used

We adopted the global PSF solution of Gilliland et al. (2015) in each HST filter in order to separate the stellar components of each of the three systems. This global PSF was empirically generated from our observations of apparently single stars, and is a function of target color, HST focus (which changes by small amounts from thermal stresses), and sub-pixel centering of the target. We extracted the necessary parameters for the PSF from the drizzled image of each system of interest, and iteration of the PSF fitting returned the separation and orientations of the components of the systems and their fractional contributions in each HST bandpass. Lastly, combining the fractional contributions in the HST filters with the Kp – HST conversion in Eq. 2.2 returned the fractional contribution of light from each component in Kp, which is directly relevant to the planetary parameters inferred from the Kepler transit depth.

Application of this algorithm for Kepler-296 shows that component A contributes 80.9% of the light in the Kepler bandpass, while component B contributes 19.1% (Lissauer et al. 2014). Estimated uncertainties for these percentages are 3%. We found that component B is offset from the brighter component A by $0'.217 \pm 0'.004$ at
Figure 2.5: Drizzled image of KOI-3049 in the F775W filter showing a 1′′0 scale bar and orientation. The fainter component, B, is towards the top. Scale and units as in Fig. 2.1. The FWHM of the PSF is 0.5563′′ for blended system.

a position angle of 217.3 ± 0.8 north through east.

We used the same aforementioned global PSF and fitting algorithm for KOI-2626 using the appropriate color, focus, and offset values. We inspected the drizzled image minus the PSF fit for both F555W and F775W and found no evidence for yet further components in the KOI-2626 system. For KOI-2626, component A contributes 54.5% in the Kepler bandpass, component B contributes 31.0%, and component C contributes 14.5%. Estimated errors for these fractions are 6%. We found that component B is separated from component A by 0′′.201 ± 0′′.008 at a position angle of 212.7 ± 1.6, and component C is separated from component A by 0′′.161 ± 0′′.008 at 181.6 ± 1.6.

Fitting of the global PSF for KOI-3049 using the corresponding color and focus values for this system showed that component A contributes 62.3% in the Kepler bandpass and component B contributes 37.7%, with estimated errors of 2%. We found that component B is separated from component A by 0′′.464 ± 0′′.004 at a position angle of 196.9 ± 0.8. The estimated error for this system is lower than for either Kepler-296 or KOI-2626 as the components of the system are both brighter and more widely separated, and thus the PSF fitting was able to more distinctly separate the components.

In addition to the derived WFC3-based magnitudes and colors for the individual
Table 2.3: Observed Photometry of Kepler-296, KOI-2626, and KOI-3049

<table>
<thead>
<tr>
<th>Star</th>
<th>F555W</th>
<th>F775W</th>
<th>Ks</th>
<th>Kp</th>
<th>F555W-F775W</th>
<th>i − J</th>
<th>F775W-Ks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>16.997</td>
<td>15.040</td>
<td>-</td>
<td>-</td>
<td>16.076 ± 0.045</td>
<td>1.957</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>18.874</td>
<td>16.396</td>
<td>-</td>
<td>-</td>
<td>17.641 ± 0.053</td>
<td>2.478</td>
<td>-</td>
</tr>
<tr>
<td>A + B</td>
<td>16.820</td>
<td>14.766</td>
<td>-</td>
<td>-</td>
<td>15.845 ± 0.047</td>
<td>2.053</td>
<td>1.807</td>
</tr>
<tr>
<td>B − A</td>
<td>-</td>
<td>1.356</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
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<th>Star</th>
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<th>i − J</th>
<th>F775W-Ks</th>
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<td>16.076 ± 0.047</td>
<td>2.045</td>
<td>-</td>
<td>2.198</td>
</tr>
<tr>
<td>B</td>
<td>18.406</td>
<td>16.107</td>
<td>13.838</td>
<td>17.280 ± 0.051</td>
<td>2.299</td>
<td>-</td>
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<tr>
<td>A+B+C</td>
<td>17.057</td>
<td>14.886</td>
<td>12.634</td>
<td>16.016 ± 0.049</td>
<td>2.172</td>
<td>1.807</td>
<td>2.252</td>
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<tr>
<td>B − A</td>
<td>-</td>
<td>0.509</td>
<td>0.438</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C − A</td>
<td>-</td>
<td>1.302</td>
<td>1.120</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Star</th>
<th>F555W</th>
<th>F775W</th>
<th>Ks</th>
<th>Kp</th>
<th>F555W-F775W</th>
<th>i − J</th>
<th>F775W-Ks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>16.004</td>
<td>14.806</td>
<td>-</td>
<td>-</td>
<td>15.537 ± 0.035</td>
<td>1.198</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>16.646</td>
<td>15.284</td>
<td>-</td>
<td>-</td>
<td>16.080 ± 0.037</td>
<td>1.362</td>
<td>-</td>
</tr>
<tr>
<td>A + B</td>
<td>15.926</td>
<td>14.286</td>
<td>-</td>
<td>-</td>
<td>15.022 ± 0.036</td>
<td>1.259</td>
<td>1.209</td>
</tr>
<tr>
<td>B − A</td>
<td>-</td>
<td>0.478</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note—Kp magnitudes and errors derived from Eq. 2.2 and 2.3.

components of Kepler-296, KOI-2626, and KOI-3049, we also utilized the SDSS-based magnitudes ([Fukugita et al. 1996]) available in the Kepler Input Catalogue (KIC) ([Brown et al. 2011]) as well as the 2MASS near-IR photometry available for the blended components. We found that the SDSS g and r band photometry was redundant for our late-type stars given our WFC3 photometry, and the SDSS z band was unreliable at the apparent magnitudes examined here ([Brown et al. 2011]). We therefore chose to include the blended photometry for the SDSS i band, adopting the transformation to standard SDSS photometry as detailed in [Pinsonneault et al. 2012]. As 2MASS J − K is relatively constant for a large span of early M dwarfs, we chose to utilize i − J for the blended components in the fitting. Keck-AO data for KOI-2626 from NIRC-2 (Fig. 2.6) allowed PSF fitting to derive photometry for the individual components of that system in the Ks band which were used to replace the blended i − J color in the isochrone fits. Our derived WFC3-based photometry, the blended i − J colors, and the Ks band photometry for KOI-2626 used in the isochrone fitting are listed in Table 2.3 for Kepler-296, KOI-2626, and KOI-3049. We chose to use the ∆mag in F775W between components in each system as the longer wavelength of that filter should be more reliable for our late-type stars than the F555W photometry.
2.2.3.2 Reddening Corrections

As we did not assume a distance (and therefore a reddening) value *a priori* for any of our systems, we allowed for adjustment of $E(B-V)$ in order to find the best isochrone fit. We used the extinction laws for $J$, $i$, and $Ks$ bands from Pinsonneault et al. (2012) which are

$$A_J = 0.282 \times A_V$$
$$A_i = 0.672 \times A_V$$
$$A_{Ks} = 0.117 \times A_V$$

(2.4)

where $A_{\text{band}}$ is the extinction in the desired band and $A_V = 3.1 \times E(B-V)$ is the extinction in the $V$ band. We calculated the extinction laws for $F555W$ and $F775W$ with the *HST* Exposure Time Calculator for WFC3/UVIS\textsuperscript{13} to be

$$A_{F555W} = 3.11 \times E(B-V)$$
$$A_{F775W} = 1.98 \times E(B-V)$$

(2.5)

\textsuperscript{13}http://etc.stsci.edu/etc/input/wfc3uvis/imaging/
2.2.3.3 Fitting Using Victoria-Regina Isochrones

Based on the derived WFC3 photometry for the components of Kepler-296, KOI-2626, and KOI-3049, we anticipated that Kepler-296A would match the temperature of an early M dwarf, with Kepler-296B a slightly later M dwarf (Lépine et al. 2013). We also predicted KOI-2626A to be a slightly later M dwarf than Kepler-296A, KOI-2626B between Kepler-296A and Kepler-296B, and KOI-2626C slightly later than Kepler-296B. We expected both KOI-3049A and KOI-3049B to be earlier types than Kepler-296A, falling near late-K/early-M dwarfs (Boyajian et al. 2012). Dressing & Charbonneau (2013) argue that the Dartmouth Stellar Evolution Database (DSED) (Dotter et al. 2008) provides the most state-of-the-art representation of the evolution of M dwarfs and thus would provide reliable solutions for Kepler-296, KOI-2626, and KOI-3049. Feiden et al. (2011) also demonstrated the reliability of the Dartmouth isochrones in fitting for late-type stars.

We have found that the DSED isochrones systematically underestimate the temperatures, masses, and radii for M dwarfs when optical bandpasses are relied upon for the fitting. The latest release of the DSED isochrones in 2012 utilizes the BT-Settl model atmosphere line lists and physics of Allard et al. (2011). The Dartmouth Stellar Evolution Program generated their synthetic photometry using the PHOENIX atmospheric code (Hauschildt et al. 1999a,b) and inputted DSED boundary conditions from their isochrone grids. Thus, while the DSED isochrones did not use the exact model atmosphere grids released by Allard et al. (2011), the synthetic photometry included in the latest DSED release is still subject to the same strengths and weaknesses as the BT-Settl atmospheres. Examination of Fig. 2 of Allard et al. (2011) and Fig. 9 of Mann et al. (2013) shows that while the synthetic spectra for M dwarfs are remarkably accurate for infrared wavelengths, the molecular line lists for M dwarfs are incomplete in the optical and thus do not adequately represent the M dwarf spectral energy distribution in this wavelength range. These regions of the synthetic spectra are often masked out when attempting to use the BT-Settl atmospheric spectra to fit to observed M dwarf spectra. As BT-Settl appears to overestimate the SED of M dwarfs in the optical, inclusion of optical photometry when attempting to fit using BT-Settl photometry should always predict more optical flux than appears for a given stellar temperature, so would skew the fitting towards cooler temperatures. This is consistent with our comparison with Dressing & Charbonneau (2013) (see Sec. 2.2.5 for more information). The
synthetic photometry included in DSED predicts that below a certain temperature all M dwarfs have the same color in optical bandpasses, which does not match our full observational sample (Gilliland et al. 2015). The newest release of the Victoria-Regina (VR) Stellar Models (Casagrande & VandenBerg 2014; VandenBerg et al. 2014a,b) uses the MARCS model atmospheres that demonstrate increasingly red colors for decreasing stellar brightness, a much more accurate representation of observed M dwarfs in the solar neighborhood and our full target sample.

The discrepancy in photometry tabulated in DSED and VR can be traced back to the differences between the latest PHOENIX (Allard et al. 2011) and MARCS (Casagrande & VandenBerg 2014) model atmosphere inputs and physics. To solve for the emergent intensity as a function of wavelength, MARCS uses a spherical 1D, local thermodynamic equilibrium (LTE) atmosphere while BT-Settl uses a spherically symmetric, LTE 2D solution with non-LTE physics for specific species. The most significant difference between these two atmospheric models are the molecular lines and opacities included in their calculations, as well as the inclusion of dust opacities, cloud formation, condensation, and sedimentation. BT-Settl includes all of the aforementioned advanced atmospheric calculations, while MARCS contains limited ionic and molecular opacities and no dust opacity or high-order atmospheric physics. As these details are most important for M dwarfs in the infrared, it logically follows that BT-Settl more accurately models stellar photometry in that range while the missing optical molecular bands in the PHOENIX models leads to inaccuracies in optical bandpasses (Allard et al. 2011; Mann et al. 2013).

Fig. 2.7 shows solar, sub-solar, and super-solar metallicity, 5 Gyr isochrones from the VR and DSED models with stars from the RECONS project (Cantrell, Henry & White 2013; Henry et al. 1999, 2006; Jao et al. 2014) within 5 pc of the Sun overplotted. From this we can see that the stellar models are indistinguishable for stars with $F555W - F775W$ colors bluer than $\sim 1$. Stars with colors redder than 1 follow the VR models more closely than the Dartmouth models. The deviation becomes greatest for colors redder than 2.5, where the RECONS data show a continual reddening of color with decrease in magnitude, which Dartmouth models do not show. Initial analysis using the Dartmouth isochrones yielded stellar temperatures that were significantly hotter than previous studies suggested (Dressing & Charbonneau 2013; Muirhead et al. 2012) and the lack of consistency with those calculations remained troubling until the limitations of Dartmouth models for cool stars in optical
bandpasses were realized. We therefore used the synthetic photometry available for the VR isochrones for F555W, F775W, $i$, $J$, and $K_s$ bands to perform our fitting.

It has been noted in the past that stars in the solar neighborhood have a sub-solar average $[\text{Fe}/\text{H}]$ metallicity ([Hinkel et al. 2014]). Therefore, the RECONS stars should fall between the $[\text{Fe}/\text{H}] = 0$ and $[\text{Fe}/\text{H}] = -0.5$ isochrones in Fig. 2.7. The recently released Hypatia Catalog ([Hinkel et al. 2014]), which compiles spectroscopic abundance data from 84 literature sources for 50 elements across 3058 stars within 150 pc of the Sun, challenges this conclusion. After re-normalizing the raw spectroscopic data of their catalog stars to the same solar abundances, they find that the mean $[\text{Fe}/\text{H}]$ for thin disk stars in the solar neighborhood is +0.0643 and has a median value of +0.08. As the Hypatia Catalog indicates that solar neighborhood stars are actually slightly super-solar in metallicity, the location of the RECONS stars in relation to the VR isochrones in Fig. 2.7 appears consistent.

Using the data and codes provided by VandenBerg et al. (2014a) and the interpolation methods described in Appendix A of Casagrande & VandenBerg (2014), we generated ten 5 Gyr isochrones assuming a helium fraction of 0.27, $[\alpha/\text{Fe}] = 0.0$, and spanning the metallicity range $[\text{Fe}/\text{H}] = -0.5 \rightarrow +0.4$ in steps of 0.1 dex. We then linearly interpolated the generated isochrones halfway between the given points and added calculations of $L/L_\odot$ and $R/R_\odot$ from the quantities provided. The resulting isochrones contained synthetic photometry for F555W, F775W, $i$, $J$, and $K_s$ bandpasses as well as fundamental stellar parameters. The final isochrones used spanned a range of $0.12 \lesssim M_*/M_\odot \lesssim 1.2$.

The Kepler light curves for Kepler-296, KOI-2626, and KOI-3049 all show low amplitude, long period variations ($\sim$ weeks) which are characteristic of older stars. As M-dwarfs evolve little over the course of their very long lives, we have adopted an age for all systems of 5 Gyr; adjustment of this age showed insignificant impact on the results. Assuming these are systems of late-type main sequence stars, we further restricted our isochrone fitting only to stars with $M_*/M_\odot \leq 1.0$. Lastly, we required that the brightest component of each system be the most massive, with the dimmer component(s) being less massive. If the systems are truly bound then each component is at the same distance from us, meaning that the apparent magnitudes correlate with the effective temperatures and therefore with the mass.

To fit both stellar components of Kepler-296 and KOI-3049 to an isochrone, we performed a minimum-$\chi^2$ fitting between the observed and synthetic photometry
Figure 2.7: Comparison of 5 Gyr isochrones from the Victoria-Regina Stellar Models (black) and the Dartmouth Stellar Evolution Database (red). Numbers in legend indicate the isochrone value of [Fe/H]. Crosses are stars within 5 pc of the sun from the RECONS project with absolute photometry.

described above. We chose to minimize the quadrature sum of the differences for the color of component A, the color of component B, the magnitude difference of B-A in F775W, and the blended $i - J$ color, given as

$$
\chi^2_{\text{binary}} = \left( \frac{\Delta (F555W - F775W)_A}{\sigma_A} \right)^2 \\
+ \left( \frac{\Delta (F555W - F775W)_B}{\sigma_B} \right)^2 \\
+ \left( \frac{\Delta F775W_{B-A}}{\sigma_{B-A}} \right)^2 \\
+ \left( \frac{\Delta (i - J)_{A+B}}{\sigma_{A+B}} \right)^2
$$

(2.6)

where $\Delta (F555W - F775W)$ are the color differences between the observed colors and the tabulated values in the synthetic VR isochrones, $\Delta F775W_{B-A}$ is the observed difference in magnitude between components B and A in the F775W band minus the same quantity from the isochrones, and $\Delta (i - J)_{A+B}$ is the $i - J$ color for the observed blended A+B photometry minus the blended isochrone values for A+B. The $\sigma$ values represent the uncertainties in the measured photometry and were set to 0.03 mag for Kepler-296 and 0.02 mag for KOI-3049 for colors within the same photometric system, and 0.08 for cross-system colors (i.e. for $i - J$).
For the three components of KOI-2626, we performed a similar minimum-$\chi^2$ fitting, including $Ks$ band photometry in place of $i - J$ and adding appropriate terms for component C, given as

$$\chi^2_{\text{triple}} = \left( \frac{\Delta(F555W - F775W)_A}{\sigma_A} \right)^2 + \left( \frac{\Delta(F555W - F775W)_B}{\sigma_B} \right)^2 + \left( \frac{\Delta(F555W - F775W)_C}{\sigma_C} \right)^2 + \left( \frac{\Delta(F775W - Ks)_A}{\sigma_A} \right)^2 + \left( \frac{\Delta(F775W - Ks)_B}{\sigma_B} \right)^2 + \left( \frac{\Delta(F775W - Ks)_C}{\sigma_C} \right)^2 + \left( \frac{\Delta F775W_B - F775W_A}{\sigma_{B-A}} \right)^2 + \left( \frac{\Delta F775W_C - F775W_A}{\sigma_{C-A}} \right)^2 + \left( \frac{\Delta Ks_B - Ks_A}{\sigma_{B-A}} \right)^2 + \left( \frac{\Delta Ks_C - Ks_A}{\sigma_{C-A}} \right)^2 \tag{2.7}$$

Terms in Eq. 2.7 are the same as Eq. 2.6, with the addition of $\Delta(F555W - F775W)$ for the C component, $\Delta F775W_{C-A}$ for the observed difference in magnitude between components C and A in the F775W band minus the same quantity from the isochrones, and similar quantities for F775W-$Ks$ colors and $\Delta Ks$ magnitudes of all components. The $\sigma$ values in Eq. 2.7 were set to 0.05 mag for all terms except any involving component C, which were set to 0.08. The $\sigma$’s were increased to account for the larger uncertainty in the PSF fitting and thus the contributions of each component to the total magnitude. When fitting the observed photometry to the isochrones, we used the reduced $\chi^2$ metrics, where $\chi^2_{\text{binary}}$ was reduced by a factor of $(1 - \text{d.o.f.}) = 3$ and $\chi^2_{\text{triple}}$ was reduced by a factor of $(1 - \text{d.o.f.}) = 9$.

In the fitting of Kepler-296 and KOI-3049, for each primary mass value ($M_A$), the secondary mass value ($M_B$) that produced the minimum $\chi^2$ as per Eq. 2.6 was selected, assuming $M_B < M_A$. The overall best isochrone match was the combination of A and B masses that produced the global minimum $\chi^2_{\text{binary}}$. This two-level fitting was performed for the three binary permutations of components of KOI-2626 as well, to determine that each binary permutation of the system (A-B, A-C, and B-C) could also be coeval, to ensure that the photometry was producing consistent results between combinations of components, and to provide initial values for the masses of...
each component in the triple-star fitting. To perform the three-component fitting, we took the initial estimates for the masses of each component and searched a range of surrounding masses for the best fit, with the size of the range dependent on the reliability of the photometry for that component. For each mass in the range of component A, Eq. 2.7 was minimized for every combination of B and C masses. The overall combination of A, B, and C, that produced the global minimum of $\chi^2_{\text{triple}}$ was adopted as the best fit.

In order to test the systematic uncertainties in using the VR isochrones to determine the stellar mass, radius, and bolometric luminosity of our three target systems, we applied an offset to the solar metallicity VR model in order to match the RECONS stars in Fig. 2.7. We then fit the isochrones with the offset to Kepler-296 according to the method described above to test how the slight offset in metallicity affects the determination of the stellar parameters. We first fit the solar metallicity isochrone to the Kepler-296 photometry as is, then did the same by applying a shift in F555W-F775W color to match RECONS colors, and finally by applying a shift in F775W magnitude to match the RECONS magnitudes. This yielded two measurements of the systematic uncertainty when fitting for mass, radius, and luminosity. We find that the VR models required a shift of $\Delta F775W = -0.5$ or $\Delta (F555W - F775W) = +0.2$ in order to best match the RECONS sample. We note that the chosen shift in color matches the colors of the cooler stars in the sample while being slightly too red to properly match the hotter stars. The shift in magnitude did not affect the fit at all since the search range to match the magnitudes of the Kepler-296 components was larger than the model shift and so the fitting algorithm still selected the minimum $\chi^2$ fit. To calculate the systematic uncertainty of our isochrone fitting we averaged the differences between the best fit stellar parameters and the color-shifted best fit stellar parameters for the primary and secondary stars in Kepler-296. We find that $\Delta M = -0.081M_\odot$, $\Delta R = -0.071R_\odot$, $\Delta L = -0.014L_\odot$, and $\Delta T_{\text{eff}} = -154.55K$. From this we conclude that the systematic uncertainties when fitting for stellar mass, radius, and luminosity are small, but not insignificant, contributions to the total error budget.

Lacking spectroscopic determinations for metallicity for Kepler-296, KOI-2626, or KOI-3049, we fit each system to isochrones of each metallicity in our range at $E(B-V)=0$ to find the best fitting metallicity, and then increased the reddening to determine whether that would provide a better fit. In all cases, $E(B-V)=0$ provided
Table 2.4: Values of the min $\chi^2$ for changing values of metallicity for *Kepler*-296, KOI-2626, and KOI-3049.

<table>
<thead>
<tr>
<th>[Fe/H]</th>
<th>Kepler-296</th>
<th>KOI-2626</th>
<th>KOI-3049</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>3.187</td>
<td>1.610</td>
<td>0.936</td>
</tr>
<tr>
<td>-0.4</td>
<td>3.187</td>
<td>1.491</td>
<td><strong>0.908</strong></td>
</tr>
<tr>
<td>-0.3</td>
<td>6.227</td>
<td>1.313</td>
<td>1.056</td>
</tr>
<tr>
<td>-0.2</td>
<td>7.531</td>
<td>1.191</td>
<td>1.179</td>
</tr>
<tr>
<td>-0.1</td>
<td>8.365</td>
<td>1.139</td>
<td>1.086</td>
</tr>
<tr>
<td>0.0</td>
<td>6.246</td>
<td>0.941</td>
<td>0.943</td>
</tr>
<tr>
<td>+0.1</td>
<td>3.207</td>
<td><strong>0.860</strong></td>
<td>1.049</td>
</tr>
<tr>
<td>+0.2</td>
<td>0.764</td>
<td>1.258</td>
<td>1.073</td>
</tr>
<tr>
<td>+0.3</td>
<td><strong>0.218</strong></td>
<td>2.123</td>
<td>1.039</td>
</tr>
<tr>
<td>+0.4</td>
<td>1.508</td>
<td>3.987</td>
<td>1.041</td>
</tr>
</tbody>
</table>

the best fits. Table 2.4 provides the minimum $\chi^2$ for each system at each metallicity for $E(B-V)=0$. *Kepler*-296 and KOI-2626 both show a clear best fit for [Fe/H] = +0.3 and +0.1, respectively. While KOI-3049 has a best fit for [Fe/H] = −0.4, all metallicities tested show approximately the same goodness of fit, suggesting the independence of the goodness-of-fit with regard to metallicity for that system and an even weaker assertion about the true metallicity of KOI-3049. For the evaluation of planetary habitability, stellar parameters from the best fit metallicity (highlighted in bold in Table 2.4) were chosen. As the best fit $\chi^2$ for *Kepler*-296 is significantly below 1, we are likely overestimating our errors for that system.

### 2.2.3.4 False Association Odds

In addition to showing that the suspected companion stars for *Kepler*-296, KOI-2626, and KOI-3049 are coeval, we performed a Bayesian-like odds ratio analysis on the three systems to determine the probability that the isochrone fitting described in Sec. 2.2.3.3 could have produced a good match for all components without the stars being physically associated (Gilliland et al. 2015). For the components of *Kepler*-296, the odds ratio associated:random was 4101.6:1; for KOI-2626, the ratio was 2832.9:1 for the primary and secondary companions and 928.1:1 for the primary and tertiary companions; for KOI-3049 the ratio was 1923.7:1. From this we conclude that isochrone fitting utilizing the photometry of these three cases would be very unlikely to produce a good fit if the stars were random superpositions and not truly associated.
Figure 2.8: Left: variation of $\chi^2$ from Eq. 2.6 for $M_*/M_\odot$ for component A of Kepler-296. Right: same as left panel, for component B of Kepler-296. Black curve shows the variation of $\chi^2$, red dashed line shows mass of components for the minimum $\chi^2$.

Table 2.5: Best fit stellar parameters for the components of Kepler-296

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Kepler-296A</th>
<th>Kepler-296B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_*/M_\odot$</td>
<td>0.626 ± 0.082</td>
<td>0.453 ± 0.082</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ [K]</td>
<td>3821 ± 160</td>
<td>3434 ± 156</td>
</tr>
<tr>
<td>$R_*/R_\odot$</td>
<td>0.595 ± 0.072</td>
<td>0.429 ± 0.072</td>
</tr>
<tr>
<td>Distance [pc]</td>
<td>359</td>
<td>358</td>
</tr>
<tr>
<td>F555W</td>
<td>9.218</td>
<td>11.111</td>
</tr>
<tr>
<td>F775W</td>
<td>7.266</td>
<td>8.621</td>
</tr>
<tr>
<td>$F555W - F775W$</td>
<td>1.952</td>
<td>2.490</td>
</tr>
<tr>
<td>$F775W_{B - A}$</td>
<td>1.356</td>
<td></td>
</tr>
</tbody>
</table>

Note—Tabulated values were calculated for $E(B-V) = 0.00$, [Fe/H] = +0.3, age = 5 Gyr, and were matched to the observed values in Table 2.3 $\chi^2_{\text{min}} = 0.218$.

2.2.3.5 Kepler-296 Best-fit Stellar Parameters

Using the procedures described in Sec. 2.2.3.3 and Sec. 2.2.3.2 we found that the best fit for the stellar components of Kepler-296 occurred for [Fe/H] = +0.3, with $M_A/M_\odot = 0.626 \pm 0.082$ and $M_B/M_\odot = 0.453 \pm 0.082$. The tabulated temperatures that correspond to these masses in the VR isochrones are $T_A = 3821 \pm 160$ K and $T_B = 3434 \pm 156$ K. These roughly correspond to spectral types M0.0V and
M3.0V, respectively, based on the [Lépine et al. (2013)] spectroscopic catalogue of the brightest K and M dwarfs in the northern sky, which provided ranges and average temperature for each spectral subtype. The stellar radii are $R_A/R_\odot = 0.595 \pm 0.072$ and $R_B/R_\odot = 0.429 \pm 0.072$, as calculated from the tabulated values of $T_{\text{eff}}$ and stellar luminosity from the isochrones. Errors on all of these values are $\delta X = \sqrt{1\sigma_{\text{iso}}^2 + \Delta (X)^2}$, where $1\sigma_{\text{iso}}$ are the 1σ errors above the minimum reduced $\chi^2$ value of 0.218 from the isochrone fitting and $\Delta (X)$ are the systematic uncertainties in the isochrone fitting as described in Sec. 2.2.3.3. Fig. 2.8 shows the variation of $\chi^2$ (calculated as in Eq. 2.6) with the best-fit masses of the primary and secondary component of Kepler-296 indicated. The $1\sigma_{\text{iso}}$ errors were calculated by finding the two points along the $\chi^2$ curves in Fig. 2.8 that corresponded to values of $\chi^2_{\text{min}} + 1.57$, accounting for 4 degrees of freedom in the fit [Press et al. 1986]. The optimal stellar parameters and their errors are tabulated in Table 2.5.

We calculated the distance to Kepler-296 by applying the distance modulus formula to the observed and absolute magnitudes of each component in each HST filter then averaging the four estimates. The absolute magnitudes from the isochrone match combined with the apparent magnitudes from our HST imaging implies a distance to Kepler-296 of $360 \pm 20$ pc. At this distance, the empirically measured separation of $0\farcs217 \pm 0\farcs004$ translates to a physical separation of $80 \pm 5$ AU and an orbital period of $660 \pm 60$ years. The true values of both the separation and period are likely larger due to projection effects foreshortening the true separation and orbital period.

### 2.2.3.6 KOI-2626 Best-fit Stellar Parameters

The best fit for KOI-2626 occurred for $[\text{Fe/H}] = +0.1$, with $M_A/M_\odot = 0.501 \pm 0.086$, $M_B/M_\odot = 0.436 \pm 0.086$, and $M_C/M_\odot = 0.329 \pm 0.085$. The tabulated temperatures that correspond to these masses in the VR isochrones are $T_A = 3649 \pm 166$ K, $T_B = 3523 \pm 160$ K, and $T_C = 3391 \pm 158$ K. These temperatures translate roughly to M1.0V, M2.0V, and M2.5V, respectively based on [Lépine et al. (2013)]. The stellar radii are $R_A/R_\odot = 0.478 \pm 0.075$, $R_B/R_\odot = 0.415 \pm 0.077$, and $R_C/R_\odot = 0.321 \pm 0.076$ as calculated from the tabulated values of $T_{\text{eff}}$ and stellar luminosity from the isochrones. These parameters are tabulated in Table 2.6. Curves showing the variation of $\chi^2$ (calculated as in Eq. 2.7) as a function of stellar mass similar to Fig. 2.8 were created and used to determine the best fit and $1\sigma_{\text{iso}}$ points. The listed errors are calculated
Table 2.6: Best fit stellar parameters for the components of KOI-2626

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KOI-2626A</th>
<th>KOI-2626B</th>
<th>KOI-2626C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_\star / M_\odot$</td>
<td>$0.501 \pm 0.086$</td>
<td>$0.436 \pm 0.086$</td>
<td>$0.329 \pm 0.085$</td>
</tr>
<tr>
<td>$T_{\text{eff}} [K]$</td>
<td>$3649 \pm 166$</td>
<td>$3523 \pm 160$</td>
<td>$3391 \pm 158$</td>
</tr>
<tr>
<td>$R_\star / R_\odot$</td>
<td>$0.478 \pm 0.075$</td>
<td>$0.415 \pm 0.077$</td>
<td>$0.321 \pm 0.076$</td>
</tr>
<tr>
<td>Distance [pc]</td>
<td>337</td>
<td>342</td>
<td>333</td>
</tr>
<tr>
<td>$F555W$</td>
<td>10.907</td>
<td>10.697</td>
<td>11.690</td>
</tr>
<tr>
<td>$F775W$</td>
<td>7.953</td>
<td>8.472</td>
<td>9.274</td>
</tr>
<tr>
<td>$K_s$</td>
<td>5.732</td>
<td>6.151</td>
<td>6.839</td>
</tr>
<tr>
<td>$F555W - F775W$</td>
<td>2.054</td>
<td>2.225</td>
<td>2.416</td>
</tr>
<tr>
<td>$F775W - K_s$</td>
<td>2.221</td>
<td>2.321</td>
<td>2.435</td>
</tr>
</tbody>
</table>

Note—Tabulated values were calculated for $E(B-V) = 0$, $[\text{Fe/H}] = +0.1$, age = 5 Gyr, and were matched to the observed values in Table 2.3. $\chi^2_{\text{min}} = 0.860$.

Table 2.7: Best fit stellar parameters for the components of KOI-3049

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KOI-3049A</th>
<th>KOI-3049B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_\star / M_\odot$</td>
<td>$0.607 \pm 0.081$</td>
<td>$0.557 \pm 0.081$</td>
</tr>
<tr>
<td>$T_{\text{eff}} [K]$</td>
<td>$4529 \pm 163$</td>
<td>$4274 \pm 159$</td>
</tr>
<tr>
<td>$R_\star / R_\odot$</td>
<td>$0.588 \pm 0.071$</td>
<td>$0.536 \pm 0.071$</td>
</tr>
<tr>
<td>Distance [pc]</td>
<td>485</td>
<td>484</td>
</tr>
<tr>
<td>$F555W$</td>
<td>7.567</td>
<td>8.222</td>
</tr>
<tr>
<td>$F775W$</td>
<td>6.381</td>
<td>6.858</td>
</tr>
<tr>
<td>$F555W - F775W$</td>
<td>1.186</td>
<td>1.364</td>
</tr>
<tr>
<td>$F775W_{B-A}$</td>
<td>0.478</td>
<td></td>
</tr>
</tbody>
</table>

Note—Tabulated values were calculated for $E(B-V) = 0$, $[\text{Fe/H}] = -0.4$, age = 5 Gyr, and were matched to the observed values in Table 2.3. $\chi^2_{\text{min}} = 0.907$.

as in Sec. 2.2.3.5 with $1\sigma_{\text{iso}} = \chi^2_{\text{min}} + 1.28$ above the minimum $\chi^2$ value of 0.860, accounting for the 10 degrees of freedom in the fitting (Press et al. 1986).

The absolute magnitudes from the isochrone match combined with the apparent magnitudes from our $HST$ imaging implies a distance to KOI-2626 of $340 \pm 35$ pc. At this distance, the empirically measured separation of $0''203$ between components A and B translates to a physical separation of $70 \pm 7$ AU and for the measured separation of components A and C of $0''161$ we calculated a physical separation of $55 \pm 6$ AU. Again, the real values are likely larger due to projection effects.

2.2.3.7 KOI-3049 Best-fit Stellar Parameters

The best fit for the components of KOI-3049 occurred for $[\text{Fe/H}] = -0.4$. We find that $M_A/M_\odot = 0.607 \pm 0.081$ and $M_B/M_\odot = 0.557 \pm 0.081$. The tabulated temperatures that correspond to these masses in the VR isochrones are $T_A = 4529 \pm 163$ K and
$T_B = 4274 \pm 159$ K. These effective temperatures match approximately to K4.0V and K5.5V, respectively, based on the spectral types tabulated in Boyajian et al. (2012), as the temperatures are outside the range provided by Lépine et al. (2013). We find the stellar radii to be $R_A/R_\odot = 0.588 \pm 0.071$ and $R_B/R_\odot = 0.536 \pm 0.071$. The optimal stellar parameters and their errors are tabulated in Table 2.7. Curves showing the variation of $\chi^2$ (calculated as in Eq. 2.6) as a function of stellar mass similar to Fig. 2.8 were created and used to determine the best fit and 1\sigma points. The listed errors are determined as in Sec. 2.2.3.5, with 1\sigma_{iso} calculated using the minimum $\chi^2$ value of 0.907.

The absolute magnitudes from the isochrone match combined with the apparent magnitudes from our HST imaging implies a distance to KOI-3049 of $485 \pm 20$ pc. At this distance, the empirically measured separation of 0
dash 464 \pm 0
dash 004 translates to a physical separation of 225 \pm 10 AU and an orbital period of 3150 \pm 205 years. Again, the true values are likely larger due to projection effects.

### 2.2.3.8 Isochrone Fit Discussion

To compare the best-fit stellar properties of Kepler-296, KOI-2626, and KOI-3049 we plotted each component atop their respective best fit isochrones in Fig. 2.9. The observed photometry tabulated in Table 2.3 was converted to absolute photometry using the distances derived from the respective isochrone fits. From Fig. 2.9 we note that our initial guesses at the relative magnitudes of the components of all three systems were correct, and that Kepler-296, and KOI-3049 are very likely bound binary systems based on their close fits to the VR isochrones. The only star that falls somewhat off of the isochrone is KOI-2626 B, which appears to be slightly redder than the isochrone fit would suggest. However as KOI-2626 B still fits the isochrone within its 1\sigma error on color, we still report with high confidence that KOI-2626 is a bound triple star system.

### 2.2.4 Planetary Habitability

The multiplicity of Kepler-296, KOI-2626, and KOI-3049 have interesting implications on the habitability of the planets in each system. Dressing & Charbonneau (2013) determined that the planets Kepler-296 d (the third planet in the system) and KOI-2626.01 (the only detected planet candidate in the system) were habitable,
Figure 2.9: Absolute photometry of stellar components of Kepler-296, KOI-2626, and KOI-3049 plotted over their respective best fit 5 Gyr isochrones. Kepler-296 components are in red circles plotted over an [Fe/H] = +0.3 isochrone (red solid line), KOI-2626 components are in blue squares plotted over an [Fe/H] = +0.1 isochrone (blue dashed), KOI-3049 components are in green triangles plotted over an [Fe/H] = -0.4 isochrone (green dotted). Error bars are 1σ. Spectral types are from Lépine et al. (2013) for types later than K6.0 and from Boyajian et al. (2012) for types earlier than K6.0.

given the systems’ previously assumed single-star properties. Mann et al. (2013) re-evaluated the temperatures of these stars using stellar temperatures derived from mid-resolution spectra and found that those two planets were actually interior to their respective Habitable Zones. However, neither of those studies accounted for the multiplicity of those systems, and thus their HZ analyses are inaccurate for these targets. Knowing now that Kepler-296, KOI-2626, and KOI-3049 are multiple-star systems, we recalculated the planetary parameters of all detected planets around each potential stellar host using the best-fit stellar parameters in order to re-evaluate the planetary habitability.

Circumbinary and circum-triple planetary orbits were not tested for habitability, as the wide physical separations of the systems coupled with the short transit periods preclude planetary orbits around multiple stars. Our projected separations of the stellar components of Kepler-296, KOI-2626, and KOI-3049 indicate that they are either close or moderately separated systems14 but as we cannot correct for projection

14We define “closely separated” as < 100AU and “moderately separated” as 100 to ∼ 200AU.
effects the systems could be more widely separated. While circum-primary orbits reduce the likelihood of the additional stellar component(s) interacting catastrophically with the planetary orbits, we tested the habitability of each planet assuming an orbit around each stellar component separately, as we currently lack data indicating which stars host which (or any) planets in these systems\textsuperscript{15}.

The existence of other bright stars in the \textit{Kepler} photometric aperture (in this case due to the stellar multiplicity of the systems) required that the recorded transit depth be corrected for the light dilution from the additional star(s). To account for the transit dilution, we scaled the blended transit depth observed by \textit{Kepler} by the photometric contribution of the star of interest, as

\[
\Delta F_{\text{true}} = \Delta F_{\text{MAST}} / \text{dilution}
\]

where \(\Delta F_{\text{MAST}}\) is the transit depth as measured by \textit{Kepler}, and \textit{dilution} is the fraction of the blended light in the \textit{Kepler} aperture that is contributed by the individual stellar components. The dilutions to the transit depth were calculated using the PSF fitting (Sec. 2.2.3.1) coupled with the Kp – HST conversion (Sec. 2.2.2.3), and are listed in Sec. 2.2.3.1. As each star is smaller and cooler than the raw \textit{Kepler} photometry indicates (as \textit{Kepler} only shows the blended system), the relative drop in the stellar flux due to the transit is actually larger than was measured, which in turn increases the ratio of \(R_p/R_*\). The input transit parameters used in the habitability calculations are found in Table 2.8. The errors listed for \(\Delta F_{\text{true}}\) were calculated using the detection S/N and the archive-listed transit depth in parts per million.

\textbf{2.2.4.1 Calculation of Planetary Parameters}

Using the transit parameters listed in Table 2.8, we calculated the planet radius, the semi-major axis, the equilibrium temperature, and incident stellar flux of each planet around each of its potential host stars using the equations listed in Seager & Mallén-Ornelas (2003). Planetary masses and bulk densities were calculated using

\textsuperscript{15}Future observations may resolve this ambiguity by observing these systems during transit using high-resolution telescopes (either space- or ground-based) to determine which of the stars is the transit host. Qualitatively, the more massive star in each system is more likely to host the transit, as we assume that more massive stars begin with more protostellar and protoplanetary material, that the higher-mass star is more likely to retain that material long enough to form planets, and that the lower-mass star is less likely to perturb the orbits of planets around its more massive companion than \textit{vice versa}.
Table 2.8: Transit Parameters for Kepler-296, KOI-2626, and KOI-3049

<table>
<thead>
<tr>
<th>Planet</th>
<th>( \Delta F_{\text{MAST}} ) (^{a} )</th>
<th>( \Delta F_{\text{true}} ) (^{b} )</th>
<th>Period (^{c} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Kepler} )-296 Ac</td>
<td>1423.0 ± 28.1</td>
<td>1767.7 ± 34.9</td>
<td>5.842</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Ad</td>
<td>1567.0 ± 41.2</td>
<td>1946.6 ± 51.2</td>
<td>19.850</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Ab</td>
<td>820.0 ± 36.3</td>
<td>1018.6 ± 45.1</td>
<td>10.864</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Af</td>
<td>979.0 ± 60.8</td>
<td>1216.1 ± 75.5</td>
<td>63.338</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Ae</td>
<td>787.0 ± 45.8</td>
<td>977.6 ± 56.8</td>
<td>34.142</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Bc</td>
<td>1423.0 ± 28.1</td>
<td>7297.4 ± 143.9</td>
<td>5.842</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Bd</td>
<td>1567.0 ± 41.2</td>
<td>8035.9 ± 211.5</td>
<td>19.850</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Bb</td>
<td>820.0 ± 36.3</td>
<td>4205.1 ± 186.1</td>
<td>10.864</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Bf</td>
<td>979.0 ± 60.8</td>
<td>5020.5 ± 311.8</td>
<td>63.338</td>
</tr>
<tr>
<td>( \text{Kepler} )-296 Be</td>
<td>787.0 ± 45.8</td>
<td>4035.9 ± 234.6</td>
<td>34.142</td>
</tr>
<tr>
<td>KOI-2626 A.01</td>
<td>818.0 ± 47.3</td>
<td>1506.4 ± 87.1</td>
<td>38.098</td>
</tr>
<tr>
<td>KOI-2626 B.01</td>
<td>818.0 ± 47.3</td>
<td>2690.8 ± 155.5</td>
<td>38.098</td>
</tr>
<tr>
<td>KOI-2626 C.01</td>
<td>818.0 ± 47.3</td>
<td>5346.4 ± 309.0</td>
<td>38.098</td>
</tr>
<tr>
<td>KOI-3049 A.01</td>
<td>540.0 ± 32.0</td>
<td>866.8 ± 51.3</td>
<td>22.477</td>
</tr>
<tr>
<td>KOI-3049 B.01</td>
<td>540.0 ± 32.0</td>
<td>1432.4 ± 84.8</td>
<td>22.477</td>
</tr>
</tbody>
</table>

\(^{a}\) "Kepler-296 Ac" etc. indicates the solution for planet c around component A of Kepler-296.

\(^{b}\) From MAST.

\(^{c}\) Corrected for dilution from the stellar companion via Eq. 2.8.

the formalisms of Weiss & Marcy (2014) and Lissauer et al. (2011). These formalisms do not take into account stellar limb darkening, instead assuming a uniform stellar disk. We provide these results as a first order calculation, and provide the results of limb darkened model fits to the full folded time series in the next subsection.

The planetary radius was directly calculated from the stellar radius and the transit depth using the equations of Seager & Mallén-Ornelas (2003), as

\[
R_p = R_\star \sqrt{\Delta F_{\text{true}}} \quad (2.9)
\]

where \( \Delta F_{\text{true}} \) is the dilution-corrected transit depth from Eq. 2.8 and \( R_\star \) is the stellar radius. The planetary orbital semi-major axis was calculated from the KIC transit period and the best-fit stellar mass, using

\[
a_p = a_\oplus \left( \frac{P_p}{P_\oplus} \right)^{2/3} \left( \frac{M_\star}{M_\oplus} \right)^{1/3} \quad (2.10)
\]

where \( P_p \) is the planetary orbital period and \( M_\star \) is the stellar mass. The semi-major axis calculated in Eq. 2.10 was combined with the best-fit stellar effective temperature and radius to get the planetary equilibrium temperature via
where $A$ is the assumed Bond albedo of 0.3 and $a_p$ is the planetary semi-major axis as calculated in Eq. 2.10. This equilibrium temperature does not account for any potential greenhouse effects, which would warm the surface and are unavoidable if there is any liquid water on the surface. Next, the stellar flux incident on the planet was calculated relative to the flux received at Earth by

$$\frac{S_{\text{eff}}}{S_0} = \left( \frac{1 \text{AU}}{a_p} \right)^2 \left( \frac{R_*}{R_{\odot}} \right)^2 \left( \frac{T_*}{T_{\odot}} \right)^4$$

where $a_p$ is the planetary semi-major axis, $R_*$ is the stellar radius, $T_*$ is the stellar temperature, and $T_{\odot} = 5779 \, \text{K}$ is the adopted value of solar effective temperature.

Lastly, the mass and density of the planets were calculated using the empirical relations of Weiss & Marcy (2014) for planets less than 4 Earth-radii, given as

$$\rho_p = 2.43 + 3.39 \left( \frac{R_p}{R_{\oplus}} \right) \text{g/cm}^3$$

for $R_p/R_{\oplus} < 1.5$ and

$$\frac{M_p}{M_{\oplus}} = 2.69 \left( \frac{R_p}{R_{\oplus}} \right)^{0.93} \text{g/cm}^3$$

for $1.5 \leq R_p/R_{\oplus} < 4$. The relation of Lissauer et al. (2011) was used for planets with $R_p/R_{\oplus} \geq 4$, as

$$M_p = \left( \frac{R_p}{R_{\oplus}} \right)^{2.06} M_{\oplus}$$

which fits exoplanet observations for planets smaller than Saturn. Conversion between mass and density was done using

$$\frac{\rho_p}{\rho_{\oplus}} = \frac{M_p/M_{\oplus}}{(R_p/R_{\oplus})^3}$$

We used the formalism of Kopparapu et al. (2013) to determine the habitability of the planets. Using Eq. 2 from that paper, we calculated the locations of the
moist greenhouse limit (inner) and the maximum greenhouse limit (outer) for each of our component stars and compared the limits to the calculated effective stellar flux incident on the planets from Eq. 2.12. If a planet falls between the moist and maximum greenhouse limits, we considered it to be habitable. The moist and maximum greenhouse limits were chosen to be conservative locations of the Habitable Zone, though for stars with $T_{\text{eff}} \lesssim 5000$ K the moist greenhouse limit is indistinguishable from the runaway greenhouse limit.

The projected separations of the stellar components in both systems range from $\sim 50 - 225$ AU, while the orbital periods of the planets as measured by *Kepler* are on the order of weeks. The wide separations of the components of each system greatly reduce the chances that the stellar components produce overlapping Habitable Zones like in close (i.e. $< 50$ AU) multi-star systems. Furthermore, censuses of the populations of protoplanetary disks in wide ($\gtrsim 40$ AU) binary systems show that the influence of a binary companion reduces the lifetime of the disk by a few Myr, which decreases the likelihood of planet formation. As these systems successfully completed planet formation, the protoplanetary disk was likely only affected minimally by the stellar companion(s), further suggesting independent Habitable Zones.

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16Here, “calculated the locations” means that we calculated the inner and outer edges of the HZ in units of incident stellar flux as a function of stellar temperature. We did not calculate the orbital separations that correspond to these inner and outer flux limits. By instead defining the HZ in terms of incident stellar flux, we are able to more directly compare the habitability of planets around stars of different temperatures. For example, planetary orbits of 1AU around a G-dwarf and an M-dwarf have different habitabilities, but $S_{\text{eff}} = 1S_0$ has the same habitability for all stellar temperatures.

17*Kaltenegger & Haghighipour (2013)* report an outer limit on overlapping HZs at stellar separations of $\sim 50$ AU. As the projected separation between A and C components of KOI-2626 is $55 \pm 6$ AU, an overlapping HZ is within 1\(\sigma\) of the projected separation, and potentially only a few \(\sigma\) away from the true separation. Overlapping HZs are ruled out for the remaining stellar multiples.

18Correction—The phenomena of overlapping HZs and suppression of planet formation from stellar companions are functionally unrelated. But, as discussed in Sec. 2.1, some surveys of the stellar multiplicity rate of planet hosts suggests that tight binaries may suppress planet formation, likely through disruption of protoplanetary disks. This is an indication that the presence of a nearby star is affecting the development of the target star and any planets that may have formed, in an analogous way to the influence of overlapping HZs. Stars that are close enough to suppress planet formation around another star are likely also close enough to produce overlapping HZs, and so the slightly ambiguous case of KOI-2626AC (which has a planet) likely does not have an overlapping HZ.
2.2.4.2 Transit Light Curve Fitting

The above evaluation of planet habitability in each system is accurate to first order, but the equations in Sec. 2.2.4.1 do not account for stellar limb darkening, orbital eccentricity, inclination, or impact parameter. These exclusions affect our calculation of the planetary radius and mass, and thus could potentially change our conclusions about planetary habitability. We adopted a more robust method of transit analysis by fitting a transit model using an MCMC algorithm to iteratively solve for the best fitting transit model. Attempts at using publicly available MCMC transit fitting software, including the Transit Analysis Package (TAP; Gazak et al. 2012), EXOFAST (Eastman et al. 2013), and PyKE packages (Still & Barclay 2012), illuminated limitations in dealing with low mass and low stellar temperature cases. We found that the transit identifying function autokep built in to TAP was unable to identify the transits of these systems without first stitching together light curves from all of the quarters, folding them on their linear ephemerides, and binning the phase-folded light curve using PyKE packages. The EXOFAST transit fitter, attempted first through the TAP GUI and then use of the function directly, showed that their stellar mass-radius relation (Torres et al. 2010) was unable to handle stellar masses below 0.6 M$_\odot$ and that their limb-darkening interpolation functions were unsupported for stellar temperatures below 3500 K. While tests using EXOFAST showed that the transit solutions for $M_\ast > 0.6M_\odot$, $T_{\text{eff}} > 3500$K transits were reliable, the mass and temperature limits imposed by the program during execution were unsuitable for the stellar solutions in this study.

We modified both the EXOFAST code itself and the input transit light curves. We applied an adaptive binning algorithm to the input transit light curves to ensure that the transit itself was properly sampled. This properly preserved the shape and depth of the transits while reducing computation time with broader bins outside of transit. We took the mean time of all the data points within a bin as the bin time value, rather than the bin midpoint, to account for any clumps or gradients within a bin and aid in accurate reproduction of transit shape. We used Poisson statistics to calculate the uncertainty in the mean flux value of each bin; this led to smaller uncertainties in the out-of-transit points and larger uncertainties within the transit, which allowed EXOFAST to properly weight each binned flux value. Finally, after binning the light curves for each planet in our sample, we applied the stellar dilution corrections directly to the light curves themselves using Eq. 2.8 as before. This
produced a separate light curve for each possible planet/star permutation. EXOFAST
was then used in a mode that integrates the Mandel & Agol (2002) light curve model
over a long cadence period (29.4 minutes), a smoothing to the data that applies even
when binning within transits to shorter intervals.

Within the EXOFAST package itself, we overrode the built-in stellar mass-radius
relation from Torres et al. (2010) since the function was unreliable when extrapolated
to stellar masses below 0.6 M_☉. As we wanted to enforce our isochrone solutions for
the stellar mass and radius, we imposed those solutions as prior values and calculated
the prior widths from our uncertainties in the stellar mass and radius solutions. We
then added a penalty to the χ²calculation within EXOFAST for deviating from the
desired stellar mass and radius. The uncertainties in the stellar mass and radius
from the isochrone fitting are then accurately propagated through EXOFAST into
the posterior distributions and resulting uncertainties for the planetary values. We
utilized the online limb darkening applet from Eastman et al. (2013) to calculate
stellar limb darkening priors for our transit fitting to support calculation of limb
darkening coefficients for stellar temperatures below 3500K. The online limb darkening
utility interpolates the quadratic limb darkening tables of Claret & Bloemen (2011)
given a bandpass, effective temperature, surface gravity, and stellar metallically.
We calculated the quadratic limb darkening separately and imposed those values
as additional priors with small prior widths. In addition to priors on the stellar
properties, the planetary orbital period, and transit center time, we included a prior
restriction on the orbital eccentricity to downweight high eccentricity solutions that
are unphysical and skew the posterior distributions of all related variables.

We applied these modifications to EXOFAST and the input transit light curves
and then fit transit models to the light curves for each possible permutation of
planet and star as done previously with the analytic solutions. Before accepting
the EXOFAST solution as “good,” we assured that the reduced χ² of the transit fit
was ~ 1, that the best fit stellar parameters indicated by EXOFAST (especially the
stellar effective temperature) matched our isochrone solutions within 1σ, and that
the calculated R_P/R_☉ matched the value calculated analytically in Eq. 2.9. As the
MCMC fitting did not account for the observed HST photometry which constrained
our stellar solutions, these checks ensured that the MCMC algorithm did not diverge
from the isochrone fits or indicate a solution that was not consistent with observations.
Table 2.9: Analytic and EXOFAST Solutions for *Kepler*-296, KOI-2626, and KOI-3049 Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>$R_p$ [R$_\oplus$]</th>
<th>$a_p$ [AU]</th>
<th>$M_p$ [M$_\oplus$]</th>
<th>$\rho_p$ [g/cm$^3$]</th>
<th>$T_{eq}$ [K]</th>
<th>$S_{eff}$ [$S_0$]</th>
<th>HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Kepler</em>-296 Ac</td>
<td>2.75 ± 0.43</td>
<td>0.054</td>
<td>6.9</td>
<td>1.8</td>
<td>558.6 ± 41.0</td>
<td>22.92 ± 4.73</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>3.35 ± 0.21</td>
<td>0.054</td>
<td>8.3</td>
<td>1.2</td>
<td>606.0 ± 32.0</td>
<td>22.63 ± 2.20</td>
<td>no</td>
</tr>
<tr>
<td><em>Kepler</em>-296 Ad</td>
<td>2.88 ± 0.35</td>
<td>0.123</td>
<td>7.2</td>
<td>1.7</td>
<td>371.5 ± 27.3</td>
<td>4.49 ± 1.32</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>2.69 ± 0.21</td>
<td>0.123</td>
<td>6.8</td>
<td>1.9</td>
<td>403.0 ± 21.5</td>
<td>4.26 ± 0.98</td>
<td>no</td>
</tr>
<tr>
<td><em>Kepler</em>-296 Ab</td>
<td>2.09 ± 0.26</td>
<td>0.082</td>
<td>5.3</td>
<td>3.2</td>
<td>454.2 ± 33.3</td>
<td>10.02 ± 2.94</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>2.15 ± 0.21</td>
<td>0.082</td>
<td>5.5</td>
<td>3.0</td>
<td>495.0 ± 25.5</td>
<td>10.07 ± 4.58</td>
<td>no</td>
</tr>
<tr>
<td><em>Kepler</em>-296 Af</td>
<td>2.28 ± 0.28</td>
<td>0.266</td>
<td>5.8</td>
<td>2.7</td>
<td>252.4 ± 18.5</td>
<td>0.95 ± 0.28</td>
<td>maybe</td>
</tr>
<tr>
<td><em>Kepler</em>-296 Ae</td>
<td>2.08 ± 0.21</td>
<td>0.266</td>
<td>5.3</td>
<td>3.2</td>
<td>274.0 ± 15.0</td>
<td>0.88 ± 0.46</td>
<td>yes</td>
</tr>
<tr>
<td><em>Kepler</em>-296 Be</td>
<td>2.04 ± 0.25</td>
<td>0.176</td>
<td>5.2</td>
<td>3.4</td>
<td>310.1 ± 22.8</td>
<td>2.18 ± 0.64</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>1.86 ± 0.17</td>
<td>0.176</td>
<td>4.8</td>
<td>4.1</td>
<td>337.0 ± 17.5</td>
<td>2.04 ± 0.62</td>
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<tr>
<td>KOI-2626 A.01</td>
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<td>0.049</td>
<td>17.7</td>
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<td>450.3 ± 42.9</td>
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<td></td>
<td>3.78 ± 0.45</td>
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<td>9.3</td>
<td>0.9</td>
<td>497.0 ± 27.0</td>
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<td>KOI-2626 B.01</td>
<td>4.23 ± 0.71</td>
<td>0.110</td>
<td>19.5</td>
<td>1.4</td>
<td>299.5 ± 28.6</td>
<td>1.89 ± 0.72</td>
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<td></td>
<td>4.00 ± 0.45</td>
<td>0.110</td>
<td>17.4</td>
<td>1.5</td>
<td>331.0 ± 21.5</td>
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<tr>
<td>KOI-2626 C.01</td>
<td>3.06 ± 0.52</td>
<td>0.074</td>
<td>7.6</td>
<td>1.5</td>
<td>366.1 ± 34.9</td>
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<td></td>
<td>2.91 ± 0.63</td>
<td>0.074</td>
<td>7.3</td>
<td>1.6</td>
<td>395.0 ± 33.0</td>
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<td>KOI-2626 D.01</td>
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<td>0.239</td>
<td>8.3</td>
<td>1.2</td>
<td>203.4 ± 19.4</td>
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<td>436.0 ± 22.0</td>
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[a] The notation “*Kepler*-296 Ac” etc. indicates the solution for planet c around component A of *Kepler*-296.
[b] HZ indicates falling between the moist greenhouse inner limit and max greenhouse outer limit. A HZ value of “maybe” indicates falling within 1σ of the HZ.

### 2.2.4.3 Implications on Habitability

Table 2.9 lists the calculated planetary parameters for each planet around each potential stellar host for both the analytic method and the EXOFAST method. The tabulated EXOFAST solutions are the median values and the 68% confidence intervals on the posterior MCMC distributions. We find planetary radii that range from 1.57R$_\oplus$ to 4.23R$_\oplus$ and are larger than those listed in the Mikulski Archive for Space Telescopes\(^{19}\) (MAST) due to the dilution corrections. Regardless of the host star around which the planets orbit, all planets around *Kepler*-296 and the

\(^{19}\)http://archive.stsci.edu/
single planets around KOI-2626 and KOI-3049 are super-Earths/mini-Neptunes. Our calculated values of planetary radius are larger than those tabulated in Dressing & Charbonneau (2013) and Muirhead et al. (2012) for Kepler-296 c, Kepler-296 d, and Kepler-296 b, and larger than the radii recorded in MAST for all planets in the Kepler-296 system due to our inclusion of the transit depth dilution. Our planetary radius for KOI-2626.01 is also larger than those recorded in MAST and Dressing & Charbonneau (2013), and our radius for KOI-3049.01 is larger than the MAST value for the same reason.

Upon comparison of the analytic and EXOFAST solutions, we note that the planetary radius (rather, $R_p/R_\star$ in the calculation) and the effective stellar flux are mildly dependent on the inclusion of limb darkening, and consequently the planetary mass and equilibrium temperatures are also mildly dependent on the inclusion of higher order calculations. As expected, planets that fall in the HZ according to the analytic solutions are still habitable with the EXOFAST calculations, either falling directly within the HZ or within 1σ of the inner edge of the HZ.

Figure 2.10 displays a subset of planets that fall in or near the Habitable Zones of their potential host star according to the EXOFAST solutions and helps highlight the differences between our calculations and those of Dressing & Charbonneau (2013) and Muirhead et al. (2012). Both Dressing & Charbonneau and Muirhead et al. determined that Kepler-296 d was in the Habitable Zone of the assumed single star. Using our stellar solutions for Kepler-296, Kepler-296 d is not habitable around either star, and in fact falls significantly interior to the Habitable Zone of either star. The outermost planet in the system (Kepler-296 f) now falls comfortably within the Habitable Zones of both the primary and the secondary stars. Kepler-296 e also falls just barely interior to the Habitable Zone of the secondary, but the uncertainty on the effective stellar flux at that planet makes it another likely habitable candidate. Neither Dressing & Charbonneau nor Muirhead et al. reported on the status of Kepler-296 f or Kepler-296 e due to the timing of the two studies.

The multiplicity of KOI-2626 also changes our understanding of the habitability of its single planet. Dressing & Charbonneau report that KOI-2626.01 falls within the Habitable Zone of the assumed single star, but our results show that this is only possible around the tertiary star. The uncertainty in the effective stellar flux indicates that KOI-2626.01 may also be habitable around the primary and secondary stars despite its location interior to the HZ.
Figure 2.10: Stellar effective temperature versus effective incident stellar flux from EXOFAST in solar units for planets in and near the Habitable Zones of their respective stars. Red circles indicate *Kepler*-296 A, gold squares indicate *Kepler*-296 B, and blue triangles indicate KOI-2626. Moist and max greenhouse curves are calculated using formalism of Kopparapu et al. (2013). Any planets not shown fall significantly interior to the Habitable Zone. Planet labels as in Table 2.8.

Lastly, we find that the multiplicity of KOI-3049 does not improve its planet’s chances of habitability. Even with the stellar dilution to the transit depth accounted for, KOI-3049.01 remains well interior to the Habitable Zone around both the primary and secondary components, as it also did for the initial single-star analysis.

### 2.2.5 Discussions and Future Work

Dressing & Charbonneau (2013) report a temperature for the blended *Kepler*-296 of $3424 \pm 50$ K, while Muirhead et al. (2012) report a temperature of 3517 K based on spectral index matching. Our best-fit isochrone temperatures for both components A and B are warmer than the Dressing & Charbonneau values. However, our
temperatures do straddle the blended temperature of Muirhead et al. (2012) as expected. Mann et al. (2013) report $T_{\text{eff}} = 3622$ K for Kepler-296, which also falls between our temperatures of the individual components as expected. Likewise for KOI-2626, Dressing & Charbonneau (2013) adopt a value of $T_{\text{eff}} = 3482$ K, which falls between our values for components B and C, while Mann et al. (2013) report $T_{\text{eff}} = 3637$ K which falls between our solutions for components A and B. That our solutions agree with blended temperature estimates derived using two different methods suggests that the VR isochrones provided a logical solution for both Kepler-296 and KOI-2626. Muirhead et al. (2012) did not include the KOI-2626 system in their studies, and none of the aforementioned reports included KOI-3049.

Our initial analysis attempted to follow the procedure outlined in earlier sections of this paper, but utilizing the DSED isochrones in place of the VR isochrones. This was initially an attempt to best compare to the studies of Dressing & Charbonneau (2013) and Muirhead et al. (2012), the former of which also fit to Dartmouth isochrones and the latter which produced consistent results using spectroscopic methods. Our first results from using the Dartmouth isochrones indicated temperatures for all components that were much hotter than the temperatures reported by both studies (and later reported by Mann et al. (2013) as well). Investigating the cause of this difference, we attempted first to replicate the results of Dressing & Charbonneau (2013) regarding the temperature of Kepler-296, using the same seven bands that were used in that study (grizJHK). We were able to match the Dressing & Charbonneau (2013) $T_{\text{eff}}$ to within 100 K, and found that the inclusion on the SDSS $g$ band photometry skewed the isochrone fitting to significantly cooler temperatures. Dropping the $g$ band photometry produced a warmer midpoint between A and B temperatures and a large drop of $\chi^2$, while exclusion of any other band made little difference on the temperature midpoint or $\chi^2$. Knowing a priori the late spectral types of the targets, we observe that the inclusion of $g$ band photometry may bias some of the isochrone solutions of Dressing & Charbonneau. Photometry in the $g$ band is also observationally suspect in the KIC at those faint magnitudes (Brown et al. 2011). The photometric issues are then coupled with the uncertainties of the Dartmouth isochrones for late-type stars as discussed in Sec. 2.2.3.3. We also note that our analysis is limited to the use of optical and near-optical bandpasses, which are not the most reliable wavelength ranges for cooler stars. To mitigate this we relied more heavily on our NIR bandpass over our optical bandpass when fitting our photometry to the VR isochrones. Inclusion of
infrared bands for these targets will likely affect the temperatures derived from the isochrone fitting and reduce the differences between VR and Dartmouth isochrones.

Habitable planets in the canonical sense must not only have the capability for liquid water on the surface, but also have a solid surface on which that water can exist. In short, the planets must be rocky and not gaseous. Using radial velocity measurements coupled with Doppler spectroscopy, high-resolution imaging, and asteroseismology, Marcy et al. (2014) measured the radii and masses for 65 planet candidates and concluded that only planets with radii less than $\sim 1.5 R_\oplus$ are compatible with purely rocky compositions. Planets larger than that must have a larger fraction of low-density material, e.g. H, He, and H$_2$O. Our updated planet radii from EXOFAST indicate that none of our potentially habitable planets ($Kepler$-296 Af, $Kepler$-296 Bf, $Kepler$-296 Be, KOI-2626 A.01, KOI-2626 B.01, and KOI-2626 C.01) are small enough to have purely rocky compositions according to Marcy et al. (2014), and thus are not habitable in the canonical sense. KOI-3049 A.01, however, is within 1$\sigma$ of the purely rocky composition limit and so may still be a rocky planet. We cannot exclude the possibility of a very massive yet rocky planet like $Kepler$-10c (Dumusque et al. 2014) as we lack radial velocity measurements needed to calculate the planetary masses and densities directly. Even if $Kepler$-296 Af, $Kepler$-296 Bf, $Kepler$-296 Be, KOI-2626 A.01, KOI-2626 B.01, and KOI-2626 C.01 remain too large to be rocky, the possibility of habitable exomoons would remain.

2.2.6 Conclusion

Using the results of our $HST$ GO/SNAP program GO-12893 we derived $HST$-based photometry for the hosts of some of the most interesting $Kepler$ planet candidates and created a conversion between the broad-band Kp and our two filters from $HST$. We utilized the empirical PSF from Gilliland et al. (2015) for $Kepler$-296, KOI-2626, and KOI-3049, three $Kepler$ targets that were recently discovered to be tight multi-star systems with small and cool planets. Based on the goodness of the binary isochrone fitting, we determined that components A and B in $Kepler$-296 are almost certainly a bound, coeval system consisting of two early-M dwarfs. Based on the updated stellar properties from the Victoria-Regina Stellar Model isochrone matches, we found that the system still contains a potentially habitable planet around its primary star and two potentially habitable planets around its secondary star, with all other combinations
of star-planet producing too-hot planets. Likewise, we found that KOI-2626 is likely a bound, coeval, triple star system containing three early- to mid-M dwarfs with a single planet that is potentially habitable around any of the stellar components. Lastly, while KOI-3049 is likely also a bound, binary K dwarf system, its single planet is not habitable around either stellar component. While the sizes of Kepler-296 A, Kepler-296 B, Kepler-296 C, KOI-2626 A, KOI-2626 B, and KOI-2626 C indicate that those planets are most likely gaseous, KOI-3049 A likely has a mostly rocky compositions based on the work of Marcy et al. (2014), though it is well interior to the HZ of its star. The six potentially habitable planets have densities more consistent with a higher gaseous fraction and are not likely habitable in the canonical sense.

2.2.7 Acknowledgments

KMSC and RLG have been partially supported through grant HST-GO-12893.01-A from STScI. We thank Don VandenBerg for permitting use of the latest Victoria-Regina Stellar Models before publication. We also thank Sharon X. Wang for discussion on error analysis for our isochrone fitting.

Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts. This paper makes use of data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate. Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium. We gratefully acknowledge the use of SOA/NASA ADS, NASA, and STScI resources.
Chapter 3  
The Exo-Atmosphere of  
WASP-103b: Near Infrared Emission  
Spectrum

3.1 Near-IR Emission Spectrum of WASP-103b using  
*Hubble Space Telescope*/Wide Field Camera 3

We present here our observations and analysis of the dayside emission spectrum of the  
hot Jupiter WASP-103b. We observed WASP-103b during secondary eclipse using two  
visits of the *Hubble Space Telescope* with the G141 grism on Wide Field Camera 3 in  
spatial scan mode. We generated secondary eclipse light curves of the planet in both  
blended white-light and spectrally binned wavechannels from 1.1–1.7 µm and corrected  
the light curves for flux contamination from a nearby companion star. We modeled the  
detector systematics and secondary eclipse spectrum using Gaussian process regression  
and found that the near-IR emission spectrum of WASP-103b is featureless across the  
observed near-IR region down to a sensitivity of 175 ppm, and shows a shallow slope  
toward the red. The atmosphere has a single brightness temperature of $T_B = 2890$ K  
across this wavelength range. This region of the spectrum is indistinguishable from  
isothermal, but may not manifest from a physically isothermal system, i.e. pseudo-  
isothermal. A solar-metallicity profile with a thermal inversion layer at $10^{-2}$ bar fits  
the spectrum of WASP-103b with high confidence, as do an isothermal profile with  
solar metallicity and a monotonically decreasing atmosphere with C/O>1. The data  
rule out a monotonically decreasing atmospheric profile with solar composition, and  
we rule out a low-metallicity decreasing profile as unphysical for this system. The
pseudo-isothermal profile could be explained by a thermal inversion layer just above the layer probed by our observations, or by clouds or haze in the upper atmosphere. Transmission spectra at optical wavelengths would allow us to better distinguish between potential atmospheric models.

This section is published in the Astronomical Journal (AJ) as Cartier et al. (2017), and contains contributions from Kimberly M. S. Cartier\textsuperscript{1,2}, Thomas G. Beatty\textsuperscript{1,2}, Ming Zhao\textsuperscript{1,2}, Michael Line\textsuperscript{3,4}, Henry Ngo\textsuperscript{3}, Dimitri Mawet\textsuperscript{5,6}, Keivan G. Stassun\textsuperscript{7,8}, Jason T. Wright\textsuperscript{1,2}, Laura Kreidberg\textsuperscript{1}, Jonathan Fortney\textsuperscript{10} and Heather Knutson\textsuperscript{3}. Work in this section is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. The text in this section was written by KMSC, with editorial oversight by TGB and MZ. All authors reviewed and approved the text before publication. MZ performed the image reduction in Sec. 3.3.1 and Sec. 3.3.2 and the comparison parametric regression in Sec. 3.5.1; KS performed the SED fitting in Sec. 3.4; ML performed atmospheric retrieval in Sec. 3.6; all other analysis were performed by KMSC.

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3.2 Introduction

Spectroscopic measurements of exo-atmospheres are essential for a full characterization of exoplanet composition, temperature, and, eventually, habitability. Given the state of our current technology, transiting hot Jupiters, especially very hot Jupiters and ultra-short period Jupiters, are the best candidates for both transmission and emission spectroscopy because of their large radii, extended atmospheres, and hot equilibrium temperatures (Charbonneau et al. 2002; Deming et al. 2013; Kataria et al. 2016; Knutson et al. 2007; Sing et al. 2016; Snellen et al. 2008). Consequently, the study of exo-atmospheres has been largely limited to hot Jupiters, with super-Earths 55 Cancri e (Demory et al. 2016), HD 97658 (Knutson et al. 2014b), and GJ1214b (Bean et al. 2010; Berta et al. 2012; Désert et al. 2011; Kreidberg et al. 2014a) as notable exceptions with measured transmission spectra. Thermal emission spectroscopy, however, which measures the ratio of dayside planetary emission relative to the host star during secondary eclipse, is easily applied only to the hottest planets. By measuring the planet/star flux ratio as a function of wavelength, we can probe the atmospheric temperature at a range of pressures and heights to determine the vertical thermal profile of the atmosphere, and potentially detect the presence of molecular absorption.

A key feature of the Earth’s atmospheric profile, the stratospheric temperature inversion, is caused by absorption of UV insulation by ozone, which is an essential atmospheric component for the protection of life. A similar temperature inversion in an exo-atmosphere, detectable by thermal emission spectroscopy, would be indicative of an analogous protective compound, and is therefore a highly sought-after atmospheric feature. While hot Jupiters are much too hot for life as we know it regardless of a temperature inversion, exo-atmospheric spectra have been consistently tested against atmospheric models containing temperature inversions to seek proof of concept for future application to cooler planets. As a result of temperature constraints, titanium oxide (TiO) or vanadium oxide (VO) are prime suspects for the additional heating of
hot Jupiter stratospheres, rather than ozone or hydrocarbons (Fortney et al. 2008; Mollière et al. 2015).

However, evidence against a strong thermal inversion layer has been found for most exoplanets (Brogi et al. 2012; Charbonneau et al. 2008; Diamond-Lowe et al. 2014; Line et al. 2016; Madhusudhan & Seager 2010; Madhusudhan et al. 2011a; Schwarz et al. 2015; Stevenson et al. 2014c), supporting the hypothesis that inversions are only present in very highly irradiated hot Jupiter atmospheres ($\gtrsim 2000$ K; Charbonneau et al. 2008; Fortney et al. 2008). Spiegel et al. (2009) suggests this may be due to titanium and vanadium being constrained to solids and raining out in all but the hottest atmospheres, which would require an unusually large amount of macroscopic mixing to overcome this and produce inversions. Knutson et al. (2010) postulate that the existence of temperature inversions might be limited by the incoming stellar UV flux that likely destroys TiO and VO in the exo-atmosphere. Haynes et al. (2015) and von Essen et al. (2015) presented compelling evidence for the presence of a thermal inversion layer in the atmosphere of the highly irradiated hot Jupiter WASP-33b ($T_{\text{eq}} = 3000$ K). However, WASP-33b orbits a 7430 K star, receives a large amount of stellar UV flux, and therefore challenges the theory put forth by Knutson et al. (2010). Together, the hypotheses of Spiegel et al. (2009) and Knutson et al. (2010) suggest that thermal inversions will only be detectable in highly irradiated exo-atmospheres that receive low-UV flux, or have some mechanism to overcome TiO depletion.

The hot Jupiter WASP-103b (Gillon et al. 2014) is one of the best candidates for emission spectroscopy known to date. WASP-103b has an orbital period of only 0.92 day and orbits at only 2.978 times the stellar radius. This makes WASP-103b one of the hottest known exoplanets with a zero-albedo, complete redistribution equilibrium temperature of 2890 K. While being both highly irradiated and having an ultra-short period make WASP-103b an ideal candidate for thermal emission spectroscopy, it also orbits a relatively quiet F8V star ($T_{\text{eff}} = 6110$ K) and receives low-UV flux compared to other ultra-short period hot Jupiters. This would allow us to test the theory of Knutson et al. (2010) regarding the connection between incident UV flux and inversion strength by comparing two very hot planets (WASP-103b and WASP-33b) that receive different UV flux.

We have used Gaussian process (GP) regression to extract the first thermal emission spectrum of WASP-103b from Hubble Space Telescope/Wide Field Camera 3 (HST/WFC3) observations of WASP-103b at secondary eclipse. Gaussian process
regression has previously been used to construct the transmission spectra of HD 189733b (Gibson et al. 2012a), WASP-29b (Gibson et al. 2013a), HAT-P-32b (Gibson et al. 2013b), and most recently, CoRoT-1b (Schlawin et al. 2014), and has been applied to eclipse observations of HD 209458b (Evans et al. 2015) and LHS 6343 C (Montet et al. 2016) taken with Spitzer/Infrared Array Camera. This paper presents the first Gaussian process regression analysis of an exoplanet thermal emission spectrum taken with HST/WFC3.

We describe our HST/WFC3 observations, data calibration, and spectral extraction methods in Sec. 3.3. Sec. 3.4 details the detection of a nearby stellar source in our field of view, a probabilistic determination that the source is physically associated with WASP-103, and the modeling of the spectral energy distribution of this source. Sec. 3.5 outlines our Gaussian process regression method as applied to the blended white-light and the spectrally resolved eclipse light curves, compares our GP regression to a more traditional parametric regression technique, and presents the measured thermal emission spectrum of WASP-103b. We present atmospheric modeling of that spectrum in Sec. 3.6 and compare the spectrum of WASP-103b to those of other exoplanets to supplement our interpretation the atmospheric profile of WASP-103b and motivate future studies.

### 3.3 Secondary Eclipse Observations

We observed WASP-103 during two visits of HST on UT 2015 June 15 and 2015 June 17, and used the WFC3-IR camera and the G141 grism in spatial scan mode to provide slitless spectroscopy at wavelengths from 1.1μm to 1.7μm. Details of

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**Table 3.1: Summary of Spatial Scan Observations**

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<td>2457191.0608</td>
</tr>
<tr>
<td>Time of last scan (JD)</td>
<td>2457189.4979</td>
<td>2457191.3540</td>
</tr>
<tr>
<td>Number of HST orbits</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Observations per orbit*</td>
<td>(11)12</td>
<td>(11)12</td>
</tr>
<tr>
<td>Total number of observations</td>
<td>118</td>
<td>118</td>
</tr>
<tr>
<td>Scan rate (′′/s)</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Scan duration (s)</td>
<td>81.089</td>
<td>81.089</td>
</tr>
<tr>
<td>Detector subarray size (pixels)</td>
<td>256 × 256</td>
<td>256 × 256</td>
</tr>
<tr>
<td>Median S/N per spectral column</td>
<td>5946.43</td>
<td>5871.51</td>
</tr>
</tbody>
</table>

*The first orbit in each visit had only 11 observations, while orbits 2, 3, 4, and 5 in each contained 12 observations.*
our observations are found in Table 3.1. We obtained 10 orbits in total over the two visits, with scan durations of 81.089 s using SPARS10 and NSAMP = 12. This multivisit approach has been used in many recent WFC3-IR G141 observations of transiting planets, which have generated reliable high-precision results (e.g., 15 visits in [Kreidberg et al. (2014a); 4 visits in [Knutson et al. (2014a); 2 visits in [Huitson et al. (2013)]). The second visit of the eclipse, which proved to be consistent with the first, demonstrates repeatability and allows us to achieve higher precision at similar spectral resolution (see Sec. 3.5.6).

As shown in previous observations ([Berta et al. 2012; Deming et al. 2013; Knutson et al. 2014a; Kreidberg et al. 2014a]), the first orbit of a new WFC3-IR observing sequence always displays larger-than-usual instrumental effects as the charge traps fill from an empty state before reaching steady state in subsequent orbits ([Long et al. 2013]). We used the first orbit of each visit to capture these instrument systematics and used orbits 2 through 5 to observe the eclipse and pre- and post-eclipse baselines. Use of spatial scan mode increased the observing efficiency, minimized detector systematics caused by imperfect flat fielding, and allowed for longer observing times without saturation. We alternated between forward and reverse scan directions in order to further reduce overheads, as previously demonstrated in [Kreidberg et al. 2014a] and [Knutson et al. 2014b].

We used the 256 × 256 pixel subarray mode to reduce both readout time and data volume, which minimized overhead and time loss due to serial buffer dumps. The signal-to-noise ratio (S/N) per spectral column of each visit spanned an order of magnitude across the dispersion direction, peaking near the middle of the wavelength range, and falling off toward the edges. For Visit 1, the S/N ranged from S/N = 32.14 – 7376.23, with a median value of 5946.43, and the Visit 2 S/N ranged from S/N = 26.37 – 7371.68, with a median value of 5871.51 (Table 3.1). When measured across several (6-8) binned columns, this yielded an average regression scatter of 515 ppm for Visit 1 and 543 ppm for Visit 2, which are 3.7 and 3.9 times the photon noise levels of 139 ppm and 138 ppm, respectively. Read noise for the WFC3/IR detector is between 10 and 20 electrons according to [Dressel 2013]. This corresponds to a read noise of 0.4 ppm for a white-light curve and 7.4 ppm for a spectrally resolved light curve near the middle of the detector.
3.3.1 Background Subtraction, Flat Fielding, Subframe Alignment, Cosmic Ray Correction

To better subtract background and account for a tiny dispersion drift during spatial scan, we subtracted sequential pairs of up-the-ramp readouts within each exposure (81.089 s) to generate a set of subframe images. Each subframe image represents a shorter exposure of 7.347 s along the spatial scan direction.

Because our scan speed is very slow (0.025 s\(^{-1}\)), the point spread function (PSF) of each subframe image is substantially undersampled. This resulted in varying subframe PSFs that could not be combined as an average for outlier rejection because of under sampling and changing centroid while scanning. Therefore, we used the subframe only for trimming nearby contaminations, removing background (due to the trimming), and realignment in wavelength.

After examining the subframes, we found that the starlight from WASP-103 is strictly constrained in a relatively small area, outside of which there is only background flux. We defined a conservative mask for subframe images and used the remainder of the readout outside the mask to determine and subtract the background from each subframe image. The background is spatially flat and uniform due to the short exposure time. That background was subtracted so that all pixels in the background area of each subframe image would be zero plus noise. We then defined a smaller mask following Deming et al. (2013) and Knutson et al. (2014a), and zeroed all pixels outside of the mask. This helps to reduce noise and exclude cosmic rays (CRs) in the background area when later combining all subframes to determine the flux for each exposure. We found the optimal trim height (from the center of the image “band”) to be 25 pixels, which excludes 1.12% of total flux from the extended halo of the PSF per image.

As discussed in Mandell et al. (2013), the .flt images provided by the WFC3 calwf3\(^{12}\) calibration pipeline often yield time series with higher RMS than those with flats produced by .ima files. We therefore chose to create our own flat fields for data reduction. We determined the centroid in both the dispersion direction (\(X\)) and scan direction (\(Y\)) of each subframe and checked if there was any significant drift in the \(X\)–position of the scan on the detector. We found that the \(X\)–position drifts from different up-the-ramp subframes were well within \(\sim 0.05\) pixels. To examine if this

\(^{12}\text{Version 3.3: http://www.stsci.edu/hst/wfc3/pipeline/wfc3_pipeline}\)
tiny drift can affect final extracted flux, we convolved each column-summed subframe spectrum with a 5-pixel Gaussian kernel and then cross-correlated and aligned each subframe using a cubic spline interpolation. The resulting summed fluxes for each exposure agree well with each other before and after the alignment. Any added uncertainty from these shifts were negated by wavechannel binning (see Sec. 3.3.2).

We used the centroid information and the initial image position to generate flat fields, assuming each column had the same wavelength, since the column direction is perpendicular to the dispersion direction. We applied these flat fields to each subframe. The dispersion drift along each column was small and was accounted for during subframe alignment, and produced negligible effects during wavelength calibration.

We identified and corrected for additional CRs and bad pixels on the PSF that were not trimmed by the mask by first taking the average of multiple exposures (not subframes) from each orbit and same scan direction for normalization. We then applied a moving median filter to reject additional bad pixels and CR hits for the normalized image. Two applications of the filter with slightly different median rejection windows removed all visible spurious effects. Because of the slight drift between two different scan directions, each direction needed to be treated separately.

3.3.2 Spectral Extraction

We used the background-subtracted CR-corrected scans to extract the “white-light” flux time series in both the forward- and backward-scan directions. We summed along
each column of the subframe-aligned exposures to construct a single spectrum for each exposure (Fig. 3.1), which we then used to convolve, interpolate, and calibrate each exposure to the same wavelength scale. The spectrum for each exposure was then integrated across wavelength to generate a single white-light flux for each exposure, and it was used to create the white-light time series shown in Fig. 3.2. We used the photon noise of each exposure, calculated as $1/\sqrt{\text{rawflux}}$, as the uncertainty for each flux point in the time series. We found that any sources of noise unaccounted for in this uncertainty were later accounted for in the GP regression (see Sec. 3.5). We found the average uncertainty of the white-light time series to be $\sigma_{\text{flux}} = 138$ ppm in normalized flux units, well above the read noise of $\sim$ few ppm.

In spatial scan mode, light from the target is dispersed by the grism onto the detector, which means that the wavelength solution of each exposure is sensitive to the $X - Y$ position of the image on the detector. To create the spectrally resolved time
series for each visit and scan direction, we determined the \(X\)- and \(Y\)-centroids of each exposure, aligned each extraction aperture based on the centroids, and extracted the flux using partial pixels. This alignment accounted for any centroid shifts between exposures. We then summed the aligned spectra for incremental aperture sizes in \(Y\) and \(X\) directions. This method allowed for later optimization of the apertures for spectrophotometric extraction. The aperture optimization is discussed in more detail in Sec. 3.3.3.

The spectrum of each exposure was binned into 22 wavechannels spanning the first-order wavelength range of the grism, at a constant \(\Delta \lambda = 0.02788 \mu m\) for all but the edge bins, which were slightly wider in wavelength. The spectrally resolved time series show similar systematics to those seen in Fig. 3.2. We found that the common centroid of the aligned spectra in the dispersion direction differed from Visit 1 to Visit 2 by \(\Delta X_{V1-V2} = -0.105\) px, which produced slightly different wavelength solutions for each visit. We found that the shortest wavelength from Visit 1 was \(1.3 \times 10^{-6} \mu m\) shorter than for Visit 2, and that the Visit 1 spectrum covered a wavelength range \(4 \times 10^{-7} \mu m\) wider than Visit 2. When binned into the spectral wavechannels, this caused a shift in central bin wavelength of \(\Delta \lambda_{V1-V2} = -0.00465 \mu m\) for all wavechannels. This slight shift in central wavelength was accounted for in the flux decontamination of a nearby star (Sec. 3.4) and construction of the visit-averaged thermal emission spectrum of WASP-103b (Sec. 3.5.6).

### 3.3.3 Aperture Optimization

We found the optimum aperture for spectrophotometric extraction of each scan to determine how much the extraction aperture affected our results. We first tested for the optimum aperture in the dispersion (\(X\)) direction by extracting white-light spectra at 60 \(\Delta X\) apertures starting at \(X_{\text{centroid}} \pm 60\) pixels and increasing in 0.5-pixel increments, keeping the aperture in the scan direction fixed. We chose the aperture that produced the lowest Bayesian information criterion (BIC) at a fixed \(\Delta Y\), and found that a dispersion aperture of \(\Delta X = 68\) pixels from the \(X\)-centroid is preferred.

We then tested for the optimum aperture in the scan (\(Y\)) direction by extracting white-light spectra at 50 \(\Delta Y\) aperture heights starting at \(Y_{\text{centroid}} \pm 8\) pixels and increasing in 0.5 pixel increments, keeping the \(\Delta X\) aperture fixed at its optimum value. We then applied the initial maximization procedure as detailed in Sec. 3.5.2 to
Figure 3.3: Aperture optimization for Visit 1 (top row) and Visit 2 (bottom row), showing changing \( \ln P \) (left), standard deviation of the residuals (center), and eclipse depth (right) as a function of aperture height from \( Y - \)centroid. The vertical dashed line indicates the optimal aperture. In the rightmost panel, the horizontal dashed line and shaded region indicates the white-light eclipse depth and 1\( \sigma \) uncertainties at the optimum aperture fitted with the MCMC sampling.

the white-light eclipse curves extracted at these apertures, keeping fixed all parameters describing the physical and orbital condition of WASP-103b (i.e. system parameters as defined in Sec. 3.5) and only fitting for parameters associated with detector systematics, eclipse depth, and eclipse time (i.e. hyper- and eclipse parameters as per Sec. 3.5). This was done for both visits using only the initial amoeba maximization (downhill simplex method; Nelder & Mead 1965). We did not correct for contamination from the companion star described in Sec. 3.4. We chose the aperture with the maximum log-likelihood (Eqn. 3.3), lowest residual scatter, and a stable eclipse depth as the optimum \( \Delta Y \) aperture for spectrophotometry.

Fig. 3.3 shows the results of the aperture optimization for Visit 1 (top) and Visit 2 (bottom). We find that \( \Delta Y = 12.5 \) pixels is optimum for Visit 1 and \( \Delta Y = 16.0 \) pixels is optimum for Visit 2. The scatter in eclipse depth across apertures after the eclipse depth has stabilized is 5.8 ppm and 16.5 ppm for Visit 1 and Visit 2,
Figure 3.4: Keck NIRC2 AO image of the WASP-103 system in the $K_S$ band, with 1"0 marked for scale. In this image, the upper right star is the primary (A), and the bottom left star is the companion star (B). North is oriented upwards and east is oriented to the left. Intensity is on a logarithmic scale.

Table 3.2: Photometry of the Companion Star

<table>
<thead>
<tr>
<th></th>
<th>$J$ band</th>
<th>$H$ band</th>
<th>$K_S$ band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blended Photo</td>
<td>11.100 ± 0.023</td>
<td>10.857 ± 0.030</td>
<td>10.767 ± 0.018</td>
</tr>
<tr>
<td>$\Delta(B - A)$ (mag)</td>
<td>2.45 ± 0.07</td>
<td>2.21 ± 0.05</td>
<td>2.06 ± 0.03</td>
</tr>
<tr>
<td>Separation (mas)</td>
<td>240.5 ± 1.5</td>
<td>239.8 ± 1.4</td>
<td>239.7 ± 1.5</td>
</tr>
<tr>
<td>Position Angle</td>
<td>131.36 ± 0.35</td>
<td>131.38 ± 0.35</td>
<td>131.41 ± 0.35</td>
</tr>
</tbody>
</table>

Note—Blended photometry is from 2MASS. Separation and position angle are from Ngo et al. (2016), and $\Delta(B - A)$ is from our own PSF-fitting method.

respectively, which are much smaller than our final eclipse depth uncertainties of 63 ppm and 49 ppm. We are confident that a slight deviation in the height of our chosen aperture would not significantly impact our results.
3.4 Detection of the Companion Star

Wöllert & Brandner (2015) reported the detection of a previously unknown stellar source 0''242 ± 0''016 away from WASP-103 in i′ and z′. We imaged the WASP-103 system again in 2016 January and confirmed the nearby source using Keck NIRC2 AO observations in JHK_s. Fig. 3.4 shows a 2.5'' × 2.5'' snapshot of the full 10'' × 10'' image in K_s. There were no additional stars observed in the full NIRC2 image.

We reduced the NIRC2 images and calculated the photometry of the companion following an approach similar to that used in Zhao et al. (2014) and Bechter et al. (2014). We measured the flux ratios of WASP-103 and the companion star in J, H, and K_s bands by simultaneously fitting PSF models for both stars. We used a

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13 As discussed in Chapter 2, the presence of a closely-separated star to the transit host dilutes the transit depth (or in this case, the eclipse depth) and affected the extraction of planetary parameters from the eclipse light curve. So, in order to extract an accurate secondary eclipse spectrum from these light curves of WASP-103, we need to know the fractional contribution of flux from the companion star as a function of wavelength.

14 Regarding the timeline of detection and analysis of the companion star: Wöllert & Brandner (2015) reported the detection of a companion star near WASP-103, but did not confirm physical association with WASP-103 or a spectral type. Co-author MZ requested that co-authors HN and DM observe WASP-103 as part of their “Friends of Hot Jupiters” survey, and Ngo et al. (2016) independently detected the companion to WASP-103, performed their own PSF fitting, and reported a spectral type and angular separation for the companion. They did not confirm physical association.
Gaussian function to characterize the core of the PSF and a Moffat function to trace the extended PSF halo. Because of high Strehl ratios in the $H$ and $K_S$ bands, the images are diffraction limited and Airy rings were clearly seen in these two bands. We therefore added an Airy function to the PSF model to account for the diffraction pattern. To examine the effects of different PSF components and avoid overfitting, we fit each image with three sets of models: 1. sum of Moffat and Gaussian; 2. sum of Airy and Gaussian; 3. sum of Airy, Gaussian, and Moffat.$^{15}$ We selected the best model using the BIC. We assumed the same PSF shape for the two stars and only allowed their flux ratio to vary. Because of the high Strehl ratios in $H$ and $K_S$, the Airy, Gaussian, and Moffat is preferred in these two bands, while the Gaussian and Moffat model is preferred in the $J$ band where the Airy rings are overwhelmed by the PSF halo.

To better model the extended PSF halo while avoiding fitting on the noisy sky background, we limited the fitting range to two circular apertures of the same size (see below), centered on the centroids of the two stars. Because of their proximity, the flux of the companion star depends on the halo of WASP-103, which in turn depends on the size of the aperture. To avoid bias in choosing the best size for the field of view, which is hard to determine because of the noisy background and the faintness of the PSF halo, we fit the PSFs with a set of aperture sizes ranging from 10 to 30 pixels with a step size of 1 pixel. The flux ratio stabilizes beyond 20 pixels once the halo S/N is low and becomes dominated by background noise. The final value and uncertainty of the flux ratios are determined by taking the median and standard deviation resulting from all aperture sizes and all images in each band.$^{16}$

from their astrometric analysis, Southworth & Evans (2016) fit a spectral energy distribution to the two stars and performed an isochrone matching to extract mass, radius, and spectral types for the two stars, and also probabilistically showed that the two stars were likely bound companions. Cartier et al. (2017), working with the authors of Ngo et al. (2016), obtained NIRC2 observations of WASP-103 and very preliminary PSF fitting for the two stars. As Cartier et al. (2017) and Ngo et al. (2016) were written simultaneously, but independently, we performed our own precise PSF fitting at the same time Ngo et al. (2016) performed their more precise fitting. So, despite working from the same set of observations, these two projects obtained slightly different results from the two PSF methods.

$^{15}$Ideally, an obscured Airy function should be used. However, the low S/N ratio of the Airy rings in the images means that a normal Airy function with a Gaussian component in the center can still properly model the bulk of the ring patterns.

$^{16}$Traditional model selection techniques such as BIC are not suitable here because changing the aperture size also changes the data in the fit since many more background pixels will be included (proportional to radius$^2$). Thus, comparing BICs means comparing different data sets. As a result, the minimization of least-square residual will be biased toward fitting the background rather than...
We find that the companion star has photometry $\Delta J = 2.45 \pm 0.07$, $\Delta H = 2.21 \pm 0.05$, and $\Delta K_S = 2.06 \pm 0.03$ relative to WASP-103. (Table 3.2). The NIRC2 AO observations are also published in Ngo et al. (2016). Their reduction and PSF-fitting method of the candidate companion yielded photometry consistent with a K or M spectral type, and is described in detail in Ngo et al. (2015, 2016). Our reduction and PSF methods yielded photometry values consistent with those provided in Ngo et al. (2016). From the analysis of Ngo et al. (2016), the separation between WASP-103 and the companion star is $240.0 \pm 1.5$ milliarcseconds when averaged between bandpasses, and the companion star is located at an average position angle of $131.37 \pm 0.35$.

The companion star (source B) contributes a significant amount of flux in the near-infrared (NIR), and has a small enough separation from the WASP-103 (source A) that it contaminates our observed secondary eclipse light curves. In order to estimate the flux contamination from the companion star as a function of wavelength, we determined the spectral energy distribution (SED) of the companion star. The flux contamination ratio, $F_B/F_A$, is primarily only dependent on the effective temperature of the two stars. The SEDs of a dwarf star and a giant star at the same effective temperatures do not vary significantly at the wavelengths of interest, and so it does not have significant bearing on our SED fit whether WASP-103 and the companion star are physically associated. However, we first determined probabilistically whether the companion star is likely located at the same distance as WASP-103, then modeled the SED of the companion.

Based on highly uncertain astrometric measurements of common proper motion and companion separation, Ngo et al. (2016) were unable to conclusively determine the physical association between WASP-103 and the companion star, but retained it as a “candidate companion.” The high galactic latitude of the WASP-103 system ($l = 23.4099, b = +33.0215$) implies a low background stellar density and low probability of the random superposition of a background or foreground star. However, we quantitatively validated this assumption by simulating the stellar population along the line of sight for various fields of view (FoV) using the Besançon stellar population synthesis of the Milky Way (Robin et al. 2003). The Besançon online utility

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generates a list of stars that could theoretically be observed in a given FoV, with the option of restricting the generated list of stars based on luminosity class, galactic structure component, and a variety of stellar and observational parameters.

We wish to determine the probability of a star at least as bright as the companion star being observed in the NIRC2 images, and we wish to know the likelihood of any of those observed stars to be physically bound to WASP-103. Raghavan et al. (2010) find that physically bound companion stars follow a Gaussian distribution with respect to $\log P$ measured in days, with $\mu_{\log P} = 5.03$ and $\sigma_{\log P} = 2.28$. Statistically, the majority of companion stars with $\log P_C \leq (\mu_{\log P} + \sigma_{\log P})$ will be physically bound to the primary star. Assuming a total stellar mass of $1.5 M_\odot$, this upper limit on $\log P$ is equal to a physical separation of $\sim 10^3$ AU. When observed at the distance of the WASP-103 system ($d = 470 \pm 35$ pc), this physical separation corresponds to a projected angular separation of $2''13$. Therefore, we choose to simulate a circular FoV with a radius $r = 2''13$ centered on WASP-103, and can then state that any stars that fall within this FoV are likely to be bound to WASP-103.

Our “bound star” FoV with a radius $r = 2''13$ has an area $1.1 \times 10^{-6} \text{deg}^2$, which is smaller than the resolution of the Besançon simulation (minimum resolution of $0.01 \text{deg}^2$). In order to calculate the probability that a single star with the observed photometry could randomly fall into the bound star FoV, we simulated 28 fields of view logarithmically spaced between $0.01 \text{deg}^2$ to $10 \text{deg}^2$ and applied the Poisson probability distribution to extrapolate the probability of a single star in our field of view. For each tested FoV, we simulated a full stellar population (i.e. no assumptions on luminosity class or galactic population). To determine the probability of detecting a star at least as bright as the companion star, we filtered out stars more than $3\sigma$ fainter than the companion star in $J$, $H$, and $K_S$ (Table 3.2).

We fit a linear model to the resulting star counts as a function of FoV area ($\chi^2_{\text{lin/1.d.o.f.}} = 1.767$) and found that an average of $n = 1677.733$ stars at least as bright as the companion star are expected for a $1 \text{deg}^2$ FoV. We used the linear model to scale this value to find the average number of stars expected in our bound star FoV. Finally, using the Poisson probability distribution, we calculate $P(1 \text{ star in the bound star FoV}) = 1.842 \times 10^{-3}$. From this we conclude that the source B is likely not a random fore- or background star superimposed on the NIRC2 image, but instead is likely physically associated with the WASP-103 system.

Presuming the two stars are physically associated, we fit a theoretical SED to the
blended flux from WASP-103 and the companion star using two dwarf star spectra with model atmospheres from Castelli & Kurucz (2004). The Castelli & Kurucz (2004) models with $T_{\text{eff}} = 4000 - 7000 \, \text{K}$, $\log g = 2.0 - 4.5 \, \text{cgs}$, and $[\text{Fe/H}] = -1.5 - 0.5$ dex were selected for fitting. All available photometry was used in the SED fitting, including GALEX near-UV, APASS $BVgr$, 2MASS $JHK_{S}$, and W1 to W3 from WISE. We required that the two SED components obey the $J$, $H$, and $K_{S}$ band $\Delta$-magnitudes from the NIRC2 image listed in Table 3.2 and applied prior stellar parameters about the primary star (Gillon et al. 2014; Southworth et al. 2015) to separate out the contributions to the combined flux from each star. The SED fitting also allowed $A_{v}$ to be a fitted parameter, limited by the maximum line of sight $A_{v}$ from the Schlegel et al. (1998) dust maps. The theoretical SED solutions were verified by reblending them and determining the goodness-of-fit to the observed blended photometry.

The final reblended SED solution reproduced the observed blended photometry with a reduced $\chi^{2} = 1.02$, and is shown in Fig. 3.5. The SED fit indicates $T_{\text{eff}} = 4400 \pm 200 \, \text{K}$ for the companion star, which is consistent with a K5 V spectral type (Boyajian et al. 2012). Using the bolometric flux ratio from the SED fits and the $T_{\text{eff}}$ ratio, we obtain a radius ratio of $R_{B}/R_{A} = 0.52 \pm 0.05$. This SED solution is consistent with the values reported by Ngo et al. (2016) and Southworth & Evans (2016), who also report the mass of the companion star as $0.72 \pm 0.08 \, M_{\odot}$. We used the SED fit here to later correct the secondary eclipse spectrum of WASP-103b for contamination from the companion star. The flux decontamination is detailed in Sec. 3.5.2.

### 3.5 Gaussian Process Regression of Light Curves

Previous studies have successfully applied parametric models to capture detector systematics in spatial scan mode, and have been applied to emission and transmission spectroscopy for a multitude of exoplanets (Crouzet et al. 2014; Knutson et al. 2014b, for example). Enforcing a prespecified choice of parametric model of the systematics works well when the form of the systematics is known a priori or can be easily determined. Although we have functional forms for the WFC3 systematics in the form of a linear trend over a visit and an exponential ramp within an orbit (Deming et al. 2013; Knutson et al. 2014b; Wilkins et al. 2014), and we have some indication that
the ramp may be due to charge trapping in the detector (Agol et al. 2010), we lack a clear understanding why it would take that specific shape. Therefore, we choose a more flexible method for modeling the instrumental effects in our HST/WFC3 light curves.

GP regression eliminates the need for prespecifying a parametric model of the unknown systematics in favor of a more elastic representation of systematics and long-term trends (for a more in-depth discussion, see Gibson et al. 2012a; Grunblatt et al. 2015; Rasmussen & Williams 2006). Gibson et al. (2011) was the first to demonstrate the necessity of GP regression for modeling HST/NICMOS systematics. Subsequently, the successful application of GP regression was demonstrated on the HST/NICMOS (Gibson et al. 2012a) and later HST/WFC3 (Gibson et al. 2012b) transmission spectra of HD 189733b. While the uncertainties reported by a GP regression will often be larger than those reported by regression using a parametric model, these uncertainties and parameter values will likely be more accurate.

To find the best-fit secondary eclipse model of our data via GP regression, we calculated the likelihood function, \( L_{\text{model}} \), given by

\[
L(r|X, \Phi)_{\text{model}} = \frac{1}{(2\pi)^{n/2}|\Sigma|^{1/2}} \exp\left(-\frac{1}{2}r^T \Sigma^{-1} r\right)
\]

where \( r \) is the vector of residuals between the data values and the eclipse model, \( X \) is the vector of data locations (i.e. observation times), \( \Phi \) is the set of hyperparameters that characterize the behavior of the covariance matrix \( \Sigma \), and \( n \) is the number of data points. This likelihood function is a multivariate normal distribution. The secondary eclipse light-curve model (Mandel & Agol 2002) is explicitly calculated as part of the residual vector and is the mean of the multivariate normal distribution.

The covariance matrix, \( \Sigma \), captures the behavior of the data that cannot be attributed to the eclipse model and depicts how each value depends on each other value in the set. The matrix is populated by a covariance kernel, and by choosing an appropriate kernel to populate the covariance matrix, we can account for the effects of detector systematics without prespecifying a parametric model for these systematics. The residuals to the model should not exhibit any non-normal behavior if an appropriate kernel is chosen.

We observed in our data that not only are sequential points correlated with each other, but there is also periodicity in the correlation that corresponds to each HST
orbit. This is easily seen in Fig. 3.2 as a linear trend across the separate orbits and an exponential ramp creating a hook shape within each orbit. Therefore, we chose a quasi-periodic kernel to populate the individual elements of the covariance matrix (Grunblatt et al. 2015). Each matrix element $\Sigma_{ij}$ is given by

$$
\Sigma_{ij} = A^2 \exp\left(-\frac{\sin^2[\pi(x_i - x_j)/\theta]}{2\Omega^2} - \frac{(x_i - x_j)^2}{L^2}\right) + \delta_{ij}\sigma_i^2
$$

where $A$ is the amplitude of the covariance kernel, $\theta$ is the characteristic timescale of the periodicity, $\Omega$ is the coherence scale of the periodicity, $L$ is the characteristic time lag, $\delta_{ij}$ is the Kronecker delta, and $\sigma_i$ is the white-noise uncertainty associated with data point $x_i$. $A$, $L$, $\theta$, and $\Omega$ are the four hyperparameters that characterize the covariance kernel ($\Phi$ in Eq. 3.1) and capture the behavior of the instrument systematics. The periodic component of Eq. 3.2 containing $\theta$ and $\Omega$ accounts for the exponential ramp, and the squared-exponential component containing $L$ accounts for the linear trend in the light curve.

We also included $R_p/R_s$, $a_p/R_s$, $\cos i$, $\sqrt{e}\sin \omega_*$, $\sqrt{e}\cos \omega_*$, $R_s$, and the orbital period $P$ as free parameters in the GP regression. This set of parameters comprises the system parameters, and were included in the calculation of the eclipse model.

It should be noted that we used the nearest preceding transit center time ($T_C$), period, $\sqrt{e}\sin \omega_*$, and $\sqrt{e}\cos \omega_*$ to predict the eclipse center time, $T_S$. $T_C$ was used as a free parameter in the regression to account for inaccuracies in the linear ephemeris. The eclipse depth and transit center time are the eclipse parameters$^{18}$.

In addition to the likelihood due to specific hyperparameters and model parameters, we included additional likelihoods based on prior previous measurements of the system and logical constraints on hyperparameters. In our GP regression, we therefore maximized the combined prior and model log-likelihood function

$$
\ln(P) = \ln(L_{model}) + \ln(L_{prior})
$$

where $P$ is the complete set of parameters used in the GP regression, $L_{model}$ is the

---

$^{18}$Technically, the system and eclipse parameters are also hyperparameters of the GP as defined by Gibson et al. (2012a). However, we refer to the system and eclipse parameters separately for clarity.
likelihood from the systematic and light curve model, and $L_{\text{prior}}$ is the likelihood of the prior information. The prior probability distributions were chosen to be uniform, normal, or have no restrictions.

### 3.5.1 Comparing GP to Parametric Regression

GP regression is a relatively new technique as applied to exoplanet spectra, and thermal emission spectra in particular ([Evans et al. 2015](#) [Montet et al. 2016](#)). Exo-atmosphere spectrophotometry is typically plagued with instrumental systematics and noise that can only partially be attributed to known physical sources, such as the hook seen in HST/WFC3 scans being attributed to charge trapping in the detectors ([Long et al. 2013](#) [Wilkins et al. 2014](#)). The physical origins of other observed systematics are unknown. Even in cases where some observed systematic effect can be attributed to a physical source, we lack understanding as to why the systematic can be modeled by a particular parametric form.

Additionally, when modeling transit or eclipse light curves with a parametric approach, great care needs to be taken when attempting to combine data from multiple visits or multiple scan directions. The instrumental noise is likely different between visits and directions, and additional parameters like a multiplicative flux offset need to be included. When using the parametric approach, most studies tend to treat multiple visits and different scan directions separately, which can reduce the S/N of the light curves. The effects of common-mode (white-light) noise need to be removed from the spectrally resolved light curves before fitting to ensure that uncertainties due to common-mode noise are not being counted twice, and overestimating the uncertainties on eclipse depth. This is sometimes done by first calculating differential light curves for each wavechannel by dividing the spectrally resolved light curve by its corresponding white-light curve (preserving visit and scan direction). Each new source of noise accounted for in a parameterized regression will add a handful of new free parameters, which can quickly become computationally challenging with many visits, orbits, and scan directions.

Most of these details become much less crucial, or altogether irrelevant, when GP regression is applied to the problem. The individual sources of noise or systematic effects (e.g. common-mode, read noise, photon noise, background subtraction, charge trapping, etc.) do not need to be explicitly considered in a GP regression. Rather,
GP regression deals with the cumulative effect of all potential sources of noise on the measured light curve, and simply requires that the chosen covariance kernel is flexible enough to account for any behavior not determined by the eclipse model (Gibson et al. 2012a,b). This prevents double-counting of common-mode noise, over- or underparameterization of noise, and unknown sources of noise.

Combining different scan directions becomes trivial with GP regression, as any flux offset between the directions (which would require an additional free parameter in a parametric fit) is implicitly accounted for in the predictive mean (noise+eclipse model) of the GP regression. We verified this by first fitting the forward- and backward-scanned white-light curves separately, then combined, and compared the solutions. We found that the forward- and backward-scan solutions produced nearly identical hyperparameter solutions, but that the uncertainties on the individual fits were larger than the combined fit. When combined, any minor differences in the noise solutions of the two directions were accounted for by the covariance kernel, and the resulting uncertainties were smaller. We still chose to fit the two visits separately to demonstrate the repeatability of our measurements; if that had not been a concern, we might have combined data from two visits with similarly improved results.

We likewise tested whether fitting differential light curves instead of the spectrally resolved light curves improved the precision of the GP regression. We found that when using the same covariance kernel for the differential and non-differential fits, the resulting spectra differed by an average of only 6 ppm and had identical shapes and slopes. However, the eclipse depth uncertainties were 3% larger for the differential fits. The residuals to the differential fits also still exhibited more non-normal behavior than the non-differential fits. As the differential light curves lack the periodicity observed in the white-light curves by design, it is logical that the quasi-periodic kernel may no longer be appropriate. It is possible that regression of differential light curves using different covariance kernels might yield a precision that surpasses the non-differential fits, but they may run the risk of overfitting the data and attributing all variation to noise and none to the actual eclipse. While differential light curves present a distinct advantage when using parametric regression techniques, that advantage is not needed with GP regression provided an appropriate kernel is used, and so we fit the non-differential spectrally resolved light curves.

Ingalls et al. (2016) tested the repeatability and accuracy of various exoplanet eclipse fitting techniques, including GP regression, using real and simulated *Spitzer*
light curves of XO-3b. When compared to other fitting techniques, such as nearest neighbor kernel regression, pixel level decorrelation, and independent component analysis, GP regression produced eclipse depths that were consistent with other techniques but had larger uncertainties on those depths (see Fig. 8 and Tables 3 and 4 of Ingalls et al. 2016). However, other techniques that produced inconsistent eclipse depths had very small uncertainties. This highlights a key benefit of GP regression: a good fit produces realistic solutions and uncertainties, while a poor fit produces unrealistic parameters and unrealistic uncertainties. In short, GP produces either obvious correct answers or obvious incorrect answers. With other, less flexible methods, an incorrect answer can still have small uncertainties, which could lead to false confidence in a poor result.

We note that GP can become computationally expensive for larger datasets, as each attempt at solving Eq. 3.1 requires inversion of an $n \times n$ matrix to obtain the likelihood value. Calculating the predictive mean requires inverting a $n \times n_{\text{test}}$ matrix, with $n_{\text{test}}$ as the number of times a measurement is to be predicted, typically $\sim 10 \times n$. For datasets with hundreds or thousands of measurements, parallel computing is necessary, or application of sparse GP methods (e.g. Quiñonero-Candela & Rasmussen 2005; Walder et al. 2008).

While the GP regression should accurately account for all undesired detector behavior, we also fit our observations using a traditional parametric approach to verify that our results were not dependent on methodology. We parameterized the data with an exponential+linear trend model similar to Knutson et al. (2014b), given by

$$F(t) = c_1 \left( 1 + c_2 \times t + \sum_{i=2}^{5} c_{3,i} \times e^{-p_i/c_{4,i}} \right) \times F_{\text{LC}}(t)$$

where $t$ is the time from the start of observations, $p_i$ is the time from the start of orbit $i$, $c_1$ and $c_2$ characterize the behavior across the duration of the observation, $c_{3,i}$ and $c_{4,i}$ characterize the behavior of each orbit $i$, and $F_{\text{LC}}(t)$ is the eclipse light curve given by Mandel & Agol (2002). Each scan direction and visit was considered separately. We used bootstrap resampling to obtain uncertainties in the parametric fit in Eq. 3.4 and a Markov chain Monte Carlo (MCMC) to obtain the uncertainties in the GP regression in Eq. 3.3.

Fig. 3.6 compares the thermal emission spectrum resulting from each fitting tech-
nique for the scan-direction-combined visit-averaged light curves. We first combined the scan directions in each visit, then combined each visit to generate a visit-averaged spectrum via parametric regression. These spectra were also corrected for flux from the companion star. We found that our parametric regression and our GP regression produced spectrum behavior and eclipse depths consistent within $1\sigma$, but that the parametric fit produced larger eclipse depths than the GP regression at an average offset of $+125.72$ ppm. The RMS of the residuals to the GP regression were only slightly larger than the parametric regression (GP: 526 ppm; parametric: 521 ppm), so we know that the offset cannot be attributed to the quality of each regression.

Examination of the normality of the residuals to the (scan and visit-separated) parametric fits reveals five wavechannels that fail the Anderson-Darling normality test at the highest significance level; residuals to only one wavechannel fail the normality test in the case of GP regression. We therefore interpret the eclipse depth offset between techniques to mean that the data contain non-Gaussian noise that remains unaccounted for by the parametric model, so that additional variation was instead attributed instead to the eclipse. The GP regression produced slightly larger uncertainties in the eclipse parameters (GP: 175 ppm; parametric: 139 ppm), which was in line with our expectations for GP regression.

We verified that the GP did not overestimate the uncertainties by comparing the uncertainties on the eclipse depth generated with GP for each spectral wavechannel to what would be expected if the data had perfectly white noise. For perfectly white noise, we would expect uncertainties equal to

$$\sigma_{\text{white}} = \frac{\text{RMS(residuals)}}{\sqrt{n/2}}$$

where RMS(residuals) is the root-mean-square of the residuals to the GP regression and $n$ is the number of data points for each light curve ($n = 88$ for each wavechannel). If we had observations with perfectly white noise added, we would expect to obtain eclipse depth uncertainties of $\sim 70$ ppm. We find that, on average, the eclipse depth uncertainties are $2.5 \times$ greater than the expected white-noise uncertainty (without accounting for contamination from the companion star). It is clear, however, that the data show time-correlated noise, and accounting for the presence of this correlated noise inflates the GP depth uncertainties up by a factor of 2.5.

While the uncertainties produced by GP regression are typically larger than those produced by parametric regression, these uncertainties will account for both white
Figure 3.6: Visit-averaged spectra generated using parametric fitting (blue triangles and line) and GP regression (red points and line). Both spectra have been decontaminated for flux from the companion star. The spectra produced by each technique are both featureless and have the same slope, and the parametric regression indicates an overall hotter planet.

and time-correlated noise in the data, and will therefore be more accurate. We report the results of our GP regression for the remainder of this manuscript.

3.5.2 Regression Procedure

Here we describe the machinery of our GP regression procedure, the application of which is described in Sec. 3.5.3.

We extracted the aperture-optimized eclipse light curves from the forward and backward scans of each visit to use in our regression. We found that modeling the forward-scan direction and the backward-scan direction separately yielded worse fits, therefore we combined the forward and backward scans for the entirety of the regression. We did not combine light curves from the two visits because potentially different detector systematics visit-to-visit might not have been corrected by the GP, also to investigate the repeatability of our results. Before combining scan directions,
we trimmed the light curves to remove the first orbit of each visit, which captured the greatest detector systematics, and trimmed the first point in each remaining orbit for the same reason. Each light curve contained 88 flux measurements after trimming and combining scan directions.

We defined priors on all hyperparameters and system parameters, the values and widths of which were the same for each visit for the white-light eclipses (except for $T_C$). For the spectral data we used priors based on the results of each visit’s white-light results. We set the prior value of the characteristic timescale of the periodicity, $\theta$, to match the timescale of an HST orbit ($\theta = 0.06628 \pm 0.00003$ day) for all light curves, knowing a priori that this is the timescale on which the systematic trend repeats. We determined the $\theta$ prior from observations of the HST’s orbital elements, provided by archival two-line element sets for HST for the dates of our two visits obtained by emailing the United States Joint Functional Component Command for Space.

While this prior is very restrictive, in initial tests where we allowed $\theta$ more freedom to vary, the posterior on $\theta$ still converged on the orbital periodicity. However, when coupled with similarly unrestricted priors for $A$, $L$, and $\Omega$, the GP sometimes attempted to fit the noise rather than the eclipse, reported erroneously small eclipse depths, and yielded very poor fits on other parameters. Since a prior value and uncertainty on $\theta$ is physically motivated by our system (but not so for other hyperparameters), we adopted the listed value to gain higher confidence in the GP regression and allow freer exploration of the other hyperparameters. We are confident that restricting $\theta$ to the HST orbital timescale does not adversely affect the regression.

Given these prior values, we used an amoeba maximization to find an initial best fit to the eclipse light curve, the results of which were then fed as starting values into an MCMC sampling of Eq. 3.3. We used the differential evolution Monte Carlo algorithm from the EXOFAST package (Eastman et al. 2013) to explore the parameter space around the amoeba solution. The median and 1σ values from the MCMC chains were used to calculate the predictive mean (eclipse model and systematics) of the likelihood function defined in Eq. 3.1.

### 3.5.3 White-light and Spectral Regression

We first fit secondary eclipse light curve models to the blended white-light data for each visit as described in Sec. 3.5.2. In the initial fits, we used as priors the Southworth
Table 3.3: Prior values, widths, and shapes for white-light regression

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value±Width</th>
<th>Distribution Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1 ± 0.1</td>
<td>Unrestricted</td>
</tr>
<tr>
<td>L (day)</td>
<td>$\tau_{14,s}/2 \leq L \leq 20$</td>
<td>Uniform</td>
</tr>
<tr>
<td>$\theta$ (day)</td>
<td>0.06628 ± 0.00003</td>
<td>Normal</td>
</tr>
<tr>
<td>$\Omega$ (day)</td>
<td>$\tau_s \leq \Omega \leq 20$</td>
<td>Uniform</td>
</tr>
<tr>
<td>$R_P/R_S$</td>
<td>0.1158 ± 0.0006</td>
<td>Normal</td>
</tr>
<tr>
<td>$a_P/R_S$</td>
<td>2.9398 ± 0.03</td>
<td>Normal</td>
</tr>
<tr>
<td>$\cos i$</td>
<td>0.032 ± 0.017</td>
<td>Normal</td>
</tr>
<tr>
<td>\sqrt{\varepsilon\cos \omega_*}</td>
<td>0 ± 0.01</td>
<td>Normal</td>
</tr>
<tr>
<td>\sqrt{\varepsilon\sin \omega_*}</td>
<td>0 ± 0.01</td>
<td>Normal</td>
</tr>
<tr>
<td>$R_S$ ($R_\odot$)</td>
<td>1.419 ± 0.055</td>
<td>Normal</td>
</tr>
<tr>
<td>Period (day)</td>
<td>0.9255 ± 0.00002</td>
<td>Normal</td>
</tr>
<tr>
<td>Eclipse Depth (ppm)</td>
<td>0.001 ± 0.001</td>
<td>Unrestricted</td>
</tr>
<tr>
<td>$T_{C,V1}$ (JD)</td>
<td>2457188.923 ± 0.001</td>
<td>Normal</td>
</tr>
<tr>
<td>$T_{C,V2}$ (JD)</td>
<td>2457190.774 ± 0.001</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Note—All priors are the same for Visit 1 and Visit 2 except where explicitly indicated with “V1” and “V2.” For Distribution Type “Unrestricted,” no prior limits were placed on this parameter, and the listed values were used as starting points and scale lengths for the amoeba maximization.

Southworth et al. (2015) values for $R_P/R_S$, $\cos i$, orbital period, and $a_P/R_S$ and assumed a near-circular orbit with small argument of periastron. The prior values, widths, and shapes for all hyperparameters, system parameters, and eclipse parameters are listed in Table 3.3. $R_S$ together with $a_P/R_S$ was used to calculate and correct for the Roemer delay (i.e. the light travel time) across the orbit to accurately determine the secondary eclipse time. The lower limits on $L$ and $\Omega$ were chosen to be half of the transit duration ($T_{14,s}/2 = 0.054$ day) and the ingress/egress duration ($\tau_s=0.01$ day), respectively. This ensured that the GP regression modeled the systematics across the orbit instead of fitting the scatter between the points. The upper limits on $L$ and $\Omega$ ensured that these hyperparameters did not become so large that changes to these hyperparameters dominated the calculation of $\ln(P)$.

Southworth et al. (2015) found that WASP-103b is slightly aspherical as a result of its close-in orbit. It has a Roche-lobe filling factor of 0.58 and an equatorial radius 2.2% larger than the polar radius. We tested whether assuming a spherical or aspherical prior value for $R_P$ affected the measured eclipse depth while using a spherical eclipse model, i.e. how robust the GP regression is to small changes in $R_P$ prior without changing the eclipse model. We fit the light curve model to the white-light data of each visit via GP regression and MCMC sampling using both the best-fit spherical and aspherical radius values from Southworth et al. (2015) as priors.
Table 3.4: White-light Solutions from GP Regression

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Visit 1</th>
<th>Visit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.141 ± 0.19</td>
<td>0.049 ± 0.045</td>
</tr>
<tr>
<td>L (day)</td>
<td>9.8 ± 3.4</td>
<td>10.3 ± 3.4</td>
</tr>
<tr>
<td>θ (day)</td>
<td>0.06628 ± 0.00004</td>
<td>0.06628 ± 0.00004</td>
</tr>
<tr>
<td>Ω (day)</td>
<td>9.7 ± 3.4</td>
<td>9.6 ± 3.4</td>
</tr>
<tr>
<td>(R_P/R_S)</td>
<td>0.1158 ± 0.0008</td>
<td>0.1158 ± 0.0009</td>
</tr>
<tr>
<td>(a_P/R_S)</td>
<td>2.86 ± 0.048</td>
<td>3.006 ± 0.058</td>
</tr>
<tr>
<td>cos i</td>
<td>0.025 ± 0.021</td>
<td>0.035 ± 0.026</td>
</tr>
<tr>
<td>(\sqrt{e}\cos\omega_*)</td>
<td>−0.003 ± 0.014</td>
<td>−0.039 ± 0.025</td>
</tr>
<tr>
<td>(\sqrt{e}\sin\omega_*)</td>
<td>0.000 ± 0.014</td>
<td>−0.001 ± 0.018</td>
</tr>
<tr>
<td>(R_S (R_\odot))</td>
<td>1.436 ± 0.056</td>
<td>1.436 ± 0.057</td>
</tr>
<tr>
<td>Period (day)</td>
<td>0.92555 ± 0.00003</td>
<td>0.92555 ± 0.00003</td>
</tr>
<tr>
<td>Eclipse Depth (ppm)</td>
<td>1246 ± 63</td>
<td>1196 ± 49</td>
</tr>
<tr>
<td>(T_S) (JD)</td>
<td>2457189.38 ± 0.0008</td>
<td>2457191.23 ± 0.0012</td>
</tr>
<tr>
<td>(T_C + t_*) (JD)</td>
<td>2457188.92 ± 0.0008</td>
<td>2457190.99 ± 0.0008</td>
</tr>
<tr>
<td>(T_{14,S}) (day)</td>
<td>0.1177 ± 0.0021</td>
<td>0.1113 ± 0.0012</td>
</tr>
<tr>
<td>(\tau_S) (day)</td>
<td>0.0128 ± 0.00027</td>
<td>0.0121 ± 0.00033</td>
</tr>
</tbody>
</table>

\textit{Note}—The eclipse depth and uncertainties have not been decontaminated for flux from the companion star.

for the regression. In comparing the two solutions, we found that the residuals within each fit are 374.1 times greater than the residuals between the two solutions. From this we conclude that any impact on our regression caused by the planetary asphericity is accounted for in the MCMC sampling\(^{19}\). We set the prior value of the planetary radius to the spherical value, \(R_P = 1.554 ± 0.044\), for simplicity.

We fit the blended white-light data for each visit at the optimum aperture via GP regression with MCMC sampling using the priors listed in Table 3.3. The eclipse, system, and hyperparameter solutions from GP regression of the white-light eclipses are listed in Table 3.4. We used the white-light solutions to calculate the corrected transit center time, \(T_C + t_*\), eclipse duration, \(T_{14,S}\), and the eclipse ingress/egress duration, \(\tau_S\), for completeness.

We find that the white-light solutions for Visit 1 and Visit 2 are consistent with each other within 1σ, with similar uncertainties on parameters for each visit. We find that except for the characteristic timescale of periodicity in the covariance kernel (\(\theta\)), which was known very precisely a priori, each of the hyperparameters has relatively large uncertainties. This is because once the timescale for \(L\) or \(\Omega\) greatly exceed the duration of our observations, the covariance matrices generated using these large

\(^{19}\)That is, any differences are much smaller than our regression precision.
Figure 3.7: Secondary eclipse light curves for spectral wavechannel data detrended for detector systematics via GP regression, before correction for flux contamination. Open circles and solid line indicate Visit 1 data and model, respectively, and open squares and dashed lines indicate Visit 2 data and model, respectively. A vertical offset is added for clarity. Wavechannels are color coded and labeled by the visit-averaged wavelength, $\bar{\lambda}$.

hyperparameter values are degenerate within the timescale of our data. For example, the covariance between our first and last observations, which are separated by $\sim 0.29$ day, is effectively the same for covariance timescales of $L = 5$ and $L = 15$. However, as long as $L$ and $\Omega$ remain above their lower limit values, we find that the uncertainties on these hyperparameters do not significantly impact the precision of the eclipse depth.\footnote{For regression attempts where $L$ or $\Omega$ was allowed to reach values below the lower limit listed in Table 3.3, the GP model effectively attributed all inter-orbit variations to noise and not to the eclipse itself, resulting in anomalously small eclipse depths.} As expected, the posterior widths for nearly all fitted parameters, including $\theta$, are slightly wider than the prior widths, as the GP and MCMC compound the parameter uncertainties regardless of the prior distribution shape (within allowed boundaries).

We used the white-light solution at the optimum aperture as starting values and prior probabilities for fitting the binned spectral data via GP regression. We used the same priors on $L$ and $\omega$ as used in the white-light fit. As the binned spectral data do
not have much leverage on the system parameters, we held all system parameters \((R_P/R_S, a_P/R_S, \cos i, \sqrt{e \cos \omega_s}, \sqrt{e \sin \omega_s}, \text{and } R_S)\) fixed at their white-light values for the regression (Table 3.4), and only fit the four hyperparameters \((A, L, \theta, \text{and } \Omega)\) and the two eclipse parameters (eclipse depth and eclipse center time) for each of the 22 spectral wavechannels as described in Sec. 3.5.2. We also combined forward- and backward-scan directions in each wavechannel to improve the S/N of the data.

Fig. 3.7 shows the eclipse light curves in each wavechannel with the detector systematics removed and the best-fit eclipse models overplotted. As seen in Fig. 3.7, the GP regression was able to capture the correlated noise in the eclipse light curves, which allowed for more precise light-curve regression.

### 3.5.4 Flux Decontamination

Before constructing the final thermal emission spectrum, we corrected each wavechannel for contamination from the companion star as described in Sec. 3.4. The eclipse depths obtained through the GP regression do not represent the true planet/star flux ratio until after flux decontamination. We extracted flux contamination ratios at the central wavelengths of each wavechannel on each visit from the SED models for the primary and companion components, accounting for slight differences in wavelength solutions for each visit. The contamination ranged between \(\sim 9\%\) for the shortest wavelengths and \(\sim 17\%\) for the longest wavelengths. The decontaminated eclipse depth yields the true planet/star flux ratio, \(F_P/F_S\), which is given by

\[
\frac{F_P}{F_S}(\lambda) = d_\lambda \times \left[1 - \frac{F_B}{F_A}(\lambda)\right]^{-1}
\]

where \(d_\lambda\) is the eclipse depth before flux decontamination and \(F_B/F_A(\lambda)\) is the fractional contribution of flux from the companion star at wavelength \(\lambda\). The flux contamination ratios for each visit in each wavechannel are listed in Table 3.5. The contamination ratios we calculate are consistent with the values reported by Southworth & Evans (2016), who calculate the contamination from the companion star for Bessel RI and griz passbands. We note that with this method we are simply scaling the eclipse depths and uncertainties by the contamination ratio, and do not incorporate the added (minor) uncertainty of the flux contamination ratio itself.
Table 3.5: Flux contamination ratio due to the companion star for Visits 1 and 2

<table>
<thead>
<tr>
<th>λ1 (µm)</th>
<th>F_B/F_A(λ1)</th>
<th>λ2 (µm)</th>
<th>F_B/F_A(λ2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0783</td>
<td>0.0922</td>
<td>1.0829</td>
<td>0.0923</td>
</tr>
<tr>
<td>1.1108</td>
<td>0.0952</td>
<td>1.1155</td>
<td>0.0955</td>
</tr>
<tr>
<td>1.1387</td>
<td>0.0965</td>
<td>1.1433</td>
<td>0.0968</td>
</tr>
<tr>
<td>1.1666</td>
<td>0.0997</td>
<td>1.1712</td>
<td>0.1004</td>
</tr>
<tr>
<td>1.1945</td>
<td>0.1016</td>
<td>1.1991</td>
<td>0.1015</td>
</tr>
<tr>
<td>1.2233</td>
<td>0.1050</td>
<td>1.2270</td>
<td>0.1055</td>
</tr>
<tr>
<td>1.2502</td>
<td>0.1074</td>
<td>1.2549</td>
<td>0.1080</td>
</tr>
<tr>
<td>1.2781</td>
<td>0.1118</td>
<td>1.2828</td>
<td>0.1163</td>
</tr>
<tr>
<td>1.3060</td>
<td>0.1132</td>
<td>1.3107</td>
<td>0.1126</td>
</tr>
<tr>
<td>1.3339</td>
<td>0.1158</td>
<td>1.3385</td>
<td>0.1167</td>
</tr>
<tr>
<td>1.3618</td>
<td>0.1186</td>
<td>1.3664</td>
<td>0.1199</td>
</tr>
<tr>
<td>1.3897</td>
<td>0.1228</td>
<td>1.3943</td>
<td>0.1242</td>
</tr>
<tr>
<td>1.4175</td>
<td>0.1273</td>
<td>1.4222</td>
<td>0.1279</td>
</tr>
<tr>
<td>1.4454</td>
<td>0.1315</td>
<td>1.4501</td>
<td>0.1321</td>
</tr>
<tr>
<td>1.4733</td>
<td>0.1352</td>
<td>1.4779</td>
<td>0.1364</td>
</tr>
<tr>
<td>1.5012</td>
<td>0.1360</td>
<td>1.5058</td>
<td>0.1376</td>
</tr>
<tr>
<td>1.5291</td>
<td>0.1454</td>
<td>1.5337</td>
<td>0.1463</td>
</tr>
<tr>
<td>1.5570</td>
<td>0.1508</td>
<td>1.5616</td>
<td>0.1512</td>
</tr>
<tr>
<td>1.5848</td>
<td>0.1547</td>
<td>1.5895</td>
<td>0.1559</td>
</tr>
<tr>
<td>1.6127</td>
<td>0.1600</td>
<td>1.6174</td>
<td>0.1602</td>
</tr>
<tr>
<td>1.6406</td>
<td>0.1639</td>
<td>1.6453</td>
<td>0.1647</td>
</tr>
<tr>
<td>1.6824</td>
<td>0.1660</td>
<td>1.6871</td>
<td>0.1662</td>
</tr>
</tbody>
</table>

3.5.5 Normality of Residuals

For a GP regression to be deemed successful, the residuals to the model should not contain any non-Gaussian behavior. We therefore tested the residuals of the spectral GP regression for normality using the Anderson-Darling test (A-D test; D’Agostino & Stephens 1986; Feigelson & Babu 2012; Gross & Ligges 2015). The A-D test states that if the A-D statistic, $A^2$, is above a critical value, then the hypothesis that the data are drawn from a normal distribution is rejected at a specified significance level. A significance level of $\alpha = 0.01$ (1% significance) corresponds to the probability of observing the tested phenomenon by chance. The critical values depend on the number of points in the sample and the desired significance level of the result.

We adjusted the A-D statistic for the unknown mean and variance of the prior distribution (i.e. a Case 3 A-D test) using

$$A^* = A^2 \left(1 + \frac{0.75}{n} - \frac{2.25}{n^2}\right),$$

(3.7)

where $A^2$ is the unadjusted A-D statistic and $n$ is the number of points in the sample. For our spectral GP regression, $n = 88$ for each light curve after clipping the first orbit, trimming the first point in each remaining orbit, and combining the forward
Figure 3.8: Left: empirical distribution function of residuals to Gaussian process regression of Visit 1, $\lambda = 1.0783$ $\mu$m light-curve in ppm (black connected dots), which passes the A-D test for normality at 10% significance, compared to that of a normal distribution (red solid line). Right: same as left for Visit 2, $\lambda = 1.1155$ $\mu$m, which does not pass the A-D test at 1% significance.

and backward scans.

We computed the adjusted A-D statistic for the white-light and each wavechannel in Visit 1 and Visit 2 for 10% ($A_{\text{crit}} = 0.6287$), 5% ($A_{\text{crit}} = 0.7468$), and 1% ($A_{\text{crit}} = 1.0379$) significance levels. The A-D test indicates that we cannot reject normality for white-light residuals for either visit at the 1% significance level. The A-D test further indicates that we cannot reject normality at the 1% significance level for any wavechannel except $\lambda = 1.5058$ $\mu$m in Visit 2 ($A^{*2} = 1.069$), and the normality of only a few wavechannels is rejected at the 5% or 10% level in either visit. When comparing the empirical distribution function (EDF) of the residuals for Visit 2 $\lambda = 1.5058$ $\mu$m to the EDF of a normal distribution (Fig. 3.8 right), we clearly see the deviation from normality when compared to the EDF of a wavechannel that passes the A-D test at high significance level (Fig. 3.8 left). As Visit 2 $\lambda = 1.5058$ $\mu$m is only 0.4401 higher than the 10% critical value, we are confident that the effects of non-normality on the residuals of that wavechannel are minimal, and are accounted for in the uncertainties generated from MCMC.
3.5.6 Thermal Emission Spectrum of WASP-103b

The methods described in Sec. 3.5 were applied to the secondary eclipse light curves in each spectral wavechannel observed during each of the two visits with HST to produce the thermal emission spectrum shown in Fig. 3.9 and listed in Table 3.6. The longest wavechannel, centered around 1.7\(\mu\)m showed an anomalously low eclipse depth with a very poor fit for both visits. This was likely due to edge effects resulting from the wavechannel binning, and so the final wavechannel was dropped from both Fig. 3.9 and further analysis. We averaged spectra between the two visits of HST to calculate the average wavelength, \(\bar{\lambda}\), and average planet/star flux ratio, \(\bar{F}_P/\bar{F}_S\), which were used to retrieve atmospheric models and compare to other exo-atmospheres.

The thermal emission spectrum of WASP-103b is featureless across the observed near-IR region down to a sensitivity of 175 ppm, and it exhibits a shallow positive slope toward the red. No significant water absorption is apparent in the 1.4\(\mu\)m water
Table 3.6: Thermal emission spectrum of WASP-103b for separate and averaged visits

<table>
<thead>
<tr>
<th>Visit 1</th>
<th></th>
<th>Visit 2</th>
<th></th>
<th>Averaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ (Â-1)</td>
<td>(F_P/F_S)(ppm)</td>
<td>λ (Â-1)</td>
<td>(F_P/F_S)(ppm)</td>
<td>λ (Â-1)</td>
</tr>
<tr>
<td>1.0783</td>
<td>1320.3±341</td>
<td>1.0829</td>
<td>1353.6±312</td>
<td>1.0896</td>
</tr>
<tr>
<td>1.1108</td>
<td>1326.8±259</td>
<td>1.1155</td>
<td>1321.3±238</td>
<td>1.1131</td>
</tr>
<tr>
<td>1.1387</td>
<td>1256.7±237</td>
<td>1.1433</td>
<td>1255.2±223</td>
<td>1.1410</td>
</tr>
<tr>
<td>1.1666</td>
<td>1327.4±227</td>
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<td>1.1689</td>
</tr>
<tr>
<td>1.1945</td>
<td>1120.1±220</td>
<td>1.1991</td>
<td>1290.3±212</td>
<td>1.1968</td>
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<tr>
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<tr>
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<td>1341.3±211</td>
<td>1.2526</td>
</tr>
<tr>
<td>1.2781</td>
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<td>1.2828</td>
<td>1209.7±218</td>
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<tr>
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<td>622.5±362</td>
<td>1.6871</td>
<td>962.6±392</td>
<td>1.6848</td>
</tr>
</tbody>
</table>

Note—These flux ratios have been corrected for flux from the companion star.

21 A future test to verify the lack of absorption features in the emission spectrum could include creating a synthetic multicolor photometry transit curve for WASP-103b with and without water absorption at 1.4 Â-1 to see if the GP regression does in fact recover the water absorption correctly for realistic S/N data with real noise spectrum. This would ensure that the GP regression process is not somehow optimizing away important features in the data.
Figure 3.10: Left: atmospheric models (binned to low resolution) tested against the visit-averaged thermal emission spectrum of WASP-103b in the near-IR (black points). Blue corresponds to a solar metallicity atmosphere with a thermal inversion, yellow corresponds to a decreasing atmosphere with C/O>1, red corresponds to an isothermal atmosphere at solar metallicity, and green and gray correspond to a decreasing atmosphere at low-metallicity and solar metallicity, respectively. Reduced \( \chi^2_r \) values are listed for each model. Right: the vertical pressure-temperature profiles associated with the tested atmospheric models. Model colors are the same as in the left panel, and the gray shaded region indicates the atmospheric pressures probed by our observations. The low-metallicity solar and high C/O profiles are identical, and overplotted with alternating dashed colors.

3.6 The Atmosphere of WASP-103b

Here we discuss using the emission spectrum of WASP-103b to model the planetary atmosphere, and compare the spectrum of WASP-103b to the emission spectra of other exoplanets measured with HST/WFC3. We also discuss directions for future research that would further help our understanding of the WASP-103b atmosphere.

3.6.1 Atmospheric Modeling

We used the thermal emission forward model outlined in Line et al. (2013a) to retrieve the thermal profile of the WASP-103b atmosphere, which uses the Parmentier & Guillot (2014) analytic parameterization of an irradiated non-grey atmosphere. This method uses four parameters to control the “shape” of the thermal profile (a visible
opacity, two infrared opacities, and the fractional energy split between the two infrared opacities), and one parameter that controls the temperature shift. The relatively featureless nature of the WASP-103b spectrum made finding a unique atmospheric model fit to the data difficult.

Because of this, we selected a few fiducial atmosphere types that appear frequently in the literature to provide representative solutions. For each atmosphere type, the shape of the temperature profile was held fixed to some standard profile shape, and the fit was reduced to the best temperature shift for that shape. It is possible that better-fitting atmospheric models could be found by iterating shape and shift adjustments (e.g. Line et al. 2016), but significant improvement on the model atmosphere fits would require additional data with better leverage on the models.

We tested our visit-averaged spectrum against five fiducial models: monotonically decreasing atmospheres at solar metallicity, 0.01×solar metallicity ([Fe/H] = −2), and a C/O ratio >1, an isothermal atmosphere at solar metallicity, and a solar-metallicity atmosphere with a stratospheric thermal inversion (Fig. 3.10). The monotonically decreasing atmosphere at solar metallicity is rejected via a $\chi^2$ rejection test with 20 degrees of freedom at $\chi^2/d.o.f. = 2.166^{22}$.

The other four scenarios all provide similar, acceptable fits to the spectrum, and therefore we cannot determine which is likely to be correct. Planets are more likely to be enhanced in refractory metals relative to their host star, rather than depleted (Ramírez et al. 2014; Thorngren et al. 2015). Given the reported near-Solar metallicity of WASP-103 of [Fe/H] = 0.06 ± 0.13, it is unlikely that WASP-103b is significantly depleted in metals, therefore we disfavor the 0.01×solar decreasing model case based on physical, rather than statistical, grounds ($\chi^2/d.o.f. = 0.439$). The enhanced C/O atmosphere provides an acceptable fit to the spectrum at $\chi^2/d.o.f. = 0.670$. As no causal link has been established between enhanced C/O and other observable properties of the planetary system, we cannot rule out the enhanced C/O atmospheric model. However, as no other compelling evidence yet exists to suggest that WASP-103b has an enhanced C/O ratio, we do not find this model very plausible.

Solar metallicity profiles with an isothermal structure at $T = 2890$ K ($\chi^2/d.o.f. = 0.517$) and a thermal inversion layer near the $10^{-2}$ bar pressure level ($\chi^2/d.o.f. = 0.398$) provide equally acceptable fits to our spectrum. Across the region of interest, the isothermal and inversion model both show little to no variation in temperature.

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22 The longest wavechannel was left out of the $\chi^2$ tests.
Given the narrow wavelength range probed and uncertainties of our eclipse depths, we have little power to distinguish between any model that is approximately isothermal in this region. However, the isothermal and thermally inverted models both have a hotter temperature at high altitudes than expected in a monotonically decreasing atmosphere in radiative equilibrium. Since a monotonically decreasing atmosphere should be a good zeroth-order model for an exo-atmosphere, the isothermal and inverted atmospheric models both would require high-altitude absorbers.

Fig. 3.10 (right) highlights that our observations probe an atmospheric pressure at which most models deviate only slightly from the isothermal case, making it extremely difficult to differentiate between models. While the spectrum may be indistinguishable from isothermal across this wavelength range, it may therefore not manifest from a physically isothermal system, i.e. pseudo-isothermal. The pseudo-isothermal spectrum indicated by these data could be due to any number of atmospheric phenomena that we cannot detect with our spectrum, including a cloud deck at $P \sim 10^{-2}$ bar, high-altitude haze, or a large radiative zone. Alternately, as the right-hand side of Fig. 3.10 suggests, the region probed by our observations may capture the inflection point just below a thermal inversion layer. Our HST observations have restricted the range of possible thermal profiles, including the altitude of a potential absorber, and indicate a single brightness temperature of $T_B = 2890$ K across this wavelength range.

If the isothermal or inverted models are correct, then some additional heating is required in the upper atmosphere, which is indicative of some species of higher-altitude molecule that absorbs radiation in the visible and radiates that energy isotropically in the infrared, thus heating the lower layers in the atmosphere. For WASP-103b, this high-altitude absorber is probably TiO \cite{Fortney et al. 2008}, which could be detected through observations probing higher altitudes in the atmosphere (i.e. shorter wavelengths). Additional eclipse or transit observations at wavelengths shorter than those considered in this study would likely be able to distinguish more clearly between clearly between the enhanced C/O, isothermal, and inverted models and reveal the presence of a high-altitude absorber or other atmospheric phenomena.
Figure 3.11: Comparisons of normalized planetary spectra taken with HST/WFC3/G141 across the 1.1–1.7 µm range. In all panels, the visit-averaged spectrum of WASP-103b is shown in open black squares and the comparison planet's spectrum is shown in solid red points. Spectra have been normalized to the average flux value between 1.2–1.3 µm. Published values of planetary temperature and atmospheric features are included for each comparison planet. References for spectra are found in the text.
3.6.2 Comparisons to Other Planets

We compare the planetary spectrum of WASP-103b to other exoplanets for which a 1.1–1.7\(\mu\)m emission spectrum has been measured with HST/WFC3 G141 in Fig. 3.11. We calculated the absolute planetary emission spectra by retrieving stellar spectra from the NASA Infrared Telescope Facility Spectral Library (IRTF; Rayner et al. 2009) matched to the nearest spectral subtype, and using the planet/star flux ratio to rescale the stellar spectrum to planetary values. For solar- and earlier-type stars, use of an IRTF spectrum had minimal effect compared to stellar spectra approximated as a blackbody. For K-type stars (WASP-43 and TrES-3) the IRTF spectra accounted for molecular absorption and were measurably different from a blackbody, therefore we used IRTF spectra for all spectral types to facilitate comparison. All planetary spectra were normalized to their continuum flux levels between 1.2–1.3\(\mu\)m for ease of comparison.

Observations of WASP-33b (Haynes et al. 2015; von Essen et al. 2015) have provided strong evidence for the presence of a thermally inverted atmosphere. When we compare the planetary spectrum of WASP-103b to that of WASP-33b binned to similar wavechannels (Fig. 3.11; top left), we note that the two spectra appear to be very similar in this wavelength range. When combined with their additional ground-based, HST, and Spitzer data, Haynes et al. (2015) were able to make a stronger case for a thermally inverted atmosphere than we are able to make with our single measurement of the WASP-103b spectrum.

When compared to the spectrum of WASP-43b (Kreidberg et al. 2014b) and HD 209458b (Line et al. 2016), which have significant water absorption at 1.4\(\mu\)m, it becomes clear that the WASP-103b spectrum does not display any significant absorption that would be due to \(\text{H}_2\text{O}\) (Fig. 3.11; top center and right, respectively). The decreasing atmospheric profiles of TrES-3b (subsolar \(\text{H}_2\text{O}\); Ranjan et al. 2014) and HD 189733b (solar \(\text{H}_2\text{O}\); Crouzet et al. 2014) adequately match the WASP-103b spectrum because of the large scatter and uncertainties in their data (Fig. 3.11; middle center and right, respectively). However, at the higher S/N of the WASP-4b spectrum (Ranjan et al. 2014) the WASP-103b spectrum is inconsistent with an \(\text{H}_2\text{O}\)-depleted decreasing profile (Fig. 3.11; middle left).

The isothermal profile of TrES-3b (Ranjan et al. 2014) and the pseudo-isothermal profile of CoRoT-2b (Wilkins et al. 2014) also closely agree with WASP-103b (Fig.
as does the monotonically decreasing profile of Kepler-13b reported by Beatty et al. (2016a) (Fig. 3.11; bottom center) and the enhanced C/O-decreasing profile of WASP-12b of Stevenson et al. (2014b) (Fig. 3.11; bottom right), each to within $2\sigma$. These are consistent with our atmospheric matches shown in Fig. 3.10. That the WASP-103b spectrum appears to be similar to those of planets with varying profile shapes indicates that WFC3 observations are not very discriminatory in this wavelength range given the lack of absorption features, and at best indicate a pseudo-isothermal profile.

The fact that we only see evidence of inversions and (perhaps) TiO absorption in the transmission spectra of the most highly irradiated planets, such as WASP-33b and WASP-103b, is consistent with the hypothesis that cold traps in the interior and on the night side are removing TiO from the atmospheres of more moderate hot Jupiters such as HD 209458b and WASP-43b (Spiegel et al. 2009). WASP-103b will be a key planet for understanding the behavior of TiO in a hot Jupiter atmosphere, and for validating hypothesis about the origin of thermal inversions. Further measurements of WASP-103b are necessary towards this effort.

### 3.6.3 Future Work

Future work on WASP-103b should focus on verifying the presence of a thermal inversion in its atmosphere by probing the atmospheric layers in different wavelength regions. Transmission spectra in optical bandpasses would probe atmospheric heights where the isothermal, non-inverted, and thermal inversion models are measurably divergent.

Optical transmission spectra would also be able to detect potential absorption features from TiO or VO, the most likely causes of a thermal inversion in the WASP-103b atmosphere. If TiO or VO are present in observable quantities, we could rule out an enhanced C/O atmospheric composition and give more consideration to an inverted atmospheric profile, as an enhanced C/O ratio suppresses formation of TiO and VO (Madhusudhan 2012; Madhusudhan et al. 2011b). Detection of IR CH$_4$ features would support the existence of an enhanced C/O atmosphere, low TiO and VO levels, and non-inverted atmospheric profile. The Spitzer 3.6\textmu m band covers a large CH$_4$ absorption feature, and differencing against a 4.5\textmu m eclipse could measure the relative CH$_4$/CO levels.
High-altitude clouds could be identified through optical transmission spectroscopy, which would show a flat transmission spectrum if clouds exist. However, the presence of clouds would likely prevent TiO, VO, or C/O measurements which might allow us to better distinguish between possible atmospheric profiles.

Southworth et al. (2015) observed the transit of WASP-103b in Bessell RI and SDSS griz and reported an abnormally steep downward slope in the transmission spectrum from blue to red (see Figure 7 of that paper). The reported slope in the transmission spectrum is too steep to be caused by Rayleigh scattering from haze in the upper atmosphere or by stellar activity (Ballerini et al. 2012; Czesla et al. 2009; Oshagh et al. 2013), but could possibly be attributed to TiO absorption between $\sim 0.45\mu m$ and $0.8\mu m$. Southworth & Evans (2016) also report that the spectral slope measured from their transmission spectroscopy of WASP-103b is too strong for Rayleigh scattering and cannot be attributed to effects from the companion star. Additional transit observations in the optical could verify the results of Southworth et al. (2015) and Southworth & Evans (2016), could lend support to the idea that TiO is present in the WASP-103b atmosphere, and help distinguish between the atmospheric models discussed here.

3.7 Summary

We observed two secondary eclipses of WASP-103b from 1.1$\mu m$ to 1.7$\mu m$ using the G141 grism on HST/WFC3 in spatial scan mode. We used Gaussian process regression with MCMC sampling to model both the white-light and spectrally resolved eclipse light curves to extract the planet-to-star flux ratio of the system as a function of wavelength. We corrected this thermal emission spectrum for flux contamination from a nearby star that we probabilistically showed was physically associated with the WASP-103 system.

We combined the decontaminated thermal emission spectra from each visit of HST into a visit-averaged spectrum, which was used to retrieve atmospheric models for WASP-103b. After rejecting monotonically decreasing atmosphere models for solar composition and $0.01\times$ solar composition, we found that an isothermal or a thermally inverted atmospheric profile could explain our thermal emission spectrum, as could a monotonically decreasing atmosphere with a C/O ratio $>1$. We conclude that the

\footnote{The “super-Rayleigh” slope is discussed in more detail in Chapter 4.}
WASP-103b atmosphere is approximately isothermal across the region probed by our observations, with a brightness temperature of $T_B = 2890$ K, giving us little power to discern between the fiducial models we tested.

Additional transit observations in the optical and NIR would test the existence of the steep slope reported by Southworth et al. (2015) and Southworth & Evans (2016), which would tell us if the atmosphere is truly isothermal or merely pseudo-isothermal as a result of the presence of clouds or haze. A transit spectrum at optical wavelengths would also be able to measure absorption from TiO, which, if detected, would favor an inverted atmospheric profile over an enhanced C/O ratio. Alternatively, the detection of IR CH$_4$ absorption during secondary eclipse would support an enhanced C/O ratio and disfavor an inverted profile.

WASP-103b, along with other highly irradiated hot Jupiters, will be a key planet for understanding the behavior of TiO in a hot Jupiter atmosphere, and validating hypotheses about the existence and origin of thermal inversions.

### 3.8 Acknowledgements

This work is partially funded by *Hubble Space Telescope* grants HST-GO-13660.005 (PI Wright) and HST-GO-13660.001-A (PI Zhao), and partially supported by funding from the Center for Exoplanets and Habitable Worlds. The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium. Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. Support for MAST for non-*HST* data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts. Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this
mountain. We gratefully acknowledge the use of SOA/NASA ADS, NASA, and STScI resources.
4.1 Verification of WASP-103b “super-Rayleigh” transmission slope using MINERVA

WASP-103b, one of the hottest and shortest period hot Jupiters detected to date, was reported to have an optical transmission slope far steeper than could be produced by traditional Rayleigh scattering off of upper atmosphere haze. We sought to verify the presence of this “super-Rayleigh” slope by observing two sequential transits of WASP-103b using the MINiature Exoplanet Radial Velocity Array (MINERVA) in $g'$ and $i'$ passbands. We obtained six near-simultaneous light curves of each transit using MINERVA’s four telescopes. We corrected the transit light curves for dilution from the confirmed nearby companion star. We used Gaussian process regression to detrend the light curve and derived values for the effective planetary radii in these passbands. Due to large uncertainties and scatter in extracted planetary radii, our calculated spectral slope was consistent with both a “super-Rayleigh” and normal Rayleigh levels of scattering in the atmosphere. Further analysis will be needed to more tightly constrain the optical transmission slope and decisively verify or refute this claim. Finally, we introduced a technique which we term “chromometry,” which may significantly improve light curve precision and expand exo-atmosphere studies to 3 – 4 times the current number of observable planets.
4.2 Review of WASP-103b and Introduction to MINERVA Observations

WASP-103b is an ultra-short period hot Jupiter orbiting less than three stellar radii away from a late-F star. Gillon et al. (2014) first reported the detection of WASP-103b, and their radial velocity measurements revealed that the planet’s ultra-short orbital period of 0.92 day causes a Roche lobe filling factor of 58% and a 10% asphericity. Cartier et al. (2017) (Ch. 3) used near-infrared (NIR) emission spectro-photometry from Hubble Space Telescope to show that the planet’s dayside atmosphere contains no water absorption feature at 1.4\m, has a dayside temperature of $T_{\text{day}} = 2891 \pm 150$ K, and has an atmospheric profile consistent with either an isothermal atmosphere or a stratospheric thermal inversion.

Lucky imaging in $i'$ and $z'$ by Wöllert & Brandner (2015) revealed a previously unknown nearby companion star $0.242 \pm 0.016$ away from the 6110 $\pm$ 50K primary star in the WASP-103 system. Ngo et al. (2016) confirmed the nearby source with Keck NIRC2 AO observations in $JHK_s$, though they were unable to conclusively determine a physical association between the two stars solely using astrometric measurements. Ch. 3 applied Poisson statistics to a stellar population synthesis of the Milky Way (Robin et al. 2003) to prove a physical association between the primary and companion stars with $> 99.8\%$ likelihood. Southworth & Evans (2016) (hereafter SE16) independently confirmed the likelihood of physical association via statistical

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means and co-evolution using isochrone fitting of $K_S$ vs. $J - K_S$ absolute magnitudes of the two stars.

Ngo et al. (2016), SE16, and Ch. 3 each independently solved for the radius and temperature of the companion star, and their solutions agree that the companion star’s photometry is consistent with a K5V spectral type with $T_{\text{eff}} = 4400 \pm 200$K, and $R_B / R_A = 0.52 \pm 0.05$ (these numbers from Ch. 3 are adopted for the remainder of this manuscript).

Southworth et al. (2015) (hereafter SE15) followed up the initial planet detection with multi-bandpass ground-based transit observations of the planet in Sloan $ugriz$ and Bessel $RI$, and discovered an inexplicably steep spectral slope across this region at more than double a traditional Rayleigh scattering slope of $\alpha_R = -4.0$. Rayleigh scattering has been seen in the atmospheres of some exoplanets, and is likely due to upper-atmosphere clouds or hazes (for example, Dragomir et al. 2015; Gibson et al. 2017; Lecavelier Des Etangs et al. 2008; Sing et al. 2013; Stevenson et al. 2014a). After the detection and subsequent confirmation of the companion star, SE16 re-calculated the previously reported “super-Rayleigh” slope from the SE15 transmission spectrum. SE16 concluded that the presence of the faint companion star cannot be the cause of the super-Rayleigh slope in the transmission spectrum, leaving no viable explanation for the anomaly.

As both the SE15 and SE16 reports of the super-Rayleigh slope utilize the same set of observations, we sought to verify the presence of this odd feature through independent ground based observations across the same wavelength range. We utilized the MINiature Exoplanet Radial Velocity Array (MINERVA²) to test this claim.

MINERVA began full photometric science operations in May 2015 at the Fred Lawrence Whipple Observatory on Mt. Hopkins, AZ (Swift et al. 2015). MINERVA consists of four 0.7-meter robotic telescopes (labeled T1 – T4) capable of operating independently or in tandem. Each telescope has a field of view $> 20'$ and can observe in $ug'r'i'z'$ passbands. This telescope array is well-suited for multiwavelength observations of bright stars (like WASP-103 at $K_S = 10.767 \pm 0.018$) and has provided follow-up observations of disintegrating planetesimals orbiting WD 1145+017 (Croll et al. 2017; Vanderburg et al. 2015).

To attempt to verify the presence of a super Rayleigh slope, we observed two consecutive transits of WASP-103b using MINERVA and obtained six near-simultaneous observations.

²https://www.cfa.harvard.edu/minerva/
transit light curves of each transit event (Sec. 4.3). We perform a Gaussian process regression on the transit light curves and decontaminate the transit depths for contamination from the companion star (Sec. 4.4). We report stellar, planetary, and hyper-parameters from the Gaussian process regression (Sec. 4.5) and present our inconclusive calculations of the optical transmission slope (Sec. 4.6). We conclude by describing future applications of these observations to a technique called “chromometry” and outstanding questions regarding WASP-103b’s exo-atmosphere (Sec. 4.7).

4.3 MINERVA Observations

We observed sequential transits of WASP-103b on UT 2016 May 29 (N1) and 30 (N2) using T1–T4 on MINERVA in $g'$ ($\lambda_{\text{eff}} = 464.04\pm57.92$ nm) and $i'$ ($\lambda_{\text{eff}} = 743.95\pm52.2$ nm) passbands (Rodrigo & Solano 2013; Rodrigo et al. 2012). Both T1 and T2 alternated exposures between $g'$ and $i'$ passbands, while T3 observed in $i'$ only and T4 in $g'$ only. Throughout this chapter, shorthand such as “N1-T2$g'$” refers to the observations taken on the first evening (UT 2016 May 29) on T2 in the $g'$ filter.

Our observing plan resulted in six near-simultaneous light curves of each transit event in order to examine the systematics in each of the four telescopes, optimize our observing time, and (in a later analysis) to calculate the color of the planet through transit. Details on each of the light-curves are listed in Table 4.1. The telescopes were deliberately defocused to increase the signal-to-noise (S/N) of each light curve by allowing for longer exposures without saturation.

The observing sequences were set up to start as soon as WASP-103 rose above airmass = 2 and continue until the star fell below the airmass limit, for a total of $\sim6.6$ hours of observing per night. With a transit duration of 2.6 hours, this gave us four full hours of out-of-transit observations to properly characterize the detector systematics and noise. Pointing errors on UT 2016 May 29 cut off some of the pre-transit baseline observations and truncated the observing time that night to $\sim5$ hours for all six light curves. This pointing error did not affect any of the calibration images from that night and we were still able to fully capture the transit.

T2 and T3 suffered some technical difficulties during the observing run which negatively affected the quality of their light curves. T2 experienced a failure of the altitude-azimuth derotator on UT 2016 May 29, resulting in pointing errors and a few
Table 4.1: MINERVA Observing Log

<table>
<thead>
<tr>
<th>UT Date</th>
<th>Telescope</th>
<th>Filter</th>
<th>BJD$_{UTC}$-2457000 Start</th>
<th>BJD$_{UTC}$-2457000 End</th>
<th>$N_{obs}$</th>
<th>Exposure Time (seconds)</th>
<th>Avg. S/N</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 May 29</td>
<td>T1</td>
<td>$g'$</td>
<td>537.743</td>
<td>537.949</td>
<td>46</td>
<td>180</td>
<td>484.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>$i'$</td>
<td>537.745</td>
<td>537.951</td>
<td>46</td>
<td>180</td>
<td>345.81</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>$g'$</td>
<td>537.744</td>
<td>537.945</td>
<td>36</td>
<td>180</td>
<td>547.37</td>
<td>Rotator failure</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>$i'$</td>
<td>537.747</td>
<td>537.952</td>
<td>37</td>
<td>180</td>
<td>279.29</td>
<td>Rotator failure</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>$i'$</td>
<td>537.745</td>
<td>537.951</td>
<td>93</td>
<td>180</td>
<td>304.82</td>
<td>Pointing drift</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>$g'$</td>
<td>537.750</td>
<td>537.952</td>
<td>92</td>
<td>180</td>
<td>463.38</td>
<td></td>
</tr>
<tr>
<td>2016 May 30</td>
<td>T1</td>
<td>$g'$</td>
<td>538.675</td>
<td>538.949</td>
<td>61</td>
<td>180</td>
<td>496.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>$i'$</td>
<td>538.677</td>
<td>538.951</td>
<td>61</td>
<td>180</td>
<td>345.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>$g'$</td>
<td>538.675</td>
<td>538.950</td>
<td>58</td>
<td>180</td>
<td>182.57</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>$i'$</td>
<td>538.677</td>
<td>538.947</td>
<td>57</td>
<td>180</td>
<td>274.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>$i'$</td>
<td>538.675</td>
<td>538.947</td>
<td>124</td>
<td>180</td>
<td>350.20</td>
<td>Pointing drift</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>$g'$</td>
<td>538.677</td>
<td>538.949</td>
<td>123</td>
<td>180</td>
<td>483.18</td>
<td></td>
</tr>
</tbody>
</table>
exposures where all stars were trailed across the detector. T3 experienced pointing errors on both nights which caused the field to drift across the detector over the course of the night. While the issues with T2 and T3 were partially rectified by calculating the astrometric plate solution after the fact using Astrometry.net (Lang et al. 2010), the resulting light curves have noticeably more scatter than for telescopes without technical issues, though S/N was only slightly affected.

4.3.1 Data Reduction and Photometric Extraction

MINERVA’s automated observing pipeline took 10 dark and 10 bias images at the start of each evening for each telescope, which we then combined into median dark and bias images using AstroImageJ (Collins et al. 2017). Darks were scaled and de-biased before combination into the median dark image.

Flat field images were taken both at twilight and dawn for each telescope in each observing filter. We discarded any flat field images that approached saturation ($\gtrsim 45,000$) or were underexposed ($\lesssim 10,000$). We then used AstroImageJ’s standard process to remove any gradient in the flats, which fits a plane to all calibrated flat-field images and divides out the illumination gradient prior to median combining the raw images. We treated morning and evening sky flats the same and combined them together into a master flat for each telescope in each of its observing filters for each evening.

For each image sequence, separated by telescope and filter, we subtracted the median bias and median dark images, then divided by the median flat field image for that telescope and filter. We then attempted to align each image sequence using multiple reference apertures, placed either by pixel locations or world coordinate system (WCS) coordinates. The image alignment resulted in better precision when placing apertures for extracting the photometry of WASP-103 and the comparison stars.

Several technical issues complicated the image alignment needed for photometric extraction, including coordinate errors and the pointing and rotation errors mentioned previously and listed in Table 2.3. While the MINERVA pipeline attempts to provide the astrometric plate solution for each exposure, the WCS solution failed more often than not for each of the image sequences. For image sequences with stable pointing and rotation this did not present an issue; we simply set the apertures for photometric
extraction based on pixel coordinates in place of right ascension and declination.

However, for those with both technical and WCS issues we solved for the WCS externally using Astrometry.net and then set the apertures for photometric extraction based on the plate solution. While we attempted as best as possible to use the same comparison stars for each of the image sequences, the aforementioned issues forced us to drop one or two comparison stars from the imaging sequences that drifted or rotated out of view and caused processing errors.

We performed differential photometry on each of the imaging sequences to extract the WASP-103 light curves using \( \gtrsim 12 \) comparison stars selected to have a similar magnitude to WASP-103 and constant brightness across the imaging sequence. We placed apertures with radius \( r_o = 35 \text{pix} \) around each object, surrounded by a sky background annulus with inner radius \( r_{b,i} = 50 \text{pix} \) and outer radius \( r_{b,o} = 60 \text{pix} \) centered on each object. Where possible, we used object RA and Dec to place the apertures and re-centered each aperture based on the object’s point spread function before measurements. As part of the sky background subtraction process, AstroImageJ then iteratively identifies and rejects any pixel with counts \( > 2\sigma \) above the mean sky background to remove any background stars and other anomalous pixels (Collins et al. 2017). After the sky background cleaning processes converges (or reaches the maximum number of iterations), the remaining pixels in the sky background annulus were averaged and the value subtracted from each pixel in the aperture.

The twelve resulting transit light curves are plotted in Fig. 4.1 and the average S/N of each is given in Table 4.1. From visual examination of the light curves, we make the following qualitative observations about how our observing program affected light curve quality:

1. Telescopes that flipped between filters (T1 and T2) produced more scattered light curves than telescopes with single filters.

2. Baseline trends (systematics) of individual telescopes appear the same in both filters. The systematics of each telescope appear different.

3. Of single-filter telescopes, T4 yielded a cleaner light curve than T3. This may be due to the pointing errors in the T3 observations, but may also be a result of detector sensitivity varying with wavelength.
While alternating filters on a single telescope yielded more light curve scatter than or known parametric form, a flexible regression procedure is necessary to ensure that cases (e.g. N2- did single-filter telescopes, the transit signal is still detectable in all but the worst clean, high S/N light curves when pointing and rotation remain stable (e.g. Light curves from UT 2016 May 29 are in the top row and from UT 2016 May 30 in the bottom row. Light curves in $g'$ are in the left column and $i'$ in the right column. Light curves from T1 are black points, from T2 in red points, and from T3 and T4 in blue points. Horizontal dashed lines indicate the added vertical offset for each light curve, included for clarity.

4. Uncertainties of individual points are larger for $i'$ light curves than $g'$ for most light curves (except for N2-T2), but this does not hold true for the average S/N.

Our overall conclusion is that the MINERVA telescopes are capable of producing clean, high S/N light curves when pointing and rotation remain stable (e.g. T4). While alternating filters on a single telescope yielded more light curve scatter than did single-filter telescopes, the transit signal is still detectable in all but the worst cases (e.g. N2-T2).

As the baseline systematics of each telescope do not have a known physical cause or known parametric form, a flexible regression procedure is necessary to ensure that both white noise and time-correlated noise are accounted for without needing to prespecify a noise model.
4.4 Gaussian Process Regression of Transits

As discussed in Rasmussen & Williams (2006), Gibson et al. (2012b), Grunblatt et al. (2015), and more recently in Cartier et al. (2017) (Ch. 3), Gaussian process (GP) regression is a robust regression method for capturing uncharacterized detector behavior due to the use of a flexible covariance matrix in place of a pre-specified parametric noise model. Previous studies have successfully applied parametric models to characterize systematics in well-tested detectors like Hubble Space Telescope’s Wide Field Camera 3 (HST/WFC3; Crouzet et al. 2014; Deming et al. 2013; Knutson et al. 2014b; Wilkins et al. 2014, for example), but those models only gained widespread acceptance after many years of application and verification of their accuracy. Even so, the physical cause of those parametric trends are still not entirely understood (Agol et al. 2010), and Gibson et al. (2011; 2012a; 2012b; 2013a), Evans et al. (2015), and Montet et al. (2016) have shown that parametric models often only capture the underlying trends in the data but not time-correlated noise.

For comparatively new detectors like those on the MINERVA telescopes, no such parametric models exist. The MINERVA/T3 observations of WD 1145+017 presented in Croll et al. (2017) and Vanderburg et al. (2015) suffered a failure of the altitude-azimuth field derotator, similar to the mid-observation failure experienced on both evenings of our WASP-103b observations. They chose to scale up the photometric errors by 10% to account for this failure, but reported that the MINERVA detectors otherwise performed as expected across the near-ultraviolet to the near-infrared.

Aside from the additional uncertainty in the T2 and T3 observations due to pointing and rotation errors (for which we could follow the example of Croll et al. (2017) and scale up photometric errors), we observe trends in the baseline flux of some of the light curves seen in Fig. 4.1 that cannot be accounted for by a changing airmass over the course of observations. For example, we observe a decreasing linear trend in N2-T4, increasing linear trends in both filters of N2-T2, and what may be quasi-periodic variations in some of the other light curves. These trends do not have obvious physical causes and no verified parametric forms, so we choose to use the more flexible and robust GP approach.

Our GP regression follows the approach in Cartier et al. (2017), which we summarize below. We maximize the likelihood function (Gibson et al. 2012a; Rasmussen & Williams 2006) given as
where $r$ is the vector of residuals between the data values and the transit model, $X$ is the vector of data locations (i.e. observation times), $\Phi$ is the set of hyperparameters that characterize the behavior of the covariance matrix $\Sigma$ and transit model, and $n$ is the number of data points. This likelihood function is a multivariate normal distribution. The transit light curve model of Mandel & Agol (2002) and implemented as per Eastman et al. (2013) is explicitly calculated as part of the residual vector and is the mean of the multivariate normal distribution.

The covariance matrix, $\Sigma$, captures the behavior of the data that cannot be attributed to the transit model and depicts how each data value depends on each other value in the set (Grunblatt et al. 2015). The matrix is populated by a covariance kernel. By choosing an appropriate kernel to populate the covariance matrix we can account for the effects of detector systematics without prespecifying a parametric model for these systematics (Grunblatt et al. 2015). The residuals to the model should not exhibit any non-Gaussian behavior if an appropriate kernel is chosen.

We tested two covariance kernels in the GP regression procedure described in Sec. 4.4.1. We first tested the simpler of the two kernels, a squared-exponential kernel defined as

$$
\Sigma_{ij}^{se} = A^2 \exp \left( \frac{(x_i - x_j)^2}{L^2} \right) + \delta_{ij} \sigma_i^2
$$

and then a quasi-periodic kernel defined as

$$
\Sigma_{ij}^{qp} = A^2 \exp \left( - \frac{\sin^2 [\pi (x_i - x_j)/\theta]}{2\Omega^2} - \frac{(x_i - x_j)^2}{L^2} \right) + \delta_{ij} \sigma_i^2
$$

In Eqs. 4.2 and 4.3, $A$ is the amplitude of the covariance kernel, $\theta$ is the characteristic timescale of the periodicity, $\Omega$ is the coherence scale of the periodicity, $L$ is the characteristic time lag, $\delta_{ij}$ is the Kronecker delta, and $\sigma_i$ is the white-noise uncertainty associated with data point $x_i$. $A$, $L$, $\theta$, and $\Omega$ are four hyperparameters that characterize the covariance kernel (included in $\Phi$ in Eq. 4.1) and capture the behavior of the instrument systematics.

The transit model of Mandel & Agol (2002) as applied by Eastman et al. (2013)
takes $a_P/R_S$, $\cos i$, $\sqrt{e} \sin \omega_s$, $\sqrt{e} \cos \omega_s$, $R_S$, $T_{\text{eff}}$, $\log g$, $[\text{Fe}/\text{H}]$, secondary eclipse depth, and orbital period $P$ as free parameters in the GP regression. This set of parameters comprises the system parameters that were included in the calculation of the transit model. $T_{\text{eff}}$, $\log g$, $[\text{Fe}/\text{H}]$ were used to retrieve quadratic limb darkening parameters $u_1$ and $u_2$ from Claret & Bloemen (2011). The $R_P/R_S$ and transit center time $T_C$ are the transit parameters.

In addition to the likelihood due to specific hyperparameters and model parameters, we included additional likelihoods based on prior previous measurements of the system and logical constraints on hyperparameters. In our GP regression, we therefore maximized the combined prior and model log-likelihood function

$$L(r|X, \Phi)_{\text{total}} = \ln(L_{\text{model}}) + \ln(L_{\text{prior}})$$

(4.4)

where $\Phi$ is the complete set of parameters used in the GP regression, $L_{\text{model}}$ is the likelihood from the systematic and light curve model (Eq. 4.1), and $L_{\text{prior}}$ is the likelihood of the prior information. Priors for each of the system and transit parameters listed here, as well as priors for the hyperparameters required by the covariance kernel, were included in the calculation of $\ln(L_{\text{prior}})$. The prior probability distributions were chosen to be uniform, normal, or have no restrictions.

### 4.4.1 GP Regression Procedure

Initial GP regression of individual light curves with priors listed in Table 4.2 did provide reasonable solutions, but the stellar parameters returned by each of the 12 regressions were not self consistent. That is, GP regression of the individual light curves provided inconsistent values for stellar and planetary parameters. While some scatter in the fitted value of $R_P/R_S$ was expected due to the variable quality of the light curves, the stellar and planetary parameters must, physically, be the same for each transit.

To ensure that the regressions to the transit light curves yielded a consistent set of stellar and planetary solutions, we first grouped the twelve light curves by filter into two groups of six. We fit all light curves within each filter group simultaneously, applying the same stellar and transit parameters ($R_P/R_S$, $R_S$, $a_P/R_S$, $\cos i$, $\sqrt{e} \sin \omega_s$, $\sqrt{e} \cos \omega_s$, $R_S$, $T_{\text{eff}}$, $\log g$, $[\text{Fe}/\text{H}]$, secondary eclipse depth, and orbital period $P$) as free parameters in the GP regression. This set of parameters comprises the system parameters that were included in the calculation of the transit model. $T_{\text{eff}}$, $\log g$, $[\text{Fe}/\text{H}]$ were used to retrieve quadratic limb darkening parameters $u_1$ and $u_2$ from Claret & Bloemen (2011). The $R_P/R_S$ and transit center time $T_C$ are the transit parameters.

Technically, the system and transit parameters are also hyperparameters of the GP as defined by Gibson et al. (2012a). However, we refer to the system and eclipse parameters separately for clarity.
Table 4.2: Prior values, widths, and shapes for single-filter GP regression

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value±Width</th>
<th>Distribution Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$0 \leq A \leq 10$</td>
<td>Uniform</td>
</tr>
<tr>
<td>$L$ (day)</td>
<td>$\tau_{14} \leq L \leq 10$</td>
<td>Uniform</td>
</tr>
<tr>
<td>$\theta$ (day)</td>
<td>$\tau \leq \theta \leq 5$</td>
<td>Uniform</td>
</tr>
<tr>
<td>$\Omega$ (day)</td>
<td>$\tau \leq \Omega \leq 5$</td>
<td>Uniform</td>
</tr>
<tr>
<td>$R_P / R_S$</td>
<td>$0.1158 \pm 0.0006$</td>
<td>Normal</td>
</tr>
<tr>
<td>$a_P / R_S$</td>
<td>$2.9398 \pm 0.03$</td>
<td>Normal</td>
</tr>
<tr>
<td>$\cos i$</td>
<td>$0.632 \pm 0.017$</td>
<td>Normal</td>
</tr>
<tr>
<td>$\sqrt{e} \cos \omega_*$</td>
<td>$0 \pm 0.01$</td>
<td>Normal</td>
</tr>
<tr>
<td>$\sqrt{e} \sin \omega_*$</td>
<td>$0 \pm 0.01$</td>
<td>Normal</td>
</tr>
<tr>
<td>$R_S$ ($R_\odot$)</td>
<td>$1.419 \pm 0.055$</td>
<td>Normal</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>$6110 \pm 50$</td>
<td>Normal</td>
</tr>
<tr>
<td>$\log g$ (cgs)</td>
<td>$4.22 \pm 0.09$</td>
<td>Normal</td>
</tr>
<tr>
<td>$[\text{Fe/H}]$ (dex)</td>
<td>$0.06 \pm 0.13$</td>
<td>Normal</td>
</tr>
<tr>
<td>$u_{1,g}$</td>
<td>$0.544 \pm 0.05$</td>
<td>Normal</td>
</tr>
<tr>
<td>$u_{2,g}$</td>
<td>$0.276 \pm 0.05$</td>
<td>Normal</td>
</tr>
<tr>
<td>$u_{1,i}$</td>
<td>$0.394 \pm 0.05$</td>
<td>Normal</td>
</tr>
<tr>
<td>$u_{2,i}$</td>
<td>$0.272 \pm 0.05$</td>
<td>Normal</td>
</tr>
<tr>
<td>Period (day)</td>
<td>$0.9255 \pm 0.00002$</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Note—All priors are the same for both nights and both filters except where explicitly stated.

$\sqrt{e} \cos \omega_*$, $\sqrt{e} \sin \omega_*$ and period) to all six light curves within a set. As each filter group contained three light curves from each evening, we fit for both $T_{C,1}$ and $T_{C,2}$ within each group, applying the appropriate transit center variable to each light curve. Only the hyperparameters $A$, $L$, $\theta$, and $\Omega$ were independent for each light curve.

We noticed during the tests of the single-filter regressions that outliers within individual light curves were significantly affecting the $R_P / R_S$ solutions, as outlying points still had small uncertainties. These individual points, which were many $\sigma$ away from their expected values, held disproportionate leverage over the GP solutions, so we removed one point each from N1-T2$g'$ and N2-T2$i'$ and four points near transit center from N2-T3$i'$.

Due to the variable quality of the light curves and the unknown systematics, we chose not to explicitly fit for the quadratic limb darkening parameters $u_1$ and $u_2$ during the GP regression. We retrieved prior values of $u_1$ and $u_2$ from the Claret & Bloemen (2011) tables using the prior values of $T_{\text{eff}}$, $\log g$, and $[\text{Fe/H}]$ listed in Table 4.2. We used an online utility provided by Eastman et al. (2013) to retrieve these
values and imposed narrow prior probabilities on them in the GP regression. However, our GP regression does not hold constant the values of $T_{\text{eff}}$, $\log g$, and $[\text{Fe}/\text{H}]$ for the simultaneous GP regression, as these values are coupled to other parameters aside from limb darkening. We ensure that the fitted values for $T_{\text{eff}}$, $\log g$, and $[\text{Fe}/\text{H}]$ remain consistent with the narrowly-constrained limb darkening priors by retrieving temporary limb darkening parameters based on the adjusted $T_{\text{eff}}$, $\log g$, and $[\text{Fe}/\text{H}]$ and applying a Gaussian penalty of width $\sigma = 0.05^4$ to $\ln P$ should they differ from the nominal values.

We applied a quasi-periodic kernel to all six light curves within a set during the simultaneous GP regression, with the expectation that the detectors may have imposed onto the light curves periodic systematics with a period ranging from a few minutes to the duration of the observations. Based on the variable quality of the light curves of a single filter (and also of a single evening), it is unlikely that all six light curves within a set would be best fit with the same covariance kernel. However, as discussed in Cartier et al. (2017) (Ch. 3), one advantage of a GP framework is robustness against over-parameterization. Hyperparameters of a covariance kernel that are unnecessary to characterize non-desired behavior very quickly lose leverage on the likelihood function, so long as wide enough priors are defined. However, a covariance kernel that under-parameterizes the systematic variability in the dataset yields an obviously poor fit.

For example, if little to no quasi-periodic behavior exists in a dataset (as is seen in the N1-T4 $g'$ transit), $\theta$ and $\Omega$ will regress to values larger than the duration of the observations, essentially “flattening out” their contribution to the covariance matrix. Small variations in those hyperparameters will no longer significantly change $\ln P_{\text{total}}$, and the total log-likelihood of an unnecessary quasi-periodic GP regression will only differ from the more straightforward squared-exponential GP regression by $1 - 2\%$. Because of this, we are confident that enforcing a single covariance kernel for all six light curves within a grouping does not negatively affect our GP regression.

For each group of six single-filter transit light curves, we find the a posteriori

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4This error on the limb darkening parameters was taken from Eastman et al. (2013), who in turn estimated them from figures in Claret & Bloemen (2011).

5As discussed in a later section, this was a misstep in the GP procedure. It effectively “double counts” the uncertainties on these three parameters, first on the parameters as they are coupled with other planetary and stellar parameters and then again separately as they contribute to the retrieval of limb darkening parameters in each filter. This led to unphysically small uncertainties on $T_{\text{eff}}$ for the single-filter GP regressions, and needs to be fixed in later passes at these data.
distributions of stellar and transit parameters for all six simultaneously using a Markov
Chain Monte Carlo (MCMC; Eastman et al. 2013) exploration of parameter space to
obtain robust uncertainties. This also yielded an independent set of hyperparameters
for each light curve. The median value of the posterior probability distribution of
$R_P/R_S$ for each filter serves as an accurate gauge of the predicted value independent
of single-telescope systematics or noise.

We also wished to understand how much potential scatter there could be in the
value of $R_P/R_S$ for measurements in a single filter but with different observing
modes. To do this, we applied as priors the best fit MCMC solutions from the
simultaneous regressions to single-light curve GP regression. We fit each light curve
independently for $A$, $L$, $\theta$, $\Omega$, and $R_P/R_S$, and held all other parameters fixed at
their best-fit single-filter values. We applied a quasi-periodic covariance kernel to each
GP regression. This also helped restrict the GP regression to physically meaningful
solutions.

For the individual regressions, we tested both the squared-exponential and quasi-
periodic kernels and found that while the difference in $\ln P$ was negligible for the
cleaner light curves, for other light curves a quasi-periodic kernel produced a sig-
nificantly higher probability, lower RMS in the residuals to the model, and smaller
uncertainties in $R_P/R_S$. Though the periodicity ($\theta$) did not settle on a single value
across all of the light curves, nor was the periodicity associated with any known noise
source, we chose to retain the solutions from use of a quasi-periodic kernel for all
light curves for consistency.

4.4.2 Flux Dilution Correction

Wöllert & Brandner (2015) first detected a nearby companion star to WASP-103, and
Ngo et al. (2016) verified that the companion star is separated from the primary star
by $240 \pm 15$ milliarcseconds using Keck/NIRC2. Both SE16 and Ch. 3 probabilistically
showed that the companion is physically associated with the planetary host star at
$\gtrsim 99\%$ likelihood (Ch. 3). SED modeling and isochrone matching of the system
reveals that the companion is a K5 V main sequence star with $T_{\text{eff}} = 4400 \pm 200$K
(SE16; Ch. 3). From this, SE16 and Ch. 3 calculate that the companion contributes
$2.46 \pm 0.32\%$ of light in $g'$ and $6.41 \pm 0.41\%$ of light in $i'$, and has a radius ratio of
$R_B/R_A = 0.52 \pm 0.05$ between the secondary and primary star.
Our MINERVA transits are diluted by contaminating flux from the companion star, so we calculate the true planet/star radius ratio, \( \left( \frac{R_P}{R_S} \right)^* \), of WASP-103b after the GP regression as

\[
\left( \frac{R_P}{R_S} \right)^* = \left( \frac{R_P}{R_S} \right) \times \left[ 1 - \frac{f_B}{f_A} \right]^{-1/2}
\] (4.5)

where \( \frac{R_P}{R_S} \) is the planet/star radius ratio as calculated via GP regression and \( \frac{f_B}{f_A} \) is the fraction of light contributed by the companion in a given passband as calculated by SE16. We note that Eq. 4.5 assumes that the transit depth, \( \Delta F \), is equal to the square of the planet/star radius ratio, which is an approximation. We apply this flux correction factor to the uncertainties on \( \left( \frac{R_P}{R_S} \right) \), as well. We compare our dilution-corrected transit depths to those of SE16, which were already corrected for dilution, in Sec. 4.6.

### 4.4.3 Normality of Residuals

A successful GP regression will account for all non-Gaussian behavior in the data and leave only Gaussian white noise in the detrended dataset. We tested the residuals to the GP regressions for normality using the Anderson-Darling test (A-D test; D’Agostino & Stephens 1986; Feigelson & Babu 2012; Gross & Ligges 2015). The A-D test states that if the A-D statistic, \( A^2 \), is above a critical value, then the null hypothesis (that the data are not drawn from a Gaussian distribution) is rejected at a specified significance level. For example, a sample passing the A-D test at 5% significance and failing at 1% means that there is 95–99% confidence that the sample is truly Gaussian; passing at 1% significance means > 99% confidence in normality. The critical values against which \( A^2 \) is tested depend on the number of points in the sample and the desired significance level.

We calculate the A-D statistic using the nortest package from The Comprehensive R Archive Network (Gross & Ligges 2015) and adjusted the statistic for a Case 3 A-D test (unknown mean and variance in the dataset). The adjusted A-D statistic is given by

\[
A^{*2} = A^2 \left( 1 + \frac{0.75}{n} - \frac{2.25}{n^2} \right)
\] (4.6)

where \( n \) is the number of points in the sample. We calculated \( A^{*2} \) separately for each
light curve due to the different number of observations after outlier removal. We test for significance at 1% ($A^2_{\text{crit}} = 1.0379$), 5% ($A^2_{\text{crit}} = 0.7468$), and 10% ($A^2_{\text{crit}} = 0.6287$).

Figures 4.2 and 4.3 show the empirical distribution function (EDF) of the residuals to each of the individual GP regressions compared to the EDF of a normal distribution of the same mean and variance as the residuals. The highest level of significance achieved by each light curve is included in each panel. The residuals to each of the $g'$ light curves pass with > 99% confidence. In the $i'$ passband, residuals N2-T3 have < 90% confidence in normality, N2-T1 has 90 – 95% confidence, N1-T3 and N2-T2 have a 95 – 99% confidence, and N1-T1 and N1-T2 pass normality with > 99% confidence.

We note that while it is important that the residuals to a GP regression pass a normality test, that does not ensure that the GP regression has yielded an accurate set of physical parameters or that the uncertainties from the MCMC will be reasonably small. One advantage of a GP regression is that the solutions tend to be either “obviously right” or “obviously wrong.” That is, the solutions will either be accurate and have small uncertainties or the solutions will be inaccurate and have unreasonably large uncertainties. If a sample passes the normality test with high confidence, yet has large uncertainties on physical parameters (as we observe with the regressions to the $g'$ light curves), the GP regression has likely overfitted the noise and lost leverage on the physical parameters. Either the priors on the hyperparameters need refinement or a different kernel should be used.

### 4.5 Stellar and Planetary Parameters

Table 4.3 contains the best-bit stellar parameters for both single-filter GP regressions. The values of each parameter are consistent between the two filters, and we also calculate an average value for each parameter from the solutions to each filter. These values were used as priors and starting values for the individual light curve regressions. Priors and starting values of the four hyperparameters were reset to their values in Table 4.2. $A$, $L$, $\theta$, $\Omega$, and $R_p/R_s$ were fit for each light curve, with all other parameters held fixed to the values in Table 4.3.

In Table 4.3, a critical thing to note is that the uncertainties on the stellar effective temperature are un-physically small. That is, it is impossible to extract effective temperatures that precise only using transit light curves, and even more dubious when
the light curves are of mixed quality like those here. These too-small uncertainties are the result of fitting $T_{\text{eff}}$, $\log g$, and [Fe/H] independently from the limb darkening parameters within the GP regression when they are actually dependent within the transit model. The transit model retrieves limb darkening parameters from Claret & Bloemen (2011) at every stage of the MCMC using $T_{\text{eff}}$, $\log g$, and [Fe/H]. Also fitting $u_1$ and $u_2$ in each filter effectively double-counts those uncertainties and imposes too-harsh penalties on $\ln p_{\text{prior}}$ for small deviations from prior values. If errors of $\sim 0.2$K were actually reasonable, then generating two sets of light curves differing by only $\sim 1$K should produce unique light curves at a level where the time series data could indeed support this. Given that quality of the time series data is too poor to extract temperature variations at that level, these uncertainties on $T_{\text{eff}}$ indicate a mistake in the setup of the GP regression. Future attempts to fit these data will need to correct this mistake.

The companion-corrected ($R_p/R_s$)* and hyperparameters from the individual regressions are given in Table 4.4. We used the hyperparameters listed in Table 4.4 to detrend the light curves for systematics and plot them in Fig. 4.4 for $g'$ light curves.
When plotted on the same vertical scale, it is easy to see that there is a wide variance in the planet/star radius ratios of the $g'$ light curves. Though the residuals to each of the light curves have a small RMS (Table 4.5), this is likely due to an overfitting of the systematics which led to a lack of leverage on other parameters.

and Fig. 4.5 for $i'$. We over plot the predictive mean calculated using the best-fit stellar and transit parameters for each light curve.

Table 4.3: Stellar parameters from 6-Light Curve GP Regression

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>$g'$</th>
<th>$i'$</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_S$</td>
<td>AU</td>
<td></td>
<td></td>
<td>$1.455 \pm 0.057$</td>
</tr>
<tr>
<td>$a_P$</td>
<td>AU</td>
<td>0.02013$^{+0.00086}_{-0.00093}$</td>
<td>0.02006$^{+0.00080}_{-0.00064}$</td>
<td>0.020095$ \pm 0.000815$</td>
</tr>
<tr>
<td>$T_{eff}$</td>
<td>K</td>
<td>$6110.00 \pm 0.24$</td>
<td>$6110.13 \pm 0.12$</td>
<td>$6110.065 \pm 0.190$</td>
</tr>
<tr>
<td>log $g$</td>
<td>cgs</td>
<td>$4.274^{+0.087}_{-0.12}$</td>
<td>$4.194^{+0.078}_{-0.10}$</td>
<td>$4.234 \pm 0.098$</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>dex</td>
<td>$0.00^{+0.19}_{-0.14}$</td>
<td>$0.16 \pm 0.14$</td>
<td>$0.08 \pm 0.15$</td>
</tr>
<tr>
<td>$T_{C,1}$</td>
<td>BJDUTC</td>
<td>$2457537.8496^{+0.00013}_{-0.00009}$</td>
<td>$2457537.85026^{+0.000097}_{-0.000094}$</td>
<td>$2457537.8499 \pm 0.0010$</td>
</tr>
<tr>
<td>$T_{C,2}$</td>
<td>BJDUTC</td>
<td>$2457538.8003^{+0.00080}_{-0.00080}$</td>
<td>$2457538.80036^{+0.00098}_{-0.00113}$</td>
<td>$2457538.8003 \pm 0.0010$</td>
</tr>
<tr>
<td>$\sqrt{e} \cos \omega_*$</td>
<td>—</td>
<td>$-0.002^{+0.020}_{-0.015}$</td>
<td>$0.005 \pm 0.019$</td>
<td>$0.0015 \pm 0.0192$</td>
</tr>
<tr>
<td>$\sqrt{e} \sin \omega_*$</td>
<td>—</td>
<td>$0.001^{+0.013}_{-0.017}$</td>
<td>$-0.006^{+0.020}_{-0.017}$</td>
<td>$-0.0025 \pm 0.0169$</td>
</tr>
<tr>
<td>Inclination</td>
<td>deg</td>
<td>$88.3 \pm 1.4$</td>
<td>$87.6 \pm 1.45$</td>
<td>$87.95 \pm 1.43$</td>
</tr>
<tr>
<td>$a_P / R_S$</td>
<td>—</td>
<td>$2.963^{+0.048}_{-0.038}$</td>
<td>$2.994^{+0.041}_{-0.047}$</td>
<td>$2.9785 \pm 0.0437$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>day</td>
<td>$0.0115 \pm 0.0018$</td>
<td>$0.01109 \pm 0.00082$</td>
<td>$0.01129 \pm 0.00198$</td>
</tr>
<tr>
<td>$T_{14}$</td>
<td>day</td>
<td>$0.1123 \pm 0.0028$</td>
<td>$0.1106 \pm 0.0022$</td>
<td>$0.1115 \pm 0.0036$</td>
</tr>
</tbody>
</table>

Note—“Average” is the parameter value averaged over the two filters.
which affect the transit depth and shape.

This is reflected in the comparison of GP regression uncertainties, expected white noise uncertainties, and photon noise uncertainties given in Table 4.5. We calculate the expected uncertainty just from white noise as $\sigma_{\text{white}} = \frac{\text{RMS}(\text{residuals})}{\sqrt{n/2}}$, and the average photon noise as $\sigma_{\text{phot}} = \frac{1}{n} \times \sum \frac{1}{\sqrt{\text{raw flux}}}$. We compare both of those uncertainties to the uncertainty on the transit depth, $\sigma_{\Delta F}$, rather than on $\sigma_{R_p/R_S}$, so as to only compare uncertainties in flux. Values of $\sigma_{\Delta F}$ were calculated from the MCMC chain of $R_p/R_S$ rather than from the median and $1\sigma$ of that chain.

Looking at the variance in $\sigma_{\Delta F}$, the uncertainties in $i'$ are very consistent across telescope and evening, whereas there is much more variation in the uncertainties in $g'$. When compared to the expected uncertainty due solely to white noise, we note that uncertainties in each light curve are $\gtrsim 1.5 \times \sigma_{\text{white}}$, and in some cases more than $10\times$ the expected white noise uncertainty. While we expected values near $\sim 4 - 5 \times \sigma_{\text{white}}$, light curves with higher uncertainties than that will need a more careful GP regression.

With MINERVA photometry, we expect to be able to achieve uncertainties around $\sim 2 \times \sigma_{\text{phot}}$ for a star of this brightness (Swift et al. 2015). The clearest indicator that the regressions to the $i'$ light curves are much more stable than those in $g'$ is the comparison of $\sigma_{\Delta F}$ to $\sigma_{\text{phot}}$. All light curves in $i'$ approach the expected level above the photon noise limit, where the $g'$ uncertainties vary from twice as high as expected to one that even (unphysically) falls below the photon noise limit. However, since in each filter we found that $\sigma_{\text{white}}/\sigma_{\text{phot}} < 1$, it is likely that the GP regression chose to fit the noise rather than the data in each filter, resulting in inaccurately small residuals. We keep these issues in mind as we calculate the spectral slope across $g'$ and $i'$ in the next section.

### 4.6 Verification of Super-Rayleigh Slope

Figure 4.6 (left) shows the low-resolution optical transmission spectrum of WASP-103b resulting from these MINERVA observations compared to those of SE16, plotted as the change in effective planetary radius as a function of wavelength. Our transmission spectrum is consistent with that of SE16 in $g'$ and $i'$ and has a similar slope, but we note that our values of planetary radii are systematically lower than those of SE16.

While some of the $g'$ transit light curves indicate a planetary radius nearly identical
Figure 4.4: Best-fit individual regressions $g'$ transit light curves of WASP-103b in hours from mid-transit. Each panel is labeled according to the observation date (N1 for UT 2016 May 29 and N2 for UT 2016 May 30) and telescope number T1 – T4. In each panel: Top—Normalized light curves of WASP-103b detrended for telescope systematics via GP regression (black points) with predictive mean overplotted (red curve). Error bars are 1σ uncertainties on normalized photometry; Bottom—Residuals to the GP regression in percent.
The same as Figure 4.4 for best-fit simultaneous GP regression to six transit light curves of WASP-103b.
Table 4.4: $R_p / R_S$ and Hyperparameter Solutions

<table>
<thead>
<tr>
<th>Light Curve</th>
<th>$(R_p / R_S)^*$</th>
<th>$\Lambda$</th>
<th>$L$ (day)</th>
<th>$\theta$ (day)</th>
<th>$\Omega$ (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>g' Simultaneous</td>
<td>0.1087$^{+0.0081}_{-0.0094}$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>N1-T1</td>
<td>0.0952$^{+0.0017}_{-0.0023}$</td>
<td>0.0098$^{+0.0053}_{-0.0052}$</td>
<td>4.1$^{+3.9}_{-3.6}$</td>
<td>0.47$^{+0.79}_{-0.29}$</td>
<td>0.053$^{+0.089}_{-0.033}$</td>
</tr>
<tr>
<td>N1-T2</td>
<td>0.1104$^{+0.0052}_{-0.0022}$</td>
<td>0.0098$^{+0.0038}_{-0.0032}$</td>
<td>5.0$^{+3.4}_{-1.9}$</td>
<td>0.56$^{+0.85}_{-0.54}$</td>
<td>0.044$^{+0.072}_{-0.026}$</td>
</tr>
<tr>
<td>N1-T4</td>
<td>0.1183$^{+0.0011}_{-0.0055}$</td>
<td>0.07$^{+0.61}_{-0.33}$</td>
<td>5.4$^{+5.2}_{-3.7}$</td>
<td>2.7$^{+1.5}_{-1.6}$</td>
<td>2.8$^{+1.5}_{-1.7}$</td>
</tr>
<tr>
<td>N2-T1</td>
<td>0.1259$^{+0.0011}_{-0.0034}$</td>
<td>0.019$^{+0.014}_{-0.012}$</td>
<td>4.5$^{+5.2}_{-5.2}$</td>
<td>4.5$^{+2.9}_{-2.8}$</td>
<td>0.19$^{+1.3}_{-0.07}$</td>
</tr>
<tr>
<td>N2-T2</td>
<td>0.1401$^{+0.0046}_{-0.0038}$</td>
<td>0.50$^{+0.36}_{-0.33}$</td>
<td>5.4$^{+3.1}_{-1.6}$</td>
<td>3.3$^{+1.2}_{-1.6}$</td>
<td>3.1$^{+1.4}_{-1.6}$</td>
</tr>
<tr>
<td>N2-T4</td>
<td>0.1215$^{+0.0039}_{-0.0019}$</td>
<td>0.55$^{+0.50}_{-0.42}$</td>
<td>4.8$^{+4.3}_{-3.3}$</td>
<td>1.8$^{+1.8}_{-1.1}$</td>
<td>2.4$^{+1.8}_{-1.6}$</td>
</tr>
</tbody>
</table>

| i' Simultaneous | 0.1104$^{+0.0013}_{-0.0019}$ | — | — | — | — |
| N1-T1 | 0.1075$^{+0.0014}_{-0.0012}$ | 0.0112$^{+0.0028}_{-0.0019}$ | 4.1$^{+3.9}_{-3.6}$ | 0.47$^{+0.79}_{-0.29}$ | 0.053$^{+0.089}_{-0.033}$ |
| N1-T2 | 0.1085$^{+0.0012}_{-0.0024}$ | 0.090$^{+0.076}_{-0.0042}$ | 5.0$^{+3.4}_{-1.9}$ | 0.56$^{+0.85}_{-0.54}$ | 0.044$^{+0.072}_{-0.026}$ |
| N1-T3 | 0.1096$^{+0.0024}_{-0.0012}$ | 0.0107$^{+0.0016}_{-0.0012}$ | 5.4$^{+5.2}_{-3.7}$ | 2.7$^{+1.5}_{-1.6}$ | 2.8$^{+1.5}_{-1.7}$ |
| N2-T1 | 0.1166$^{+0.0067}_{-0.0073}$ | 0.64$^{+0.56}_{-0.58}$ | 4.5$^{+5.2}_{-5.2}$ | 4.5$^{+2.9}_{-2.8}$ | 0.19$^{+1.3}_{-0.07}$ |
| N2-T2 | 0.1085$^{+0.0012}_{-0.0024}$ | 0.026$^{+0.014}_{-0.012}$ | 5.4$^{+3.1}_{-1.6}$ | 3.3$^{+1.2}_{-1.6}$ | 3.1$^{+1.4}_{-1.6}$ |
| N2-T3 | 0.1034$^{+0.0011}_{-0.0014}$ | 0.0165$^{+0.0020}_{-0.0018}$ | 4.8$^{+4.3}_{-3.3}$ | 1.8$^{+1.8}_{-1.1}$ | 2.4$^{+1.8}_{-1.6}$ |

Note—$(R_p / R_S)^*$ are the dilution-corrected planet/star radius ratios, rather than the un-corrected values directly from the GP regressions.

Table 4.5: Comparison of GP regression uncertainties, white noise, and photon noise

<table>
<thead>
<tr>
<th>Light Curve</th>
<th>$\sigma_{\Delta F}$ mmag</th>
<th>$\sigma_{\text{white}}$ mmag</th>
<th>$\sigma_{\text{phot}}$ mmag</th>
<th>$\sigma_{\Delta F}/\sigma_{\text{white}}$</th>
<th>$\sigma_{\Delta F}/\sigma_{\text{phot}}$</th>
<th>$\sigma_{\text{white}}/\sigma_{\text{phot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1-T1g'</td>
<td>3.40</td>
<td>0.42</td>
<td>0.88</td>
<td>8.17</td>
<td>3.89</td>
<td>0.48</td>
</tr>
<tr>
<td>N1-T2g'</td>
<td>4.90</td>
<td>0.35</td>
<td>1.13</td>
<td>14.14</td>
<td>4.33</td>
<td>0.31</td>
</tr>
<tr>
<td>N1-T4g'</td>
<td>1.20</td>
<td>0.33</td>
<td>0.97</td>
<td>3.62</td>
<td>1.23</td>
<td>0.34</td>
</tr>
<tr>
<td>N2-T1g'</td>
<td>2.15</td>
<td>0.52</td>
<td>0.91</td>
<td>4.14</td>
<td>2.37</td>
<td>0.57</td>
</tr>
<tr>
<td>N2-T2g'</td>
<td>1.30</td>
<td>0.73</td>
<td>1.18</td>
<td>1.77</td>
<td>1.70</td>
<td>0.62</td>
</tr>
<tr>
<td>N2-T4g'</td>
<td>0.94</td>
<td>0.30</td>
<td>1.01</td>
<td>3.12</td>
<td>0.93</td>
<td>0.30</td>
</tr>
<tr>
<td>N1-T1i'</td>
<td>2.30</td>
<td>0.28</td>
<td>0.93</td>
<td>8.16</td>
<td>2.48</td>
<td>0.30</td>
</tr>
<tr>
<td>N1-T2i'</td>
<td>2.60</td>
<td>0.77</td>
<td>1.15</td>
<td>3.38</td>
<td>2.26</td>
<td>0.67</td>
</tr>
<tr>
<td>N1-T3i'</td>
<td>2.55</td>
<td>0.16</td>
<td>1.84</td>
<td>15.94</td>
<td>1.38</td>
<td>0.09</td>
</tr>
<tr>
<td>N2-T2i'</td>
<td>1.50</td>
<td>0.98</td>
<td>0.95</td>
<td>1.53</td>
<td>1.57</td>
<td>1.03</td>
</tr>
<tr>
<td>N2-T3i'</td>
<td>2.50</td>
<td>0.77</td>
<td>1.18</td>
<td>3.25</td>
<td>2.13</td>
<td>0.65</td>
</tr>
<tr>
<td>N2-T3i'</td>
<td>2.25</td>
<td>0.29</td>
<td>1.92</td>
<td>7.79</td>
<td>1.17</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Note—$\Delta F$ uncertainties calculated from MCMC chain of $R_p / R_S$, not from median and 1$\sigma$ values of $R_p / R_S$.

Note—$\Delta F$ uncertainties calculated from MCMC chain of $R_p / R_S$, not from median and 1$\sigma$ values of $R_p / R_S$.

to that of SE16, others of the g' transits indicate a smaller effective radius closer in size to values seen at longer wavelengths. The radius from the simultaneous GP regression of all g' light curves falls significantly below the radius given by SE16, though we note that the anomalously low and uncertain value from N1-T1 may be unduly influencing the simultaneous GP regression. Calculated values of effective planetary radius in i' are more tightly clustered around the value from simultaneous GP regression, and are all closer in value to that indicated by SE16.

We wished to verify SE16's conclusion that WASP-103b's atmosphere shows a super-Rayleigh level of scattering in the optical. To do this, we calculate the
Figure 4.6: Radii of WASP-103b as a function of wavelength corrected for contaminating flux from the companion star. Results from GP regression of individual light curves are open black squares and results from six light curve simultaneous GP regression are solid red points. A horizontal offset within each passband has been added to the MINERVA depths for clarity. Horizontal uncertainties are the FHWM of each passband.

Left: Radii of WASP-103b in units of $R_J$ as a function of wavelength. The throughput of each passband is plotted in black at the bottom. For comparison, the transmission spectra from SE16 are plotted in open grey triangles at the central wavelength of their corresponding passbands.

Right: Solutions for $R_p$ (km) vs. $\ln(\lambda)$ for WASP-103b. The solid grey line is the best fit linear regression that yields $dR_p/d\ln\lambda$ when treating each light curve separately, and the red dashed line is the linear fit of for the single-filter GP regression. The observed slope $dR_p/d\ln\lambda$ is given for each treatment in the legend, as is the value of the spectral slope $\alpha$ assuming planetary values from SE16.

spectral slope following the procedure of Lecavelier Des Etangs et al. (2008) and SE16, outlined below. The conventions of Lecavelier Des Etangs et al. (2008) and SE16 for the following equation differ by a minus sign (where SE16 includes a minus sign in the relation) but are otherwise identical. We choose to follow the convention of Lecavelier Des Etangs et al. (2008), where the change in effective planetary radius with wavelength is given by

$$\frac{dR_p(\lambda)}{d\ln\lambda} = \alpha H_s$$ (4.7)
where values of $R_P$ are extracted from transit observations at wavelengths $\lambda$, and $\alpha$ is the spectral slope we desire for comparison to Rayleigh scattering. $H_s$ is the atmospheric scale height and is calculated by

$$H_s = \frac{k_B T_P}{\mu_P g_P}$$

(4.8)

where $k_B$ is Boltzmann’s constant, $T_P$ is the planetary atmospheric temperature, $\mu_P$ is the mean molecular weight of the atmosphere, and $g_P$ is the planetary surface gravity.

Combining Eqs. 4.7 and 4.8 and rearranging for $\alpha$, we find

$$\alpha = \frac{d R_P(\lambda)}{d \ln \lambda} \frac{\mu_P g_P}{k_B T_P}$$

(4.9)

The value $d R_P/d \ln \lambda$ is the directly observable parameter from these types of observations, and so we make direct comparisons to SE16 using this value. However, since Rayleigh scattering is characterized more generally by the spectral slope $\alpha$, we also calculate $\alpha$ for our observations and use the same planetary values as SE16 to compare to their results (see Table 4.6).

SE16 calculate a value of $\alpha T = -27900 \pm 2200$ for WASP-103b (as per the convention of Lecavelier Des Etangs et al. 2008). They use the planet’s equilibrium temperature, which they calculate to be $T_{eq} = 2489 \pm 65$ K, to calculate a spectral slope of $\alpha = -11.2 \pm 0.9$. However, in Chapter 3 we show that WASP-103b has a dayside temperature of $T_{day} = 2890 \pm 150$ K based on near-IR emission spectra, far hotter than the equilibrium temperature. Without full phase curve information about WASP-103b’s atmosphere (which may be forthcoming from Spitzer observations), we lack a measurement of the heat recirculation efficiency from the dayside to nightside of the planet and, therefore, also cannot precisely estimate the temperature at the day-night terminator. We choose to calculate $\alpha$ using SE16’s equilibrium temperature instead of Chapter 3’s dayside temperature for two reasons: one, to ensure an apples-to-apples comparison with SE16; and two, in recognition that $\alpha$ as calculated from these MINERVA observations will far more heavily depend on whether $d R_P/d \ln \lambda$ is calculated using the single-filter planetary radii or the radii from single light curve GP regressions. This led to a single calculation of the atmospheric scale height of WASP-103b of $H_s = 601.48 \pm 51.55$ (km).

We plot planetary radius against the natural log of wavelength in Figure 4.6 (right)
and from this we calculate $d R_P(\lambda)/d \ln \lambda$ using a weighted least-squares algorithm to find best-fit linear models to all 12 individual GP regressions and also to just the two single-filter GP regressions. We separate out the radii from the single-filter GP regressions into their own weighted least-squares regression as they are not independent from the 12 individual radii values. The weights used in the weighted least-squares regression were equal to the inverse of the fractional uncertainty in $R_P/R_S$.

The fitted value for $d R_P(\lambda)/d \ln \lambda$ and the resulting calculated values of $H_s$, $\alpha T$ and $\alpha$ are given in Table 4.6 along with the comparison values from SE16. Unsurprisingly, $d R_P/d \ln \lambda$ as calculated with the 12 individual GP regressions has a much larger absolute uncertainty than the same calculation using the single-filter values, though the single-filter slope has a larger relative uncertainty. Given the possibly unreliable nature of the GP regressions of $g'$ light curves, we continue the comparison to SE16 values using the single-filter planetary radii, indicated by a subscript “C” for “Combined.”

We find that our MINERVA observations provide a spectral slope $\alpha_C = -5.62 \pm 12.49$ across $g'$ and $i'$ passbands, consistent with the expected Rayleigh slope of $\alpha_R = -4.0$. Given our large uncertainty on $\alpha_C$, our value of is also consistent with the slope reported by SE16 within 1σ.

Should future refinement show our measurement of $d R_P/d \ln \lambda$ and calculation of $\alpha_C$ to be in line with that of SE16, it is unlikely that the spectral slope is caused by Rayleigh scattering in the atmosphere of a much hotter object blended into WASP-103’s photometry. Assuming a value of $\alpha_R = -4.0$, we find that an object would need to have an effective temperature of $T^* = 6,975$ K to produce SE16’s value of $d R_P/d \ln \lambda$, which is un-physically hot for planet and a hotter F-star than WASP-103. Searches around WASP-103 ([Ngo et al. 2016; Wöllert & Brandner 2015]) do not show any hot stars nearby WASP-103 that could account for this slope. A blended object at either temperature would also be expected to wash out the secondary eclipses of WASP-103b. A planet that produces the secondary eclipse depths from Ch. 3 while also being contaminated by the flux of not just a K-dwarf but also an F- or B-dwarf would also need to be much hotter than physically indicated. Should this spectral slope be verified more definitively, we can conclude that it could not possibly be due to a hotter blended object.

However, if future refinement of these GP regressions show that the the planetary
radii indicated by individual light curves are consistent with these single-filter radii, we would conclude that our spectral slope is instead consistent with Rayleigh scattering in WASP-103b’s atmosphere, and therefore in line with the many other examples of Rayleigh scattering in exo-atmospheres referenced earlier. This would contradict the conclusions of SE16 and require additional independent measurements to “break the tie.”

It is clear that the largest source of uncertainty in our calculation of $\alpha$ is the large scatter and large uncertainties in radii from the $g'$ light curves. It is possible the radius from the simultaneous fit is more accurate, and that a more careful analysis of the $g'$ light curves (better outlier rejection in the light curves, a more careful photometric extraction or rotation correction, different hyperparameter priors and initializations, or an as-yet untested covariance kernel) will yield radii from GP regression of individual transits that cluster around the present value. If that is the case, then WASP-103b’s optical transmission spectrum is consistent with Rayleigh scattering.

But it is also possible that the high-S/N but very scattered N1-T1$g'$ light curve is skewing the simultaneous GP regression toward an inaccurate low value while also inflating the uncertainty on that value. If so, dropping that light curve from the simultaneous GP regression would yield a larger planetary radius and a steeper spectral slope. Certainty both T4$g'$ light curves, the cleanest and highest S/N light curves, indicate larger planet radii than the current simultaneous GP regression value. A more complete analysis will need to test how the radius indicated by the simultaneous GP regression is affected by exclusion of each light curve from the set. That is, how the value changes when fitting different combinations of five light curves per filter.

For now, we conclude that while MINERVA observations of the transit of WASP-103b across $g'$ and $i'$ passbands are roughly in agreement with those of SE16, the large uncertainties on extracted planetary radii prevent us from accurately verifying SE16’s report of a super-Rayleigh slope in the optical transmission spectrum. A more detailed analysis will be able to determine how outlying and uncertain values of effective radii in $g'$ affect our calculation of $\alpha$. 121
Table 4.6: MINERVA Values of Spectral Slope

<table>
<thead>
<tr>
<th></th>
<th>This Work</th>
<th>SE16</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_P \ (M_J)$</td>
<td>1.47 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>$R_P \ (R_J)$</td>
<td>1.596 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>$T_P \ (K)$</td>
<td>2489 ± 65</td>
<td></td>
</tr>
<tr>
<td>$\mu \ (a\cdot m\cdot u)$</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td><strong>Observed Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d \frac{R_P(\lambda)}{d \ln \lambda}_{\mid C} \ (km)$</td>
<td>$-3380.22 \pm 7507.39$</td>
<td>$-6736.56 \pm 791.46$</td>
</tr>
<tr>
<td>$d \frac{R_P(\lambda)}{d \ln \lambda}_{\mid S} \ (km)$</td>
<td>$-29661.16 \pm 12714.66$</td>
<td>—</td>
</tr>
<tr>
<td><strong>Calculated Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g_P \ (m \cdot s^{-2})$</td>
<td>14.96 ± 1.22</td>
<td></td>
</tr>
<tr>
<td>$H_s \ (km)$</td>
<td>601.48 ± 51.55</td>
<td></td>
</tr>
<tr>
<td>$\alpha T_C$</td>
<td>$-16241.8 \pm 36105.94$</td>
<td>$-27900 \pm 2200$</td>
</tr>
<tr>
<td>$\alpha C$</td>
<td>$-5.62 \pm 12.49$</td>
<td>$-11.2 \pm 0.9$</td>
</tr>
</tbody>
</table>

4.7 Future Work

4.7.1 Verification of MINERVA slope

Since we cannot verify or refute SE16’s claims of a super-Rayleigh slope in WASP-103b’s optical transmission spectrum using this treatment of MINERVA light curves, future attempts would need to perform a more detailed analysis of the $g'$ light curves to attempt to reduce the inconsistencies in planetary radii in that filter and reduce the uncertainties in the derived values.

Steps towards this end should (at a minimum) include:

1. For T1 and T2 light curves, which have a high level of scatter among individual photometric points, performing more careful differential photometry of our observations to remove the possibility that imperfections in comparison stars or the AstroImageJ’s automatic photometry pipeline has caused additional noise.

2. For the simultaneous GP regression of the $g'$ light curves, examining how inclusion or exclusion of each light curve affects the derived value and uncertainty on $R_P / R_S$. Sequentially removing one light curve at a time from the GP regression and compare the GP regression precisions would accomplish this.

3. For GP regression of individual light curves, exploring how our selection of priors on hyperparameters $A$, $L$, $\theta$, and $\Omega$ affect the GP regression. It is possible
that by allowing $\theta$ and $\Omega$ to approach $\tau$ and $T_{14}$ that the model is overfitting the noise. If that is the case, different prior probability distributions should be tried.

4. It is possible that our assumption that use of an over-parameterized covariance kernel has no negative effect on the GP regression is false. Or, that the large uncertainties and outlying radius values indicate that the wrong kernel has been selected. A simpler squared-exponential kernel might provide more accurate and precise planetary radii and should, therefore, be tested.

We hope that with these tests we will be able to tighten up the scatter in the $g'$ effective planetary radii and decisively verify or refute the detection of a super-Rayleigh slope in WASP-103b’s optical transmission spectrum.

4.7.2 Chromometry

When designing the observing program that led to the transit light curves presented here, we also had the goal of calculating differential transit light curves between the two filters in a state-of-the-art technique we call “chromometry” (Beatty et al. 2015). By dividing the light curve in one filter by the light curve in a different filter we can get a measure of the planet’s color over time through a transit event, a “color curve.” Beatty et al. (2015) outline some of the potential benefits of transit chromometry of hot and warm planets. Most importantly, they point out that effectively “detrending” a light curve against a light curve of the same star in a different filter reduces noise due to selection of imperfect comparison stars in differential photometry. Knutson et al. (2014b) and similar studies that observe planetary spectra with HST/WFC3 perform similar same-star “detrending” by fitting differential light curves that divide curves in wavechannel bins to a blended white-light curve. Doing this improves the signal to noise of a light curve, widening the observable parameter space of exoplanet atmospheres.

Validation of this technique could place moderately-hot and warm Jupiters within the grasp of current technology, increasing the number of observable exo-atmospheres by $3 - 4 \times$ the current number. Successful application of chromometry could also let us observe the atmospheres of planets around very bright stars, which are often skipped over because the integration time needed to measure the planet’s spectrum would saturate the detectors of larger telescopes. The increase in precision that chromometry
offers would make those planetary spectra observable by smaller telescopes which would not be saturated by the brighter stars.

Our MINERVA observing program was designed to answer the following questions:

1. What is the optical color of WASP-103b’s atmosphere during transit and if it varies over time, how so?

2. What is the optimal mode for chromometric measurements: alternating filters on a single telescope or single filters on separate identical telescopes?

3. How does the precision of a color curve depend upon use of individual telescopes?

Answers to the second and third questions would have wider relevance outside of this work. Each of the two observing options provides potential advantages and disadvantages. Alternating filters on a single telescope would remove the possibility of additional noise due to different detectors and allow the technique to be used by telescopes which are not part of an array of identical telescopes like MINERVA. It would also ensure that the time lag between observations in each filter would be constant throughout an observing sequence. However, time resolution of observing sequences in that mode would be limited by the overhead time needed to switch between filters, and the constant filter swapping may add additional systematic noise into the color curves depending on the telescope stability.

Conversely, using single filters on separate identical telescopes would allow for more observations in a single evening, critical for faint stars requiring longer integration times or for characterizing the ingress and egress of quick transits. However, that may introduce unforeseen noise into the color curves due to different detector systematics or conditions, as no two systems are completely identical. And, the time lag between observations made on the two telescopes may be less constant throughout the course of an evening due to different overheads, readout times, or other technological factors.

To demonstrate the viability of chromometry, we calculate very preliminary color curves of WASP-103b in \( g' - i' \) as

\[
C(t) = \frac{F_{g'}(t)}{F_{i'}(t)} \left/ \langle \frac{F_{g'}(t)}{F_{i'}(t)} \rangle \right.
\]

(4.10)

with uncertainties \( \sigma_C \) given as
\[
\sigma_C = C(t) \sqrt{\left( \frac{\sigma_{F_g'}}{F_g'} \right)^2 + \left( \frac{\sigma_{F_i'}}{F_i'} \right)^2}
\]  
(4.11)

where \( C(t) \) is the normalized color of the planet at time \( t \), \( F_x(t) \) is the sky-subtracted, un-normalized flux of the star in band \( x \) at time \( t \), and \( \sigma_{F_x} \) is the uncertainty in the raw flux in that band.

Our MINERVA observing program produces three chromometric color curves per observing evening: \( T_1g' - T_1i' \), \( T_2g' - T_2i' \), and \( T_4g' - T_3i' \). The color curves of WASP-103b from these observations are shown in Fig. 4.7. The long-term trend seen clearly in the single-telescope color curves is a result of changing airmass over the \( \sim 5 \) hours of observations.

From Fig. 4.7 we can begin to answer Questions 2 and 3 from the above list. It is clear that on both evenings, the single-telescope color curves have higher S/N and more stability than the multi-telescope color curves. Both \( T_1 \) and \( T_2 \) provide color curves of near-equal high quality. Especially for telescopes which did not suffer from technical failures (like the de-rotator failure of N1-T2), observing in alternating filters on a single telescope yields a clean, high-S/N color curve with little scatter and little variation in quality between telescopes.

Our qualitative understanding of optimal observing modes for chromometry suggests that telescope arrays like MINERVA are ideal systems for obtaining many near-simultaneous color curves of a single target or color curves of many targets, thus optimizing observing time. Any added noise due to filter swapping is minor when compared to the noise and uncertainties added when creating color curves from different telescopes.

Future work on the chromometry of WASP-103b will include Gaussian process regression of the color curves to derive physical parameters for the system to test the improvement in precision over traditional transit observations. We also plan to more quantitatively determine the optimal observing mode for chromometry and how reliable the precision improvement is across telescope and observing times.

### 4.8 Summary

We observed two sequential transits of WASP-103b using the MINERVA telescope array in \( g' \) and \( i' \) in an attempt to verify the presence of a super-Rayleigh slope in
the optical transmission spectrum of the planet. We obtained six, near simultaneous transit light curves per evening, which we corrected for diluting flux from the nearby companion star. Gaussian process regression of six, single-filter light curves guided the GP regression individual light curves to ensure consistent and physically meaningful solutions. Calculation of the spectral slope $\alpha$ was complicated by large variation and uncertainties in the derived planetary radii from $g'$ light curves. Due to large uncertainties, our calculated spectral slope is consistent with both SE16’s super-Rayleigh slope and with normal Rayleigh scattering in an atmospheric haze. Further testing on the robustness of our calculations will need to be done to ensure that poor-quality light curves are not unduly influencing our calculation of the optical transmission slope. Lastly, we introduce a new technique, which we term “chromometry,” that may significantly improve the precision of exo-atmosphere observations and increase the number of observable exo-atmospheres by $3 - 4$ times the current number.
4.9 Acknowledgements

This work was partially supported by funding from the Center for Exoplanets and Habitable Worlds. The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium. We gratefully acknowledge the use of SOA/NASA ADS, NASA, and STScI resources.
Chapter 5  
The Signatures and Information Content of Transiting Megastructures

Researchers in the Search for Extraterrestrial Intelligence (SETI) have previously noted that planet-sized artificial structures could be discovered with Kepler as they transit their host star, and might distinguish themselves from exoplanets through anomalous silhouettes, orbits, or transmission properties. Several anomalous detections, such as KIC 12557548, have transit depth variability and asymmetric shapes consistent with predicted artificial “beacons” and artificial constructs. Since well motivated physical models have so far provided natural explanations for these signals, the ETI hypothesis is not warranted for KIC 12557548, but it still serves as a useful example of how non-standard transit signatures might be identified and interpreted in a SETI context. We develop the normalized information content statistic $M$ to quantify the information content in a signal embedded in a discrete series of bounded measurements, such as variable transit depths, and show that it can be used to distinguish among constant sources, interstellar beacons, and naturally stochastic or artificial, information-rich signals. We apply this formalism to KIC 12557548 and a specific form of a SETI beacon to illustrate its utility.

Megastructures.” This work contains contributions from Jason T. Wright, Kimberly M. S. Cartier, Ming Zhao, Daniel Jontof-Hutter, and Eric B. Ford. Sections 5.3, 5.3.2, 5.4, 5.5, 5.6, and 5.7 contain text that KMSC wrote as part of Wright et al. (2016). Among the sections of this chapter which have been previously published, JTW conceived of and initiated this research and provided overall guidance and editing of this text; EBF contributed to the theoretical basis for the analysis of information content in Section 5.3. Authors’ additional contributions to this project that do not appear in this chapter can be found in the acknowledgments of Wright et al. (2016).

In this chapter, Sections 5.1, 5.2, 5.3, and 5.7 contain text original to this dissertation that summarizes analogous sections of Wright et al. (2016), provides the necessary background and context for this project, or describe scientific advances since the publication of this project.

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5.1 Distinguishing Beacons From Natural Signals Via Their Information Content

Advanced, spacefaring civilizations might have significant effects on their circumstellar environment, including the construction of planet-sized structures or swarms of objects (see Wright et al. 2014b and references therein). Such “megastructures” might be...
detectable by the starlight they block, and therefore might be observable from Earth using the same methods by which we search for transiting planets.

The most commonly suggested motivation behind the construction of orbiting megastructures is for the collection of starlight as a free and sustainable energy source (e.g., Dyson 1960; Wright et al. 2014a). However, Arnold (2005) suggests that large transiting objects could provide a long-lived, low-maintenance, and low-energy means of interstellar communication through “beacons”—signals of unambiguously intelligent origin that are unlikely to be mistaken for natural sources. Kardashev (1964) suggests that starlight collection might be motivated not just as a free energy source but as a means of powering interstellar radio beacons.

Arnold (2005) argues that long-term, precise photometric monitoring of stars, like during the prime Kepler mission, is equally capable of detecting transiting megastructures as transiting exoplanets. Arnold goes on to present one way we might distinguish between natural and artificial transiting objects—through a series of transits that change in depth and/or timing in a predictable and unambiguously unnatural sequence. Wright et al. (2016) discusses ten potential anomalies caused by transiting megastructures that could distinguish them from planets or stars, and natural mechanisms that might cause a similar anomaly.

Given the potential for Kepler to have observed natural and artificial mechanisms that produce similar observable phenomena, we sought a way to distinguish between artificial “beacons” produced by transiting megastructures and their natural counterparts. To that end, we developed a normalized information content metric to quantify the information contained within a time series of transit depths observed by Kepler. Sec. 5.2 presents two anomalous Kepler target of interest and the ways in which they might be mistaken as having artificial origins. Sec. 5.3 introduces the concept of ETI beacons that present as variable transit depth time series, and details our use of the Kullback-Leibler divergence (Sec. 5.3.1) to develop the normalized information content metric, $M$ (Sec. 5.3.2). Sec. 5.4 presents our calculation of the $M$ metric for two natural and normal transit sequences (Kepler-5b and Kepler-4b), one anomalous transit sequence (KIC 12557548), and two examples of artificial beacons at different signal-to-noise levels. Sec. 5.5 presents the same examples using a frequency-space development of $M$, and Sec. 5.6 presents the results of the information content analysis in both time- and frequency space.

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4This analysis has some parallels in the statistics used for paleoclimatology research.
5.2 Transit Signals with Significant Information Content

Arnold (2005) and Wright et al. (2016) postulate that transiting megastructures, whatever their intended purpose, may have non-spherical shapes and potentially variable transit cross sections. *Kepler* was capable of detecting megastructures with a triangular cross section and a rectangular screen of adjustable louvres (Arnold 2005), or a swarm of smaller structures that collectively block measurable starlight (Korpela et al. 2015), any of which would produce anomalous ingress and egress shapes in a transit profile. Each of these examples could potentially also produce a transit shape or transit depth that varies on an orbital timescale through intentional or chaotic rotation (for a single solid structure) or manipulation (for a multi-component structure). Blatantly non-spherical transit profiles combined with complex variations in transit depth might indicate an artificial object.

*Kepler* did detect one such object, KIC 12557548b (hereafter KIC 1255b; Rappaport et al. 2012) during its prime mission, which has a non-spherical transit profile and highly variable transit depth, but for which there is a completely natural explanation. This section presents the peculiar case of KIC 1255b, its potential natural explanation, and why we focus on this target to contrast to hypothetical artificial structures. This section also discusses another *Kepler* target, KIC 8462852, which gained notoriety after the publication of Wright et al. (2016). Though we did not include KIC 8462852 in the analysis presented in Sec. 5.4, it would be a compelling target for inclusion in this type of analysis if future observations allow. For discussion of other variable transit targets, like KOI-2700 (Rappaport et al. 2014) and K2-22b (Sanchis-Ojeda et al. 2015), please see Wright et al. (2016).

5.2.1 KIC 1255b—A disintegrating sub-Mercury size planet

Rappaport et al. (2012) announced the discovery of KIC 1255b, a transiting planet on a 16-hour orbit with a non-typical transit profile. The KIC 1255b transit depths measured by *Kepler* vary from a maximum of 1.3% to less than ~ 0.2% with no predictable pattern. The shape of its transit shows an obvious asymmetry (see Fig. 5.1 and Croll et al. 2014). Rappaport et al. explain KIC 1255b as a small disintegrating planet that is shedding material due to the intense stellar radiation.
The loose material ostensibly trails behind the solid “core” and forms a comet-like tail; the tail causes the asymmetric transit profile and the stochastic nature of the disintegration causes the variable transit depth.

Brogi et al. (2012) and Budaj (2013) model the transit profile using a changing cometary cloud and tail. Their theoretical cloud causes forward scattering of the stellar flux off of dust particles, observable as the slight brightening seen before ingress in Fig. 5.1. Budaj (2013) constrains the dust particle size to $0.1 - 1 \mu m$, and Perez-Becker & Chiang (2013) find that, assuming that the evaporating planet model is correct, KIC 1255$b$ has likely lost up to 70% of its mass. van Werkhoven et al. (2014) note two significant departures from true randomness in KIC 1255$b$'s transit depth time series (DTS). The first are “quiescent” periods with transit depths $\lesssim 0.1\%$ near the start and end of the prime Kepler mission, clearly seen in the transit DTS of KIC 1255$b$ (see Fig. 5.2 bottom). van Werkhoven et al. (2014) also noted a few sections of the DTS that have alternating deep and shallow transits that they explain using a two-component cloud model.

A completely natural model can explain the peculiar shape and DTS of KIC 1255$b$, but one could conceive of an artificial explanation for the variability and non-spherical transit profile. We were particularly interested in whether a large artificial structure with an alterable transit profile could mimic the transit DTS variability (i.e. Arnold 2005) and a static geometric shield occulting the host star (i.e. Forgan 2013). Sec. 5.3 explores the types of artificial beacons we might expect to see and how we can use the information content of the DTS to distinguish natural and artificial transit sequences.

5.2.2 KIC 8462852—Boyajian’s Star

Boyajian et al. (2016) announced an even more peculiar Kepler star, KIC 8462852, after citizen scientists at Planet Hunters noticed the star’s non-planet-like “dips” in flux. The dips occurred at irregular intervals during the prime Kepler mission, had irregular and non-repeating shapes, and caused drops in stellar flux up to 20% (see Boyajian et al. 2016; Wright et al. 2016, for examples of the light curve occultations).

KIC 8462852 is a seemingly ordinary F-type star in the Kepler field, with an optical spectrum typical of a slightly evolved main sequence star and a brightness
consistent with a distance of $\sim 450$pc. A combination of low-level photometric variability and rotational broadening of spectral lines indicates a $\sim 1$ day rotation period. Of the more than 100,000 *Kepler* stars, Boyajian et al. (2016) identified only a handful of stars that showed drops in flux $> 10\%$, and that set consisted of eclipsing binaries, heavily spotted stars, and KIC 8462852.

Boyajian et al. suggest several explanations, but settle on a “family of exocomet
fragments, all of which are associated with a single previous breakup event” as the one “most consistent with the data.” Wright et al. state, “Given this object’s qualitative uniqueness, given that even contrived natural explanations appear inadequate, and given predictions that Kepler would be able to detect large alien megastructures via anomalies like these, we feel is the most promising stellar SETI target discovered to date.”

Since its initial announcement in Boyajian et al. (2016) and subsequent mention in Wright et al. (2016) as a promising SETI target, interest in KIC 8462852 has grown to near viral levels as astronomers continue to propose, and then later shoot down, potential explanations for this odd phenomenon. This section summarizes new information that astronomers have collected about KIC 8462852 since the publication of Wright et al. (2016). For an updated and detailed analysis of families of solutions to KIC 8462852, see Wright & Sigurðsson (2016) and the references contained therein. KIC 8462852 is known more formally now as Boyajian’s Star, after Dr. Tabetha Boyajian, and we refer to it as such for the remainder of this section.

5.2.3 Recent Observations

Boyajian et al. (2016) noted the lack of excess infrared (IR) flux around Boyajian’s Star prior to the Kepler campaign, and Lisse et al. (2015) and Marengo et al. (2015) verified that the lack of IR excess was a persistent phenomenon. Thompson et al. (2016) reported no significant millimeter or sub-millimeter emission, which places upper limit on the mass of any circumstellar dust in the system.

Boyajian’s Star invited additional controversy when Schaefer (2016) reported that archival DASCH photometry indicates that Boyajian’s Star had faded at a rate of $\sim 1.6$ mag per century from 1890 to 1989. Montet & Simon (2016) added to this claim of long-term dimming by using full frame Kepler images to show that Boyajian’s Star had faded by 4% over the course of the Kepler mission, a rate of $\sim 0.7$ mag per century.

Schaefer’s claim of long-term dimming was challenged by Hippke et al. (2016), who re-analyzed the photometric plates from the DASCH archive and reported slight underlying systematics on the order of $\lesssim 0.2$ mag per century from 1889-1990 for most steady point sources. For this reason, they claim that the century-long dimming reported by Schaefer cannot be treated as significant. Lund et al. (2016)
further analyzes the DASCH plates, with a specific focus on F stars and finds that suggestions of long-term variability in many F stars are artifacts of the “Menzel Gap” in the DASCH data (between \( \sim 1954 - 1970 \); Grindlay et al. 2012), and so DASCH photometry of Boyajian’s Star is consistent with constant flux for the time period in question.

Hippke et al. (2017) follows up the DASCH analyses with examination of an independent set of archival plates from Sonneberg Observatory, Germany, covering the years of 1934 – 1995, and a second set of independent observations from Sternberg Observatory, Moscow, from 1895 – 1995. They find Boyajian’s Star to have constant brightness within 0.03 mag per century (3%). Their result is inconsistent with that of Schaefer (2016) at 5\( \sigma \), but remains consistent with the 3% dimming reported by Montet & Simon (2016). They also note an additional possible short-term dimming event on 1978 October 24 which has yet to be verified.

As of the date of this dissertation, it appears more likely that the century-long fading of Boyajian’s Star claimed by Schaefer (2016) is an artifact of systematics within the DASCH plates. As it is consistent with the independent analysis of Hippke et al. (2017), the shorter-term dimming reported by Montet & Simon (2016) is more likely a real phenomenon. The families of solutions discussed by Wright & Sigurðsson (2016) treat both the century-long fading and short-term dimming as real phenomena as well as the Kepler eclipse events.

Initial calculation of the distance to Boyajian’s Star from the GAIA mission (Gaia Collaboration et al. 2016b,a; Hippke & Angerhausen 2016; Lindegren et al. 2016) indicates a distance of \( 391.4^{+122.1}_{-75.2} \) pc, which is consistent with previous estimates of distance based on the distance modulus for an F3V star and interstellar reddening. While this analysis based on GAIA DR1 does not provide any new constraints on potential scenarios to explain Boyajian’s Star, Hippke & Angerhausen note that future GAIA data releases should constrain the distance to within 1%, which will allow us to rule out some families of explanations.

LaCourse (2016) finds no stars similar to Boyajian’s Star among the \( \sim 150,000 \) Kepler prime mission stars or any of \( \sim 165,000 \) K2 targets. Lacki (2016) focuses on the Kepler fading reported by Montet & Simon (2016) and calculates how common the phenomenon must be for an individual star in order to have been found by Kepler. Lacki reports that the 3% dimming would need to occur at a rate of \( \gtrsim 30 \text{Gyr}^{-1} (t_{\text{anom}}/100\text{yr})^{-1} \) for each Kepler and K2 star. A phenomenon spanning the
A few studies have followed up on the SETI angle initially proposed by Wright et al. (2016). Abeysekara et al. (2016) found no evidence for optical flashes of Boyajian’s Star using the VERITAS gamma-ray observatory. Harp et al. (2016) and Schuetz et al. (2016) found no evidence of narrow-band radio communication or pulsed laser emission during simultaneous observations using the Allen Telescope Array and the Boquete Optical SETI Observatory (Wright & Sigurðsson 2016).

5.2.4 Potential Explanations

In the initial discovery paper, Boyajian et al. (2016) discuss a swarm of comets as a potential explanation to the anomalous dips seen by Kepler. Bodman & Quillen (2016) simulated these scenarios and were able to reproduce the shapes and depths of the anomalous dips in the final two months of Kepler data, but were unable to reproduce the long, slow, deep event observed during Kepler Quarter 8. The other events required families of hundreds or thousands of comets at once, which would be indicative of a recent collision and likely produce finer circumstellar dust visible as IR excess. Neslušan & Budaj (2017) also simulated families of comets with extended shrouds and were able to qualitatively reproduce the shapes and depths of some, not all, of the Kepler dips. Because comets cannot explain every Kepler event nor the 3% dimming, a cometary explanation is less plausible.

Makarov & Goldin (2016), published a few months after Wright & Sigurðsson (2016), explored the origin of the reported 0.88 day rotation period of Boyajian’s Star through a principle-component analysis of all 16 Quarters of Kepler light curves. They report that the 0.88 day periodicity in weak-amplitude flux variations cannot be attributed to Boyajian’s Star due to inconsistencies in variability-induced motion within the same Quarter of data. Because of this, they suggest that the 0.88 day period is instead due to some form of external obscuration rather than from starspots on the stellar surface.

Metzger et al. (2016) explore the hypothesis that Boyajian’s Star recently merged with a substellar companion, temporarily increased in brightness, and that the Kepler
dips and dimming are a return to the equilibrium luminosity. They report that recent consumption of companions with masses ranging from a brown dwarf to Io would produce rate of post-merger luminosity decrease consistent with both the Montet & Simon and Schaefer rates. Additionally, they note that whatever mechanism caused the merger in the first place could have also displaced other material that cause the *Kepler* events (i.e. Bodman & Quillen 2016, Neslušan & Budaj 2017). This is the first scenario analyzed that could plausibly explain both the dimming and the dips within the constraints set by IR, millimeter, and sub-millimeter observations. The flaw in this is the unlikelihood of the short-term *Kepler* mission catching this type of rare event in action, as the complete “return to normal” process would occur in $10^2 - 10^5$ yr.

Sheikh et al. (2016) explore the statistics of the *Kepler* events, and shows that it is possible that the dips follow a power law similar to the power law seen in other natural physical processes common to stars. They posit that this supports the hypothesis that the *Kepler* dips result from internal stellar processes rather than external obscuration.

Foukal (2017) also explores the scenario of intrinsic variations of the luminosity of Boyajian’s Star due to internal physical processes rather than external obscuration. They note that modeling of variations in solar luminosity has shown that convective stars can internally store the required fluxes efficiently, and posit that the *Kepler* events may be indicative of unknown processes related to stellar magneto-convection.

A radio observing campaign of Boyajian’s Star is ongoing using the Greenbank Telescope through collaboration with the Breakthrough Listen Initiative (Isaacson et al. 2017), and seeks to obtain a complete $1 - 100$ GHz spectrum of the star. Additionally, an observing program by the Las Cumbres Observatory Global Telescope (LCOGT) network, funded by a successful Kickstarter campaign, has been monitoring Boyajian’s Star starting late 2016 tying to detect the next time a *Kepler*-like dip occurs. During the next dip, multiple telescopes plan to swing over to obtain multi-wavelength observations of the star in an attempt to characterize the obscuring material.

On UT 19 May 2017, multiple observatories noted a significant dip in the flux of Boyajian’s Star, the first seen since the completion of the prime *Kepler* mission. The new event lasted for a total of $\sim 5$ days, after which the star seemingly returned to its normal flux levels. Analysis of multi-band photometry and spectra taken during the event is currently ongoing, and aims to constrain the size, composition, and placement of any obscuring material. At this time, the only explanatory scenarios that have
been completely ruled out are that the dips are \textit{Kepler} instrumental artifacts and that the dips were caused by a one-time chance alignment of two objects.

### 5.2.5 No Consensus at Present

As this literature review shows, there is currently little consensus as to the best possible explanation for the \textit{Kepler} “eclipse” events, and no firm consensus as to the presence (or explanation) of the long- or short-term dimming reported by \citet{schaefer2016} and \citet{montet2016}. A more precise measurement of distance from GAIA parallax will constrain the intrinsic stellar luminosity and amount of energy lost during dips and dimming. The calculations of absolute (rather than relative) changes will constrain whether internal processes can account for the energy loss during events, or if external processes must be invoked. Lastly, analysis of multi-band photometry and spectra observations of a new “eclipse” event will hopefully constrain the size of any particles obscuring starlight if, in fact, they do exist.

### 5.3 The Normalized Information Content, $M$, of Beacons and More Complex Signals

Two categories of signals from ETIs that we might expect to detect are “beacons” and “leaked” communication. The former might be employed by ETIs seeking to be discovered by other intelligent species, and so might be obvious, easily detected, simple, and unambiguously artificial. These qualities make beacons the focus of many SETI efforts \citep[e.g.][]{cocconi1959, oliver1979}, and many efforts since then. Indeed, pulsars appeared to exhibit many of these qualities, and until its physical nature was deduced the first pulsar discovered was jocularly referred to as “LGM-1” (for “Little Green Men”) by its discoverers \citep{burnell1977, hewish1968}.

By contrast, leaked communication, since it is not intended to be discovered or interpreted by humans, might have none of these qualities. In particular, it might be characterized by high bandwidth and/or high levels of compression, making its signal highly complex with an extremely high information content. For a signaling process of a given bandwidth, increasing the information content results in the measurements more closely resembling a random signal, potentially thwarting attempts to distinguish an artificial signal from the natural variability of an astrophysical source.
If an alien signal is detected, it will be important to determine if it is a beacon, whose purpose and message might be discernible, or a much more complex signal, which might be beyond our comprehension. A first step, then would be to characterize the complexity of the signal. Similarly, the case for a potentially alien signal being an artificial beacon would be strengthened if its information content were low but non-zero, and not maximal (as in the case of pure noise).

SETI would therefore benefit from a quantification of signal complexity that clearly distinguishes beacons, signals with zero information content, and signals with maximal information content.

A signal can serve as both a beacon and a high-information-content signal by being simple in the time domain but complex in the frequency domain, or vice versa. For instance, a simple sinusoidal signal could act as a carrier wave, and small variations in the amplitude and/or frequency of the wave could carry complex information. An ideal statistic of information content should therefore be applicable in both the time and Fourier domains, and be able to give different values in each.

We have chosen to use the Kullback-Leibler divergence, $K$, as the basis of our metric, and we describe its calculation from our discrete DTS in detail in Sec. 5.3.1. In short, the Kullback-Leibler divergence computes the relative entropy between two distributions. In the time domain, we use the probability density function (PDF) of the measured signal, produced from the DTS via kernel density estimation (KDE), and compare to synthetic PDFs of constant and uniformly random signals. In this formalism, $K$ has a small value for constant signals ($\delta$-function distributions) and large values for uniformly random signals (uniform distributions). In the frequency domain, we use the discrete Fourier transform in place of the PDF. In frequency space, $K$ has a small value for signals with power at a single frequency (or constant signals) and maximal values for white noise. This formalism can also be expressed in other bases in which information might be transmitted.

To help interpret the $K$ values we compute for given time discrete series, we propose the normalized information content metric, which quantifies the complexity of a signal in the time or Fourier domains on a simple scale from zero (no information).

---

6Given that ETIs might be arbitrarily more technologically and mathematically more advanced than us, interpreting a complex signal might be an impossible task, akin to Thomas Edison attempting to tap the telecommunication signal carried by a modern optical fiber cable. Even if we were to somehow notice, intercept, and successfully record the signal, there is no guarantee we would be able to decipher it.
to one (maximal information), with beacons having intermediate values. The value of $M$ measured for a given signaling process will depend on many factors, including the precision of the measurements and the length of portion of the signal observed. Measuring a low value of $M$ means that the signal appears constant at a given precision, and measuring a very high value means that it appears to be uniformly random.

5.3.1 Kullback-Leibler Divergence: $K$

The Kullback-Leibler Divergence (KL divergence), also known as the relative entropy, estimates the amount of information lost when one probability distribution is used to approximate another. The KL divergence of a continuous probability distribution is given by

$$K = \int_{-\infty}^{\infty} p(x) \times \ln \left( \frac{p(x)}{q(x)} \right) dx \quad (5.1)$$

were $p(x)$ is the PDF of the signal and $q(x)$ is the probability distribution used to approximate the signal. (Note that the integrand in Equation 5.1 evaluates to zero for values of $x$ such that $p(x) \to 0$). A signal with high information content will take on many values, while a signal with no information content takes on exactly one value. So, a “maximal” signal is represented by a uniform distribution and a “minimal” signal is represented by a delta function at the mean value of the data $p(x) = \delta(x - \mu)$.

For our purposes, we wish to quantify the information lost when our signal is approximated by a uniform probability distribution. This is a measure of the information content of the signal relative to its maximal value. We thus choose a normalized, uniform comparison distribution ($q(x) = \text{constant}$) for all possible values $x$ of the signal. The KL divergence of a maximal signal (with distribution $p(x)$) will then be zero, indicating that there is no difference between the signal and the uniform distribution, and a minimal (empty) signal with no measurement error will be infinite (since the integrand of Eq. 5.1 diverges for $x = \mu$).

\footnote{There should be relatively few cases where completely natural transit sequences are well-approximated by a uniform random distribution. However, as is discussed in Sec. 5.4.2 and 5.6, the time-based KL divergence of KIC 1255\textit{b} approaches a truly random distribution when measured at a simulated signal-to-noise level higher than obtained by \textit{Kepler}. Based on the best physical models, this is likely due to the stochastic evaporation processes that create the cometary tail of 140}
We note that the KL divergence is not symmetric: exchanging \( p(x) \) and \( q(x) \) does not preserve the value of \( K \). We have chosen \( p(x) \) and \( q(x) \) as we have because the alternative—using minimal signals as our comparison—produces infinite KL divergences (where the comparison signal has zero probability, the formula diverges) which we cannot meaningfully compare.

Since we will compute the KL divergence numerically, we must approximate this integral with a discrete sum. This will also allow us to naturally apply the KL divergence to distributions in frequency space, computed using discrete Fourier transforms (DFTs). In this approximation, Eq. 5.1 becomes

\[
K = \frac{R}{N} \sum_{i=1}^{N} p(x_i) \times \ln (R p(x_i)) \tag{5.2}
\]

where \( R \) is the domain over which the PDF is sampled (so \( q(x) \equiv 1/R \)), \( N \) is the number of bins along the PDF, and \( p(x_i) \) is the probability associated with events having values in the bin centered on \( x_i \). The fraction \( R/N \) assumes that all of the bins in the PDF are of equal width. If this is not the case, \( R/N \) is removed from in front of the sum and replaced by the variable bin width \( \Delta x_i \) within the sum.

The sum in Eq. 5.2 is over the entire allowed range of the signal, and the summand evaluates to zero for values of \( x_i \) such that \( p(x_i) \to 0 \).

### 5.3.1.1 KL Divergences for Transit DTS

Our instant application of the KL Divergence will be to Arnold beacons of Sections 5.4.3–5.4.4, to the transit DTS of ordinary exoplanets (Kepler-4b and Kepler-5b), and the DTS of one with variable transit depths (KIC 1255b). For these purposes we choose \( R = 1 \) and define our PDFs on the domain \([0, 1]\) in order to encompass the physically meaningful range of possible transit depths. Applications to other signals may use different values for \( R \).

We approximate our signal PDFs via KDE of a series of measurements. This procedure convolves the distribution of transit depths with a Gaussian kernel of width equal to the typical depth measurement uncertainty. This produces a continuous material behind the planet. We might expect similarly complex transit depth sequences for other evaporating planets. If they could be measured at a higher S/N than obtained for the KIC 1255b Kepler sequence, their transit depth sequences might approach true randomness. For other examples of non-singular transit depth sequences, see Wright et al. (2016).
distribution, and removes the problems of false precision that come with binning small numbers of points more finely than measurement precision warrants.

The resulting PDF can extend outside the defined range $R = [0, 1]$, both because the kernel widens the distribution and because real measurement noise can yield negative transit depths. Simply rejecting the parts of the PDF outside our range leads to problems with normalization and introduces artificial features in the PDF that can yield misleading measures of the information content. Since the signals we will consider here never have values near 1 (total obscuration) and our precision is high, we simply shift our depth measurements by a small constant to ensure that the resulting KDE falls entirely within our range $R$. A more robust approach would redefine our KL divergence to account for the wings of our PDF outside of our range due to measurement noise and our KDE procedure, but for high precision measurements the effects on the resulting statistic will be small, so we adopt this simpler procedure here for illustrative purposes.

5.3.1.2 KL Divergences in Frequency Space

There are many ways in which information might be encoded in a signal conveyed as a discrete sequence within a specified range, and our analysis of the time series only explores one way in which the signal might be simple or complex. For instance, while the KL divergence for a DTS as described above can measure how variable or discrete a sequence of transit depths may be, it does not distinguish between simple, repeating signals and stochastic signals that take on only discrete values.

For example, when using a joint distribution $q(\mathbf{x})$ that factorizes as $\prod_{i=1}^{n} q(d_i)$, as in the previous section, the sequence $[1, 2, 3, 1, 2, 3, 1, 2, 3, \ldots]$ will apparently have the same relative information as the sequence $[1, 3, 2, 2, 1, 2, 3, 3, 1, \ldots]$, even though the first is strictly repeating and the second is not. Therefore, we extend our metric into frequency space. This corresponds to an alternative choice of $q(\mathbf{x})$ which is not separable in terms of $d_i$, but is separable in terms of the DFT coefficients $\mathbf{c}$, i.e., $q(\mathbf{x}) = \prod_{i=1}^{n} q(c_i)$.

---

8With this, the domain $R$ is now defined as $R = [-\epsilon, (1 - \epsilon)\) for small values of $\epsilon$.

9It is possible that a signal contains a blend of both stochastic and periodic signals. This might be caused by a physically periodic signal measured at very low S/N, a physically stochastic signal measured by an instrument with un-characterized periodic systematics (due to temperature variations, pixel imperfections, etc.), or the superposition of a physically periodic signal and a physically random signal measured by a single observation (e.g. a pulsar observed through a nebula.
Because we are dealing with real-valued signals, we elect to fold our DFTs by using only the amplitudes of the positive frequencies to calculate the relative entropy. To account for the power contained within the negative frequencies, we double the power contained in the positive frequencies (except that for sequences with an even number of elements, we did not double the power at the Nyquist frequency, which has no negative counterpart). We then rescale the frequency axis to have domain [0, 1] (so, $R = 1$; note that in Figure 5.8 we show these power spectra in physical units of frequency, not from [0, 1]).

We would like to use this folded DFT as $p(x)$ (in place of the PDF of the DTS) in our calculation of Eq. 5.2, however there is a complication, because $p(x)$ must be normalized to have unit area. The value for $K$ in frequency space will thus be very sensitive to one’s choice for the value of the DC (zero frequency) term. For instance, real constant signals measured with some amount of measurement uncertainty will have a power spectrum consistent with white noise, with typical amplitude determined by the precision of the measurement. The normalization procedure will rescale this white noise so that the entire DFT has unit area, making the final values at most frequencies dependent on the value of the DC term and the number of frequencies sampled.

Thus, when comparing values of frequency-space $K$ from different signals (as we will do when we compute our normalized information content $M$) it is important that the DFTs of the signals have identical DC terms. We choose the mean transit depth of measured signal (squared, since we are using power spectra).

### 5.3.1.3 KL Divergences in Other Bases

Our purpose in this section is to provide a quantitative, statistical description of “beacons” in a SETI context. In our development of the normalized information content, we have considered only bases in the time and frequency domains, since those are the ones in which most of the beacons proposed in the literature are simple and obviously artificial. Of course, an alien (or human) signal might encode information in or protoplanetary disk). Depending on the relative strength of the periodic and random signals (physical or not) it might be possible to separate the contributions from each source by calculating the information content in both time and frequency bases, or using a different base altogether. An analogous information content analysis of other measurable parameters (like instrument statistics for each observation, or the shape of the signals) might reveal whether an information-rich signal is a blend of two sources.
some other basis than we have considered here, making neither the time nor frequency domains the appropriate ones for our information-content analysis. Applications of the KL divergence to many other domains can be developed straightforwardly, and at any rate the two we have developed here will suffice to illustrate their utility and dependence on some of the properties of a received signal.

5.3.2 Normalized Information Content: $M$

5.3.2.1 Effects of Measurement Noise on Ideal Values of $K$

We wish to normalize the KL divergence $K$ onto a scale with range $[0, 1]$, spanning the zero and maximal information cases. We thus define the KL divergence for a maximal distribution, $K_{\text{max}}$, the divergence for a constant signal, $K_0$, and the divergence of a real, measured signal, $K_m$. According to our formalism, ideal signals with no measurement noise will have $K_{\text{max,ideal}} = 0$ and $K_{0,\text{ideal}} = \infty$.

However random measurement noise and finite signal lengths will alter the information content of any real signal. This and the details of the construction of the underlying PDF (for instance, the KDE width) make the measured values of $K_{\text{max}}$ and $K_0$ for maximal and empty signals non-zero and finite.

This allows us to rescale $K_m$ from the values of $K_0$ to $K_{\text{max}}$ that one would calculate from empty and maximal signals at the same S/N and same signal length as the measured signal. The normalized information content will thus be a function of the S/N of the signal.

5.3.2.2 Calculating $K_0$ and $K_{\text{max}}$ in the Presence of Measurement Noise

The numerical values of $K_0$ and $K_{\text{max}}$ in the presence of measurement noise depends on three quantities: the length of the measurement series, the precision of the measurements, and the range the values of those measurements can take. To compute them, we match these values to the equivalent values of the signal we used to compute $K_m$.

For instance, consider a real signal consisting of $n_d$ discrete measurements $d_i$, having mean $\mu_d$, maximum $\max(d)$, measured with precision $\sigma_d$. We compute $K_0$ from an artificial, constant signal as $n_d$ random values drawn from a normal distribution $N(\mu_d, \sigma_d)$, and we compute $K_{\text{max}}$ from $n_d$ random values drawn from a uniform distribution with Gaussian noise, $U(0, \max(d)) + N(0, \sigma_d)$. 

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For the computation of $K$ in the time domain, we apply a Gaussian kernel with width $\sigma_d$ to the distributions of values from all three signals to construct a continuous distribution, $p(x)$, and numerically compute the KL divergence via Eq. 5.2 (using $2^{16}$ points to ensure that the function is well sampled).

In the frequency domain, we fold the DFT of each series as described in Section 5.3.1.2 and set the DC term in the in all three cases to $\mu_2^d$ (since we are using the power spectrum). We then normalize this function to unit area (i.e. the sum of the terms of the folded DFT will be the number of elements in it, which, since we have folded the DFT, is $(n_d + 1)/2$). This folded, DC-corrected, normalized DFT is our $p(x)$ for Eq. 5.2.

### 5.3.2.3 Scaling $K_m$ to Compute $M$

Since the KL divergence gives the relative entropy of a signal, the entropy of the measured signal compared to what we would measure from an empty signal is

$$\Delta S = K_m - K_0 \quad (5.3)$$

If $\Delta S \approx 0$ (i.e. there is no difference between our divergences), then our signal is consistent with pure measurement noise, and we can detect no other source of information in our data. The maximum value of $\Delta S$ is that from a maximal distribution, i.e.

$$\Delta S_{\text{max}} = K_{\text{max}} - K_0 \quad (5.4)$$

We then normalize $\Delta S$ to its maximal possible value, which allows us to construct our normalized statistic of information content, $M$, on a scale from $[0, 1]$, as we desired:

$$M = \frac{\Delta S}{\Delta S_{\text{max}}} = \frac{K_m - K_0}{K_{\text{max}} - K_0} \quad (5.5)$$

### 5.3.2.4 Uncertainty in the Statistics

These are several sources of uncertainty in our information-content statistics. The first is that measurement noise itself contributes some amount of entropy to the signal. We have adjusted for this to first order by comparing the $K_m$ value we calculate with
constant and uniform cases that include noise in the statistic $M$.

The second is that the noise in the frequency-space case depends strongly on the length of the signal (the number of events observed). We account for this by measuring $K_0$ and $K_{\text{max}}$ using the same number of points as $K_m$. But different realizations of the noise will lead to different values for $K_m, K_0, K_{\text{max}},$ and therefore $M$. We account for these effects of noise on $K_0$ and $K_{\text{max}}$ by recalculating these quantities for 1000 draws of the Gaussian noise. The ensemble of values for $K_0, K_{\text{max}},$ and $M$ that we calculated from these draws give us uncertainties on these statistics.

The effects of noise on $K_m$ cannot be robustly calculated without knowledge of the underlying signal, which we cannot assume one has. This is related to the third source of uncertainty, which is that we may have only measured a small portion of the signal, and that other parts of the signal may have a different information content. For both reasons, we frame the problem as that of measuring the information content of the portion of the signal we have actually measured, understanding that if we repeated the measurement we would get a (perhaps slightly) different number, both because of measurement noise and because the underlying signal would be different.

5.4 Time Series Analysis of Beacons and Real Transiting Systems

To illustrate the normalized information content $M$, we apply it to several different cases, enumerated below. The source code for these calculations, written in R, is available as supplemental electronic tar.gz files associated with Wright et al. (2016).

We use the Kepler time series of the apparently evaporating planet KIC 1255b to illustrate a complex, near maximal signal, as might be expected from a stochastic natural source or an information-rich signal transmitted via an Arnold beacon. We use the Kepler time series for Kepler-4b (Borucki et al. 2010a) as an “ordinary” transiting planet (so, having near-zero information content) because it has a S/N very similar to KIC 1255b and so makes a good comparison. We also consider the specific beacon signal proposed by Arnold (2005) to illustrate its intermediate relative $M$ values (at least, in the high-S/N case).

\[^{10}\text{For our particular interest in exoplanet transits, we would expect an information-free signal for the majority of transiting exoplanets. The directly observable parameter of interest, the transit depth, is related analytically to the planet/star radius ratio (see Chapter 2 and Sec. 2.2.4.1 for a}\]

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To illustrate the effects of S/N on the detectability of beacons and entropy measurements, generally, we also consider Kepler-5b (Koch et al. 2010b), which has a much deeper transit and so is measured at much higher S/N than Kepler-4b. We also consider a hypothetical version of KIC 1255b observed at a similarly high S/N but with the same measured depth values, and the same Arnold beacon as in the lower S/N case.

Although our depth measurements are slightly heteroskedastic, our derived uncertainties in transit depth of real systems are sufficiently close to constant that in what follows we choose to use the mean of the uncertainties for a given system as characteristic of the noise.

5.4.1 **Kepler-4b and Kepler-5b**

In order to illustrate an “information free” DTS, we chose Kepler-4b, a $\sim 4R_\oplus$ planet with a 3.21 day period orbiting a 1.2 $M_\odot$ star, and Kepler-5b, a $\sim 1.4R_\oplus$ planet with a 3.5 day period orbiting a 1.4 $M_\odot$ star. Their transit depths are $\mu_d = 728 \pm 30$ ppm and 6600 $\pm$ 60 ppm, respectively. Figure 5.2 (middle) shows the DTS for Kepler-4b, for quarters 1–17 (excepting 8, 12, and 16). From this we see that the Kepler-4b transits are very regular, and so we anticipate little information content in the time series. The gaps in the Kepler-4b DTS are due to missing long cadence data from quarters 8, 12, and 16, part of quarter 4, and regular instrument shutdown times. The mean transit depth of Kepler-4b is a bit lower than the mean transit depth of KIC 1255b, our benchmark “false positive” case, but since the star is brighter it has a comparable S/N to KIC 1255b which makes it an ideal comparison target.

We generated the Kepler-4b and Kepler-5b DTS’s from all available quarters Kepler long-cadence data for these targets. We downloaded the light-curves from the Mikulski Archive for Space Telescopes (MAST) and removed low-frequency variability using the Pyke function kepflatten (Still & Barclay 2012). We then ran the flattened light curves through the autoKep function of the Transit Analysis Package (Gazak et al. 2012) to identify the planetary transits, which we then folded and jointly fitted to a transit light curve model using exofast (Eastman et al. 2013) and the stellar

more detailed presentation of this). Since we expect neither the star nor the planet to measurably change in size from one orbit to the next, a sequence of transit depths should ideally repeat the same value for any transit. In that case, each subsequent transit provides no new information about the system. Any deviation from a singularly valued transit depth indicates that additional information is present in the transit depth sequence.
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Figure 5.2: Depth time series of Kepler-5\textit{b} (black points, top), Kepler-4\textit{b} (middle), and KIC 1255\textit{b} (bottom), shown at the same vertical scales (the horizontal scales are slightly different). We show a moving average (width = 7 transits) in red. Kepler-4\textit{b} is missing data from quarters 8, 12, 16, and part of quarter 4 due to instrument failure on the spacecraft. KIC 1255\textit{b} lacks data from quarters 0 and 17. Characteristic uncertainties are indicated in the legends (note the inflation factors applied for clarity).

Having solved for the parameters of the system, we then re-fit each transit individually fixing all transit parameters (using very narrow priors) except transit depth in the \texttt{exofast} fitting. In a few cases, we identified anomalous fits (reduced $\chi^2 > 5$), which we rejected.

\footnote{https://cfop.ipac.caltech.edu/home/}
In principle, hypothetical unseen planets in the Kepler-4\textsubscript{b} or Kepler-5\textsubscript{b} systems could affect the fitting of the transit DTS, since we have forced the transit centers to fit a strictly linear ephemeris. However, we are not motivated to perform more detailed investigations considering the large parameter space for undetected planets and the results of a Durbin-Watson test\textsuperscript{12} that show no evidence for a significant positive or negative autocorrelation in either dataset.

This method generated a DTS for Kepler-4\textsubscript{b} and Kepler-5\textsubscript{b}, with 282 and 351 transits, respectively, including depths, depth uncertainties, and transit center times. The DTS’s and their PDF’s of the Kepler-4\textsubscript{b} and Kepler-5\textsubscript{b} light curves are shown in Figures 5.2 and 5.3. Our DTS’s are included in our supplemental electronic files associated with this paper.

5.4.2 KIC 1255\textsubscript{b}

Figure 5.2 also shows the DTS of KIC 1255\textsubscript{b} for Q1-Q16 on the same vertical scale as the Kepler-4\textsubscript{b} and Kepler-5\textsubscript{b} DTS plots. Notable in this DTS are the two quiescent

\textsuperscript{12}This test finds p values for the alternative hypotheses that the true autocorrelation in the DTS is greater than and less than zero. For Kepler-4\textsubscript{b} we find a Durbin-Watson statistic of 1.8653, so \( p = 0.1036 \) and 0.8964 for positive and negative autocorrelations, respectively. For Kepler-5\textsubscript{b} we find a statistic of 1.9609, so \( p = 0.3328 \) and 0.6672, respectively.
periods at the beginning and end of the DTS where the measured transit depth is nearly zero, and between those two quiescent areas where the depths are highly variable. This DTS was kindly provided by Bryce Croll (2015, private communication) who describes its construction in Croll et al. (2014). We rejected one highly negative depth in the KIC 1255b time series as unphysical.

Figure 5.4 shows the PDF for the KIC 1255b DTS. The PDF on the left was generated in the same manner as the Kepler-4b DTS, with a kernel width equal to the average measurement uncertainty of the transit depths (Croll et al. 2014). The smoothness of the PDF is due to the larger width of the convolving kernel, but the width of the PDF is notably much wider than for Kepler-4b and does stretch below depth = 0 owing to the quiescent periods. To illustrate the information content that could exist in a KIC 1255b-like system observed by Kepler, we simulated a system with the same measured depths, but at ~ 10 times better precision (consistent with the S/N level of Kepler-5b, labeled as “KIC-1255b (high S/N)” in figures). The PDF generated from the convolution of the KIC 1255b DTS with a kernel with the width of the Kepler-5b uncertainties is shown on the right of the figure.

5.4.3 Beacon 1: [1, 2, 3, 5]

A simple beacon that has been considered for decades is a sequence of repeating prime numbers (Sagan 1985), a simplified version of which constitutes Arnold’s beacon: a
A series of co-orbital objects whose combined signature is a repeated series transits with depths following the pattern $[1, 2, 3, 5]$. We test this signal at both a high S/N and a low S/N to simulate our current detection capabilities.

We generate the high-S/N DTS case for Beacon 1 (labeled as “B1-high S/N”) by repeating $[1, 2, 3, 5]/5 \times \max(d)$ (where $\max(d)$ is the maximum depth of the Kepler-5$^b$ signal) an integer number of times to match as closely as possible the length of the Kepler-5$^b$ DTS, as would be observed by Arnold’s suggestions, ignoring the gaps between the transits. We then add to this noise at the level of the Kepler-5$^b$ uncertainties by randomly sampling from the Gaussian distribution $N(\mu = 0, \sigma = \sigma_{d,K5})$. The PDF for this case is shown on the right side of Figure 5.5. This was generated by convolving the B1-high S/N DTS with a Gaussian kernel with a width equal to $\sigma_{d,K5}$.

We then generate the low-S/N DTS case for Beacon 1 (labeled as “B1-low S/N”) by repeating the same sequence an integer number of times to most closely match the length of the KIC 1255$^b$ DTS, this time adding to this noise at the level of the KIC 1255$^b$ uncertainties by randomly sampling from the Gaussian distribution $N(\mu = 0, \sigma = \sigma_{d,K1255})$. The PDF for this case is shown on the left side of the figure. This was generated by convolving the B1-low S/N DTS with a Gaussian kernel with a width equal to $\sigma_{d,K1255}$.
Figure 5.6: PDF of the DTS of B2 at low- and high-S/N, using a convolving kernel with width equal to the mean measurement uncertainty of KIC 1255b (left) and Kepler-5b (right).

5.4.4 Beacon 2: [1, 2, 0, 3, 0, 0, 5, 0, 0, 0, 0]

Arnold’s beacon also encoded the prime number sequence a second way: in the spacings of the transit events (see Figure 8 of Arnold 2005). We accommodate this with a second interpretation of the signal of Arnold’s beacon, by constructing a DTS as a repeating sequence with events spaced by the narrowest gap between transits, and containing an appropriate number of null transits (depth = 0) between the more widely spaced transits: [1, 2, 0, 3, 0, 0, 5, 0, 0, 0, 0].

We again test this beacon at both a high and low S/N to simulate our current detection capabilities. The high-S/N and low-S/N synthetic DTS for Beacon 2 were generated in the same way as for Beacon 1, as described in Sec. 5.4.3.

The PDF for the high-S/N case is shown in the right side of Figure 5.6. This was generated by convolving the B2-high S/N DTS with a Gaussian kernel with a width equal to $\sigma_{d,K5}$. The PDF for the low-S/N case is shown on the left side of the figure. This was generated by convolving the B2-low S/N DTS with a gaussian kernel with a width equal to $\sigma_{d,K1255}$. 
Figure 5.7: Comparative normalized, folded DFTs for the six cases of Kepler-4b, Kepler-5b, and the beacons at high and low S/N. Frequency units are $1/p\, (day^{-1})$. Note the large variation in the scales of the (logarithmic) y-axes. Kepler-4b and Kepler-5b appear consistent with constant depth plus nearly white noise. B1 and B2 show significant power at a small number of frequencies. Note that the normalization procedure makes the level of the noise sensitive to the amount of power in the frequencies present in the signal (see text for more detail.)

5.5 Frequency-space Analysis of Beacons and Real Transiting Systems

We implemented the same procedure described above in order to calculate the relative information content of the folded, normalized power spectrum of the depth sequences, that is, the $M$-values in frequency space. For the high-S/N cases of the beacons, we used the length, measurement noise, and DC term associated with Kepler-5b, and for the low-S/N cases of the beacons we used the length and measurement noise, and DC term associated with KIC 1255b.

The Fourier transform of a time series is sensitive to the treatment of missing data. This is important because the full depth sequences of Kepler-4b, Kepler-5b, and KIC 1255b contain gaps between the 17 “quarters” that defined the Kepler observing campaign, and in some cases whole quarters are missing due to module failure on the spacecraft. In our calculations of the discrete Fourier transform (DFT) of the full sequences, we chose to linearly interpolate between the endpoints of each quarter and generate simulated depths with simulated measurement noise at each expected transit time. There are also some missing depths within each quarter due to instrumental
Figure 5.8: Comparative normalized, folded power spectra for KIC 1255\textit{b}, B2 at low S/N, the uniform (maximal information) case, and the constant (zero-information) case. Note the log y-axis, and that the frequency units are $1/p_{1255}$ (day$^{-1}$), so the Nyquist frequency is at 0.5. The overall level of the power at most frequencies for KIC 1255\textit{b} is intermediate between the constant and uniform cases, as we expect for a stochastic, but sub-maximal, signal. KIC 1255\textit{b} shows no obvious periodicities, except for some power at low frequencies due to the long “quiescent” periods at the beginning and end of the \textit{Kepler} observations (see Figure 5.2, bottom). Note how, because of the normalization procedure, the noise level for the beacon appears lower than the constant case, although the two signals actually have the same amount of noise.

...
serve to distinguish these cases slightly from ideal constant cases. B1 shows power primarily at frequencies of 0.25 and 0.5, while B2 shows power at five frequencies, due to the more complex nature of the way we have interpreted the signal.

Figure 5.8 shows the normalized, folded DFTs for KIC 1255\(b\), the constant and uniform (maximal) comparison cases, and the low-S/N case of B2. As expected, the KIC 1255\(b\) power spectrum is consistent with noise at a level intermediate to the constant and uniform cases, though significantly closer to the uniform case. The beacon, consistent with its nature, shows a simple structure with power at small number of discrete frequencies. The normalization of the DFTs serves to make the level of the noise in the beacon appear lower than that in the constant case, although the time series contain the same amount of noise.

### 5.6 Results of the Information Content Analysis

#### 5.6.1 Results for the DTS Analysis

Following the procedure described above, we calculated normalized information content \(M\). Table 5.1 contains the values that went into calculating Eq. 5.5 as well as the final statistic values for each case. Figure 5.9 (top) shows where the information content of each case falls on the statistic.

From both of these we can see that the constant cases of Kepler-4\(b\) and Kepler-5\(b\) are well measured as having near-zero information content. Their non-zero values are likely due to small systematic errors in the photometry in excess of the (very low) shot noise, which broaden the PDF of the measured depths slightly in excess of that for an ideal Gaussian with a width given by the median of the formal measurement errors. The error bars do not encompass zero in part because we have not simulated measurement noise in our calculation of \(K_m\) (as described in Section 5.3.2.4).

The high-S/N cases all have S/N\(\approx\) 100, as the beacons would if they had been observed by Kepler and they had the depth, brightness, and transit frequency of Kepler-5\(b\). We see that, as we anticipated, the beacons have intermediate information content, with \(M\) values near 0.5. The B2 case scores slightly lower because we have chosen to represent the gaps with many zeros, making the distribution of “depths” less uniform.

Also as we expected, KIC 1255\(b\) scores very high on the \(M\) statistic if we grant the
Table 5.1: Depth Time Series Relative Entropy Values

<table>
<thead>
<tr>
<th>Case</th>
<th>max(d) (ppm)</th>
<th>$\sigma_d$ (ppm)</th>
<th>$K_m$</th>
<th>$K_0$</th>
<th>$K_{\text{max}}$</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler-5b</td>
<td>6670</td>
<td>64</td>
<td>7.6833</td>
<td>7.8833 ± 0.0185</td>
<td>5.0385 ± 0.0113</td>
<td>0.0215 ± 0.0073</td>
</tr>
<tr>
<td>B1-high S/N</td>
<td>6670</td>
<td>64</td>
<td>6.4921</td>
<td>7.8837 ± 0.0188</td>
<td>5.0362 ± 0.0117</td>
<td>0.4887 ± 0.0039</td>
</tr>
<tr>
<td>B2-high S/N</td>
<td>6670</td>
<td>64</td>
<td>6.7204</td>
<td>7.8833 ± 0.0195</td>
<td>5.0374 ± 0.0126</td>
<td>0.4086 ± 0.0045</td>
</tr>
<tr>
<td>KIC 1255b-high S/N</td>
<td>10900$^a$</td>
<td>32</td>
<td>4.8589</td>
<td>8.5507 ± 0.0079</td>
<td>4.5331 ± 0.0034</td>
<td>0.9189 ± 0.0008</td>
</tr>
<tr>
<td>Kepler-4b</td>
<td>790</td>
<td>40</td>
<td>8.2801</td>
<td>8.3412 ± 0.0207</td>
<td>7.0821 ± 0.0193</td>
<td>0.0483 ± 0.0157</td>
</tr>
<tr>
<td>KIC 1255b</td>
<td>10900$^a$</td>
<td>561</td>
<td>4.7908</td>
<td>5.7207 ± 0.0083</td>
<td>4.3877 ± 0.0070</td>
<td>0.6976 ± 0.0043</td>
</tr>
<tr>
<td>B1-low S/N</td>
<td>10900</td>
<td>561</td>
<td>4.5466</td>
<td>5.7204 ± 0.0079</td>
<td>4.3876 ± 0.0071</td>
<td>0.8806 ± 0.0048</td>
</tr>
<tr>
<td>B2-low S/N</td>
<td>10900</td>
<td>561</td>
<td>4.7189</td>
<td>5.7211 ± 0.0080</td>
<td>4.3876 ± 0.0067</td>
<td>0.7516 ± 0.0041</td>
</tr>
</tbody>
</table>

Note—Values listed for $K_0$, $K_{\text{max}}$, and $M$ are the mean and 1σ of the ensemble of values calculated.

$^a$—The median and 99th percentile depths for KIC 1255b are 3200 and 7950 ppm, giving S/N values of ~100 and 250 in the high-S/N case, and ~6 and 14 in the low-S/N case.

measured depths false precision and assign them the very low measurement noise of Kepler-5b. What we are seeing here is that the measurement noise is information-rich in the sense that it spans many of the values within its range, unlike the beacons which take on only a few values.

The low-S/N cases give very different results. Because the S/N in this case is much lower (~15), the beacons are no longer detected as having a discrete series of depths. Rather, they appear to span the range from $[0, \text{max(depth)}]$ rather uniformly, and so have very high $M$-values. Interestingly, at this S/N KIC 1255b actually scores lower than the beacons (or itself at high S/N) because we are now more sensitive to the non-uniformities in the depth PDF (the highest depths are underrepresented).

We conclude from this that the relative entropy statistic of the DTS data is a good way to distinguish constant stars, simple beacons, and “random” or information-rich signals if those signals are detected at high S/N. We also conclude that KIC 1255b cannot be yet be distinguished from a beacon (in its DTS) because it has not been measured at sufficient precision to exclude the possibility that the transits exhibit only a small number of discrete depths.

5.6.2 Results for Frequency Space Analysis

We present the results for the DFT calculation of the relative entropy statistic for the several cases explored in Table 5.2 and in Figure 5.9 (bottom). We present the solutions for the individual quarters in Table 5.3. As in our time series analysis, the constant cases show low information content, consistent with zero, and the beacons in the high-S/N case again have intermediate values of $M$, around 0.5.
Figure 5.9: Normalized information content, $M$, of the depth time series data (top) and their power spectra (bottom) for various cases discussed in the text. “High-S/N” cases, as red squares, refer to Kepler-5b, the beacons observed and analyzed at the same number of transits and same S/N ratio as Kepler-5b, and (in the top panel) a hypothetical version of KIC 1255b where we have treated the actual, measured time series of depths as if they were measured at this S/N. “Low-S/N” cases, as blue and yellow symbols, refer to Kepler-4b, the beacons observed and analyzed with the same number of transit events and S/N as KIC 1255b, and KIC 1255b itself. In the bottom panel, individual *Kepler* quarters appear as open symbols, and the large ellipses have horizontal axes widths equal to the standard deviation of the quarters they are centered on.

The vertical axis is not quantitative and serves only to separate the various cases for clarity. The horizontal bars within each symbol represents the uncertainty in $M$, with important caveats described in Sec. 5.3.2.4.

In all cases, Kepler-4b and Kepler-5b are seen to be clearly nearly information-free, and high-S/N beacons have intermediate values of $M$ in both bases, as expected given their simple structure.

In the time domain (top), KIC 1255b exhibits near-maximal information content, consistent with the nearly uniform distribution of its measurements. At lower S/N, the beacons have higher $M$ values, because the lower precision obscures the small number of values they take on, making their depth distributions more consistent with a uniform distribution.

In the frequency domain (bottom), KIC 1255b exhibits intermediate values for $M$, revealing significant non-random structure in the depth time series that is nonetheless significantly more complex than the simple beacons. The much longer time series of the “low-S/N” case makes the $M$ values much more precise in this domain, overwhelming the effects of the lower S/N.

In contrast to the time-series analysis, our frequency analysis properly distinguishes KIC 1255b from the beacons, even at low S/N. This makes sense because our “low” S/N case actually contains five times as many data points as the high-S/N case, which enhances the power of the beacons in frequency space and makes their simple structure more prominent. The constant cases, the pseudo-random KIC 1255b case,
Table 5.2: Frequency Space Relative Entropy Values

<table>
<thead>
<tr>
<th>Case</th>
<th>n_d</th>
<th>K_m</th>
<th>K_0</th>
<th>K_max</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler-5b</td>
<td>413</td>
<td>5.3296</td>
<td>5.3312 ± 0.0001</td>
<td>4.6411 ± 0.0249</td>
<td>0.0023 ± 0.0002</td>
</tr>
<tr>
<td>B1-high S/N</td>
<td>412</td>
<td>4.9872</td>
<td>5.3312 ± 0.0001</td>
<td>4.6424 ± 0.0246</td>
<td>0.5001 ± 0.0179</td>
</tr>
<tr>
<td>B2-high S/N</td>
<td>407</td>
<td>4.8558</td>
<td>5.3166 ± 0.0001</td>
<td>4.6287 ± 0.0258</td>
<td>0.6708 ± 0.0253</td>
</tr>
<tr>
<td>Kepler-4b</td>
<td>456</td>
<td>5.3512</td>
<td>5.3843 ± 0.0029</td>
<td>4.4028 ± 0.0353</td>
<td>0.0337 ± 0.0032</td>
</tr>
<tr>
<td>KIC 1255b</td>
<td>2182</td>
<td>4.8283</td>
<td>6.6762 ± 0.0084</td>
<td>3.0761 ± 0.0340</td>
<td>0.5133 ± 0.0049</td>
</tr>
<tr>
<td>B1-low S/N</td>
<td>2180</td>
<td>5.8540</td>
<td>6.6750 ± 0.0087</td>
<td>3.0748 ± 0.0335</td>
<td>0.2280 ± 0.00294</td>
</tr>
<tr>
<td>B2-low S/N</td>
<td>2178</td>
<td>5.4401</td>
<td>6.6747 ± 0.0082</td>
<td>3.0742 ± 0.0334</td>
<td>0.3429 ± 0.0036</td>
</tr>
</tbody>
</table>

Note—Values listed for K_0, K_max, and M are the mean and 1σ of the ensemble of values calculated. See Table 5.1 for σ_d and max(d) values.

and the simulated beacons thus land roughly where we expect them to.

The individual quarters group around their full time series average very well for the Kepler-4b and Kepler-5b cases, as we expected. However, for KIC 1255b the full series shows significantly less information constant than the average of the individual quarters—indeed the statistic values for the individual KIC 1255b quarters do not encompass the value for the full depth sequence. When we examine the DTS of KIC 1255b (Fig. 5.2, bottom) we see that there are two quiescent periods at the start and end of the DTS, which adds power at low frequency in the power spectrum for the full sequence (see Figure 5.8) that is not apparent in the individual quarters.

Three quarters had fewer than 10 detected transits because they were shorter than usual: quarters 0 and 4 for Kepler-4b, and quarter 0 for Kepler-5b. Because of the extremely low n_d for these quarters, the statistic values were unreliable, and we do not include them in the plot.

5.6.3 Effects of S/N and Signal Length on the Normalized Information Content Metric

As we have seen, the value of M for a given signal can be strongly dependent on the S/N at which it is observed and the length of the signal, because the metric is normalized by the maximal information one could measure at a given S/N and signal length. In the time domain, the S/N is determined by the measurement precision, and the value of K_max is sensitive to the signal length.

This means that at low S/N, one is somewhat sensitive to information content in the signal (i.e. K_0 and K_max are similar, especially for short signals). The actual behavior of M with increasing S/N depends on the nature of the underlying signal, and how information is revealed with higher precisions.
recall that our “low-S/N” test case is KIC 1255 signal length and S/N as the signal in question Arnold beacons, this effect dominates over the photometric precision improvement in an infinitely long signal. smaller error bars in the “low-S/N” case, and lie nearer the values they would have Kepler-5 one’s sensitivity to strictly periodic components of a signal. In our analysis of the to break into many discrete peaks at high S/N. at high S/N the shallower peak might resolve into a large number of discrete peaks, low S/N there might appear to be a single, narrow, well-defined peak (low M), but at high S/N the shallower peak might resolve into a large number of discrete peaks, and thus show very high information content. Indeed, this is similar to the behavior of KIC 1255b in the time domain, which has a preferred range of depths that appears to break into many discrete peaks at high S/N.

In the frequency domain, increasing the length of a time series strongly increases one’s sensitivity to strictly periodic components of a signal. In our analysis of the Arnold beacons, this effect dominates over the photometric precision improvement (recall that our “low-S/N” test case is KIC 1255b which, having a shorter period than Kepler-5b, has many more depth points). As a result, the Arnold beacons have much smaller error bars in the “low-S/N” case, and lie nearer the values they would have in an infinitely long signal.

Use of the $M$ statistic thus requires comparison to nominal signals at the same signal length and S/N as the signal in question. In the case of KIC 1255b we can

<table>
<thead>
<tr>
<th>Quarter</th>
<th>Kepler-5b</th>
<th>Kepler-4b</th>
<th>KIC 1255b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q0</td>
<td>$-0.0247 \pm 1.6156$</td>
<td>$0.6930 \pm 9.1294$</td>
<td>—</td>
</tr>
<tr>
<td>Q1</td>
<td>$-0.0023 \pm 0.0021$</td>
<td>$-0.0092 \pm 0.0463$</td>
<td>$0.7296 \pm 0.0796$</td>
</tr>
<tr>
<td>Q2</td>
<td>$0.0034 \pm 0.0010$</td>
<td>$0.0378 \pm 0.0158$</td>
<td>$0.6870 \pm 0.0351$</td>
</tr>
<tr>
<td>Q3</td>
<td>$0.0029 \pm 0.0009$</td>
<td>$0.0562 \pm 0.0184$</td>
<td>$0.6729 \pm 0.0368$</td>
</tr>
<tr>
<td>Q4</td>
<td>$0.0026 \pm 0.0009$</td>
<td>$0.0368 \pm 0.0264$</td>
<td>$0.6219 \pm 0.0302$</td>
</tr>
<tr>
<td>Q5</td>
<td>$0.0026 \pm 0.0008$</td>
<td>$0.0170 \pm 0.0176$</td>
<td>$0.7726 \pm 0.0384$</td>
</tr>
<tr>
<td>Q6</td>
<td>$0.0036 \pm 0.0010$</td>
<td>$-0.0203 \pm 0.0181$</td>
<td>$0.6994 \pm 0.0407$</td>
</tr>
<tr>
<td>Q7</td>
<td>$0.0044 \pm 0.0011$</td>
<td>$-0.0036 \pm 0.0197$</td>
<td>$0.6953 \pm 0.0374$</td>
</tr>
<tr>
<td>Q8</td>
<td>$0.0055 \pm 0.0012$</td>
<td>—</td>
<td>$0.6315 \pm 0.0368$</td>
</tr>
<tr>
<td>Q9</td>
<td>$0.0005 \pm 0.0007$</td>
<td>$0.0467 \pm 0.0183$</td>
<td>$0.7278 \pm 0.0347$</td>
</tr>
<tr>
<td>Q10</td>
<td>$0.0036 \pm 0.0009$</td>
<td>$-0.0219 \pm 0.0190$</td>
<td>$0.5613 \pm 0.0264$</td>
</tr>
<tr>
<td>Q11</td>
<td>$0.0022 \pm 0.0008$</td>
<td>$0.0141 \pm 0.0175$</td>
<td>$0.6047 \pm 0.0340$</td>
</tr>
<tr>
<td>Q12</td>
<td>$0.0009 \pm 0.0008$</td>
<td>—</td>
<td>$0.6211 \pm 0.0298$</td>
</tr>
<tr>
<td>Q13</td>
<td>$-0.0003 \pm 0.0008$</td>
<td>$-0.0077 \pm 0.0188$</td>
<td>$0.6847 \pm 0.0309$</td>
</tr>
<tr>
<td>Q14</td>
<td>$0.0042 \pm 0.0010$</td>
<td>$0.0210 \pm 0.0168$</td>
<td>$0.5896 \pm 0.0273$</td>
</tr>
<tr>
<td>Q15</td>
<td>$0.0040 \pm 0.0009$</td>
<td>$0.0414 \pm 0.0191$</td>
<td>$0.7809 \pm 0.0355$</td>
</tr>
<tr>
<td>Q16</td>
<td>$0.0001 \pm 0.0008$</td>
<td>—</td>
<td>$0.6281 \pm 0.0365$</td>
</tr>
<tr>
<td>Q17</td>
<td>$-0.0017 \pm 0.0018$</td>
<td>$0.1151 \pm 0.0583$</td>
<td>—</td>
</tr>
</tbody>
</table>

This is illustrated nicely by the opposing behaviors of KIC 1255b and the Arnold Beacons in Fig. 5.9 at high S/N, the Arnold beacons clearly take on only a few discrete values (low information content). But because these peaks are roughly evenly distributed about the span of the depths, at lower precision the discreteness is lost and the values appear uniformly distributed, and the normalized information content goes up. In a hypothetical case of much more tightly spaced beacon values (say, a hundred discrete values between 0.10 and 0.11), the opposite effect might occur: at low S/N there might appear to be a single, narrow, well-defined peak (low $M$), but at high S/N the shallower peak might resolve into a large number of discrete peaks, and thus show very high information content. Indeed, this is similar to the behavior of KIC 1255b in the time domain, which has a preferred range of depths that appears to break into many discrete peaks at high S/N.
conclude that we have measured much more information than a constant signal or our beacons in frequency space, which is consistent with the signal being complex but not maximally random. In the time domain we measure a very high information content (as expected from a complex signal) but, because our S/N is low, this is similar to the result we get for our beacons in the time domain, showing that our precision does not give us sensitivity to very complex signals.

5.7 Summary

We have developed the normalized information content statistic $M$ to quantify the information content in a signal embedded in a discrete series of bounded measurements, such as variable transit depths, and show that it can be used to distinguish among constant sources (i.e. those with zero information content), interstellar beacons (having small but non-zero information content), and naturally stochastic or artificial, information-rich signals. We have developed a treatment for $M$ in both the time and frequency domains, noting that a signal can be a beacon in one and information-rich in the other. We have also shown how the measurement of $M$ is affected by measurement uncertainties, and (in the frequency domain) the length of the signal being analyzed.

We have applied this formalism to real Kepler targets and a specific form of beacon suggested by Arnold to illustrate its utility. We have used KIC 1255b as an example of a stochastic signal, our stand-in for a beacon or an artificial, information rich signal; Kepler-4b as a constant source measured at similar S/N as KIC 1255b; and Kepler-5b as a constant source measured at high S/N. We have shown that in the time domain, the measurement uncertainties for KIC 1255b are too large to distinguish the signal we see from a beacon (that is, we cannot determine whether the spectrum of depths is continuous or composed of a small number of discrete depths). In the frequency domain, however, the system shows no significant periodic structure, and is easily distinguished from simple beacons.

5.8 Acknowledgments

We thank Bryce Croll for sending us time series depth data for KIC 12557548, and Tim van Kerkhoven for discussing the details of their careful time series analysis of the data. We thank Steinn Sigurðsson, Thomas Beatty, Ben Nelson, Sharon Wang,
and Jason Curtis for helpful discussions, and the anonymous referee for their helpful comments.

The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium. E.B.F. acknowledges NExSS funding via NASA Exoplanet Research Program award #NNX15AE21G; and MZ and JTW acknowledge NExSS funding via NASA Origins of Solar Systems award #NNX14AD22G.

This research has made use of NASA’s Astrophysics Data System. Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This paper includes data collected by the Kepler mission, funding for which is provided by the NASA Science Mission directorate.

The results reported herein benefited from collaborations within NASA’s Nexus for Exoplanet System Science (NExSS) research collaboration network sponsored by NASA’s Science Mission Directorate.
Chapter 6  
Multimedia Astronomy Communication: strategies for effectively telling astronomy stories

Science communication is intimately linked to a career in science research. In this respect, astronomy is no different from any other scientific discipline in its foundational basis on communication. Astronomers communicate scientific content to a wide variety of audiences. Each potential audience has a different set of prior knowledge, uses different key points to access a scientific message, and will expect and value different aspects of the science. And yet, because few programs have an explicit, required science or scientific communication component, researchers interested in improving their communication skills can turn to classes, workshops, and other resources outside of their program.

The focus and scope of an astronomy story is first determined by the target audience and then by the desired communication medium. This chapter targets professional astronomers and aims to review communication practices applicable during a career in astronomy. This chapter applies these practices to astronomy-specific examples and emphasizes the need for incorporating communication training into the educational process.

Acknowledgments: The contents of this chapter draw heavily on the contents of the PSU graduate level courses GEOSC 597F “Words to Live By,” taught by K. Freeman in the spring of 2016, and HI ED 546 “College Teaching,” taught by L. Lenze in the summer of 2016. The author is grateful to both instructors for organizing courses that address important issues related to scientific careers, for sharing many useful resources and references to aid in additional independent learning,
and for their guidance in developing personal philosophies about communication and teaching. The author also thanks J. T. Wright for his invaluable suggestions and support in developing this chapter and his encouragement to share it with others.

6.1 The need for effective astronomy communication

A fundamental aspect of a career in astronomy is communicating our work to others. Be it to peers through journals and conferences, a funding source review board, students in a classroom, or the general public, the value of our community’s work is enhanced by our abilities to disseminate that information to others.

While simply publishing or presenting research is necessary for survival as an academic (i.e. “publish or perish”), that does not actually measure how successful a researcher is at producing quality work that others note and use (Schimel 2012). Academic journals note the success of a paper through impact factors, rankings, and metrics like the H-index, and scientists attempt to publish their work in the most visible and noteworthy journal appropriate for the paper. Common steps within an academic career path, including postdoctoral fellowships, professorships, and tenure awards, have applications which require a listing of papers published, invited presentations, and awards granted. These accomplishments become easier to accumulate with better skills in communicating science to others. Additionally, science literacy of the general public plays a critical in the development of science policy and federal funding of astronomy research—which astronomers can only obtain through grant proposals and which comprise up to $\sim 85\%$ or more of all astronomy research dollars\footnote{https://www.aaas.org/fy16budget/astronomy-and-astrophysics}.

In this dependence on communication for success, the field of astronomy holds the double-edged sword of ubiquitous fascination: the topic has been of interest to nearly the entire global population at some point in their lives, yet the learning curve is steep within any subfield and rife with difficult-to-synthesize details.

Compounding this issue is the ever-expanding array of methods to reach people in today’s “Information Age.” Beyond “Cosmos,” research papers, and magazine articles, astronomers have at their disposal (to name a few): enhanced and alternate reality journal publications, social media, blogs and vlogs, pod- and webcasts, online-only news sources, and many more. Each of these media has its own strengths and
weaknesses, is appropriate in different situations, and requires its own specific skillset in order to maximize functionality. The spectrum of expertise held by potential audiences adds to the complexity. Therefore, the skills necessary to communicate a message to an expert audience may not transfer when attempting to communicate that same message to a lay audience, and vice versa.

Despite the necessity, little attention is given to training astronomers in effective communication techniques. Of the top ten U.S. universities in 2017 with astronomy and/or physics programs\(^2\) only three of the ten list graduate level courses or degrees related to science communication (MIT, Stanford University, and Yale University). The science communication courses for each of those three universities was listed in a non-astronomy and non-physics division or department of the university. While the remaining universities had each hosted at least one workshop or open lecture related to science communication in the past three years, most of them only hosted a single event per year and focused mainly on communicating science to non-scientists. None of the top 10 astronomy/physics schools had courses, workshop, or lectures related specifically towards communicating astronomy or for improving technical communication skills.

These statistics show that early-career astronomers must pick up communication strategies by mimicking others and assuming that a firm grasp on the subject matter will make up for deficiencies in communication skill. This can restrict astronomers to a narrow set of ineffective communication techniques, harming both the communicators and the audience who may struggle to access the information as presented in the “traditional” way.

This chapter applies well-developed communication theories and best practices to the specific instance of astronomy communication, which is important for astronomers to grasp but rarely done in a rigorous way. With a focus on the needs of professional astronomers, the author first synthesizes the requirements of effective astronomy communication into a few key questions that every communicator needs to answer. The author then discusses some of the most common media professional astronomers currently use to communicate astronomy and provides key strategies to consider when communicating via each medium to the desired audience.

6.2 Quantity necessitates quality

In total, scientists worldwide publish more scientific journal articles per year than the combined annual number of homicides, professional athletic games, and political elections in the United States\(^3\) [Blum, Knudson, & Henig 2006]. Scientists have been publishing journal articles at a steadily increasing rate for over 100 years [Larsen & von Ins 2010], and the number of scientific research articles published per year is only 18.7% less than the number of new books published annually worldwide, reaching 1.66 million in 2016\(^4\) [IPA 2016].

On the subject of astronomy alone, researchers published 49,207 journal articles in 2016\(^5\) wrote \(\sim 1,690\) abstracts for the 227\(^{th}\) AAS meeting, and presented \(\sim 1070\) oral presentations and \(\sim 620\) research posters. On an average day in early 2017, astronomers submitted 120 new research papers to the open source arXiv.org\(^6\). Looking at more informal methods of communication, over 2.61 million blogs include the word “astronomy,” and hundreds of unique Tweets per hour include “#space,” “#astronomy,” or “#astro,” which received over 800,000 views per hour combined\(^7\).

Yet despite the staggering quantity of astronomy communication that happens within the astronomy community and directed at the world, little to no training is provided for current and future astronomers during their formal education (see Sec. 6.1). The few schools that have well-defined and frequently-taught courses in science communication host those courses separate from science programs. Most astronomy graduate programs require applicants to submit personal and/or research statements, but the writing style for a personal statement has little resemblance to a the style of

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\(^3\)In 2016, there were 15,809 fatal homicides [Kochanek et al. 2016], 5,187 major professional athletic games, and 519,682 elected political officials in the United States. The number of major professional athletic games counts events hosted by Major League Baseball (2,430; MLB 2012), National Basketball Association (1,230; Bonner 2011), National Football League (256; Aiello et al. 2012), and National Hockey League (1,271; NHL 2015) in each of their regular seasons, not including any variable number of postseason, championship games, or “All Star” games. The number of elected US political officials is calculated by the number of elected officials at federal, state, and local levels in 2012. Likely, this number has only varied slightly since 2012, and mostly due to local level redistricting and restructuring [Lawless 2012]. To contrast, scientists published 1.35 million research journal articles in 2006 [Björk et al. 2009].

\(^4\)This number counts the number of new titles released in the 24 top publishing countries worldwide.

\(^5\)SAO/NASA Astrophysics Data System (ADS)

\(^6\)Number of submissions received from Friday March 17, 2017 to Monday March 20, 2017.

\(^7\)ritetag.com/hashtag-stats
a research paper. Unless an applicant has published research as an undergraduate student, personal essays do little to indicate what type of academic writer the student might become.

When first learning to write academic research papers, undergraduate and graduate students often mimic the type of academic writing they see in journals. They tend to assume that poor quality papers are not published, and often lack the formal training or guidance to distinguish between good and poor writing techniques when applied to technical writing. The same lack of training applies to academic research posters presented at professional conferences, which can include figures and text directly copied from the accompanying research paper rather than deliberately designed to be hung up on display. Powerpoint slides for research talks, another ubiquitous communication method in astronomy, are often flooded with text that distract from the oral presentation. As discussed in later sections, each of these common practices is ineffective at best and misleading at worst.

Students train in how to read academic papers as they are and how to interpret certain code phrases and jargon. Without any examples to show other ways, novice paper writers will learn what they see. But the propagation of ineffective communication methods is not inevitable. Astronomy undergraduate and graduate programs can begin to course-correct by introducing astronomy-specific examples of effective communication, providing accessible resources for additional independent study, and explaining the benefits to learning how to more clearly communicate science.

Though many early career scientists (and their more experienced superiors) dread needing to present their work in a paper or presentation, consciously working to improve communication practices follows the law of increasing returns—spending a little effort at practicing and improving one’s communication techniques leads to higher than proportionate returns on the community’s recognition and understanding of the research, on the longevity of the ideas in the audience’s mind, and on one’s efficiency at communicating science.

Communicating science is integrally linked to a career as a professional scientist and so both individual scientists and the overall scientific community would benefit from communication techniques that are taught as purposefully as any other part of professional training. As Illingworth & Allen (2016) state, “We communicate our research because we should do, because we want to, and because we have to.” As they go on to explain, scientists “have to” communicate their research to receive funding,
6.3 Science is a story and and you are the storyteller

Every academic research paper, the most straightforward way astronomers communicate, tells a story. As Schimel (2012) explains, “If we didn’t tell stories, we would write papers with only Methods and Results; we could skip the Introduction and Discussion.” Research projects are not designed in a vacuum (or rather, not funded in a vacuum). They are motivated by previous work and seek to answer pre-existing questions. They interpret facts and seek out the underlying truth.
One of the first lessons a budding scientist learns is to not just present the sequence of tasks they performed and a numerical list of factual findings, but to explain why they performed the steps, how they interpret the results, and where the research goes from there. That, in essence, is storytelling.

Storytelling and science have much in common. They both have a protagonist and an audience; a set of characters, a setting, and a plot; a beginning, middle, and end; conflict, action, and resolution; and a message to convey. The fundamental outline of a scientific research project closely parallels the dramatic structure of a story outline discussed by Aristotle (c. 335 BCE), Gustav Freytag, and many others (Fig. 6.1; Aristotle, Poetics 1450b27; Freytag 1894).

In astronomy, the characters are astronomers, stars, galaxies, the interstellar medium, Bremsstrahlung radiation, Rayleigh scattering, etc. The behavior and interactions of the characters organically create a plot that we listen to by analyzing data with an open mind (Schimel 2012).

Schimel (2012) outlines six characteristics (originally from Heath & Heath 2007) that ensure that an idea remains exciting, relevant, and persistent long after it has been introduced. Schimel’s and Heath & Heath’s mnemonic, SUCCES, is given below, with short descriptions for clarity.

S Simple—the core essence in a clear, compact way
U Unexpected—novel questions, interpretations, or counterintuitive results
C Concrete—specific, definite, focused
C Credible—establishing a logical chain from past to future works
E Emotional—curiosity, excitement, wonder, fascination
S Stories—characters, plot development, resolution

To effectively communicate science, the scientific story must be simple, concrete, and credible. These three are “must haves” for the story to merely be understandable. That is not to say that the science must be simple in design or have concrete or definitive results, but that the science must be told in a clear and definitive manner. Invoking all six SUCCES aspects gives the story staying power.

Unexpectedness enhances a story because it triggers our brains to begin thinking about why. Stories that tell something already known or understood, or merely make incremental advancements in a particular area are generally forgettable. A story must emphasize what is new and novel about the questions being asked or the
interpretations being made. As per the knowledge gap theory of Heath & Heath (2007), a storyteller must highlight the unknown amidst the knowledge (the “negative space,” as it were) to invoke unexpectedness and engage an audience’s curiosity.

Emotion can be difficult to reconcile with a scientific story in the abstract, as scientists are trained to be objective and detach our needs from our work. Yet to be objective and detached is not to be unemotional. Curiosity, excitement, and wonder drive scientists to pursue their work in the first place, and evocative storytelling will incite those emotions in an audience. Research shows that memories associated with emotions are easier to recall (e.g. Cahill & McGaugh 1995; Hamann 2001), and the most enduring science stories take advantage of that aspect of human physiology.

A science story is modular, composed of discrete and self-contained sub-stories that fit together to create a larger picture. These modules can be sections of a paper (introduction, methods, results, conclusions), examples from a personal narrative that highlight a message within a public science talk, brief interludes into the history of the topic, or self-contained data analysis steps. Each module is a complete story in its own right, with an identifiable conclusion, so that the audience can wrap their minds around that one piece before delving into the next and so the modules can be strung together. Breaking a larger story into more discrete units like this aids audience understanding and retention (Schimel 2012).

6.4 Creating the storytelling strategy

This section breaks down the act of creating a story into four fundamental questions to answer that aid in building a focused story targeted at a specific audience: 1) Who is the audience? 2) What does the audience already know? 3) What does the audience need to learn? and 4) Why should the audience care? These questions help the storyteller to plan and outline the story, and guide the storyteller in creating an audience-centric story.

6.4.1 Who is the audience?

The act of telling a story makes it about the audience and the audience’s needs. The scientific process itself is structured this way: scientists observe the consequences of immutable facts of nature, seek to understand the what, why, and how of the
The importance of choosing the target audience before constructing a scientific story cannot be overemphasized. The audience determines the type of information and the level of detail that should be included in the story. For example, an exoplanet’s atmosphere either contains CO$_2$ in this instance or it does not—that fact does not change. But that fact cannot advance scientific understanding without the astronomer sharing their observations and interpretation of the fact. Which raises the question, “Who is the intended audience?”

The most important decision to make before constructing a scientific story is choosing the target audience. Who most needs the information within the story? If the story reaches no one else, the target audience must be able to access the information and receive the message. The choice of target audience informs the rest of the decisions that need to be made when designing the story: what is the audience’s
prior knowledge, what does the audience need to learn through the story, and what
will the audience expect and value in the story?

Target audiences vary along a two-dimensional spectrum based on knowledge of
the subject matter and level of academic formality. Figure 6.2 qualitatively shows
the position of potential audiences along this spectrum with the goal of guiding the
storyteller towards the right target audience. Descriptions and examples of audience
Types I-IV are given in subsequent subsections. While this listing of potential target
audiences is by no means exhaustive, it includes the most common audience types
that professional astronomers interact with in their communications.

Broadly speaking, we distinguish academic audiences by whether or not the
majority of individuals within an audience group has personally conducted scientific
research on the story topic (”On-Topic Researcher”) or has conducted research in
a different area of science (”Off-Topic Researcher”). Depending on the focus and
scope of the story, an “On-Topic” audience could span anything from “has performed
astronomy research of any kind” to “has analyzed broad absorption lines in $z = 2$ active
galactic nuclei.” “Off-Topic” researchers could range from biologists and neurolinguists
to any astronomer who has never performed a Gaussian process regression on space
telescope observations. For a journal article with a broad scope, “on-topic” will be
correspondingly broad; for a journal article with a narrow focus, the number of those
who qualify as “on-topic” will be much smaller.

Furthermore, academic audiences (on- or off-topic) are broken down by the most
advanced degree audience members have earned. Researchers that have earned a
doctorate have gone from conceptualization, through actualization, to presentation of
a scientific project—the on-the-ground understanding of the scientific process—but
also retain a grasp of the larger of scientific picture. Graduate students may have a
grasp of the former but are still developing the latter, and undergraduate students
may still be struggling with both.

A well-told story can certainly appeal to more than one audience type. A research
paper can grab the attention of on- and off-topic researchers, science writers, and
amateur astronomers alike. However, an astronomer must begin telling a story with a
clear target audience in mind to ensure a cohesive message, appropriately highlighted
key facts, and effective communication techniques. A storyteller that tries to reach
too many audiences at once can obscure the message they are trying to send. As
discussed more in subsequent sections, each type of audience will access different
bank of prior knowledge, will expect and value different aspects of a story, and will respond to different key points. If a storyteller splits their attention between too many audiences at once, they run the risk of not fully connecting with any audience at all by not having the time, space, or resources to fully develop the story at so many levels.

Interdisciplinary research papers (e.g. astrobiology, astrostatistics, cosmology, etc.) may reach more than one audience type, or may have sections of the paper that are more accessible to one type of audience than another. In cases like this, the primary author might need to take care that they give appropriate context, references, implications of the work so that readers outside of the primary author’s field can still engage with the paper.

When uncertain about the appropriate target audience for a story, it is better to err on the side of caution and assume an audience with a lower amount of on-topic knowledge, within reason (Greene 2013). This ensures a minimal amount of confusion and may actually expand the story’s reach and accessibility to non-target audiences. We expound on each audience type in the following subsections.

6.4.1.1 Type I—Knowledgeable and Academic

Type I audiences (Fig. 6.2, top-right quadrant) are academics who conduct scientific research in the same area as the story topic (thereby being “on-topic”). Type I can include, but is not limited to, Ph.D. researchers (e.g. postdoctoral researchers, research associates/scientists, and professors), on-topic graduate researchers currently enrolled in a masters or Ph.D. program, on-topic undergraduate student researchers, and referees selected to peer-review submitted academic journal articles. The highest degree held by the audience determines knowledge level to the first-order, followed by a second-order ranking by familiarity with the subject matter. We qualitatively rank journal referees between graduate and Ph.D. researchers due to the potential lack of familiarity with the subject matter.

Audiences that are both knowledgeable in the story topic and hold academic positions are perhaps the most common audiences that academic astronomers communicate with on a professional basis. These audiences are most often the target audiences of the most common types of communication for an academic astronomer, like peer-reviewed academic journals, colloquia or other professional research talks given within a subfield, and work emails.
Type I audiences can likely recognize the technical jargon of the story topic, can differentiate between astronomy subfields, and can place the story topic within the larger astronomy picture. For this audience type, the storyteller can assume a high level of prior general astronomy knowledge and some level of on-topic technical knowledge. Stories targeted at this audience type typically have a narrow scope and a very specific focus.

For example, a typical story targeted at this audience group might seek to prove the presence of a temperature inversion within the atmosphere of a hot Jupiter through analysis of *Hubble Space Telescope (HST)* observations (e.g. Cartier et al. 2017, Ch. 3). A Type I audience for this story would likely know the general present state of exoplanet research (detection methods, planet demographics, commonly used telescopes etc.) and have some familiarity with recent exoplanet atmosphere studies (know that this is not the first time exo-atmospheres have been observed, can differentiate between emission spectra, transmission spectra, and phase curves, etc.), as well as general astronomy and exoplanet knowledge to support those understandings. The scientist could not assume familiarity with using *HST* in this specific observing mode to obtain exoplanet spectra, the most common analysis methods, previous studies of the targets of interest, nor how those targets fit within the larger framework.

### 6.4.1.2 Type II—Knowledgeable and non-Academic

Type II audiences (Fig. 6.2, top-left quadrant) are non-academics who have some level of familiarity with astronomy or the specific story topic. This audience type is by far the most diverse in prior astronomy and on-topic knowledge, expectations of an astronomy story, and parts of an astronomy story to which they assign value. Type II audiences can include representatives or researchers in a STEM industry (e.g. spectrograph technicians and engineers), professional science writers and public information officers (either with an astronomy-specific or general science beat), subscribers to an astronomy blog or podcast, non-researching undergraduate astronomy students, and local amateur astronomy groups. The common threads among Type II audiences are a pre-existing interest in astronomy at some level, some amount of prior general astronomy knowledge, and jobs without a scientific research component.

Often times the most serious misstep a scientist makes when communicating to Type II audiences is misjudging the audience’s prior level of astronomy-specific knowledge or story aspects that will hold value. Assuming a higher level of astronomy
knowledge than an audience possesses will lead to, at best, a thoroughly confused audience with many questions or, at worst, an audience with a serious misunderstanding of astronomy or the scientific process. Misjudging story aspects an audience will value will most likely just lead to an audience tuning out of the story and not caring about the outcome.

To communicate the example exo-atmosphere story in Sec. 6.4.1.1 to a general science writer, an astronomer would not only need to explain how they performed the observations and analysis and what results they discovered in non-technical language, but also why they decided to study this planet in particular and exo-atmospheres in general. This audience will appreciate an emphasis on the necessity of exo-atmosphere observations and where this science is likely to lead in the future. While a professional science writer knows how to read a technical paper well enough to understand the outline of the methodology, they would likely not know why that particular methodology was needed, if it was a novel application or technique, or where else it could be applied unless specifically stated. Any definitions or phrases that the scientists suspects are ambiguous to a non-scientists need to be explicitly stated at the outset to avoid miscommunication.

### 6.4.1.3 Type III—Novice and non-Academic

Type III audiences (Fig. 6.2, bottom-left quadrant) are both outside of the academic sphere and are novices in the topic of interest. These audiences include members of the general public in the myriad of ways astronomers communicate with them, such as through open social media platforms (e.g. Twitter, blogs, and Instagram), radio or television, general news sources, and sometimes even members of the political system. With only 33% of the adult U.S. population holding at least a bachelor’s degree (Ryan & Bauman 2016), the common threads tying together audiences of this type are a lack of formal science training or studies beyond what is offered in most public high schools, little to no pre-existing interest in astronomy, and the greater possibility for science and astronomy misconceptions that need to be overcome.

A key aspect of communicating effectively with Type III audiences is an understanding of what the audience will value from the story, what they expect the story to contribute, and perhaps most importantly, what the story can do for them. That last is not entirely selfish on the audience’s part, but merely a reality of living in an information-saturated world. The story must connect to the audience on a more
personal level than for other audiences, and do so in as direct and unambiguous way as possible.

For a Type III audience, the exo-atmosphere example previously discussed holds little appeal, as it only marginally connects to the lives of the general public, makes no true groundbreaking strides in understanding, nor does it revolutionize our understanding of the universe. To the public, at best a story like that would have a “wow” factor, as many have not considered that we are, at present, capable of measuring the atmospheres of worlds thousands of light years away. A story with a “wow” factor can be understood by a Type III audience, even passed on later, but will generally lack any lasting sense of urgency, more a tale of “science for the sake of science.”

To better exemplify the personal strategy needed to connect with a Type III audience, consider a recent segment from the late-night comedic news show “The Late Show with Stephen Colbert.” On March 15, 2017, noted astronomy communicator Neil deGrasse Tyson appeared on the weeknight T.V. show[8] and discussed China’s Five-hundred-meter Aperture Spherical Telescope (FAST), a technological development which has surpassed the Arecibo Observatory as the largest telescope in the world. In the segment, Tyson explained,

(Times refer to YouTube video linked in previous footnote)

2:36 Stephen Colbert: Explain to me what this thing is right here (holding up a photo of China’s FAST). What is this? And what are we going to do with it?

2:41 Neil deGrassse Tyson: This is currently the largest telescope in the world. It’s a radio telescope 500 meters across. That is so large, you could play 25 football games in the area of that—of that telescope. And the aliens who are trying to talk to us—you can ask who the first people who are going to hear these aliens—is the people [who are] running this telescope.

3:02 SC: Who is running this telescope?

3:04 NT: China.

3:05 SC: Okay. Why aren’t we running this telescope?

3:08 NT: Because we—we lost our mojo.

3:10 SC: What?

[8]https://www.youtube.com/watch?v=5nqT7XRcRc&t=159s
3:11 NT: Yeah, mojo.
3:11 SC: That’s a science term.
3:13 NT: That’s a scientific term \(\text{(laughter)}\). The mojo— the science mojo is, this has never been done before, we’re going to invest in it, and we’re going to be first at it. If you don’t have those three pistons [aligned], other people [will] do it. That’s the thing about science, it doesn’t matter where it happens. It will happen somewhere. [You] don’t own science. Science is for anyone who is curious and wants to invest there. And right now the world is passing us by.

(Transcript from YouTube clip, corrected where marked for minor errors)

Tyson, in just over one minute, built up a story about a grand scale telescope capable of achieving first contact with an extraterrestrial civilization, created a sense of excitement and drive for achievement within the American public, and then dashed their hopes with the revelation that the Chinese would be the ones with first access to any such accomplishment. While this type of bait-and-switch tactic can not always be used (though effective for an audience like that which expects a bit of comedy with their candor), it demonstrates the need to create a fully-rounded story with a beginning, a middle, and an end, and particularly a story that creates an emotional resonance within the audience. A story like that will last within the minds of this type of audience.

6.4.1.4 Type IV—Novice and Academic

Type IV audiences (Fig. 6.2 bottom-right quadrant) span a similar range of academic formality as Type I audiences, yet their research interests do not align with the story topic. Type IV audiences include off-topic Ph.D, non-Ph.D., and undergraduate researchers, or audiences for which a near-majority or more are off-topic. This category also includes astronomers who sit on time allocation committees for telescope observations, none of whom may research in the same topic as the proposal. Scientists serving on grant or fellowship committees for non-astronomy funding sources like the National Research Foundation or Department of Energy, none of whom may even research within any branch of astronomy, are also Type IV.

Audiences that are academic, yet do not conduct research in the same topic area as the story can be some of the most difficult audiences to connect with. Their familiarity
with research terminology and procedure can often fool a storyteller into assuming familiarity with the story topic, background, or research motivations. Astronomers often encounter Type IV audiences for research talks to whole astronomy departments (as is typical when on a short-list for a job), funding or observing proposals, and lectures in graduate courses. Type IV audiences are also the targets of general science journals like *Nature* and *Science*.

As the target audience for many career successes, astronomers need to take additional care when addressing Type IV audiences. While Type IV audiences will be able to follow research techniques and be familiar with technical jargon and abstract writing, scientific justification and motivation need to be emphasized, as does the explanation of the project’s place within the larger scope of astronomy. Stories targeted at Type IV audiences can use a specific scientific focus or study as illustrative example of a wider message.

For the story example presented in Sec. 6.4.1.1, the storyteller could focus on why the study of exo-atmospheres is a critical step in our understanding of planet formation, evolution, and habitability, and potentially allude to our own solar system. To illustrate this message, the story still needs to clearly explain the goals, process, and results of the *HST* observations of that particular hot Jupiter, but make sure to demonstrate how that study contributes to the larger understanding of exo-atmospheres. The scientist can still assume prior knowledge of general scientific ideas and familiarity with the scientific process (and possibly prior general astronomy or exoplanet knowledge), but cannot assume that the audience understands the fundamental motivation of the research topic, ultra-specific technical jargon, or impact of the research on the field.

### 6.4.2 What does the audience already know?

After a target audience has been selected, the next step is to assess what prior knowledge that audience has access to. The audience will use their bank of prior knowledge as a filter through which they process new information provided by a scientific story and as a basis to reconstruct the story in their own minds (Ambrose *et al.* 2010). Information already contained in the audience members’ minds is more firmly entrenched than the information the storyteller is trying to impart, and most researchers agree that a person must connect new information to previous knowledge.
in order to learn (e.g. Bransford & Johnson 1972; Resnick 1983).

This is true in a physical, as well as a meta-physical sense. Leamnson (1999), in his brief discussion on the biological basis of learning, explains that neurons in the human brain are most effective when they contain multiple connections to other neurons. Isolated neurons, unconnected to others, have little effect on overall understanding or neural engagement. Human brains grow when axons are created and form new pathways between neurons. Repetition and experiences stabilize and strengthen certain neural pathways, which later allow us to connect new information to prior knowledge more effectively and recall that information more easily (Changeux 1985; James 1899; Stevens 1993).

The storyteller must work with that prior knowledge and use it as a tool to their advantage. As Ambrose et al. state, a proper understanding of the audience’s prior knowledge “...allows us not only to leverage their accurate knowledge more effectively to promote learning, but also to identify and fill gaps, recognize when [audience members] are applying what they know inappropriately, and actively work to correct misconceptions” (2010, p. 15).

Assessing an audience’s prior knowledge can help the storyteller refine the style and substance of the story, select storytelling techniques, and help keep the focus on what the audience, not the storyteller, will find accessible and meaningful.

### 6.4.2.1 Astronomy and Science Prior Knowledge

A first order assessment of an audience’s prior knowledge will encapsulate any prior astronomy education, astronomy research experience, general science knowledge, and interactions with and within the scientific community. The most common way that this is discussed is by the technicality of the language used to communicate, on the scale from expert jargon to common parlance, also known as the register of the story (Greene 2013). Register describes where the story falls on the spectrum from formal to informal. As the story language becomes more formal, the story content becomes harder for an audience to access, particularly if the audience is not “on-topic” or lacks experience engaging with that type of writing.

A first order assessment of prior knowledge generally also considers what science or astronomy background knowledge the storyteller can assume the audience has access to. In Sec. 6.4.1, this is ranked by the most advanced degree held most audience member, by research experience in the area of interest, and by overall familiarity with
the story topic. With academic audiences, finding out the accessible prior astronomy knowledge can be as simple as the description of a seminar series, readership of a journal, a department’s publication history, or the pre-requisites to a graduate-level course. For non-academic audiences, prior scientific knowledge assessment may involve reaching out to the journalist, editor, high-school science teacher, or astronomy club president to ask about the target audience.

In 2015, 88% of the U.S. adults held a high school diploma or GED, while only 33% held a bachelor’s degree or higher (Ryan & Bauman, 2016). The American Institute of Physics (AIP) Statistical Research Center, which collects data on education on physics and physics-related subjects, reports that 40% of the high-school graduating class of 2013 took a physics course, a continuation of a 20-year increase in high school physics enrollment (see Fig. 6.3; White & Tesfaye, 2014). According to their census, around 35-40% of adults aged 25 years or younger have learned the basics of Newton’s laws of motion, force and momentum, inverse-squared laws, and perhaps basic electricity and magnetism. That particular statistic is relevant not only for younger Type III audiences, but also for college astronomy majors in Type II and non-majors in Type III.

Going back farther, only around 16% of adults aged 45-55 years old took a physics course during high school. Unless targeting a specific sub-demographic within the general U.S. public, this age range will apply to the average audience member. So, public T.V. or radio communication, newspaper or magazine articles, or local amateur astronomy groups will require more qualitative descriptions of fundamental physics.

Keeping that in mind, when communicating to audiences who do not hold post-secondary degrees in STEM fields it is often best to limit or completely remove mathematical expressions from explanations of the science and describing all mathematical and physical relationships in plain English (Siegel, 2016). This can be done through illustrative examples, descriptions, diagrams, and demonstrations, as well as analogies to everyday or common occurrences of similar phenomena.

Some questions that you could answer about your audience to assess their prior academic knowledge include,

1. Is your audience comprised of college graduates?

2. Has your audience ever used a telescope, and if so, was it amateur or professional observing?
3. Do your audience members have a graduate education, and if so, in what field?
4. For a student audience, what pre-requisite courses have your students taken and who were their instructors?

6.4.2.2 Lived Experiences and Social Knowledge

The prior knowledge that shapes an audience’s interactions with a science story consists of more than just academic knowledge of physics and astronomy concepts. The storyteller cannot forget that the audience, first and foremost, is comprised of individual people who each have their own set of lived experiences, social knowledge, and racial or cultural knowledge, to name a few. Significantly, the storyteller must consider how these lived experiences and social identities intersect with the demo-
Figure 6.4: Gender balance in academic astronomy at different education levels in the U.S. from 1983-2012. **Top left:** Balance of men (blue) and women (yellow) earning bachelor’s degrees in astronomy over time. **Top right:** Balance of men (blue), women (women), and total (green) first-year enrollment in graduate astronomy programs over time. **Bottom:** Number of astronomy Ph.Ds awarded to men (blue) and women (yellow) over time. These plots from Mulvey & Nicholson (2014) along with details of data collection.

The AIP Statistical research center has collected data on the demographic representation of gender, race, and citizenship in astronomy and physics education from high school graduation through the awarding of a doctorate degree (see Fig. 6.4 & 6.5 Mulvey & Nicholson 2014 White & Tesfaye 2014 White & Tyler 2014). Their data show that of the approximately 375 astronomy bachelor’s degrees awarded in 2012, only 38% of them were awarded to women, while the overall percentages of men and women holding bachelor’s degrees were nearly identical in the overall population graphics of science education in the United States. The storyteller must consider a more holistic approach to an assessment of prior knowledge in order to maintain an audience-centric approach to communicating science.
(\sim 32\%; \text{Ryan & Bauman} 2016). At enrollment, only 37% of first year graduate astronomy students identified as women, and the percentage drops to 33% when considering Ph.Ds awarded by gender (assuming a binary gender framework). This is compared to the overall US population where 12% of both men and women held advanced degrees in 2015 (\text{Ryan & Bauman} 2016). Considering that advancement to an academic astronomy career requires a Ph.D. and that gender distribution becomes more imbalanced with advancing career stage, audience Types I and IV will likely be less than one-third female overall.

When considering the citizenship status of graduate-level astronomy students, AIP reports that non-U.S. citizens earned 35% of U.S. astronomy Ph.Ds in 2012, continuing an upward trend of almost a decade (Fig. 6.5 left). This is compared to the holders of advanced degrees among the general U.S. population, approximately 12% for both native- and foreign-born census takers. This split has serious impacts when communicating to graduate student audiences or audiences that earned graduate degrees in the U.S. because of the potential for different educational and social expectations altering audience perception of the communication style or medium. Additionally, pop culture references and idiomatic phrases likely will not have the same impact on an international audience.

The percentage of graduating high school seniors that have taken a physics course...
varies significantly when split by identified race or ethnic group (Fig. 6.5, right; White & Tyler 2014). While ∼ 55% of students who identified as “Asian” reported taking a physics class in high school (of 89.1% of all high school graduates; Ryan & Bauman 2016), only ∼ 42% (of 93.3%) of those who identified as “white” and less than 30% who identified as “black” (of 87.0%) or “hispanic” (of 66.7%) reported taking a physics course in high school. As few students who do not pursue an undergraduate physics major actually take an advanced undergraduate physics course, these percentages likely carry on to the college graduates in non-physical science fields. That will affect the racial demographics in Type II and Type III audiences, in particular.

We’ve only considered here social identities based on (binary) gender, (some) racial and ethnic groups, and U.S. citizenship due to available reports from the AIP Statistical Research Center. These reports to not consider non-binary gender, sexuality, religion, physical or mental ability, or other minoritized identities at present. The American Physical Society report on the LGBT Climate in Physics (Atherton et al. 2016) indicates that these identities are even more minoritized in physics (and by extension, astronomy) than the identities discussed above.

Research related to creating a supportive learning environment for students in a college classroom discusses a supportive climate on a continuum from marginalizing to centralizing, further broken up into explicit or implicit message (Ambrose et al. 2010; DeSurra & Church 1994). On one end of the continuum, explicitly marginalizing climates—overtly hostile, discriminatory, or unwelcoming—are least conducive towards effectively learning new material. Improving slightly upon that are implicitly marginalizing and implicitly centralizing climates, which subtly exclude or affirm perspectives different from the majority. Chapter 6 of Ambrose et al. (2010) describes an explicitly centralizing climate—the most supportive type learning environment—as one where “marginalized perspectives are not only validated when students spontaneously bring them up, but they are intentionally and overtly integrated in the content.”

The survey by DeSurra & Church (1994) indicates that implicitly marginalizing climates are most common across college campuses. Research on marginalization based on gender (for example, Hall 1982; Pascarella et al. 1997; Whitt et al. 1999) and race and ethnicity (for example, Hurtado et al. 1999; Watson et al. 2002) suggest that a learning environment does not need to be explicitly marginalizing to have a negative impact on the learning and retention of knowledge. Inclusion of stereotypes,
tone of communication, content, and interactions between storyteller and audience all have an impact on the climate of a learning environment.

As with classroom learning, communicating science does not happen in a vacuum, and the storyteller cannot reasonably expect audience members to completely divorce themselves from their identities, personalities, and interplay with socioeconomic issues. While a majoritized identity can only benefit from the inclusion of alternate perspectives, persons with minoritized identities can be harmed by overt and subtle marginalizing messages.

Some questions that the storyteller needs to answer about the audience include, but are not limited to,

1. Did the audience grow up in the pre-Apollo, post-Apollo, or Apollo era?
2. Are minoritized identities (e.g. race, gender, sexuality, religion, mental or physical ability, etc.) included in the audience demographic?
3. Does the audience include non-U.S. citizens or non-native english speakers?
4. Is the audience comprised of college graduates?
5. What educational resources did the audience have access to in schools?
6. Is the audience from a region with a specific trade, focus, or industry? Examples could include agriculture, automobile industry, politics, fishing, college sports, etc.
7. What pop culture references will the audience recognize based on their age, interest, geographic, or social demographics?
8. Are you (the storyteller) focusing on a Euro-centric history of the natural sciences?

6.4.2.3 Questions to check assumptions about audiences

Once the scientists has answered questions about the composition of their audience, they need to check their assumptions about how the audience demographic affects their interaction with the story. Here are some questions, selected from DiPietro (2007), that the storyteller must answer about their own assumptions before addressing an audience.

Regarding lived experience:

1. Do I expect my audience to share my cultural and political perspectives?
2. Do I expect most audience members to come from “comfortable” backgrounds or “traditional” families?
3. Do I expect most students to share my historical, popular culture, religious or literary references?
4. Do I fail to recognize that members of the dominant group have benefited from the privileges that come from membership in that group?
5. Do I expect most students of color to come from lower income families or have weaker academic preparation?
6. Do I expect members of minoritized identities to be first-generation college students?
7. Do I expect African-Americans, Latinos, Asians, or other students of color to be all alike within their group?

Regarding ability:

1. Do I expect minority students to need extra help?
2. Do I imagine that Latinos or Blacks will express their opinion in non-academic language?
3. Do I expect that Asian students will do better than most other students, especially in math?
4. Do I expect women in scientific fields to struggle more?
5. Do I expect students from certain majors to have weaker intellectual skills?
6. Do I assume international students have less language skills?
7. Do I link certain individual characteristics with levels of intelligence and ability (e.g., political or religious beliefs, tattoos and piercings, athletic or Greek system membership)?

Regarding viewpoint:

1. Do I treat audience members as if they are all heterosexual?
2. Do I treat audience members as if they are all Christian?
3. Do I think all students look like the gender or race they identify as?
4. Do I think I can tell who has physical or mental/learning disabilities?
5. Do I think I can tell the political affiliation of my audience?

Regarding assumptions influencing attributions:

1. Do I ascribe confident-sounding (tentative) language to intellectual strength (weakness)?
2. Do I link less-than-fluent English skills (speaking and writing) to weaker preparation?
3. Do I believe that certain cultural communication styles betray a low level of preparedness, confidence, or intelligence?

Practical steps that follow from the answers to these questions all involve critical and honest evaluation of the material being presented and the communication methods, and then correction of any aspects that are harmful to audience members. For example,
one could write down the metaphors or analogies they typically use to describe scientific phenomena to novice scientists or lay-people and check them for non-inclusive or assumptive language. When discussing astronomy or science history, listing the geographic origin, religion, race, and gender of the scientists being discussed can reveal inequalities in scientific representation, but also considering how the contributions of minoritized identities are incorporated can prevent tokenism. Recording a presentation and then listening and evaluating it later can reveal unconscious speech or behavioral patterns that vary based on the identities of audience members. These suggestions are far from comprehensive, but they highlight that honest efforts towards inclusivity can only come from actively working to improve and cannot simply rely on passive absorption of inclusive rhetoric.

6.4.2.4 Accessing the Prior Knowledge

Prior knowledge must be accurate, appropriate, sufficient, and activated to help an audience learn and retain the information being communicated (Ambrose et al. 2010, Ch.1). The audience members will connect more easily with the story if they can connect it to their own prior knowledge, but the storyteller cannot assume that the audience will spontaneously access relevant prior knowledge without prompting. Instead, the storyteller can deliberately activate prior knowledge that will aid audience comprehension and retention.

An audience’s prior knowledge may be entirely accurate, but be insufficient for them to fully interpret the new information a story presents. Or, the prior knowledge may be accurate, but the audience may be applying it in an inappropriate context. Scientists see this often when addressing Type II and Type III audiences and use a simplified analogy or explanation of a concept but fail to explain where the simplification no longer works. Accurate but insufficient or inappropriate prior knowledge can distort the audience’s interpretation of the story and impede learning.

Prior knowledge that is simply inaccurate can distort new knowledge and induce a confirmation bias on their thought processes, where they selectively discount facts that contradict knowledge they believe to be true (Alvermann et al. 1985, Dunbar et al. 2007). If the inaccurate knowledge is relatively unconnected to larger conceptual models, presenting logical explanations and evidence to refute that knowledge is often sufficient to prompt correction (Broughton et al. 2007, Chi 2008, Guzetti et al. 1993). However, more deeply held misconceptions (inaccuracies that have been confirmed...
repeatedly and have proven sufficient explanation for most cases) have proven resistant
to correction despite deliberate intervention (Confrey 1990; McCloskey, Caramazza, &
Green 1980), in which case repetition or a more graduate introduction of conceptual
change may help override long-held misconceptions (Brown 1992; Brown & Clement
1989; Clement 1993).

Ambrose et al. (2010; pp.27-38) offer some strategies to identify an audience’s
prior knowledge, activate sufficient accurate knowledge in the appropriate context,
and correct inaccurate knowledge and misconceptions. Of the strategies presented
there, we highlight a few that are applicable in most instances of an astronomer
communicating their science.

1. Talk with colleagues who have either presented to similar audiences or have
presented similar material and discuss audience receptiveness. This may high-
light strategies to implement or avoid, knowledge gaps to fill in, or confusing
terminology to replace.

2. Explicitly link new knowledge to accurate prior knowledge, rather than leaving
the connection up to the audience. This may require explicitly stating, for
example, the details of an analysis method that would otherwise be left as “we
repeat the analysis method of X” within a research paper or “we leave this
exercise to the reader.”

3. Highlight conditions of applicability of prior knowledge, especially when pre-
senting an idea, analogy, or simplification that, when overextended, leads to an
incorrect conclusion.

4. Explicitly identify discipline-specific conventions or jargon that have different
meanings outside of a narrow context. When communicating to non-scientists,
this may include basic science terminology like “model” and “significant.” When
communicating to non-astronomy scientists, this may include terms like “metal-
llicity,” “point spread function,” “H-R diagram.”

By assessing the audience’s prior knowledge you can choose and implement the
most effective communication strategy, avoid confusion, and utilize your audience as
a resource. A storyteller can turn prior knowledge from a hurdle to overcome into a
set of tools to improve understanding and increase retention.

6.4.3 What does the audience need to learn?

Critical thinking about the desired message of a story and the key topical points
needed to convey that message is essential for creating a focused, direct, and cohesive
narrative that an audience can access. The message of the story is the overarching idea
Figure 6.6: Examples of story topics broken down into key topical points. Top: Story emphasizing the relevance of the *James Webb Space Telescope* while *HST* is still operational, targeted at a Type II audience. Bottom: Story emphasizing the need for additional high-resolution follow-up observations of *Kepler* planet host stars, targeted at a Type I audience.

or conclusion that the story is trying to convey. The storyteller wants the audience to leave the story with the message embedded in their minds. For a research paper or presentation this is likely the main conclusion of the research project (Whitesides 2004). For a module within an astronomy course, this is the focused learning objective(s) for the students (Ambrose et al. 2010). For a public astronomy talk, this could be the motivation for the audience’s attendance or a call to action. If the audience takes nothing else away from the story, the message needs to clearly stick in their minds.
If struggling to identify the message of a story, trying to write it as a direct learning objective with a verb from the “evaluate” level of Bloom’s Taxonomy often works (Anderson & Krathwohl 2001; Bloom 1956). A learning objective states tangible changes desired in the audience as direct consequences of engaging in the material. For example, some learning objectives after a research presentation could be, “By the end of my talk, my audience will be able to explain the differences between Type I and Type II Seyfert galaxies,” “By the end of my talk, my audience will agree that micro-telluric lines can significantly influence radial velocity calibrations,” or “By the end of my talk, my audience will be able to determine three key research advances to be made with GAIA observations.” The verbs “explain”, “agree,” and “determine” are the active verbs that define the desired level of the learning objective.

The message needs to be supported by a few (∼4) key topical points which, when combined, lead the audience to the message on their own. The key topical points form the support structure for the story and can serve as a rough outline of a talk or paper, or as touchstones during formulation of the story. If the story design has an abstract, conclusion, or summary section, these key topical points must always be there. Depending on format and data, a supporting figure or graphic for each of these points can give an additional avenue for an audience to engage with that point.

Scientific details that describe the origin of the key topical points do not belong in this organizational tool. They do not convey the message and so fall lower in the scaffold of importance. Those details can be included in the full text, speech, or visual representation of the story, but are not appropriate for supporting the main message.

Figure 6.6 contains two examples of story construction using the message-key topical points framework. Consider the first example, where the message is the relevance of the James Webb Space Telescope even through the Hubble Space Telescope is still operational. When framed as a directed learning objective, this message might read “The audience will justify construction of JWST while HST still functions.” Assuming a target audience within Type II (say, a local amateur astronomy group), key topical points to emphasize might be 1) JWST and HST observe different wavelength regions, and therefore will be able to do different science; and 2) JWST is more powerful and versatile than HST, and is as cutting-edge in technology today as HST was in 1990. When the audience accepts those two key topical points as fact, the message—that we need JWST now—is an obvious conclusion.

The second example in Fig. 6.6 conveys the necessity of high-resolution follow-
up imaging of systems with habitable zone planets to a Type I audience (Ph.D. astronomers focusing on exoplanets). This message, conveyed in a learning objective format, might read “The audience will conclude or argue that we must follow-up more habitable zone planet host stars with high-resolution imaging to accurately assess planet parameters, habitability, and demographics.” Key topical points to support this message would be 1) Previous high-resolution follow-up imaging surveys discovered a 17% rate of unknown stellar multiples in Kepler planet hosting stars; 2) Stellar multiplicity affects extraction of planetary parameters from transit light curves and changes estimates of habitability; and 3) Only 46% of Kepler host stars have been observed at high-resolution. Supporting details might include the resolution differences between Kepler and telescopes like HST or Keck, that most of our known habitable zone planets come from the Kepler dataset, and details about how stellar multiplicity affect calculation of planet parameters.

Structuring the story hierarchically ensures that the story always stays focused on the message, that key topical points will lead your audience to the message on their own, and that no confusing or unnecessary details are included in the story.

6.4.4 Why will the audience care?

The audience has the right to disengage from the story at any time. The reader does not have to finish reading the paper. The attendee does not have to listen to the talk. The conference-goer does not have to stop by the poster. The student does not have
to pay attention to the instructor. The anonymous social media audience does not have to subscribe to the Twitter feed. Excepting the case of an instructor needing to evaluate a student’s work, audiences of science communication are not held captive, nor do they have an obligation to engage with the story (Greene 2013).

It is the storyteller’s job to hook the audience and keep them engaged throughout the entire story. That is done by understanding what the audience expects from the story and what value they will find in it, and then explicitly addressing them. People direct their attention towards activities that they value and in which they have some expectancy of success (Svinicki & McKeachy 2011). As Schimel (2012) states, “It is the author’s job to make the reader’s job easy.”

Astronomy can be a very abstract science, filled with objects at difficult-to-imagine physical scales that can interact in counter-intuitive ways through physical processes that do not take place on Earth. On the two-dimensional abstract-concrete vs. active-reflective classification axes for academic disciplines Biglan (1973a); Kolb (1981), astronomy, physics, geology, and chemistry (four disciplines which host most astronomy research) are classified as two of the most abstract of disciplines, and more reflective than active (see Fig. 6.8). Non-academic and off-topic researchers (all but Type I audiences) will have a difficult time connecting with an astronomy story unless it explicitly and purposefully engages with concrete ideas, expectations and values.

Research shows that to non-scientists, concrete and active disciplines are, by design, easier to engage with as they can relate to lived experiences (Svinicki & Dixon 1987). Audiences will also display deeper levels of understanding and higher knowledge retention rates if they intrinsically find value in the story, rather than being extrinsically motivated by incentives or rewards (Svinicki & McKeachy 2011).

For example, consider an astronomy story told through an research paper published in an academic journal. Above the minimum requirements for sufficiently telling a story, Ph.D. researchers (on- or off-topic) will expect a clear abstract, conclusions, and supporting results graphic. They will value explicit mention of the impact on their own work and the takeaway for the wider field. Graduate students hoping to make use of research presented in a paper will expect descriptive methods, numerical results, and explicitly defined equations, and value information and techniques they can use in their own work and results they can easily compare to their own. And science journalists, who constantly read titles and abstracts for interesting science stories to disseminate, will expect a clear, descriptive title and an abstract that contains the
main conclusions of the paper, and will value clearly stated motivations, conclusions, and important caveats.

Finding the aspects of the story that the audience will value involves asking the question, “what’s important to my audience?” not just, “what will get the audience’s attention?” [Casagrande2010]. In astronomy, many stories that get told are “science for the sake of science or curiosity” without a tangible impact on the everyday lives of the audience. This is why Astronomy as a discipline rates high on the “Abstract” axis in Fig. 6.8. As [Casagrande] says, “Any writing that’s meant to be seen by a Reader must serve the Reader.”

The story must be about more than just the fact that molecular hydrogen was detected in the plumes of Enceladus, or the discovery of protoplanetary disks in a new star forming region, or the precise shape of galactic bulges as a function of cosmological redshift. Each of these topics is unquestionably fascinating, and would

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**Figure 6.8:** Classification of academic disciplines on the axes of abstract-concrete vs. active-reflective. Astronomy, Physics, Geology, and Chemistry (i.e. disciplines that host most astronomy research; red points and text) are located near the bottom-center of the graph. This figure reproduced from Kolb (1981).

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likely appeal in any form to an on-topic Ph.D. researcher. Yet, astronomers are astronomers precisely because of a fascination with astronomy, and so finding the non-academic value in a story requires perspective and practice.

When trying to tell a story to a new audience, or a new story to the same audience, it is helpful to begin with a face-to-face discussion about the story with someone from that audience group, or with someone who has (successfully) communicated a story to that audience. They can read or listen to a short version of the story and then explain the areas they thought were most interesting, most relevant to themselves, or most critical to their own work. If a story about cosmology needs to be told to a general astronomy department in a colloquium, an exoplanet or stellar physics can help evaluate the accessibility and appeal of the talk by identifying the areas they connected with or lost the purpose of. Asking those same questions after giving the talk (or publishing the paper or presenting the poster) will help refine these evaluations and assess audience value and expectations more swiftly and accurately.

Thoughtfully constructing the story involves finding a way to convey the most important information in a way that is easy for the audience to access and engage with. This could include considering what each sentence (written, presented, or spoken) is trying to convey. What pieces of information does a sentence include? Which pieces are important and which can be thrown away? In what order to the pieces of information appear? Are any crucial details relegated to subordinate positions in a sentence rather than in the main body? Ensuring that the information that the audience most wants to know is highlighted in the main clause of the sentence subtly emphasizes its importance (Casagrande 2010).

On a larger scale, stringing sentences together into paragraphs and sections conveys larger ideas or messages. The storyteller can build these by identifying what pieces of information each paragraph or section needs to convey, what can be left out, and what information an audience most needs to know (i.e. Sec. 6.4.3). Audiences naturally remember ideas that occur at the beginning of a section (paragraphs) and at the ends of sections (paragraphs), and expect the most important information in those locations. Placing the most critical pieces of information in the power positions of paragraphs and sections utilizes audiences expectations rather than fights against them (Schimel 2012). Important or valuable information can be easily overlooked if it exists in an unexpected location or presented in an unfamiliar way.
6.5 Making the most out of a storytelling medium

This section delves into the three most common media that astronomers use to communicate their research: academic research papers, slides for oral presentations, and research posters. This section is not meant to be a comprehensive list of strategies for each media, and most certainly not meant to be a comprehensive list of media through which astronomers communicate. This section is, however, attempting to describe some effective practices that will target the correct audiences, increase audience engagement, interest, and retention, and maximize the functionality of the medium in question.

6.5.1 Academic Research Papers

Academic research papers are the foremost way that astronomers communicate the results of research projects. Indeed, a project is often not considered complete until it has been published as a research paper in an academic journal. The majority of academic journals in which astronomers publish are aimed at the top group of Type I audiences, namely, Ph.D. astronomers researching the same or similar topics. The exception to that rule might be review papers and white papers which are aimed more broadly at the astronomy community or perhaps at the future members of general science funding committees.

A research paper must unambiguously explain the methods, analysis, and results, yes, but also explain why the scientists chose to conduct that research and what the results mean. Most importantly, the paper must explain why the audience should care, which might not necessarily be why the researcher cares about the project. Keeping in mind that a research paper is just another way of telling a scientific story, the writer must convey the story in its entirety, of which the bulk of the work only comprises the “middle” section. The “beginning” and “end” are likely to be of far more interest to an audience.

Most research papers address an expert Type I audience (on-topic Ph.D. researchers), but it is possible that this narrow audience is not intentionally targeted. Academic papers tend to use excessive jargon and abstract registers and typically gloss over background, methods, and discussions that would make it accessible to the
entireties of Type I, Type IV, and knowledgeable Type II audiences.

Section 6.5.1.1 describes how to translate the traditional research paper structure into a story structure that will tell a focused research story to a very broad audience base. Section 6.5.1.2 explains the appropriate tone, register, and writing style for an academic paper, with the goal of easing overall readability while maintaining precision and succinctness of language.

6.5.1.1 Organizational Structure

A story structure is comprised of: 1) Opening, which sets the scene, background of the characters, and provides context for the rest of the story; 2) Challenge, the specific task that the characters need to accomplish, or the question that needs an answer; 3) Action, what happens to address the posed challenge; and 4) Resolution,

\[10 \text{The reader can identify an abstract register by the use of abstract, rather than concrete, sentence subjects, overly formal language, and passive or weak active verbs.}\]
what has changed, either in the characters or their world, as a result of meeting the challenge [Schimel 2012]. The traditional organizational format of an academic research paper, IMRaD (standing for Introduction, Methods, Results, and Discussion) maps very cleanly onto the structure of a story (see Fig. 6.9).

The Introduction of a research paper serves as the opening to the story. To do so effectively, an Introduction must introduce the characters of the story (the objects of interest, the principle being tested, the instrument being used for the first time). The researchers themselves might be characters, which would also support the use of active over passive voice and centralizes the researchers instead of removing them from the action. An Introduction must explain where the characters have been before (recap past literature) and explain what the audience needs to know about the characters to grasp the importance of the Challenge. As J. T. Wright puts it, “The introduction should explain to a graduate student 50 years in the future what is known at the time the paper was written.” In terms used previously in this chapter, the Introduction needs to prompt the reader to access appropriate, sufficient, and accurate prior knowledge of the topic at hand.

The goals of a research paper, while often incorporated into the introductory section of a paper, are distinct from the Introduction to the research project. The goals encapsulate the Challenge the characters are facing, or the problems being solved and why. This Challenge is one declarative sentence that states the aim of the paper and the purpose of seeking that knowledge. For example, a Challenge statement might be phrased as “Because we do not know X, we cannot know Y,” or “We seek to understand X so that we may know Y.”

This is distinctly different than a hypothesis statement, which seeks to predict the answer to the challenge ahead of time based on prior knowledge. Keep in mind that the Challenge states the challenge within the story, which may differ from the challenge that motivated the research in the first place. Some Challenge statements for chapters of this dissertation could be,

Ch. 2 “We seek to characterize the stellar hosts of small and cool Kepler Objects of Interest through high-resolution imaging to better validate radius and temperature calculations for these potentially habitable planets.”

Ch. 3 “Because we do not know whether the emission spectrum of WASP-103b is consistent with a stratospheric temperature inversion, we cannot know whether temperature inversions are atmospheric features of the hottest of hot Jupiters.”
Ch. 4 “We seek to measure the optical transmission slope in the atmosphere of WASP-103b to determine whether WASP-103b’s atmosphere is a manifestation of previously unknown atmospheric phenomena or common Rayleigh scattering processes.”

Ch. 5 “Because we cannot quantitatively assess the information content of a changing transit depth time series, we cannot distinguish between naturally variable transits and artificially varying transits that may transmit signals.”

Assertively stating the Challenge will aid the audience in understanding the driving purpose of the Action and let them assess whether or not the challenge has been solved in by the Resolution.

Novice paper writers are likely the most familiar with the Action of the story, that is, with the methods and results, as that has been their daily focus for the duration of the project. Some mentors advise writing the Methods and Results first, both to get the writing process started with the “easiest” parts and to ensure that no details get lost to poor notes. But, how can the writer know what the relevant Actions were before considering the Challenge and Resolution? In other words, the writer must know the beginning and end before describing how they got from one to the other.

The Methods need to be descriptive enough that someone unfamiliar with the dataset in question could follow the Methods to achieve the same Results, and understand why each step is necessary. This has important ethical implications as well, as repeatability and clarity of method are essential components in order to trust scientific results. There are many cases of proven data falsification that were uncovered when other scientists followed the outlined Methods and came to different Results. Readers need to understand exactly what the researchers did to obtain results in order for them to trust the results of a paper. Vague or unclear methods can obscure the process and lead to mistrust in the results or interpretations.

Methods do not necessarily need to be listed in the chronological order in which the researchers performed them during the actual research project. Projects evolve organically, often involving missteps, tangents, and false endings that would cause an audience unnecessary confusion and lead them astray. Rather, the Methods lead the audience through the necessary steps to get from raw data to Results on an artificially smooth and direct path. Recall, the goal is not for the writer to understand what they did, but for the reader to understand what needed to be done. While this is good
paper writing, mentors should take care to emphasize to students that it is normal for their research path to look very different from what they read about in papers.

If a particular technique or equation was necessary to extract the Results from the raw data, an explicit mention or description of that technique belongs in the Methods unless the technique is completely ubiquitous (and if so, cited). Imagine handing the finished paper to a brand-new graduate student who has never worked on any similar research; that novice needs to be able to follow the Methods and achieve the same Results described in the paper. Do not worry about turning an expert audience off by being too explicit with the Methods—those audience members will gloss over details they already know. Worry instead about losing potential audiences who do not grasp what Methods were used because they were not explained in enough detail (or left to look up elsewhere). If there is not enough room due to page restrictions, include supplementary information or appendices.

Results are stated in as direct a manner as possible, supported by tables and graphs as needed. When comparing these results to their own work, a researcher will want Results that are unambiguously stated and easily located. Another aspect of journal articles is that they are examples of persuasive writing, a writing form which has different demands than a story. This is true more for the Results and Discussion sections than for Methods. Researchers use graphs to persuade the reader that the interpretation is correct, plugging up holes in the logic or addressing concerns readers might have (but that are actually not important to the story). Results that are cohesive with the story remain focused only on the results needed to answer the Challenge stated at the start of the paper.

Doubtless the researcher produces other graphs, calculations, or numbers along the way, but if they do not provide the answer to the Challenge then they are better suited for appendices or supplemental information sections; additional information there will blur the focus of the Results and detract from the details that are critical to accomplishing the Challenge. If the research produces other interesting results that are not key for the resolution of the paper, they could be included in the Discussion as possible implications or potential future directions for the research.

The Discussion section is often an ambiguously defined part of a paper, and is sometimes not explicitly separated from either Results or Conclusions. This section answers the question “what do the Results mean?” or explains, “From the Results, we learn...” In other words, it explains how the writer interpreted the results in order to
meet the goals of the paper. Discussion is sometimes separated from Results because Results are the factual results of following the methods in as pure a form as possible, whereas the Discussion inserts the writer’s opinion of the Results and is therefore more subjective than Results. A different scientist may analyze the same data using the same Methods and achieve the same Results, but their prior knowledge or different goals may lead them to a different interpretation of the Results. It is the writer’s job to convince the reader that the researcher’s interpretation helps address the goals defined at the start of the project. The Discussion may also describe other tangential results that do not directly address the Challenge, open up new applications of the work, or reveal additional Challenges that need to be addressed later.

Finally, the Conclusion of the story highlights the take home message and implications of the research, identifies whether or not the Challenge was adequately addressed, and if not, what must still be done to address it. The Conclusion is oftentimes incorporated into a summary section that first rehashes the entirety of the paper. This is fine, but within that summary section needs to be a distinct paragraph(s) actually resolving the story and leaving the audience with the main ideas lingering in their minds.

Many writers misinterpret the dictum “Tell them you’ll tell them, tell them, then tell them you told them” to mean that the abstract, introduction, and conclusion sections are supposed to be very similar and repetitive. But, as discussed throughout this section, each portion of the research paper serves a distinct purpose—enticing overview, framing and background, and resolution of the story, respectively. Using the same or very similar wording in each section can be counterproductive to each section’s goals and lead to inattentive readers at critical sections of the research paper as they pass over phrases or sentences that they have already read.

Writers can naturally fulfill that dictum by following the organizational structure outlined in this section. The Challenge is both a statement of the problem and a promise to the readers to solve it (“Tell them you’ll tell them”). Results and Discussion present the resolution to the Challenge (“Tell them”), and the Conclusion explicitly states whether or not the researchers fully addressed the Challenge (“Tell them [whether] you told them”).

To summarize, the components of a traditional paper structure, when used to tell an audience a story, answer the following questions:

Introduction “From where are we starting?
Goals “What’s the problem and why do we want to solve it?”
Methods “What did you do to solve the problem?”
Results “What did you find?”
Discussion “What does that mean, and now what?”
Conclusion “Did you solve the problem?”

6.5.1.2 Writing Style and Language

Greene (2013), and the references contained therein, make a compelling argument for writing science in plain English. “Why,” Greene asks, “should intelligent, motivated students have difficulty reading the scientific literature?” If, in fact, the entire purpose of writing scientific papers is to communicate research to others, why make the task more difficult than it needs to be? The only person benefiting from needlessly complicated terminology, convoluted sentences, and overly obscure and abstract ideas is the writer, and never the audience.

Two key characteristics of writing style, namely tone and register, are determined solely by the target audience (Greene 2013). Register describes the formality of the writing, while tone describes the writer’s attitude towards themselves, the audience, and the work itself. The majority of journal articles are written in an abstract register, where the subjects of sentences are abstractions of actions that take place without clear characters. Passive voice dominates over active voice, complicated terminology prevails, and there are many long strings of nouns tied together. It is verbose and difficult to parse.

Take for example this sentence from Chapter 5:

Although our depth measurements are slightly heteroskedastic, our derived uncertainties in transit depth of real systems are sufficiently close to constant that in what follows we choose to use the mean of the uncertainties for a given system as characteristic of the noise.

Though it uses the (weak) active voice, the noun strings like derived uncertainties in transit depth of real systems and the mean of the uncertainties for a given system dominate most of the sentence and jargon like heteroskedastic is used where a simpler word or phrase would do. The tone is dull, dry, and cautious. On top of that, the sentence is a compound of two sentences tied together with the complicated conjunction that in what follows.
Using a *conventional* register instead of an abstract one is characteristic of clearly written journal articles and proposals aimed at a broad scientific audience (Greene 2013). In a conventional register, identifiable characters actively perform identifiable actions. It features active voice, remains emotionally neutral, and assumes some (but not excessive) technical knowledge. As research papers are meant to be persuasive, and so a confident and direct tone projects intellectual surety even when explaining caveats or limitations of the research (Schimel 2012).

In his book *Style: Toward Clarity and Grace*, Joseph Williams outlines a few simple principles that are applicable towards writing science in more direct language, based on linguistic theory about what readers look for when processing complex, unfamiliar information (Greene 2013; Williams 1995). In short, readers look for 1) a story about characters and action; 2) strong verbs close to their subjects; 3) old information at the beginnings of sentences and new information at the ends; and 4) for specific kinds of information in predictable places in paragraphs and documents.

Because of this, strategic placement of passive voice does have its uses in scientific writing. Passive voice can be used to keep the same or similar subjects in sequential sentences in a paragraph, which will help readability and focus. Writers can also use passive voice to place key information in power positions within sentences, or to connect that information to preceding or subsequent sentences (Casagrande 2010; Greene 2013).

Applying these principles, the example sentence above is written as:

> We derive uncertainties in real transit depths that are approximately constant despite transit depths that vary. For this reason, we characterize the noise of a system as the mean of its transit depth uncertainties.

This sentence, originally 43 words, is now broken into two sentences 16 and 18 words long. The subject of the sentence is now the scientist, and the actions become *characterize* and *derive*. Unnecessary jargon is replaced by equally accurate language accessible to those unfamiliar without a background in statistics, yet leaves technical language like *transit depths* and *noise of a system* that the intended audience does know. These scales are based on sentence length and size of words as measures of “readability,” where shorter sentences and words allow non-expert and non-technical audiences to more easily engage with the material.

Use of conventional register, clear language, and standard placement of information is especially important when the intended audience is non-experts in a topic, like
for proposals, broad academic journals like *Nature* and *Science*, or a review article on a topic. While the particular language, tone, and register may vary between the introduction and the methods sections of a paper, using clear language is particularly important for the abstract, introduction, and conclusion sections. Those three sections may be the only parts of the paper that a busy scientist or science journalist will read ([Blum, Knudson, & Henig] 2006).

For more descriptions of effective writing styles for science, and for examples of both good and poor applications of these strategies, Schimel’s *Writing Science: How to Write Papers that get Cited and Proposals that get Funded*, Greene’s *Writing Science in Plain English*, and Casagrande’s *It was the Best of Sentences, It was the Worse of Sentences* break down sentence, paragraph, and paper structure into tractable parts and describe their tried and true strategies for using those parts to tell a scientific story.

### 6.5.1.3 Determining Appropriate Jargon

Determining necessary versus unnecessary jargon can be a difficult task for an astronomer immersed in the details of the research and out of practice at presenting their work to those unfamiliar with it. Scientific jargon—specialized language whose meaning is narrowly defined when related to the subject at hand—serves an important purpose in the day-to-day performance of research and its communication. Jargon ensures effective, unambiguous communication between two researchers that both understand the narrow definition of the language. Therefore, unnecessary or inappropriate jargon is technical language that is inaccessible to the target audience.

Some astronomy jargon is common to all astronomers with a bachelors degree regardless of research topic (e.g. stars, photons, cosmological redshift, $1\sigma$ uncertainty, stellar main sequence, etc.). This type of jargon, typically taught somewhere during an undergraduate astronomy program, simplifies text by replacing long explanations or noun strings with a concise term. Given that the target audiences of research papers are often Types I and IV, writers can use this type of jargon to avoid unnecessarily complicated or confusing explanation of phenomena well-known to their audience.

Jargon that can be easily replaced by a more conventional word or a few words without sacrificing scientific accuracy is often unnecessary. Jargon can also be unnecessary if it is inappropriate for the target audience, either by being too narrow or advanced for the audience or by having different narrow definitions for different
audiences. In the example above, the statistical term *heterosketastic* was easily replaced by a short descriptive phrase without losing accuracy or making the sentence longer. If the chapter focused on the effect of variable dataset uncertainties and scatter on statistical accuracy and was aimed at Ph.D. statisticians, then the narrow definition of *heterosketastic* may be needed to have a precise discussion about the effects of different types of variability. For a target audience of Types I and IV astronomers, *heterosketastic* is needlessly complicated and specific, and the implications of the word may differ for astronomers and statisticians.

If jargon is necessary in order to ensure writing precision, yet may be too technical or specific for the target audience, writers can help reduce confusion by including a short definition or description of the phenomenon after the first use of the word, and then follow up with a sentence like, “We refer to this phenomenon as [jargon word] for the rest of this paper for brevity.”

### 6.5.2 Slides for an oral presentation

Oral presentations of research are the second most common communication method astronomers use to during their career. An R1 astronomy department may host anywhere from two to ten oral research talks a week, presenting research during an oral exam is a requirement for obtaining a doctorate, and annual professional conferences invite and accept more than 1,000 oral presentations each meeting.

Oral research presentations are usually accompanied by a slideshow presentation,
through PowerPoint, Keynote, or an analogous piece of software. The sides accompany
the oral storytelling and, when designed effectively, serve to connect the auditory and
visual memory centers of the brain. An effective slide design allows the audience to
concentrate on both the oral story and the visual one without either one overpowering
the other.

A slide design dominated by a graphic and containing few words more effectively
combines the oral presentation with the visual one. People in general, and students
especially, are trained to focus on words that are put in front of them, whether on
pieces of paper or projected on to a screen. Just so, the audience will focus on any
words that appear on the slide at the expense of the visual and oral story (Fig. 6.10,
right).

The Assertion-Evidence slide design maximizes audience comprehension and
retention of material, particularly when accessing complicated and abstract ideas
(Garner & Alley 2013). The Assertion-Evidence slide (see Fig. 6.10, left) contains
one, and only one, title sentence. The title must be a full sentence that contains
the main point of the slide. Simple titles like “Data Analysis” and “Results” do not
describe what the slide is actually meant to explain to the audience. The titles of
all the slides tell a stripped down version of the story when strung together. When
in doubt, imagine an audience member who has gotten distracted and missed the
introduction to a slide; when that audience member tunes back in, the title explains
where they are in the story and helps them jump back in to it.

The remainder of the slide is taken up by one (or at most, two) images that aid
in telling the story. Labels and annotations on the graphics can serve as guides for
the oral presentation and anchor points for the audience, and bold colors with high
contrast to the background ensure that the projector will not wash out important
details. When possible, test potentially washed out images ahead of time to ensure
that the audience can still access the information they contain. For example, details
in dark images get washed out in a bright room, as do colors nearby on the color
wheel.

Most audiences have difficulty quickly grasping the meaning and purpose of
equations in a talk unless they are intimately familiar with them. Keeping equations
to a minimum in slide presentations unless the equations themselves are the story
helps keep audiences engaged. If equations are unavoidable, take time to go through
each component of the equation and explain why it is important to the overall message.
If the presenter cannot do that, but cannot tell the story without the equation, then audiences can still understand the equations’ relevance if they are written with words instead of symbols (e.g. “Force = mass × acceleration” rather than “F = m × a”). Keep in mind that it is typically more important that the audience understand the concepts represented by an equation rather than being able to memorize the meaning of symbols.

An effectively-designed slide helps the audience connect the image and title together into one step in the story; the accompanying oral presentation will explain the lead up to the image, how the image was created, and what the presenter wants the audience to take from it.

### 6.5.3 Academic Research Posters

Communicating via academic research posters has become more prevalent over the past few years, almost entirely at professional conferences. In lieu of presenting short oral presentations at conferences, graduate advisors are increasingly encouraging undergraduate and graduate students to present their work in a poster format. At a conference, presenting research via a poster rather than through an oral presentation will increase exposure, allow for more time and attempts to orally explain the research, and provides valuable networking opportunities.

Again, despite the popularity of presenting research in poster format, little formal instruction in effective poster design takes place. Many universities or professional organizations that do provide some type of online resource on how to design a research poster\[11\] tend to focus mostly on visual design styles (colors, fonts, image resolution, etc.) or basic content requirements (title, affiliations, introduction, results, etc.) rather than the unique shaping of research ideas, figures, or results into forms most appropriate for a static visual medium like a poster. Regardless of whether or not the student (or postdoc or professor) has presented the research previously in a journal paper or oral presentation, translating those same results to a poster requires different skills. As a poster is, first and foremost, a visual representation of the work rather than a written one, the same communication techniques that apply to writing effective papers do not transfer to designing effective posters.

\[11\]For just a few examples of this, see poster tips and examples from Northern Arizona University [https://nau.edu/undergraduate-research/poster-presentation-tips/], Washington NASA Space Grant Consortium [http://www.waspacegrant.org/for_students/](http://www.waspacegrant.org/for_students/)
This subsection contains a summary of some of the most important strategies for designing effective research posters. These strategies are discussed in more detail in Appendix A, which also includes a poster that both explains and demonstrates effective poster design (Fig. A.1). The strategies discussed here and in Appendix A were also used to create a poster that summarizes the contents of this chapter on astronomy communication. That poster, titled “Multimedia Astronomy Communication,” (Fig. A.2) was presented at the 229th American Astronomical Society (AAS) meeting in Grapevine, TX in January 2017 and won an AAS Chambliss Astronomy Achievement Student Award.

The first principle of effective poster design is the understanding that a poster is a visual aid for an oral pitch. In the majority of scenarios, the researcher is meant to stand in front of their poster for a certain amount of time and orally explain the research for a few minutes while referencing the poster. However, the researcher cannot be at their poster for the entire time it is on display, so the poster needs to both enhance the oral presentation and be able to take its place when the researcher is absent.

Given that research posters are most often utilized during professional conferences, it is no surprise that they are mostly designed for Type I and Type IV audiences. However, most often a poster is designed to target a higher knowledge level than is appropriate. On-topic experts (Type I) will visit a poster regardless of its effectiveness due to the relevance to their own work. The ideal target audience for research poster is other scientists within the larger subfield of work (knowledgeable Type IV, e.g. exoplanet researchers over experts in transit timing variations of Kepler systems), who can be drawn in by a clear presentation which highlights the broader implications of the work. These interactions at posters can provide novel interpretations of the work and inspire collaboration that enhances the quality of research. If a poster is truly designed in a way that effectively communicates both the description of the work and its implications, the poster may draw in off-topic researchers (less knowledgeable Type IV) or non-academic audiences (Type II) as a bonus. These audiences will appreciate that the motivating problem, conclusions, and implications are clearly

[student_internships/wsgc_internships/posterdesign.html], Boise State University [https://academics.boisestate.edu/studentresearch/poster-presentations/], University of Texas at Austin [https://ugs.utexas.edu/our/poster], University of North Carolina [http://gradschool.unc.edu/academics/resources/postertips.html#examples], and Utah State University [http://rgs.usu.edu/undergradresearch/posters/].
stated and prominently highlighted on the poster.

A poster is first and foremost a visual representation of research so plots and other descriptive graphics can tell the story and engage viewers better than tables or paragraphs of text. Where words must be used, short, descriptive sentences, phrases, or bulleted lists are much more effective than paragraphs. An abstract does not belong on a poster unless the abstract does not live elsewhere, like a conference booklet. The chosen graphics help the story and must be understandable on their own, through descriptive captions and annotations. The audience needs to know why the graphic is on the poster and what conclusions they should draw from it.

One of the most common missteps made in poster design is using the same graphics from a paper for a poster design. Though plots that appear in both format may display the same data, graphics on a poster need to be large enough and clear enough to be read from a few feet away. Thicker lines, larger text and axis numbers, and contrasting colors will draw the audience’s eye to important parts of the graphic and prevent confusion.

Conscientious organization and stylistic choices can aid comprehension and enhance content, but can also be detrimental to the poster when applied improperly. Group ideas into clearly separated sections, either through boxes or blank-space. Each section, then, is a self-contained story module in its own right. One section flows into the next through by using a standardized reading layout (left-to-right and top-to-bottom in English) or a clearly marked pathway using arrows (flowchart style). This ensures that audiences access the knowledge in the proper order to tell the story.

Finally, keep stylistic choices simple and consistent across the poster. Use of a few contrasting colors sparingly can highlight common ideas, numbers, or conclusions that occur in multiple places on the poster. If so, ensure that audiences with color-blindness can still perceive the differences in color so that they do not lose that additional information; online color-blindness filters can test for this.

Overall, these are only a few of the most critical strategies to consider when designing a poster that effectively communicates the science. For two examples of posters that demonstrate these strategies, see Appendix A. That appendix also contains additional information not discussed here or on the “meta-poster,” as well as links to a website to download high-resolution versions of both posters and references for some of the strategies discussed therein. A research poster, when designed thoughtfully, can be a very effective communication medium that reaches a wide
6.6 Recap of best strategies

This chapter has argued for effective communication strategies for astronomy research stories. Science, being just another type of story, requires storytelling techniques and devices like characters, plot, conflict, action, and resolution. The researcher, i.e. the storyteller, must carefully consider the target audience of the story, what that audience already knows, what key ideas and message the audience needs to know, and why the audience will care in order to craft a story that will appeal to an audience that might otherwise tune out.

The three most common communication media astronomers use—journal articles, slide presentations, and posters—share a few key communication strategies that can be liberally applied. Use of direct, precise, and plain English language to describe the science will aid in audience comprehension and retention of information. Placing information in easy-to-find areas (e.g. sections in a poster or paper, highlighted in graphics), highlighting key topical ideas as section or slide headers, and clearly identifying the goals and whether they were met will ensure that the audience cannot miss the important aspects of the work, and entice them to learn more.

The volume of science communication that takes place on a daily basis by and about the astronomy community underscores the need for effective communication strategy. No one astronomer, or science writer, or graduate student can possibly read every academic paper published each day, read every poster of interest, nor retain every piece of information contained within research talks. Now more than ever, clarity in scientific communication is a critical component of scientific success and propagation of ideas. There’s no reason to make learning new science any harder than it already is, and every reason to try to make scientific knowledge more accessible to all.
Appendix A  Supplementary Information for Chapter 6: Best Practices for Effective Poster Design

This appendix contains more information about academic research posters, how to make the most effective use of the medium, two examples of effective poster design, and references to additional sources. The necessity and relevance of academic research posters and a short discussion on the most relevant strategies can be found in Sec. 6.5.3.

The first example poster included here is a “meta-poster” that both describes and demonstrates effective poster design. In other words, the poster itself is an example of an effective poster design, and the content of the poster describes effective poster design. Accompanying this “meta-poster” is an online blog post that includes a high-resolution PDF file of the poster for download, additional poster tips not found on the poster, references for the poster practices, and suggestions from poster connoisseurs. The “Best Practices for Effective Poster Design” blog post is found at http://sites.psu.edu/astrolady/2015/05/20/poster-design/.

The second example is a poster that visually displays the content of Chapter 6 on effective astronomy communication using different media. This poster was presented at the 229th American Astronomical Society (AAS) meeting in Grapevine, TX in January 2017 and won a AAS Chambliss Astronomy Achievement Student Award. This poster can be downloaded at http://sites.psu.edu/astrolady/2017/01/06/multimedia-astronomy-communication-poster-page/.
A.1 Additional Good Poster Practices

This section contains additional good poster practices not found on the “meta-poster,” as listed on the “meta-poster” blog post.

Put a (professional) picture of the lead author on the poster. This will help people find the presenter at the conference to talk about the poster if the presenter is not standing at the poster when they visit.

This was the most controversial part of the “meta-poster” based on feedback from the inaugural Emerging Researchers in Exoplanet Science (ERES) Symposium in 2015 and at the 227th AAS meeting in 2016. Nearly everyone asked about whether it was truly necessary to have an author picture on the poster, some due to comfort levels and some due to the desire to have the science separate from the scientist.

Regarding the former issue, if the poster presenter is uncomfortable having their face on the poster, then the picture isn’t necessary and could do more harm than good. If a poster presenter is are uncomfortable about their poster, it will be noticeable in their oral pitch. And as for the latter issue, given that science is performed by scientists after all, it is impossible to separate the two. As discussed more thoroughly in Chapter 6, two scientists looking at the same data may develop different interpretations as each is influenced by their prior experience and knowledge.

On the other hand, if the presenter is comfortable with their picture on the poster, having a picture on there can only help with the networking process.

Make sure that there is a contact email address on the poster somewhere. Like specifying a corresponding author on a journal article, it lets audience members contact the presenter after the presentation with questions, comments, or suggestions. That contact email should, ideally, be of the person presenting the work rather than an advisor or P.I. of the project. Exceptions to that might be a single researcher presenting work from a larger collaboration (e.g. LIGO) that has a dedicated public relations staff to handle most inquiries.

Make sure that everything within one section is aligned along the tops and along the sides. While a minor detail compared to the actual content of the poster, aligning objects within a section make a poster look very clean. For example,
in the top section of the meta-poster, there are two clearly defined “columns” in the section. The left column has the top text box and the table. The text box and table are aligned on the left to form a straight line. The top text box in the right “column” is aligned along the same horizontal line as the text in the left “column.” Small things like this sharpen the visual impact of a poster and are a basic principle of good graphic design.

**Cite anything and everything that came from another source.** Everyone knows to cite text or results that are found in publications. Many people forget to also put citations on figures that are found in publications. Whether or not you are the author of that paper, if the figure is published in a refereed journal it is copyrighted and needs to be cited. Citing published material is an ethical issue in addition to a legal one, as it is the standard system of “payment” for others’ ideas.

In regards to citation formatting, having citations in the format [Author, et al. (year)] all over the poster is distracting and takes up a lot of space. Use of superscripted numbered citations like “cited text[1]” with a numbered reference list at the end will save space and aid in the poster’s readability.

Some people find that having a reference list on the poster to be a waste of space and not completely necessary. It is this author’s opinion that it depends greatly on the type of poster and where it is being presented. If it’s a research poster that presents a lot of content from published sources, it’s good to have a list of where it all comes from, especially if presented at a scientific conference where some of the original authors of that content might be in attendance. In that case, the citation format described above is ideal for conserving space.

If there is mostly original content on the poster, having sources listed elsewhere, like on a website or even on a separate piece of paper tacked next to your poster, is more easily justified. In this case, be sure that the location of your references is easily found (for example, with a large QR code on the poster).

Regardless of citation format, **always** cite all of your sources. A plagiarized poster is most definitely not a good poster!

**Augment the poster with additional content.** The Layar App ([https://www.layar.com/](https://www.layar.com/)) is one of the newest ways to augment a poster with additional content. It is, as the name suggests, a way to virtually layer a poster with additional infor-
mation that can be read by the Layar app on a smartphone or tablet. Layar’s and other companies’ use of “augmented reality” is a great way to show things like the simulation movies that your simulation snapshots come from, alternate plots, links and references, or even just additional content that is in that section. This type of technology is limited by the number of audience members that have access to that technology, but those limitations can be overcome by having an easily followed link to download the app or by having a tablet stationed at the poster for audience members to use (with supervision).

Adhere to the conference poster guidelines. Before taking the poster to a printer (or even before starting to design the poster) be sure to double check the poster guidelines for your conference. Then, make sure to set the page size for the poster designing program to the right size—and it may be different for each poster, or for the same poster content presented at a different conference.

Printing a poster can be expensive, so shop around and be flexible. Many copy stores, shipping stores, and office supply stores have printers large enough for posters, but the types of paper and printing options may differ. Where available, the cheapest is often the classic flat print poster on regular poster paper, but those can be flimsy and may not hold up well to travel or to multiple uses. Glossy photo paper looks high-quality really nice but it typically much more expensive. Fabric printing is gaining popularity: the quality is nice, the price is reasonable, the fabric travels really well (it can be folded in a suitcase instead of using a poster tube), and some donate the fabric afterwards to be recycled into clothing or other fabric goods. A good compromise on price and durability is to print on regular poster paper and then have it laminated for glossiness and durability. Laminating a poster is often cheaper than printing on glossy photo paper, and can be marked on with a dry erase marker for last minute touch-ups or corrections.

A.2 Suggestions to Improve the “Meta-Poster”

Following the presentations at ERES in 2015 and the 227th AAS meeting in 2016, the author compiled the most frequent comments and suggestions and posted them on the accompanying blog post. Listed below are the most frequent comments on how to improve the poster.
• While the poster presents the best practices for a research poster, it is itself an education poster. That means, on average, that there will be more words than should be found on a research poster and likely more qualitative or descriptive graphics in place of quantitative graphics representing data. The exceptions to this rule are education research posters, which should follow the research poster practices outlined here.

• Use higher resolution graphics than the large academic logo at the top of the poster. The PSU logo used there one still shows up blurry when printed full-scale.

• A research poster made with this design should use much fewer words than what is on this representation of the poster. The meta-poster, as it is, is meant to be an education and outreach poster, containing educational concepts. Some of those concepts are very difficult to put in an effective graphic, and so were left as words. A confusing or ineffectual graphic is a waste of space. For a science poster, aim for fewer words and use more graphics instead.

• The organization within the third blue box can be a bit confusing, especially on the right-hand side. There are two separate ideas (using high-quality graphics and choosing appropriate colors and symbols) that do not relate to each other well. A revised “meta-poster” would add a light horizontal division line, or more whitespace, between the two to better delineate them.

• In the table in the top box, the dots in the bullet points are pretty close to the vertical table lines and could be separated more. Again, whitespace is very useful.

A.3 Sources and Useful Tools

Below are listed sources that were used to create the content and design of the meta-poster, as well as links to useful tools to create more effective posters.

• AstroWright’s “Make Award Winning Posters”: Much of the text was contributed by Ming Zhao (with contributions from Jason Wright), and contains examples of award winning posters by Ming and by Sharon Wang as well. Found here: [http://bit.ly/2tnag2Q](http://bit.ly/2tnag2Q)

• Kathryn Tonsey’s “How to create a poster that graphically communicates your message”: This page by the Chair of Biology and the University of Miami is a
good source for how to communicate to different types of audiences and how to layout your poster effectively. Bonus: there are both good and bad examples for each of the themes she talks about. Found here: [http://bit.ly/2sT3l9F](http://bit.ly/2sT3l9F)

- AstroBetter’s on Presentation Skills: A compilation of a number of other sources for good presentation skills for both oral presentations and poster design and presentation. Found here: [http://bit.ly/2u0cDzo](http://bit.ly/2u0cDzo)

- [exoplanets.org](http://exoplanets.org) can create beautiful and functional plots using the most up-to-date exoplanet catalogs. If you want to make plots that use current exoplanet information (like the ones on the poster!) but don’t want to have to download and compile all of the data yourself, this is the place to go.

- Check your figures and your poster for colorblind-friendliness at [http://www.vischeck.com/](http://www.vischeck.com/)

- Credit for the headshot on the poster goes to 2015 Meadow Lane Photography.
Best Practices for Effective Poster Design

Kimberly M. S. Cartier, Ming Zhao, Thomas G. Beatty, Robert C. Morehead, Daniel Jontof-Hutter

Department of Astronomy and Astrophysics, Center for Exoplanets and Habitable Worlds
The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802

Your poster is the visual aid for your oral pitch

You will encounter three types of audiences for your posters, so ensure that your poster has something for each.

<table>
<thead>
<tr>
<th>Experts on your topic are not your main audience</th>
<th>Workers in your field are your target audience</th>
<th>Workers outside your field are your bonus audience</th>
</tr>
</thead>
<tbody>
<tr>
<td>These people will read your poster regardless.</td>
<td>They will be drawn to a clear presentation.</td>
<td>They will be drawn to a clear message.</td>
</tr>
<tr>
<td>Include only the most important specifics, details, or numbers.</td>
<td>Include the context of your work, and not too much background.</td>
<td>Clearly state the motivating problem and the solution.</td>
</tr>
</tbody>
</table>

Use short, effective sentences to communicate your message, and avoid large blocks of text.

Keep the number of written words low. Instead, communicate through graphics.

Graphics should help tell the story and be understandable on their own

Highlight important features of your graphics and explain what the audience should take away from it.

Show, don’t tell! Use graphics that are key to the story. All style features of your graphic should have explanations.

Use high quality graphics for posters. PDF and EPS usually turn out well.

Make the flow of the poster simple, intuitive, and easy to follow

A scientific poster usually consists of the following parts:
- A short title that clearly describe the main point/topic of the poster
- List of authors, affiliations, and contact information
- Introduction (What is it about? Why is it important?)
- Observations/Methodology/Data Analysis (How do you do it?)
- Results (What do you find?)
- Conclusion/Summary/Future prospects
- References
- Acknowledgements

Clearly define each portion of your poster using a flowchart or section boxes.

Most audiences read left —> right and top —> bottom. Use numbers to clearly define sections if you deviate from this organizational method.

Use a short sentence as a section title where possible. This will highlight the takeaway points of that section!

The colors and styles used should aid the content

Large text should be readable from about one meter away.

<table>
<thead>
<tr>
<th>Font Sizes Used in this Poster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poster Title 90pt</td>
</tr>
<tr>
<td>Author list 56 pt</td>
</tr>
<tr>
<td>Affiliations 50 pt</td>
</tr>
<tr>
<td>Section Titles 56 pt</td>
</tr>
<tr>
<td>Main Text 36 pt</td>
</tr>
<tr>
<td>Secondary Text 32 pt</td>
</tr>
<tr>
<td>Key Points 40 pt</td>
</tr>
</tbody>
</table>

Colored text can help organize into separate categories, highlight key ideas, or group numbers of the same type. Choose only a few colors to avoid a busy-looking poster.

Be consistent with how you color code within your text and within your graphics, as well as between your text and graphics.

Use a simple background so that the text and figures are easy to read.

Use a high contrast of color between text and the background.

Use bold and italic text styles to add emphasis to key points. Use sans serif type fonts for easy reading.

Left align or justify your text for a clean, professional look.

Stylistic choices should always aid content comprehension, never detract from it!

Useful Links

Find more useful information and sources on good poster design by following this QR code or the link below!
sites.psu.edu/astrolady/2015/05/20/poster-design/

Acknowledgements

We would like to thank everyone who directly or indirectly contributed ideas and content to this poster. We thank all the people who present their posters at conferences for providing a multitude of examples of poster design, both good and bad, to learn from. We apologize for this one block of text on the poster, thereby breaking the rules and example presented here.
Your science is a story and you are the storyteller. Tell it well.

Who is your audience?
The first choice you make is your intended audience, which will inform the prior knowledge you can access, the key topical points to emphasize, the hook to keep your audience engaged, and how to utilize your chosen medium.

A well-told story can appeal to more than one audience type.

What are the key points of your story?
Ask yourself, “What essential ideas do the audience need to remember to understand my message?” Pick as many key topical points as needed to frame and motivate the story—and no more!

EXAMPLE

STORY TOPIC
Relevance of the James Webb Space Telescope while Hubble Space Telescope is still functional

KEY TOPICAL POINTS
JWST and HST observe different wavelength ranges and therefore do different science.
JWST is more powerful and versatile than HST, as cutting-edge now as HST was in 1990.

The key topical points serve as an outline of your story. Explain, support, and connect points using details non-critical to the message.

What medium are you using to communicate?
Write in a conventional register, instead of abstract; identifiable characters that actively do things. Map your paper structure onto a story structure with an opening, middle, and end. [1, 5]

Academic Research Paper

Academic Research Posters
Explore the “Best Practices for Effective Poster Design” found here: and at www.KimberlyCartier.org

Slide Presentation
The Assertion-Evidence slide design maximizes audience comprehension and retention of material. Minimize text, fill the slide with a large graphic, and verbally tell the story. [7]

Science News Sources
Due to the widely variable audience type, carefully consider prior knowledge and engagement before you start storytelling. Focus on the Emotional and Stories aspects.

Write in a conventional register, instead of abstract; identifiable characters that actively do things. Map your paper structure onto a story structure with an opening, middle, and end. [1, 5]

Social Media
Thought controversial, Tyson’s “most retweeted” post fulfills all SUCCES criteria
This average tweet of Tyson’s lacks the Unexpected, Emotional, and Stories aspects.

Ideas remain interesting and relevant when they are: Simple—the core essence in a clear, compact way Unexpected—novel questions or interpretations Concrete—specific, definite, focused Credible—establishing a chain from past to future works Emotional—curiosity, excitement, wonder Stories—characters, plot development, resolution

Simple, Concrete, and Credible are “must-haves” to be merely comprehensible. Fulfilling the remaining SUCCES aspects give your stories staying power.

References
[6] “It was the best of sentences, it was the worst of sentences” Jane Casagrande, 2016

Acknowledgements
The contents of this poster comprise part of Kimberly M. S. Cartier’s doctoral dissertation, which will be published in full in May 2017.
Appendix B
Other contributions to exoplanetary studies

This appendix contains descriptions and citations to other research to which KMSC has contributed work. Each section contains a short description of the reference as a whole and KMSC’s contribution to that work.

B.1 New M, L, and T Dwarf Companions to Nearby Stars from the Wide-field Infrared Survey Explorer, 

Luhman et al. (2012)

Luhman et al. (2012) presents 11 late-type candidate companions to nearby stars discovered through a proper-motion search between the Wide-field Infrared Survey Explorer (WISE) and the Two Micron All Sky Survey (2MASS). Of the 11 candidates, 8 are likely to be companions based on their common proper motion with their respective primary stars, and 3 candidates are rejected as companions. All companion spectral types are later than M2V, and two are as late as T8. Luhman et al. (2012) highlight two objects of particular interest: 1) ULAS J095047.28+011734.3, a previously reported T8 that this study identified as a companion to a nearby star; and 2) 2MASS J17430860+8526594, a companion L5 that this study identifies as a new member of a group of L dwarfs with abnormally blue near-IR colors, and one that cannot be explained by significantly subsolar metallicities.
KMSC performed data analysis that contributed to this work. The data analysis included comparing astrometry from 2MASS and WISE to identify common proper motion companions to nearby stars, identifying candidate companions in WISE with no 2MASS counterpart, and flagging any candidate companions for further vetting. KMSC was responsible for the detection of one of the 11 candidate companions, 2MASS 03184214+0828002, a candidate late-M/early-L tertiary companion to the binary LSPM J0318+0827S/N system.

B.2 Data from Chapter 2 Published Elsewhere

Lissauer et al. (2014) and Furlan et al. (2017) both include photometry and binary-star analysis from Gilliland et al. (2015) and Cartier et al. (2015).

Lissauer et al. (2014) (“Validation of Kepler’s Multiple Planet Candidates. II. Refined Statistical Framework and Descriptions of Systems of Special Interest”) presents a procedure to validate en masse Kepler planet candidates in multiple planet systems. Their statistical framework demonstrates that the majority of candidate planets in multi-planet systems are bona fide exoplanets and not false positives. This paper, along with Rowe et al. (2014), validated hundreds of candidate Kepler planets at once. KMSC performed image reduction and photometric analysis for one of the multi-planet systems highlighted in Lissauer et al. (2014), Kepler-296, a low-mass binary star system with 5 transiting planets.

Furlan et al. (2017) (“The Kepler Follow-up Observation Program. I. A Catalog of Companions to Kepler Stars from High-Resolution Imaging”) catalogs results from high-resolution, optical to near-IR imaging of host stars of Kepler Objects of Interest identified in the original Kepler field. They combine measurements of companions to KOI host stars from different bands to create a comprehensive catalog of projected separations, position angles, and magnitude differences for all detected companion stars. This catalog includes 2297 companions around 1903 primary stars. This work includes photometry and companion-star analysis first published in Cartier et al. (2015) and the linear relation between magnitudes in Kepler’s KP and HST’s F555W and F775W bandpasses to correct transit light curves for diluting flux from the companion stars. KMSC contributed editorial comments to this work, but did not contribute new analysis or results.
B.3 Multiwavelength Observations of the Candidate Disintegrating Sub-Mercury KIC 12557548b, 

Croll et al. (2014)

Croll et al. (2014) presents multiwavelength photometry, high angular resolution imaging, and radial velocities of KIC 12557548b (KIC1255b), the unique and confounding disintegrating low-mass planet candidate (see Fig. 5.1 for phase-folded light curve). High-resolution imaging rules out background and foreground candidates wider than 0″2 bright enough to cause the transits associated with KIC1255b. Radial velocity measurements rule out low-mass stellar companions down to $0.2 \, M_\odot$ on orbits less than 10yr. Simultaneous HST/WFC3 and Kepler transits indicate no difference in effective planetary radius as a function of wavelength. They conclude that if the oddly shaped and variable-depth transits are due to scattering from single-size particles streaming from the planet in a comet-like tail, then the particles must be $\sim 0.5 \mu m$ in radius or larger, which would favor a sub-Mercury planet mass.

KMSC performed image reduction and photometric extraction on the HST/WFC3 transits used in Croll et al. (2014). The observations, taken in F125W, F140W, F160W, F555W, and F775W bandpasses, were obtained in an observing program identical to GO-12893 (for the images in Chapter 2), and KMSC reduced them using the methods described in Gilliland et al. (2015) and Cartier et al. (2015).
Appendix C
Published Works

This section contains the full text of popular astronomy and science stories that KMSC has written during the years of my graduate education. Each of the pieces contained herein were published online in professional publications and were been approved by an editorial staff before publication. Each of these pieces was written with a Type III or Type II audience, such as the general or mildly-interested public. The longer features for Sen and for Nautilus were targeted at a Type II audience with intermediate knowledge to more closely match the desired audiences of those publications.

The section opening for each piece contains authorship and editorship credit, copyright information, name of original publisher, date of original publication, link to original publication, and publication type. Where appropriate, a dateline and/or byline has been included. Any images and links from original publications have been replicated, though videos from original online publications have been replaced by screenshots from those videos due to formatting limitations and have been noted in the image caption.
C.1 Microlensing exoplanet could be missing link to planet moon formation

Author(s): Kimberly M. S. Cartier
Editor(s): Charles Black, Sen
Copyright: Space Exploration Network (Sen), Inc. Published here with permission.
Original Publisher and Link: Sen
Original Publication Date: 2015-07-17
Subject: Astronomy, Exoplanets
Type: Blog/Feature, General Audience

Sen—One of the overarching goals of extrasolar planet detection is to find out if other planetary systems look like our own Solar System, complete with small rocky planets, large gas giant planets, and hundreds of small moons. Since the discovery of the first exoplanet in the early '90s scientists have detected and confirmed nearly 2,000 exoplanets of all sizes and dozens of protoplanetary systems that are still in the process of forming planets themselves. From these discoveries we have refined our theories of planet formation and determined that planets form in stellar accretion disks from leftover star-forming material. Likewise, we think that moons must form in planetary accretion disks from leftover planet-forming material. While we have ample evidence of planet formation and have even caught it in the act, as yet we have no firm detections of moon formation.

Last week, Andrzej Udalski and collaborators announced their discovery of OGLE-2013-BLG-0723LA,B,Bb, a planetary system that may shed light on the issue of exomoon formation. This system contains a Venus-massed planet in orbit around a brown dwarf which is also in orbit around a low-mass star. The Optical Gravitational Lensing Experiment (OGLE) team first detected this system in May, 2013 at Las Campanas Observatory in Chile via the gravitational microlensing method. It was monitored for nearly a year through collaborative efforts by multiple observatories around the world. This system can be looked at as either a small binary star/planet system or a scaled-up version of a star/planet/moon system. After a great deal of analysis the OGLE team finally concluded that the system must have formed in a similar way to how a star/planet/moon system must form and could
serve as a “missing link” between what we know about planet formation and what we hope to learn about moon formation.

Microlensing is the unsung hero of exoplanet detection because microlensing events are impossible to predict and impossible to replicate, but can detect the types of planets that no other method is yet able to find. Microlensing is an indirect planet detection method since we are not measuring the planet itself, but rather the planet’s effect on another object. The transit method, the radial velocity method, and the transit timing variation method are also indirect detection methods.

A microlensing detection works like this: while you are closely observing a star (the “source”) it appears to brighten considerably over a short period of time before going back to normal—typically over a few weeks or months. The brightening occurs because a second star (the “lens”) physically crosses between your telescope and the source and magnifies the source light through general relativity. Instead of blocking the source light, the gravity of the lens star splits the light from the source and curves the light paths around the lens (see Figure C.1). This creates an Einstein ring composed of two separately magnified images of the same source star. The size of the Einstein ring—measured by how the split images move as the lens crosses the source—tells us the mass of the lens.

Because the microlensing event depends on one star moving across the sky relative to another, microlensing measurements can only be taken at that one time when the two stars align and cannot be repeated. We are unable to predict when most microlensing events will occur simply because we lack good measurements of the three-dimensional motion of most stars and so we can’t predict when one star will cross in front of another.

A microlensing event with a single lens star is a relatively simple event compared to microlensing with a two-object lens, like a binary star system or a star/planet system. If the lens system is aligned so that both objects can magnify the source, there are two periods of brightening/dimming which mark first one then the other object passing in front of the source. This makes a distinctive two-spiked magnification curve. The second object can only lens the source if one of the split and magnified images passes near it, a rare configuration. Three-object lensing systems in the right alignment are even more rare, and things get even more complicated from there.

If a star/planet system lenses a background source, we can get a very accurate measurement of the lensing star and lensing planet’s masses, distance, and physical
Figure C.1: The magnification of a source (open red circle) by a lens star (yellow star) that hosts a planet (purple dot). In this simulation the lens is kept stationary while the source moves relative to the lens (the opposite of what is physically happening). The green circle represents the size of the Einstein ring and the blue ovals represent the split source images as they move across their paths (shaded regions). If the planet lies in one of the shaded regions is will lens the source. The lens star causes the broad magnification and the planet causes the sharp spike. Simulation credit: B. Scott Gaudi, Ohio State University. Note—This figure was originally published as a .gif file, which can be found at the original publication link.

separation from each other. Even low-mass objects like planets can lens a source significantly, and so we can probe down into the very low-mass planet regime with this method and detect planets much smaller than current radial velocity or transit capabilities allow. Additionally, microlensing is the only method capable of detecting free-floating planets that no longer have a host star. While rare and hard to predict, when microlensing planets are detected they often provide insight into previously unexplored regimes of the exoplanet population.

Such is the case with the system OGLE-2013-BLG-0723LA,B,Bb. The primary component, “A”, is a low-mass star roughly one tenth the mass of the Sun, making it an M dwarf star that shines mostly in near-infrared wavelengths. The secondary component, “B”, is a brown dwarf—a star-like object that is too small to fuse hydrogen in its core—that is about three per cent the mass of the Sun, pretty large for a brown dwarf. The planetary component, “Bb” is likely a rocky or icy planet about the mass of Venus (about 70 per cent the mass of Earth) in orbit around “B”. The brown dwarf/planet system is, in turn, orbiting around “A”, forming a three-object system
Figure C.2: The magnification curve of OGLE-2013-BLG-0723 over an eight month period starting from May, 2013. The broad magnification across the image is from “A”, the double horned peaks are from “B”, and the two spikes shown in the insets are from “Bb”. The grey and blue points were observed by OGLE and the green points were observed by Wise Observatory as part of microFUN. Image credit: Udalski et al. 2015

around 1,600 lightyears away from Earth. Neither the transit method nor the radial velocity method are able to detect such a small planet so far away, which shows how incredible microlensing planets can be.

The original microlensing event was detected in May, 2013 and was observed by OGLE around once per hour for many months. This primary microlensing signal is from “A”, and appeared to be a regular, single star lensing event. However, during this time they noticed a small additional lensing event that suggested there was a planet in the system. This event was caused by “Bb” lensing the source on one part of its orbit (see Figure C.2).

Once the OGLE team realized this would be a planet detection, they contacted the Microlensing Follow Up Network, microFUN to see if someone could continue the observations and detect the planet again while it was daytime at Las Campanas, and therefore unobservable. microFUN is a global network of telescopes around the world dedicated to measuring rapidly-evolving microlensing events, and together they are capable of following an event like this with nearly 24-hours of continuous coverage. When observers could not see the event in Chile because it was daytime, observers at
the Wise Observatory in Mitzpe Ramon, Israel picked it up and detected the second planetary lens event. Just before the second planetary lens event the OGLE team detected unexpected lensing by brown dwarf “B”, and their models confirmed that “A”, “B”, and “Bb” are almost definitely in the same, coplanar system.

Because of microFUN, this discovery represents a real-time, multi-national collaboration on a single scientific project. While multi-national projects are not uncommon, they are usually the result of months-long planning processes to coordinate between the various institutions. Participants in microFUN sign up to help when needed in a global effort to track these rapidly evolving events. All told, this groundbreaking discovery has contributions from six institutions representing five different countries around the world.

Planet “Bb” is also one of the lowest-mass planets ever detected. Only two confirmed planets have smaller measured masses, one of which was also a microlensing planet discovery. Because of its very low mass, we can be relatively certain that “Bb” is a rocky/icy planet as opposed to a gaseous planet or a water world. We also learned from this that even not-quite-stars as small as “B” can have planets, which gives hope that our efforts to improve our other planet-detecting instruments will bear fruit like “Bb.”

The fact that all three objects in the system lensed the source star tells us that the three objects must all orbit in the same plane, just like the planets and moons in our Solar System do (for the most part). The mass ratios of “A”/“B” and “B”/“Bb” are similar to those of the Sun/Neptune and Neptune/Triton, so it is not a far stretch to claim that “A”/“B”/“Bb” resembles a scaled up star/planet/moon system and could have formed in a similar way. This system could indeed be our first piece of evidence to show how stars, planets, and moons all form together and provide that “missing link” to transition between binary stars with planets to stars with planets with moons.
C.2 Earth’s new potential sibling, Kepler-452b

Sen—“This is just the beginning of a very long journey,” said Professor Didier Queloz of Cambridge University, UK, at a NASA press conference July 23 announcing some remarkable discoveries from the Kepler mission: 521 new Kepler planet candidates, a dozen small exoplanets in the habitable zones of their parent stars, and one confirmed planet that has been called the most Earth-like planet ever discovered. Professor Queloz’s statement was a fitting remark made on the 20 year anniversary of his co-discovery of the first exoplanet around a Sun-like star, 51 Pegasi b.

The teleconference was attended by four big names in the field of exoplanet research: John Grunsfeld, associate administrator for NASA’s Science Mission Directorate in Washington, D.C.; Jon Jenkins, Kepler data analysis lead at NASA’s Ames Research Center in Moffett Field, California; Jeff Coughlin, Kepler research scientist at the SETI Institute in Mountain View, California; and Didier Queloz of Cambridge University.

The announcement included a new release of the Kepler Candidate Catalogue (Catalogue 7) which includes discoveries from all 17 quarters of Kepler data. Catalogue 7 is exciting because in the time since the last catalogue releases there have been tremendous updates to the analysis software that allows for the detection of smaller and longer period planets. Catalogue 7 applies this new software to not only the newly detected Kepler Objects of Interest (KOIs), but to all previously detected KOIs as well. KOIs are objects that produce planet-like transit signals, but have not yet been vetted as planet candidates. Many of the smallest candidates in Catalogue 7 may have been in the Kepler data all along, but were only detectable using the newer software. Catalogue 7 is the first fully automated and uniform assessment of the entire Kepler dataset.
Catalogue 7 adds 521 new planet candidates, bumping the total number of candidates up to 4,696. A good chunk of the new candidates are at long orbital periods, detectable only now that we are using the full Kepler baseline of about four years. Many of the new planet candidates are the Earth(ish)-sized or smaller planets that the new software can detect. Planets that are around 40 per cent larger than Earth or smaller are thought to be mostly made of rock. Planets slightly larger than that are potentially rocky, but could also be gaseous worlds like Neptune.

Among the new planet candidates are 12 new planets that are less than twice the size of Earth and are also in the habitable zone (HZ) of their host stars—the region around a star that allows liquid water to exist on a planet’s surface. 11 of these are still planet candidates whilst one of them is a confirmed planet. This confirmed planet is named [Kepler-452b](#), and it resides right at the inner edge of its HZ. Kepler-452b brings the total number of confirmed exoplanets discovered by Kepler to 1,030.

Kepler-452b is 60 per cent larger than Earth, orbits its star in 385 days, and is 1,400 lightyears away from Earth. Since Kepler-452b was discovered via the transit method no mass measurement was possible. Measuring the mass of the planet with the radial velocity method is also out of the question with the technology we currently
have since the planetary signal it would produce is too small. So, they used a mass-radius relationship derived from other planets to calculate an estimated mass of about five times the mass of Earth, though the mass could be as low as three or as high as seven times Earth’s mass.

The star Kepler-452 is also extremely similar to our own Sun. The current size of the star is ten per cent larger than the Sun and it shines 20 per cent brighter. What is exciting is that the star is six billion years old, just 1.5 billion years older than the Sun. Since stars grow larger and brighter as they age, Kepler-452 could represent what our Sun will look like in 1.5 billion years. Even though the planet orbits ten per cent farther from its star than we are from the Sun it receives ten per cent more stellar energy than the Earth does. This places it at the inner edge of the HZ, near the runaway greenhouse/maximum greenhouse limit.

So, what do all these numbers and comparisons mean for the “Earthiness” of Kepler-452b? Well, there’s first the issue of whether the planet has a rocky surface like Earth or is a small gaseous world like Neptune. The current determination of a planet’s likely composition comes from the same mass-radius relationship used to get the planet’s mass. The mass and the size of a planet determines its bulk density, which is then compared to the densities of common planet building material—rocks, gas, and metal. In general, planets 40 per cent larger than Earth or smaller are likely mostly rocky.

Just above that, where Kepler-452b falls, things get a bit muddled. The planet could be rocky, or it could be gaseous, or it could be a combination of both. Jon Jenkins calculates that there is about a 50 per cent chance that the planet has a rocky surface. If it does, then it is indeed very Earth-like. We won’t have a definitive measurement of the mass—and thus, the composition—until the next generation of telescopes can target this planet.

Then there is the fact that Kepler-452b lies at the inner edge of the HZ. This could mean that any water that was on the planetary surface has since evaporated into the atmosphere. On Venus, this process led to the eventual loss of all water on the planet. Once the water vapour is in the atmosphere, the water molecules are broken down by ultraviolet (UV) radiation into their component hydrogen and oxygen atoms. Hydrogen, being the lightest, can then achieve escape velocity from the planet and be lost to space, leaving the planet completely devoid of water in a relatively short time.
This very process could be accelerated by the more intense UV light from Kepler-452, meaning that the planet has lost its water and is no longer habitable. However, there is the additional fact that Kepler-452b is nearly five times more massive than Earth. That would mean that the escape velocity for the hydrogen atoms is much faster, and much harder to achieve. The planet could have managed to retain some of its original water during its six billion year life. How can we tell which scenario it is? Well...we can’t right now, but the next generation of telescopes, including the James Webb Space Telescope, could find out more information about the planet’s atmosphere.

One of the most common questions asked in the Q&A portion of the teleconference was regarding the possibility of life on Kepler-452b, what it would resemble, and whether we could live there (given massive upgrades in spaceflight). Well, to be clear, there have still been no detections of life anywhere else in the Universe outside of the Earth. But there is certainly the possibility that if the planet has liquid water on the surface then life could have evolved on Kepler-452b.
Given that the planet has already spent six billion years in the HZ (with 500 million years to go), if life did develop it could have thrived if it had the right atmosphere. One criticism of previous “Earth-like” planets is that they are in orbit around stars cooler than the Sun that output light more at infrared wavelengths. Plant life that develops in that type of light would be very different than Earth plant life. On Kepler-452b, however, the starlight is almost exactly the same as the Sun, so any plant life that developed there would be very similar to the plant life on Earth. Life that ate that plant life might be similar to the animal life on Earth. We already have one biological experiment with these conditions that produced life, so why not another?

All this being said, is Kepler-452b the best “Earth 2.0” ever discovered? The discovery team believes that this system is the closest Earth/Sun analog ever found. While smaller planets have been discovered with RV detections, most of them are around stars cooler than the Sun and we lack information about their size. But, we should keep in mind that there are still many unknowns with Kepler-452b that are essential to knowing whether the planet is truly Earth-like and habitable.

In the 20 years since the discovery of 51 Pegasi b we have learned that nearly every star in the galaxy has at least one planet. We have learned that between 15 and 20 percent of Sun-like stars should have an Earth-like planet in the HZ, and we improve that number every year. We have found that the exoplanet population is much more diverse than what we see in our Solar System. The Kepler mission has played a very large part in shaping what we know about the larger population of exoplanets and yesterday’s announcement has brought us closer to finally learning if our little planet has a sibling out there.
C.3 Closest Rocky Exoplanet Confirmed by NASA’s Spitzer Telescope

Sen—Astronomers have announced the confirmation of rocky exoplanet HD 219134b with new infrared observations from NASA’s Spitzer Space Telescope, making it the closest world of this type to date.

HD 219134b was originally discovered by the HARPS-North instrument on the Galilean National Telescope in the Canary Islands using the radial velocity technique. Follow-up infrared observations with Spitzer showed that the planet also transits its star, making it possible to calculate the size of the planet.

The planet orbits a star visible to naked eye a mere 21 light-years away. While it orbits too close to the star to be hospitable, its proximity to the star makes it an ideal target for future studies of its atmosphere, if it has one.

The radial velocity measurement indicates that HD 219134b has a mass four and a half times that of Earth. The Spitzer transit observations show that the radius is only 60 per cent larger than Earth, making its density consistent with a rocky composition.

The radial velocity technique reveals the mass and orbit of a planet by measuring the strength of the gravitational tug it has on its host star. If the planetary system has the right alignment it can also transit—pass between us and the star and block some of the starlight—which will reveal the size of the planet. Together the mass and the size determine the planet’s density.

Leading scientist on this discovery, Ati Motalebi of the Geneva Observatory in Switzerland, says that because HD 219134b is very nearby it is likely to be studied in great detail in the future by the James Webb Space Telescope and large ground-based
observatories. The closest confirmed exoplanet is GJ674b at a 14.8 light-years away but its composition is unknown.

This super-Earth shares its star with three other planets in a closely-packed system. Future studies of HD 219134b will help inform astronomers about more distant super-Earths that cannot be studied in detail. Michael Gillon of the University of Liege in Belgium, who led the Spitzer observations of the planet, states that HD 219134b “...can be considered a kind of Rosetta Stone for the study of super-Earths.”
C.4 Solar Twin Planet Search finds a Jupiter analog

Author(s): Kimberly M. S. Cartier
Editor(s): Charles Black, Sen
Copyright: Space Exploration Network (Sen), Inc. Published here with permission.
Original Publisher and Link: Sen
Original Publication Date: 2015-07-31
Subject: Astronomy, Exoplanet
Type: Blog/Feature, General Audience

Sen—The Solar Twin Planet Search is a multi-national astronomy initiative to detect planets around stars similar to our Sun using the radial velocity (RV) method. They detect planets using the the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph on the European Southern Observatory (ESO) telescope at La Silla Observatory, Chile. They also use the Magellan Clay Telescope at Las Campanas Observatory, Chile to narrow their target list down to only Solar-twin stars—stars with temperatures, surface gravities (masses and radii), and elemental abundances extremely similar to our Sun. The overarching goal of the Solar Twin Planet Search (STPS) is to find a solar system analogous to our own.

STPS began their search for Solar twins with planets in 2009, and after narrowing down their target list to 63 Solar twin stars, they have detected their first planet around a Solar twin star. This planet just so happens to also be a near-twin to our own Jupiter. The planet, [HIP 11519b](#), has a mass that is 99 per cent of Jupiter’s mass and orbits its star at 88 per cent of Jupiter’s orbital period. They note that based on the best fitting RV model, the possibility for terrestrial planets in smaller orbits is not ruled out for this system, which means the HIP 11519 system may be even more similar to the Solar System than we realize.

What makes the star HIP 11519 a Solar twin? STPS defines a Solar twin as having a temperature within 100 Kelvin of the Sun’s temperature, a surface gravity within 25 per cent of the Sun’s gravity, and a distribution of elements within 25 percent of the Sun’s. HIP 11519 is well within those guidelines for a Solar twin: a temperature 10 Kelvin cooler, a surface gravity seven per cent heavier, and 13 per cent fewer heavy elements. This means that HIP 11519 is slightly smaller and about the same age as
the Sun. It is also a closer Solar twin than Kepler-452, which was announced last week to have a super-Earth in the (optimistic) Habitable Zone. The moniker “HIP” means that the star was part of the Hipparcos mission to measure stellar distances. Based on the Hipparcos measurements, HIP 11519 is 2,838 light-years away.

The detection of HIP 11516b was made using the radial velocity method, which is considered by some to be the flagship method of exoplanet detection. The first exoplanet around a Sun-like star, 51 Pegasi b, was detected in 1995 by Michel Mayor and Didier Queloz using the RV method. 51 Peg was quickly followed by a dozen other exoplanets discovered the same way. It was not until the launch of the Kepler space telescope in 2009 that the transit method really took off, and other detection methods (including gravitational microlensing, pulsar and transit timing variations, and direct imaging) have not put out nearly the same number of discoveries.

The RV method (see Fig. C.6) detects an exoplanet by measuring the gravitational pull that a planet induces on its host star. A planet and a star mutually orbit each other around a common center-of-mass point, which means that while the planet is making its large orbit the star is making a much smaller orbit around itself. This is sometimes called the “stellar wobble,” since the star is only moving a very tiny amount back and forth.
The stellar wobble is measured through changes in the stellar spectrum—starlight broken up into the contributions at individual wavelengths. Lines caused by the absorption of light at a particular wavelength will shift towards the red side of the spectrum if the star is moving away from the telescope (redshifting) and will shift towards the blue side if the star is moving towards the telescope (blueshifting). Since we can only measure the motion towards or away from us, not side-to-side or up-and-down, the measured motion is all in the “radial” direction, hence the name. An RV curve shows the repetitive redshifting and blueshifting of the stellar spectrum that indicates something is causing the star to wobble. The frequency, strength, and shape of the RV curve tells us the orbital period, mass, and eccentricity of the object’s orbit around the star. Depending on these orbital characteristics, the object causing the wobble might be a planet.

Finding a Jupiter twin planet around a solar twin star with the RV method is not an easy task, for three main reasons. Firstly, a planet with Jupiter’s orbital period will take over a decade to complete one orbit. That means that in order to fully trace the radial velocity curve we would need to measure the radial velocity of that star for over ten years at a good enough precision to detect a Jupiter-sized signal.
Ideally those measurements would be spaced closely enough to see the RV of the star changing from redshifted to blueshifted. Even more ideal would be to see the full RV curve for more than one cycle, which would mean twenty years or more of RV data.

Secondly, there is the problem of the star itself confusing the RV data over such a long time period. Stars, including the Sun, go through stellar activity cycles which are the result of changing stellar magnetic fields. The Solar activity cycle causes events like Sunspots and large flares. These changes in the star’s appearance can cause an RV signal themselves—if bright material from the star is being transported in the direction of your telescope this can cause a blueshift. The Sun’s activity cycle occurs over an 11 year period—nearly the same as the orbital period of Jupiter. We would expect stars similar to the Sun to exhibit similar cycles, which complicates both measurements and analysis.

Finally, while Jupiter is the largest planet in the Solar System by far, it is still relatively small compared to the Sun, and is pretty far away. That means that the RV amplitude of Jupiter tugging on the Sun will only be about 10 meters per second. This is far from impossible for our current instruments, and we have detected planets that have much smaller RV signals, but again it is a matter of both time and precision. It is challenging to find enough data at this precision going far enough back in time to confidently detect a Jupiter-sized planet at a Jupiter-sized orbit. To date, we know of only three planets (including HIP 11915b) on orbits longer than 10 years with signals at 10 meters per second or smaller. Most planets detected with 10 year orbital periods induce much larger wobbles in their stars.

The STPS team was able to minimize each of these three problems, which allowed them to detect the RV signal from HIP 11519b. While STPS has only been in place since 2009, they were able to supplement their measurements of this star with archival data taken with HARPS going all the way back to 2003. This gave them a total span of 12 years of data, enough to fully detect a planet with the orbital period of Jupiter. Additionally, because the HARPS instrument is capable of measuring an RV signal with a nearly one meter per second precision, a planet with the RV strength of Jupiter can be measured accurately.

Determining the RV contribution from stellar activity was a much harder task. They based the amount of stellar activity on the spectral signature of calcium, which has some of the strongest spectral lines detectable. The shape, width, and depth of the calcium lines are largely dependent on variations in stellar surface temperature
(starspots) and magnetic activity in the outer chromosphere (stellar flares). They measured the variation of the calcium lines simultaneously with their RV data and found no correlation between variations in stellar activity and the RV signal. Therefore it is really unlikely that stellar activity caused the RV signal attributed to the planet, but they cannot rule it out completely.

Why is it important that we find a Jupiter twin planet around a Solar twin star? If we really want to find a solar system analogous to our own, there needs to be a Jupiter-sized planet at a Jupiter-sized orbit. When the Solar System was forming, Jupiter came together first and essentially dictated how much of what material each of the other planets could gobble up. After the planets formed, Jupiter’s mass and position determined how the orbits of the other planets interacted and evolved to their current positions. Without Jupiter exactly where it is, our Solar System would likely look radically different. If we expect to find a twin to the Solar System as a whole, it first needs to have a Solar twin star with a Jupiter twin planet. And now that STPS has shown that Solar System analogs are possible, we may find a solar system with all the matching components: star, gas giant planets, and habitable rocky worlds.
C.5 Ocean Planets in the Habitable Zone: Probably Not Habitable

Author(s): Kimberly M. S. Cartier
Editor(s): Charles Black, Sen.
Copyright: Space Exploration Network (Sen), Inc. Published here with permission.
Original Publisher and Link: Sen
Original Publication Date: 2015-08-07
Subject: Astronomy, Exoplanets
Type: Blog/Feature, General Audience

Sen—With nearly two thousand exoplanets confirmed, we’re learning that some very common types of exoplanets are absent from our own Solar System. Ocean planets, covered in global oceans potentially 100 kilometers deep, are less foreign to our Solar System than hot Jupiters or super-Earths. Jupiter’s moons Europa and Callisto very likely have global oceans beneath their icy surfaces. If Europa or Callisto had migrated in towards the Sun their surfaces could have melted, resulting in something very close to the ocean planets which are still mostly unknown. So far we have confirmed only two planets with measured densities that suggest a large water content—Kepler-22b and GJ 1214b.

While the masses of ocean planets might be similar to Earth, a larger ratio of water to rock would make the planets larger than Earth. They might be completely covered by a global ocean with over 100 times our total ocean volume. Simulations of planet formation suggest that ocean worlds could be relatively common. They would form in the outer parts of a solar system where water and other ices are common and then later migrate inwards where the ice would melt into liquid water.

An ocean planet, since it needs liquid water on the surface, must fall within the “classic” habitable zone (HZ). The exact location and size of the HZ depends mainly on the amount of energy radiated by the star and the long-term composition of a planet’s atmosphere. The atmospheric composition determines how much of the stellar energy is reflected or absorbed by the planet and how much insulation (greenhouse effect) the atmosphere provides for the surface.
Carbon dioxide is one of the most important greenhouse gases we observe in our Solar System, second only to water vapor, so many models of planetary atmospheres tend to focus on carbon dioxide as the main insulator. Despite formally being in the HZ, too much insulation will make a planet surface too hot (like Venus), while too little insulation will make the planet surface too cold (like Mars). Neither of those surfaces is particularly hospitable for life as we know it.

But the “classic” HZ may not apply for ocean planets. There is one important assumption that goes into the HZ models used by astronomers everywhere: That the level of carbon dioxide in the atmosphere of the planet is kept constant through the carbonate-silicate cycle. The carbonate-silicate cycle on Earth works to regulate the amount of atmospheric carbon dioxide through the interaction of our atmosphere, our oceans, and our plate tectonics.

The cycle requires that plate tectonics are active on the exoplanet, that is, that the planetary crust is broken up into pieces that shift around on top of a molten mantle. This is definitely not a guarantee everywhere; of the rocky planets in our Solar System, only Earth has active plate tectonics. The carbonate-silicate cycle also requires that the atmosphere be in contact with the rocky surface and that the rocky surface be in contact with the ocean floor. This is where ocean planets throw a wrench into the standard models.

Ocean planets most likely still have a rocky core and crust, but the pressure at the bottom of the deep ocean would cause a layer of high pressure ice to form. This ice layer would separate the planetary crust from the liquid water, thus breaking the all-important carbonate-silicate cycle. While some people postulate that so-called “ice tectonics” could still facilitate the transport of carbon dioxide between ocean and crust through the ice layer, this phenomenon is relatively unstudied and so cannot be counted on to regulate planetary climate.

However, all is not lost even without the carbonate-silicate cycle. A more sluggish, but still effective, ocean carbon cycle exchanges carbon dioxide directly between the atmosphere and the ocean. This process also operates on Earth and likely would on ocean planets, as well. In this case, the amount of carbon dioxide in the atmosphere is determined by the average surface temperature of the planet and the ocean volume. In an equilibrium state, where the amount of atmospheric carbon dioxide remains steady, carbon dioxide gets dissolved into ocean water at the same rate it is being evaporated into the atmosphere.
The ocean carbon cycle is not ideal, but it is not a lost cause either. Daniel Kitzmann of the University of Bern, Switzerland and his co-authors performed a detailed study of the conditions under which an ocean planet would remain habitable around a Sun-like star for six billion years. Since the atmospheres and conditions on ocean planets are completely unknown, they made a few, not unreasonable assumptions: That there is no transport of carbon dioxide through the high pressure ice layer at the ocean floor, that the total amount of carbon dioxide on the planet remains constant, that the planet has an Earth-like mass, and that the global ocean is the same temperature everywhere. These assumptions let them calculate the most optimistic cases for an ocean world around a Sun-like star.

Kitzmann and co-authors first calculate the amount of carbon dioxide dissolved into the liquid ocean at changing temperatures, also taking into account the change in ocean volume with temperature. It was this first step in the analysis which showed that the ocean carbon cycle would have a positive feedback on the planet, rendering most ocean planets inhospitable in a short time.

They then worked toward finding the conditions that would let the ocean planet remain habitable for six billion years, which is most of the star’s life. Here they also take into account that a star’s energy output increases over its lifetime. They tested a wide range of possible carbon dioxide levels, from values below Earth’s carbon dioxide content to values higher than Venus’s. They found that the long-term habitability of an ocean planet is highly restricted by the total carbon dioxide content of the planet, and that carbon dioxide levels near Venus’s is more preferred than Earth’s. A slight nudge away from the perfect carbon dioxide level leads to inhospitable planets.

Balancing the ocean carbon cycle is much more difficult than the carbonate-silicate cycle because the ocean carbon cycle has a positive feedback on itself. If there is a slight change in one direction, the cycles exacerbates the change and eventually results in a runaway effect. The ocean volume is determined by surface temperature: When the temperature is hotter more of the water is evaporated into the atmosphere, leaving a smaller ocean volume. A hotter temperature also means the water is less efficient at dissolving and storing the carbon dioxide. Both of those effects contribute to the positive feedback.

Let’s say, for example, the temperature is slightly too hot. A hotter temperature leads to a smaller ocean volume, which leads to less carbon dioxide being absorbed into and stored in the ocean. Since the ocean stores less carbon dioxide, there must
Figure C.7: The shaded green region shows the combinations of carbon dioxide content and orbital distance that leads to long-term habitable ocean planets. Blue lines show the orbital distance corresponding to the freezing point of water at a particular carbon dioxide content, and red lines show the same for the boiling point. Limits are shown for past, current, and future amounts of Solar energy, and Venus’s position is indicated for reference. Image credit: Kitzmann et al (2015).

be more carbon dioxide in the atmosphere, which produces a greenhouse effect that raises the surface temperature even more. This perpetuates the positive feedback until the ocean planet is in a runaway greenhouse effect, loses all of its water, and is inhospitable. An ocean planet can just as easily spiral into a runaway snowball effect if the surface temperature falls too low.

Even at the perfect level of carbon dioxide there is only a small range of orbital distances from the star where an ocean planet will retain liquid water on the surface for six billion years. This region is much smaller than the “classic” HZ defined for planets with the benefit of a carbonate-silicate cycle. While Venus levels of carbon dioxide are preferred, they are only effective if the ocean planet orbits at twice the orbital distance of Venus (almost as far as Mars). If Earth had to rely only on the ocean carbon cycle with our present level of atmospheric carbon dioxide we would soon evolve to a runaway greenhouse effect and no longer be habitable. Venus would have lost that race even sooner.

The moral of this story is that “habitable zone” does not automatically translate to “hospitable for life as we know it.” To understand the habitability of planets unlike our own, we need to have a better understanding of how atmospheric chemistry works
without the benefit of the carbonate-silicate cycle. There is much more to the story of what makes a planet habitable than just the surface temperature, and the “classic” HZ may not always apply (hint: Kepler-452b). In the future we might study Europa to learn more about ice tectonics, and future telescopes like the James Webb Space Telescope might teach us more about the atmospheres of ocean planets.
C.6 Two New Planets Found in Hot Jupiter System

Author(s): Kimberly M. S. Cartier
Editor(s): Charles Black, Sen.
Copyright: Space Exploration Network (Sen), Inc. Published here with permission
Original Publisher and Link: Sen.com
Original Publication Date: 2015-08-14
Subject: Astronomy, Exoplanets
Type: Blog/Feature, General Audience

Note: the wording in this piece is slightly misleading in that it might suggest that most hot Jupiters transit their host stars, when in reality only around 10% of hot Jupiters transit.

Sen—Though we now know that super-Earths are the most common exoplanets, early on it was thought that hot Jupiters were most common because they are the easiest planets to find. The first planet discovered around a Sun-like star, 51 Pegasi, is a hot Jupiter, as were the next handful discovered. Because hot Jupiters orbit so close to their stars, they are almost guaranteed to transit deeply. Since the planets are massive, they will also likely induce a large radial velocity signal on their host stars. With both transit and radial velocity measurements possible for most hot Jupiters, we can get both accurate sizes and masses which tell us about the structure and possible atmospheres.

The hot Jupiter planet, WASP-47 b, was initially discovered in 2012 as part of the Wide Angle Search for Planets (WASP). It orbits a star slightly cooler than the Sun around 650 light-years away. The system was targeted again by Juliette Becker of the University of Michigan from November, 2014 to January, 2015 when the Kepler Space Telescope in its new K2 operating mode shifted its field of view towards WASP-47’s area of the sky. Analysis of the K2 light curves showed the transits of the WASP-47 b and two other, previously unknown planets with orbits very close to that of WASP-47 b. The WASP-47 system is the first planetary system to have companion planets close-in to a hot Jupiter.

Hot Jupiters, as the name suggests, are gas giant planets in very tight orbits around their stars, usually with orbital periods less than 10 days. The existence of
hot Jupiters came as a big surprise, since theories of planet formation show that gas giant planets cannot form in the inner parts of a solar system. That close to the star the majority of the gaseous material should either have accreted onto the star itself at the beginning of the system’s life or subsequently be blown outwards by young stellar winds. Only out past the “ice line,” where temperatures are cold enough that some ices can form, is the gas density high enough to form Jupiter size planets.

How exactly hot Jupiters get so close to their stars is still a bit of a mystery. The most widely accepted theory is that a hot Jupiter forms out past the “ice line,” like our own Jupiter, and migrates inwards to its current position. The migration of such a large planet would destabilize the orbits of any smaller planets it crossed, essentially sweeping the inner solar system clean of any other planets. In this scenario, it was expected that hot Jupiters would be “lonely” planets in their solar systems. There have only been a few exceptions to the rule of lonely hot Jupiters, and most of them can be explained without radical adjustment of the accepted theory.

WASP-47 is the only planetary system to date that has two planets in orbits close to a hot Jupiter, with orbital periods of about one day, four days, and nine days. The hot Jupiter actually orbits between the inner super-Earth (WASP-47 c) and the outer Neptune-sized planet (WASP-47 d). This is a unique configuration for a hot Jupiter; to date, hot Jupiters have only been observed as either the innermost or outermost planet of the system, with other planets too far away to interact with it.

WASP-47 and its planets were observed with the Kepler Space Telescope operating in its new K2 mode. With only two working reaction wheels to hold the telescope steady while observing, the telescope now uses Solar radiation pressure as its third point of stability. This allows Kepler to observe targets with nearly the same precision as it did in its original mission. K2 now observes targets along the Solar System ecliptic plane, sweeping a band around the sky in a series of campaigns three months long.

While the transit light curves from K2 can measure the orbital periods and transit depths of the planets very precisely, current fitting techniques can only put loose constraints on other orbital parameters. In such a tightly packed system the orbital eccentricity of the planets, how circular or elliptical the orbits are, has a drastic impact on the overall lifetime of the planetary system. At high eccentricity the planets interact too much, which destabilizes the orbits. Only a small range of orbital eccentricities will allow such a system to remain stable over long periods, so Becker
and co-authors used this fact to put further constraints on the orbital parameters of each planet.

They first assume, as is typical in astronomy, that they are not observing WASP-47 at a particularly special time in its history. So, whatever the true orbital parameters are, they must keep the WASP-47 system stable for a long time. They then perform computer simulations of the planetary system evolving over 10 million years, taking into account the gravitational interactions of the planets with their star and with each other. These simulations are performed 1,000 times, each with a different set of planet masses and orbital eccentricities. A simulated planetary system is “stable” if all three planets remain in the same orbits after 10 million years of simulation time. After that, it is unlikely that the systems will evolve further.

The stability tests indicate that the WASP-47 planets must all have near-circular orbits in order to be stable over a long time. Eccentricities greater than about five percent destabilize the orbits after only 1,000 years. The stability of the low eccentricity systems, however, does not appear to depend on the masses of the planets. So, while the simulations can help further constrain the orbits of the planets, they cannot provide any more constraint on the planet masses.

There is another way to get masses for the WASP-47 planets. Since the three planets orbit so close to each other, they tug on each other gravitationally and slightly alter the exact times each planet transits. The strength of these transit timing variations (TTVs) tells us how much each planet gravitationally interacts with the others, which can reveal the masses of the planets.

TTVs work like this: In a system with a single transiting planet A, each transit we observe would happen at perfectly regular intervals (the orbital period). A second planet in the system, B, can alter the timing of the transits slightly. If B is at a position behind A when A is just about to transit, gravitational pull between A and B decelerates A’s orbit. This makes the transit of A happen a few minutes later than it would have without B. Conversely, B will transit a few minutes earlier than it would have because of the forward acceleration from A. Planets A and B will transit earlier and later in an alternating fashion, and when one slows down the other speeds up. This effect can be seen even if one planet is not transiting, and can reveal other unseen planets in a system.

In the case of WASP-47, the TTVs induced on the hot Jupiter and Neptune-sized planets were strong enough to obtain accurate masses for these planets. The TTVs
of the super-Earth were too small to get anything more than an upper limit on the mass. WASP-47 b, the original hot Jupiter, is both slightly larger and slightly more massive than our Jupiter. As the original discovery stated, WASP-47 b “is an entirely typical hot Jupiter.” Becker and co-authors find that the outer planet, WASP-47 d, is only slightly smaller than Neptune, but is only about half as massive. Therefore, it must be much less dense than Neptune and perhaps has a small, dense core with an extended “puffy” atmosphere. All they can conclude about the super-Earth WASP-47 c is that it is almost twice the size of Earth, and something less than nine times as massive.

WASP-47 is an anomaly among hot Jupiter systems because it could not have formed via the traditional migration method. WASP-47 b must have migrated “quietly,” in a way that either did not disturb the other two planets or brought them along when it migrated. Either way, astronomers now need to go back and find a logical way for this system to exist.

The WASP-47 system would be perfect for follow-up radial velocity measurements of the planetary orbits. Radial velocity measurements would help further constrain the mass of the super-Earth, and also verify the masses of the other two planets. If radial velocity measurements take place in the future, WASP-47 would be the tenth planetary system with radial velocity, transit, and transit timing variation measurements, making
it a Rosetta Stone between three major planet-hunting techniques.
C.7 EPIC-206: A nearby cool star with two Earth-sized planets

Author(s): Kimberly M. S. Cartier
Editor(s): Charles Black, Sen.
Copyright: Space Exploration Network (Sen), Inc. Published here with permission.
Original Publisher and Link: Sen.com
Original Publication Date: 2015-08-21
Subject: Astronomy, Exoplanets
Type: Blog/Feature, General Audience

Sen—Among other amazing discoveries, the Kepler mission has shown us that small planets are extremely common. Of the stars that Kepler and other missions targeted, astronomers have found that 26 per cent of Sun-like stars have an Earth-sized planet that orbits close to the host star. The occurrence rate of small planets on short orbits shoots up for the even smaller and cooler M-dwarf stars, with an average of one to two of these planets per star. Theoretically, finding planets that orbit M-dwarf stars should be easy: Because the stars are dimmer and less massive, transit and radial velocity signals will appear larger, which allows discovery of smaller planets at better precision.

In practice, however, finding planets around M-dwarfs is rather challenging, for the simple fact that M-dwarfs are generally very faint. While Kepler surveyed thousands of M-dwarfs, the mission only found about 160 planet candidates around those stars despite the fact that they should all have small planets. Stars in the Kepler field are, on average, over 1,000 light-years away so the stars appear very faint and many potential transit signatures would have been too small to be detected by Kepler. That also means that the few planets found around M-dwarf Kepler stars are very hard to follow up with measurements from other telescopes. The obvious solution—targeting closer M-dwarfs so that they are brighter—has its challenges as well, as nearby M-dwarfs are spread very thin across the sky.

That is precisely what makes EPIC-20601691 (EPIC-206) such an exciting discovery. EPIC-206 is an M-dwarf star only 212 light-years away that hosts two transiting Earth-sized planet candidates. [This discovery] is part of a larger campaign proposed by
lead author on the discovery, Dr Erik Petigura of Caltech, to measure the occurrence rate of small planets using the Kepler telescope in its K2 format. The system is named after ESA’s European Photon Imaging Camera (EPIC) onboard the XMM-Newton satellite that first imaged it, and the star just happened to fall into the observing field of K2’s third campaign which lasted from Nov. 14, 2014 until Feb. 3, 2015.

The observations of EPIC-206 fulfill all of the necessary requirements to accurately measure small planets: Around a cool star, nearby, observed with the best planet-finding telescope ever made, and capable of being followed up by either ground- or space-based telescopes. EPIC-206 has two planets, both in orbits too close their star to be habitable. EPIC-206 b, only 60 per cent larger than Earth, orbits in 9.3 days, and EPIC-206 c, 90 per cent larger than Earth, orbits in 15.5 days.

Detecting these planet candidates with Kepler’s K2 allowed for precise measurements of the properties of the planets in relation to the star. Since most Kepler stars are too far away to accurately measure the stellar properties, the planetary properties are dependent on the best guess for some of the star values. But as EPIC-206 is so nearby, Petigura and his collaborators were able to follow up on this system with additional measurements from three other instruments as well as going back into data archives to get even more information. This allows them to get very accurate values for the star EPIC-206. While EPIC-206 b and c are still only planet candidates, they are some of the most well-measured planet candidates on record.
The first set of additional measurements were taken using the SpeX spectrograph on the 3.0 meter NASA Infrared Telescope Facility (IRTF). This instrument allowed them to measure the spectrum of EPIC-206 in the near-infrared. M-dwarfs emit light primarily in the infrared, so they could observe the most interesting and telling features of the star’s spectrum to determine its exact properties. Next, they obtained additional stellar spectra using the HIRES spectrograph at the Keck Observatory. HIRES observes the entire visible part of the electromagnetic spectrum, from just past violet to just past red, and so was able to obtain information on a different part of EPIC-206’s spectrum.

The SpeX and HIRES spectra were combined and then compared to stellar spectra from “standard” stars; that is, stars whose spectra have already been well measured and matched to a set of stellar parameters like spectral type, mass, radius, and temperature. The best fitting “standard” spectra shows that EPIC-206 is an M0 star with a radius 60 per cent of the Sun, a mass 64 per cent of the Sun, and a temperature over 2,500 Kelvin cooler. Comparing the intrinsic brightness of EPIC-206 to the observed brightness revealed that the planetary system is only 212 light-years from us.

A common problem when detecting planets via the transit method are other light sources near a star mimicking a transit signal or blending in with the target star. The first scenario is often caused by a background eclipsing binary star system, where a binary star system behind the target (often very far behind) has the stars eclipsing each other, causing periodic dimming and brightening when the cooler star blocks light from the hotter star in the background system. If the eclipsing binary system appears close to the target star the light from the two systems can blend together, making it appear as if the target system has a planet. Kepler in its primary mission detected 2,165 eclipsing binary star systems. It takes a lot of follow-up observations to rule out these false-positives and makes the process of confirming a planet much harder.

Petigura and collaborators rule out the possibility of a false positive mimicking the transits of EPIC-206 b and c with a combination of new observations taken in the infrared with the NIRC2 camera at Keck Observatory and archival images from the Digitized Sky Survey taken in 1954 and 1991. In both the new and old images they searched for any nearby stars and determined that there were no nearby stars that could have produced a fake transit signal like the transits seen of EPIC-206 b
Figure C.10: Two common types of astrophysical phenomena that can masquerade as a planetary transit are grazing eclipsing binaries (left), where a pair of stars orbit each other, and background eclipsing binaries (right), where a distant binary star system is aligned very close to the star of interest. These require significant amount of ground-based observations to rule-out using radial velocity techniques. Image credit: NASA/Kepler

and c. From this they are able to conclude that the planets are real.

While EPIC-206 b and c are much too close to their host star to be habitable, this system is notable for other reasons. EPIC-206 emits a relatively low amount of light in the ultraviolet, so even though the planets are close to the star they do not receive all that much stellar irradiation. In fact, EPIC-206 is the brightest star known to host a planet smaller than twice the Earth’s size that orbits in less than 10 days and receives less than 20 times the stellar irradiation of Earth. Usually small planets with orbital periods less than 10 days are at risk for the intense starlight blasting away surface material, so EPIC-206 b is a rare case where mass-loss is not a factor, and so should be studied further.

The exact orbital periods of EPIC-206 b and c are also interesting and may contain clues to the planetary formation and orbital evolution. The inner and outer planets orbit near a 5:3 resonance, that is, the inner planet orbits five times for every three times the outer planet orbits. When two planets are in resonance they are capable of strong gravitational interactions that can lead to changes in the planetary orbits. We see the effects of orbital resonance in our Solar System in the main asteroid belt: a few orbital locations in the asteroid belt are in resonance with Jupiter and if an
asteroid is nudged into resonance the gravitational interactions quickly destabilize the orbit and fling the asteroid away. This is how we get a lot of our near-Earth asteroids.

In the case of planets, and EPIC-206 b and c in particular, the near-resonance of the orbits means that the planets could interact very strongly with each other despite their small sizes and low masses. This could lead to transit timing variations that are observable from the ground and allow us to calculate the actual masses of the planets. We could also obtain mass measurements from ground-based radial velocity instruments, and these planets are perfect targets for the James Webb Space Telescope to take spectra of the planets’ atmospheres if they exist.

As you can probably tell, a lot of work goes on in the process of detecting and following up on planet candidates. Most of this happens after the initial discovery rather than in tandem with it. Now that Petigura and collaborators have gotten most of the additional observations out of the way, it should only be a short time until EPIC-206 b and c are confirmed planets and join the growing ranks of planets discovered by K2.
C.8 Jupiter-like planets are cut from the same cloth

Sen—Jupiter-sized planets are the easiest type of planets to detect with every one of our current detection methods. Their high mass leads to easier radial velocity and microlensing observations, and their large size and young warmer temperatures lead to easier transiting and direct imaging detections. That is why the first radial velocity planet (51 Peg), the first transiting planet (OGLE-TR-056), the first microlensing planet (OGLE 2003-BLG-235L), and the first directly imaged planet (GQ Lupi b) were all Jupiter-like or larger.

But each detection method has its own pros and cons, and each one preferentially detects planets with certain characteristics. This begs the question of whether all the Jupiter-like planet detections from the different methods are really consistent with each other. This is similar to looking at a dalmatian and a miniature poodle and not knowing whether they both come from the same species. They might look similar, but are they really members of the same larger population?

Two astronomers at The Ohio State University, Christian Clanton and B. Scott Gaudi, have discovered that, yes, all Jupiter-like planets in Jupiter-like orbits do indeed represent the same population of planets. They combined results from five exoplanet surveys that use varying detection methods and were able to show that the number of Jupiter-massed planets at large orbital distances was consistent with a single population of Jupiter-like planets.

Limiting the analysis to Jupiter-sized planets at large orbital distances—two astronomical units (AU) or farther—immediately eliminates hot Jupiters from the problem. The astronomers made this cutoff in order to maximize the overlap between the radial velocity, microlensing, and direct imaging surveys. They did not want any
one method to dominate the analysis they were doing to ensure they did not retain any of the observational biases they were trying to overcome.

Unfortunately there were no planets from transit surveys to add to the analysis. When hot Jupiters are excluded, the number of large, transiting, gaseous planets drops to a flat zero. The orbital distance cutoff of two AU immediately reduces the likelihood of any planet transiting altogether. Whether or not a planet transits depends on whether we are looking at the system nearly edge-on (transiting) or from the top-down (not transiting). The range of orientations that lead to transits falls off as orbital distances grow: Small changes in the angle of the planet’s orbit become large changes in the apparent position of the planet and star, precluding a transit. Also, collecting enough data to detect a transiting long-orbit planet takes more time than Kepler had on its original field. The few confirmed transiting planets at large orbital distances generally only have two observed transits, rather than the standard three transits needed to confirm, and only one of those (KOI-351 h) is close to Jupiter-sized.

However, the two AU cutoff has an important scientific implication. Out beyond two AU, any Jupiter-sized planets are likely very close to where they actually formed. It is commonly accepted that hot Jupiters must have undergone a dramatic move from the outer parts of their solar systems to their current positions. Since one end goal is to discover how many planets of a certain mass form at a certain distance, they want to remove planets that are no longer in the places in which they formed. The orbital distance cutoff drastically improves the chances that the planets used are appropriate for this analysis.

Clanton and Gaudi included both detected planets and planetary “non-detections” to constrain their analysis. The “non-detections” place upper limits on the number of certain types of planets; that is, if there were any more planets of a certain mass or orbital distance then these surveys would have found them. The combination of radial velocity and imaging follow-up was represented by the California Planet Survey Targeting Benchmark-objects with Doppler Spectroscopy (CPS/TRENDS), a consortium of US-based universities and researchers. Additional direct imaging results were provided by the Gemini Deep Planet Survey (GDPS) out of the Gemini North Observatory in Hawai‘i and the Planets Around Low-Mass Stars survey (PALMS) out of Caltech. Lastly, microlensing results from the Microlensing Observations in Astrophysics survey (MOA) of Japan and New Zealand and the
Optical Gravitational Lensing Experiment (OGLE) of the University of Warsaw, Poland were included in the study.

They developed the model to report how the total number of planets (detected or not) is dependent on planet mass and orbital distance. They first assume that there is indeed an underlying distribution of planets that can be modeled, and that the distribution has the same shape as most distributions in astronomy: the power law. A power law simply says that smaller objects are much more frequent than larger objects. This relation holds true for stars, for galaxies, and for planets (as we have recently learned). It is a reasonable assumption that a power law can also be applied to this subgroup of planets. After assuming that a single population exists, they test whether their claim is likely true.

To accurately account for planets that exist but that we cannot find, they then had to calculate detection limits and sensitivities for each of the surveys they included. Detection limits refer to the technical specifications of the instrument used, while sensitivity refers to the physical parameters of the planetary system. Detection limits are knowing exactly how small a signal (radial velocity, microlensing, or imaging) can be and still be reliably detected by each instrument. Any signal above detection limits should have been detected if they were there.

Tied into this is the issue of sensitivity, that certain methods are more sensitive to certain masses, orbital distances, or configurations of the system. For example, a planet can only induce an observable radial velocity if it orbits nearly edge-on from our point of view, and that configuration will only induce a detectable signal if the planet is massive enough and close enough to its star.

By combining the detection limits and sensitivities with the list of detected planets and non-detections they are able to discover how many planets are missing from the population simply because we cannot observe them. This is the inferred planet population from radial velocity, microlensing, and direct imaging. They then use the inferred population to inform the specifics of their model population of planets.

The power law model population is dependent on four key parameters: How fast the number of planets changes with planet mass, how fast the number of planets changes with orbital distance, the outer-most orbital distance at which a planet can

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1Correction: this is actually wrong, as a planet with a 45° inclination will still produce a radial velocity signal with \( \sim 70\% \) of its maximum strength. One of the key strengths of the radial velocity method over the transit method is its ability to observe a wider range of orbital inclinations before the planets become undetectable.
be detected, and the combination of mass and orbital distance that produces the most planets (the “pivot point”). Each survey can only constrain some combination of these four parameters, but combining each of the constraints lets Clanton and Gaudi narrow in on the most likely set of values.

A few key things are still missing from this type of analysis. First off is the issue of planet migration. We know from hot Jupiters that Jupiter-like planets can change their orbital distance over time, so there is no guarantee that the orbital distances we are observing now are the same as when the planet formed. The inferred planet population needs work as well, since the exact values depend on how these Jupiter-like planets formed. While the two preferred theories of giant planet formation both

Figure C.11: Approximate regions of sensitivity for the various surveys considered. The solid, black lines bound the region for the OGLE and MOA microlensing surveys. The green region shows the area within which the CPS/TRENDS survey can detect long-term RV trends, while the red regions show the areas within which the GDPS (solid) and the PALMS (dashed) surveys are sensitive to directly imaged planets. The solid, black diamond shows the “pivot point” of the planet distribution model. The pivot point was chosen within the microlensing regions because the majority of their data was from microlensing, leading to a more accurate solution. Image credit: Clanton and Gaudi (2015).
indicate a single population of planets, the planet populations indicated by each model are somewhat different.

The development of this type of model population is a crucial step forward in recognizing that our disparate detection methods and telescopes are all detecting a single same population of Jupiter-like planets. The fact that a model population represents the observed planets so well tells astronomers that all of the various exoplanet surveys are looking at different sections of the same puzzle rather than different puzzles altogether.

Future versions of this analysis would hopefully include the most recently detected planets from the Gemini Planet Imager, OGLE, and MOA. Follow-up observations on some Kepler planet candidates might add transiting large-orbit Jupiters, and the Transiting Exoplanet Survey Satellite (TESS) could also contribute transiting planets to the analysis. If we find more Earth-sized or Neptune-sized planets with multiple methods this type of analysis could be applied to smaller planets, as well.

Knowing the actual distribution of Jupiter-like planets will inform our designs of future telescopes and our interpretation of future results. If we know how how many planets of a certain mass and orbital separation are supposed to be there, we can design our future telescopes to find as many as possible, or to look for planets with specific properties. And afterwards, we can compare the number and types of planets found to the number expected and know if our existing model makes sense, or if we are still missing a large piece of the puzzle.
C.9 Are rocky habitable zone planets dependent on stellar composition?

Author(s): Kimberly M. S. Cartier
Editor(s): Charles Black, Sen.
Copyright: Space Exploration Network (Sen), Inc. Published here with permission.
Original Publisher and Link: Sen.com
Original Publication Date: 2015-09-12
Subject: Astronomy, Exoplanets
Type: Blog/Feature, General Audience

Sen—Three astronomers from the Universidade do Porto, Portugal have begun tackling a very large and multi-dimensional question: How is the frequency of small habitable zone planets dependent on the properties of the host star? Knowing the answer to the question proposed in Vardan Adibekyan and his co-authors’ study would help determine which types of stars are most suitable for habitable worlds, providing a component of the infamous Drake Equation. This study makes a commendable attempt at proposing an answer to this, though as with many early attempts it is limited by the data and techniques available.

Adibekyan and collaborators set out to find how the frequency of small, rocky planets in the habitable zone is affected by the composition of the host star. One of the first exoplanet properties noted was that the frequency of giant planets increases for host stars with more heavy elements. This study is one of the first attempts at figuring out this relation for Earth-like planets.

The composition of a star is typically broken up into three main categories: The fraction of a star composed of hydrogen gas, the fraction composed of helium gas, and the fraction composed of any element heavier than helium (also in gas form). While it might seem strange to lump over one hundred chemical elements into a single category, hydrogen and helium make up over 98 per cent of a star’s total mass. While elements like oxygen, silicon, magnesium, and iron are much heavier atoms than hydrogen or helium, they are just not abundant enough to make a significant contribution on their own. For general purposes, they usually get grouped together along with the remaining elements into the term “metals.”
Astronomers assume that most stars have similar fractions of hydrogen and helium, so stellar composition is typically defined only by the quantity of metals. Hence, “metallicity” is used as a proxy for “composition.” A scale relative to the Sun is used to quantify the metallicity of a star. Stars with fewer heavy elements than the Sun are termed “metal-poor” stars and those with more heavy elements than the Sun are termed “metal-rich.”

A ratio of iron-to-hydrogen abundance is used in almost all astronomical studies as a proxy for the fraction of all metals, as iron is typically observable in a star and is one of the more abundant metals. Where there is little iron to be found, silicon and magnesium are often found to be more abundant instead.

These three elements are crucial in the formation of rocky planets: the Earth is composed of a large iron-nickel core with a silicate rock mantle and crust on top. The amount of these three elements available to make planets and where those elements can be found in a proto-planetary disk, should determine where exactly rocky planets can form and what their internal structures will be. Adibekyan seized on the importance iron, silicon, and magnesium to support the hypothesis that habitable zone rocky planet formation would depend on the composition of the host star.

Under this assumption, the authors compiled data on all low-mass exoplanets around stars larger than half the Sun’s mass that were detected via radial velocity measurements. They further culled this sample by removing any small planet that had a companion planet larger than 10 times Earth’s mass, since the larger planet would affect where the small planet naturally tended to form. This gave them 25 small planets in 12 star systems from radial velocity measurements.

The radial velocity sample was supplemented by transiting planets smaller than twice the size of Earth around stars meeting the same criteria as the radial velocity targets. This list was then filtered to remove non-confirmed planets and highly-irradiated planets that may have lost mass. This left them with 45 transiting planets in 20 star systems, for a total combined sample of 60 planets in 32 star systems.

They split their sample of stars into metal-rich and metal-poor categories, split at 80 per cent of the Sun’s metallicity. Though the reason for this choice of delineation is not made clear in the report, it is likely because the average metallicity of stars in the Milky Way is slightly lower than the Sun. Their choice reflects the average Galactic metallicity rather than the Solar value.

They examined how the orbital distances of their final sample are related to the
planetary mass and/or the planetary radius, depending on which measurements are available. Of the 60 planets examined only 15 of them fall within the habitable zone. They chose to use a single orbital distance to determine the interior edge of the habitable zone. While not ideal, it is an understandable choice since some of their target stars lack measured temperatures. They chose to use the most optimistic location for the inner edge of the habitable zone; likely, some of those 15 planets are not really habitable.

They find that of their 15 rocky habitable zone planets, 10 of them orbit metal-poor stars, while only five of them orbit metal-rich ones. Of those five, they note that three of them orbit the three coolest stars in their sample. Those three stars have the least accurately measured metallicities and might, in fact, be metal-poor. From this the authors conclude that rocky habitable zone planets around Sun-like stars are more likely to form around metal-poor stars. They then make a tenuous speculation that, since older stars are generally metal-poor, rocky habitable zone planets may have formed more frequently when the galaxy was younger.

With only 15 habitable zone rocky planets to work with, the authors caution that
their results may be dominated by the detection biases of the radial velocity and transit surveys. Since our telescopes and detection programs have only begun being sensitive enough to find a small planet in the habitable zone, it is possible the ones in this sample are not truly representative of the whole planet population, but are just the easiest ones to find. Future exoplanet missions like NASA’s Transiting Exoplanet Survey Satellite (TESS), and European Space Agency’s CHaracterising ExOPlanet Satellite (CHEOPS) and PLAnetary Transits and Oscillations of stars (PLATO-2.0) missions will bring in even more data than Kepler and help us fill out the ranks of small habitable zone planets.

While the authors do caution that their connection of habitable planet frequency with stellar age is speculation, it is a very large leap to make based on these data. Stellar metallicity, along with age, are two of the most difficult stellar parameters to nail down. Age is difficult because once a star begins burning hydrogen, it stays relatively unchanged for over 90 percent of its life. Sure, the star may become slightly larger and brighter over billions of years as it ages, but it is extremely difficult to tell whether a hydrogen-burning star began life with those characteristics or evolved there over time.

Metallicity is tough to determine for a few reasons. Firstly because the effects of slightly changing the composition of a star can easily be confused with the effects of altering other stellar properties. Without having ultra-precise stellar spectra, the exact ratio of heavy elements to hydrogen can only be broadly guessed at. Indeed, broad guesses are all we have for the majority of the stars in the Kepler Input Catalogue from which the authors draw much of their data. Many of the planet host stars included in this study have large uncertainties on their metallicities which might swing them into either the metal-rich or metal-poor category. Even with precise spectra, metallicity measurements can be obscured by looking at the star through the Earth’s atmosphere, which contributes its own highly-variable spectrum to the mix.

The composition of a star is determined first and foremost by the particular interstellar cloud from which it formed. The overall heavy-metal abundance of the galaxy does change over billions of years as stars process lighter elements into heavier ones and recycle them back into star forming material at the end of their lives. Stars born at the beginning of the galaxy usually have fewer heavy metals than young stars. But since the radial velocity and transit targets span large, diverse regions of the galaxy, the observed range of stellar metallicities could simply be a product of their
environments, and not of age.

Assuming that the frequency of observed habitable zone planets really is a result of stellar age, this begs the question of whether the planets currently observed in the habitable zone really formed there or whether they were brought into it as their star evolved. As the hydrogen-burning star evolves it pushes the habitable zone farther out. So, a planet that is exterior to the habitable zone at formation might end up in the habitable zone over time. Without having an accurate sense of the host stars’ ages, we cannot know whether the planets around metal-poor stars truly formed there, as per the authors’ conclusion.

Overall this study introduces the interesting idea that the formation of a small habitable zone planets may be controlled largely by the host-star’s composition. However, our exoplanet surveys have only just begun to detect enough habitable zone planets to attempt this type of analysis, and our understanding of stellar metallicity and planet formation is still too limited to make any firm conclusions. For sure, this idea should be revisited after future large-scale exoplanet surveys begin raking in results.
C.10 Gemini Imager Finds its First Young Jupiter-like Planet

Author(s): Kimberly M. S. Cartier
Editor(s): Paul Sutherland, Sen.
Copyright: Space Exploration Network (Sen), Inc. Published here with permission.
Original Publisher and Link: Sen.com
Original Publication Date: 2015-08-15
Subject: Astronomy, Exoplanets
Type: News Brief, General Audience

Sen—The Gemini Planet Imager Exoplanet Survey has discovered a young Jovian planet orbiting in the triple star system 51 Eridani. The planet, 51 Eri b, was discovered and observed using the new Gemini Planet Imager on the Gemini South telescope in Cerro Pachon, Chile. Lying in the constellation of Eridanus, the River, it is the first exoplanet discovered by the Gemini Planet Imager Exoplanet Survey.

“51 Eri b is the first [exoplanet] that’s cold enough and close enough to the star that it could have indeed formed right where it is the ‘old-fashioned way’,” says Bruce Macintosh, lead author on the discovery, in a statement. “This planet really could have formed the same way Jupiter did—this whole planetary system could be a lot like ours.”

The Gemini Planet Imager (GPI) directly observes exoplanets in near-infrared wavelengths by first blocking out the starlight using an advanced type of shield called a coronagraph. The coronagraph is designed to block out as much of the starlight as possible from the inner region around the star, leaving light from other nearby sources intact.

Using the coronagraph coupled with adaptive optics to correct for the effects of our atmosphere, the GPI team was able directly to detect light from 51 Eri b. The planet emits infrared light one million times fainter than the host star and is only visible once the light from the host star is obscured by the coronagraph.

GPI, like all direct imaging instruments, is most sensitive to planets that orbit farther away from their stars and those are have hot effective temperatures. At larger planetary orbital distances, the coronagraph is better able to remove the starlight
from the area around the planet. Likewise, hotter planets emit more infrared light and are more easily seen against any residual starlight. Since planets cool rapidly as they age, GPI is most sensitive to young, hot planets at large orbital distances.

51 Eri b is only 20 million years old, and orbits nearly 13 astronomical units (AU) away from the primary star in the system, 51 Eri A (one AU is the approximate distance of the Earth from the Sun). 51 Eri A is seven times brighter and about twice as massive as the Sun, giving exoplanet 51 Eri b an effective temperature between 600 and 750 Kelvin.

The 51 Eri system also contains two distant companion stars—the compact binary M-dwarf system GJ 3305AB orbiting 2000 astronomical units away from 51 Eri A and b. The four component system is approximately 95 light-years from Earth.

GPI also observed the spectrum of 51 Eri b’s atmosphere to measure the composition and try to determine whether or not the exoplanet has clouds. The team found that the planet’s atmosphere is dominated by methane and that the exoplanet might have clouds. Jupiter, also, has a methane-rich, cloudy atmosphere, which means that 51 Eri b could, indeed, very closely resemble our own Jovian planet.

Future observations of 51 Eri b will reveal more about the planet’s orbital characteristics and better determine the planet’s mass. 51 Eri b serves as “a bridge from wider-orbit, hotter and more massive planets to Jupiter-like scales.”
C.11 NASA selects Penn State to lead next-generation planet finder

Author(s): Kimberly M. S. Cartier, Barbara Kennedy
Editor(s): Barbara Kennedy, PIO, Penn State
Copyright: Penn State Eberly College of Science, Office of Media Relations and Public Information
Original Publisher and Link: [Penn State Science News](https://news.psu.edu/zo/g/2016/03/29/nasa-selects-penn-state-to-lead-next-generation-planet-finder)
Original Publication Date: 2016-03-29
Subject: Astronomy, Exoplanets, Instruments
Type: Press Release, General Audience

UNIVERSITY PARK, Pa.—A Penn State-led research group has been selected by NASA’s Astrophysics Division to build a $10-million, cutting-edge instrument to detect planets orbiting stars outside our solar system. The team, led by Suvrath Mahadevan, assistant professor of astronomy and astrophysics at Penn State University, was selected after an intense national competition. When completed in 2019, the instrument will be the centerpiece of a partnership between NASA and the National Science Foundation called the NASA-NSF Exoplanet Observational Research program (NNEXPLOR).

“We are privileged to have been selected to build this new instrument for the exoplanet community,” Mahadevan said. “This is a testament to our multi-institutional and interdisciplinary team of talented graduate students, postdoctoral researchers, and senior scientists.” The instrument is named NEID—derived from the word meaning “to discover/visualize” in the native language of the Tohono O’odham, on whose land Kitt Peak National Observatory is located. NEID also is short for “NN-EXPLORE Exoplanet Investigations with Doppler Spectroscopy.” NEID will detect planets by the tiny gravitational tug they exert on their stars.

“NEID will be more stable than any existing spectrograph, allowing astronomers around the world to make the precise measurements of the motions of nearby, Sun-like stars,” said Jason Wright, associate professor of astronomy and astrophysics at Penn State and a member of the science advisory team. “Our team will use NEID to
discover and measure the orbits of rocky planets at the right distances from their stars to host liquid water on their surfaces.”

“Winning this competition is a tremendous honor and a mark of recognition for our Center for Exoplanets and Habitable Worlds,” said Donald Schneider, Distinguished Professor and Head of the Department of Astronomy and Astrophysics. Many NEID team members are graduate students and postdoctoral researchers. Schneider added, “We are proud that our junior scientists are a significant part of this ground-breaking project.”

NEID Project Manager and Senior Scientist Fred Hearty said, “Building this instrument is a wonderful opportunity for Penn State and our partners. R&D here at Penn State established a foundation to advance the state-of-the-art in planet finding almost thirty years ago. Today’s Habitable-zone Planet Finder project is proving the entire system works as planned.”

NEID will be built over the next three years in laboratories at Innovation Park on the Penn State University Park Campus and at partnering institutions. It will be installed on the 3.5-meter WIYN telescope at Kitt Peak National Observatory (KPNO) in Arizona. NEID will provide new capabilities for the National Optical Astronomical Observatory (NOAO), which operates the Kitt Peak telescopes. When NEID is completed, astronomers worldwide will have access to this state-of-the-art planet finder.

Astronomer and Penn State Research Associate Chad Bender, who will help to oversee the construction of the instrument, noted that “NEID’s capabilities are critical to the success of NASA’s upcoming exoplanet missions. NEID will follow-up on planets discovered by the Transiting Exoplanet Survey Satellite and also will identify exciting targets to be observed by the James Webb Space Telescope and the Wide-Field Infrared Survey Telescope.”

The NEID team is a multi-institutional collaboration, consisting of exoplanet scientists and engineers from Penn State, University of Pennsylvania, NASA Goddard Space Flight Center, University of Colorado, National Institute of Standards and Technology, Macquarie University in Australia, Australian Astronomical Observatory, and Physical Research Laboratory in India.

“NEID is a transformative capability in the search for worlds like our own, Mahadevan said.”

NASA and NSF established the NN-EXPLORE partnership in February 2015 to
take advantage of the full NOAO share of the 3.5-meter WIYN telescope at KPNO, to provide the science community with the tools and access to conduct ground-based observations that advance exoplanet science, and to support the observations of NASA space astrophysics missions. KPNO is operated on behalf of NSF by NOAO. The NEID project will be managed on behalf of NASA’s Astrophysics Division by the Exoplanet Exploration Program Office at the Jet Propulsion Laboratory.

[Kimberly M. S. Cartier /Barbara K. Kennedy]

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ARCHIVE: This information will be archived online at http://science.psu.edu/news-and-events/2016-news/NEID3-2016
C.12 Historic first detection of a gravitational wave detailed at Friedman Lecture on April 28

Author(s): Kimberly M. S. Cartier
Editor(s): Barbara Kennedy, PIO, Penn State
Copyright: Penn State University, Eberly College of Science, Office of Media Relations and Public Information
Original Publisher and Link: Penn State Science News
Original Publication Date: 2016-04-25
Subject: Astronomy, Lecture Announcement
Type: Press Release, General Audience

UNIVERSITY PARK, Pa.—A free presentation titled “The Dawn of Gravitational Wave Astronomy” will take place at 7:30 p.m. on Thursday, April 28, in 102 Thomas Building on the Penn State University Park Campus. Chad Hanna, assistant professor of physics at Penn State, will present the lecture. The event is part of the 2016 Friedman Lecture Series in Astronomy, which is free and open to the public.

Hanna’s presentation will recount Albert Einstein’s first prediction of the existence of gravitational waves, made 100 years ago. He also will discuss what causes gravitational waves, how the Laser Interferometric Gravitational-wave Observatory (LIGO) searches for these faint signals, how the historic first detection of gravitational waves was achieved, and what the future holds for gravitational wave astronomy. Hanna is co-chair of one of LIGO’s largest astrophysics working groups, the Compact Binary Coalescence group, which was instrumental in identifying the source of the historic recent first detection of gravitational waves.

“I was really happy when the announcement of this detection was made,” said Chris Palma, senior lecturer in the Penn State Department of Astronomy and Astrophysics. “Many of our students in our major and colleagues in our department and in the Penn State Department of Physics have worked for years to reach this point. It was great to see all of that work payoff with this amazing detection, and I can’t wait to see what new things we will learn now that we have an entirely new window into the Universe.”
In addition to his central leadership role in the LIGO Scientific Collaboration, Hanna is a member of the Penn State LIGO group, which is part of the Institute for Gravitation and the Cosmos directed by Abhay Ashtekar, Holder of the Eberly Family Chair in Physics. Hanna’s research is focused on detecting gravitational waves emitted by pairs of very massive objects just before they merge—either two neutron stars or two black holes. He was honored in 2015 with the National Science Foundation CAREER award, the foundation’s most prestigious award in support of junior faculty who exemplify the role of teacher-scholar through research, education, and the integration of education and research.

The Friedman Lecture Series in Astronomy is hosted by the Penn State Department of Astronomy and Astrophysics and is funded largely by the Ronald M. and Susan J. Friedman Outreach Fund in Astronomy. Ronald Friedman is a member of the department’s Board of Visitors.

For more information, contact Chris Palma, senior lecturer of astronomy and astrophysics, at 814-865-2255 or cxp137@psu.edu.

[KMSC/BKK]
C.13 Fastest-spinning brown-dwarf star is detected by its bursts of radio waves

UNIVERSITY PARK, Pa.—Astronomers have detected what may be the most-rapidly-rotating, ultra-cool, brown-dwarf star ever seen. The super-fast rotation period was measured by using the 305-meter Arecibo radio telescope—the same telescope that was used to discover the first planets ever found outside our solar system.

“Our new detection of an ultra-cool dwarf emphasizes Arecibo’s amazing sensitivity, which enables measurements of the magnetic fields of very-low-mass stars, brown dwarfs, and potentially planets. Because planetary magnetic fields protect life from the harmful effects of stellar activity, it is clear that future programs of this kind using the Arecibo telescope will be crucial to our understanding of the habitability of planets around other stars,” said Alex Wolszczan, a co-discoverer with Matthew Route of radio emission form this new brown-dwarf star.

The discovery is detailed in a recent issue of The Astrophysical Journal Letters (Volume 821, L21), coauthored by Wolszczan, Evan Pugh University Professor of Astronomy and Astrophysics at Penn State University; and Route, a Senior Scientific Applications Analyst at Purdue University and a Penn State Ph.D. graduate. The repeated radio flares that they found being emitted by the brown dwarf allowed them to measure the extremely fast rotation of this exotic object. Their record-breaking detection demonstrates that even the coolest brown dwarfs, and possibly young giant planets, can be discovered and studied using radio observations.
“Our discovery of the super-fast rotation of J1122+25 poses new challenges for the theoretical models of the rotational evolution of these objects and the internal dynamos that power their magnetic fields,” Route said. J1122+25 is the short version of the scientific name of this new brown dwarf, WISEPC J112254.73+255021.5. “The radio flaring and rapid rotation of J1122+25 can reveal a lot about the origin and evolution of the magnetic fields of brown dwarfs, and how this knowledge can be applied to young giant planets,” Route said.

The data collected so far from this brown dwarf show that it could be rotating every 17, 34, or 51 minutes—an ambiguity that requires the collection of more data to identify which of the three measurements is this star’s rotational period. But, the scientists report, even the longest of these rotation periods would mean this brown dwarf rotates much faster than any measured so far.

The brown dwarf was first discovered by the Wide-field Infrared Survey Explorer (WISE) in 2011. Route and Wolszczan subsequently observed J1122+25 at five epochs spread over an eight-month period as part of an ongoing search for brown dwarfs with sudden outbursts of energy at radio wavelengths—called flaring ratio emission. “J1122+25 is about 55 light years away and is only one of six coolest brown dwarfs for which radio flares have been detected,” Route said.

Brown dwarfs like J1122+25 are sometimes called “failed stars” because they did not accumulate enough material when they formed in order to fuse hydrogen into helium, the process that enables stars to shine. The lack of continuous energy production from fusion makes brown dwarfs much colder and dimmer than most stars and gives them much different chemistry. For some of them, internal structure in connection with rapid rotation can generate strong magnetic fields and the dramatic radio flares that have been detected by the Arecibo telescope.

Many astronomers treat brown dwarfs as the “missing link” between stars and planets. Brown dwarfs share many physical traits with gas-giant planets like Jupiter. Studies of ultra-cool brown dwarfs like J1122+25 can be used to infer the properties of giant planets, which are much harder than stars to study in detail. J1122+25 is about one-sixth the temperature of the Sun, and emits light primarily in infrared wavelengths.

This discovery was supported by the Center for Exoplanets and Habitable Worlds, which is part of Penn State and its Eberly College of Science, and by the Arecibo Observatory, which is operated by SRI International in alliance with Ana C. Mendez-
Universidad Metropolitana and the Universities Space Research Association, under a cooperative agreement with the National Science Foundation (AST-1100968).

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PHOTO
A photo of a brown-dwarf star is online at
http://science.psu.edu/news-and-events/2016-news/Wolszczan6-2016
C.14 An Update From the Astronomers Who Proposed the Alien Megastructures

Where the quest to understand the most mysterious star in the galaxy stands today

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Original Publisher and Link: The Atlantic. Note: hyperlinks within the original posting have been omitted here.
Original Publication Date: 2016-05-12
Subject: Astronomy, Exoplanets, Boyajian’s Star
Type: Blog/Feature, General Audience

As first reported in this magazine, there is a star in the constellation Cygnus that behaves like no other. During the years-long stare of the Kepler space observatory, this otherwise run-of-the mill star—a bit hotter and more massive than the Sun—exhibited an extraordinary series of dimming events, as though briefly and occasionally eclipsed by an irregular series of large, opaque objects, the nature of which can only be guessed.

Discovered by citizen scientists scouring data publicly available through the crowdsourced Planet Hunters effort, these dimming events kicked off a years-long effort by a team led by Tabetha Boyajian at Yale to figure out what was going on with the star. After working with NASA to rule out technical issues that might have caused the oddities, they scrutinized the star itself for evidence that it might be unusually young, as very young stars have disks of warm dust, gas, and rocks orbiting them that can create all sorts of strange behavior.

The star proved to be completely pedestrian: Not only does it appear to be mature and lack any disk of material, it showed no other signs of peculiarity, either. If not for the Kepler data, the star would attract no attention at all.

But attract attention it has. The star with its weird behavior has not only captured the imagination of professional astronomers determined to solve the puzzle, but has also gained notoriety in the eyes of the public. The star found fame—from Saturday Night Live to Late Night with Stephen Colbert—because of a suggestion by...
astronomers (alright, we admit it was us) that radio astronomers partaking in the search for extraterrestrial intelligence (SETI) should point their telescopes that way.

SETI astronomers have long suggested that advanced alien civilizations might construct planet-sized “megastructures” to harvest massive amounts of starlight. Such objects might be detected when they happened to pass between Earth and the star and might resemble similar signatures caused by natural objects.

Meanwhile, astronomers continued to study the star for signs that its strange eclipses could have an easily explainable natural cause. Boyajian postulated that the eclipses might be caused by a family of comets around the star. While it is still the best among many contrived explanations, comets cannot explain each and every event observed by Kepler. The search for a more convincing natural explanation remains ongoing.

In October 2015, shortly after the alien megastructure hypothesis went public, Bradley Schaefer, an astronomer specializing in careful stellar brightness measurements, decided to look for previous episodes of odd behavior by examining a historical astronomical treasure: photographs of the sky stored in the plate stacks at the Harvard Astronomical Plate Collection in Cambridge, Massachusetts.

For about 100 years, small telescopes have imaged the entire sky, bit by bit, on photographic plates. These plates are now carefully archived and stored by curators at the Harvard-Smithsonian Center for Astrophysics. The center has slowly digitized and made the plates available to the public through a program known as Digital Access to a Sky Century @ Harvard (DASCH).

Schaefer constructed a historical record of Boyajian’s star using online DASCH data. While Schaefer found no evidence of obvious prior eclipse events, the DASCH data did seem to show that the star had slowly dimmed by nearly 20 percent over the past 100 years.

Intrigued, but aware of the numerous systematic errors that plague photographic plate astronomy, Schaefer visited the plate stacks in Cambridge and repeated the measurements in person. His conclusion remained unchanged and unprecedented: No other star had shown such dimming before, and no natural explanation seemed forthcoming. This provided the first evidence beyond the Kepler data that something strange was going on with the star.

But other astronomers were skeptical of Schaefer’s claim. Two teams began simultaneous efforts to verify Schaefer’s surprising result with their own analyses of
the DASCH data. One team was a collaboration between German amateur astronomer Michael Hippke and NASA Postdoctoral Fellow Daniel Angerhausen, and the other a team of professional astronomers from Vanderbilt University and Lehigh University lead by doctoral student Michael Lund.

The first rebuttal of Schaefer’s claim came from Hippke’s team who concluded that the long-term dimming of Boyajian’s star was not really there, but only an artifact of the hodge-podge nature of the photographic plates themselves.

However, as Schaefer was quick to point out in an immediate online response, Hippke had failed to account for many of the quirks that make working with photographic plates a “lost art” of astronomy, effectively refuting Hippke’s contradictory claim.

In reply to Schaefer’s precise but caustic counterargument, Hippke’s team and the Vanderbilt/Lehigh collaboration combined their efforts to re-examine the DASCH data on Boyajian’s star with more expertise. They conclude that Boyajian’s star indeed does not exhibit any extraordinary dimming over the past century. This time, their results have been peer-reviewed and recently accepted for publication in the *Astrophysical Journal*.

So where does this all leave us? If Hippke is correct (and his paper is persuasive) then we are back where we were before Schaefer’s claim, and the *Kepler* data remain the only strange thing about this star. But that still brings us no closer to a resolution of the mystery—that will require additional observations.

Efforts at the Allen Telescope Array to detect obviously artificial radio signatures came up empty, showing us that there were no very strong alien signals being sent when they looked. Our team still hopes to be awarded time on the much more powerful Green Bank Telescope to take a closer look.

On the side of natural explanations, if a recent cataclysmic event in the system created a large cloud of dust responsible for the dimming events *Kepler* saw, then it’s possible a heat signature will show up at some point in the next couple of years; another team of astronomers is using NASA’s *Spitzer* infrared space telescope to watch for that possibility.

Boyajian herself is coordinating a worldwide effort of professional telescopes to monitor the star regularly for the next several years, to catch the star in the act. Citizen scientists are still on the case, too: the American Association of Variable Star Observers is tracking brightness measurements of the star made by amateur
astronomers. When the star dims again, we will use telescopes around the world to measure how much the star dims at different wavelengths. Since different substances have characteristic absorption patterns, this will tell us the composition of the intervening material. For instance, if it dims much more at ultraviolet wavelengths than in the infrared, we will know dust is to blame. If we see the characteristic pattern of cometary gases, that will help confirm the cometary hypothesis.

And if we see the same brightness changes at all wavelengths? That would indicate that whatever is blocking the starlight is big and opaque— inconsistent with comets, but consistent with the alien megastructure hypothesis.

The public attention on the slow process of understanding this strange star has cast a light on how science really looks from the trenches. The exchange between Schaefer and Hippke, while dramatic at times, shows how a single study is not the end of the road for scientific conclusions, merely the start of a longer journey of testing, verification, and improvement.

Indeed, in Hippke’s thoughts on this controversy he explains that the choice for a fast-paced and public dialog was intentional, “so that the community, the involved media and the interested public did not have to wait many months” for the next development.

As Boyajian herself reminds us in her TED talk, “extraordinary claims require extraordinary evidence,” and as the dust settles on the Schaefer/Hippke controversy, Boyajian’s star remains the most mysterious star in our galaxy.

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C.15 When did life on Earth begin?

Our estimates for the prevalence of life in the universe depend on how quickly it arose on Earth.

Astrobiology isn’t exactly a data-rich science. We don’t know how many other lifeforms are out there or whether they exist at all, and we don’t even know where or how life on our own planet got started. But there is one question we should be able to get traction on: when life originated on Earth. And that one piece of knowledge would tell us a surprising lot.

It would tell us, to begin, the conditions under which life arose, helping us to predict where else we might find it. Moreover, it would clue us into whether the origin of life is an inherently unlikely event—a lucky roll of the organic chemical dice after hundreds of millions of years of trying—or a quick and all but certain consequence of wet planetary surfaces such as ours. If it took eons for the first microbe to appear in the geochemical muck, life must have been fairly hard to assemble and is likely a rarity in the universe; if it popped up shortly after Earth became habitable, then life would seem an inevitability, and the universe should teem with living things.

The two of us normally direct our attention upward; our own research is the study of exoplanets and the search for extraterrestrial intelligence. But our efforts are guided by what our paleontologist, geologist, and biologist colleagues have found about genesis on Earth. They have sought to box in the date on two sides: the earliest time our planet could have supported life, and the age of the oldest fossils or other organic detritus. Meteorites have been dated to around 4.5 billion years ago, which presumably marks the formation of the solar system and therefore of our
planet. The oldest surviving minerals on Earth itself are zircon crystals from Western Australia dating to 4.4 billion years ago. Coming from the other direction, the most ancient biological structures on Earth are stromatolites, which are layered mounds that cyanobacteria erect in shallow waters. Geologists have dated fossil stromatolites, also from Western Australia, to 3.5 billion years ago, and this year they found others in Greenland that go back 3.7 billion years. Since cyanobacteria are a fairly complex form of life, there must have been a substantial period of evolution that stretched back even further. Isotopic signatures of life have been found in rocks as old as 3.8 billion years.

All these data are hard-won, and none has gone unchallenged. In the past few months, an intense debate has broken out over what has been arguably the single most influential discovery concerning the biological starting line.

In the final Apollo landings of the early 1970s, astronauts filled bags with rocks from lunar impact craters. In these samples, geologists measured the amount of argon, an element that is chemically foreign to the rock; it appears only because potassium was locked into the crystalline structure when the rock solidified and the potassium later decayed radioactively to argon. Because the decay occurs at a known rate, the relative amounts of argon and potassium provide an estimate of a rock’s age.

What the geologists found was surprising. Many of the rocks dated to a narrow range of time, between 4.1 and 3.9 billion years ago. Apparently, an unexpectedly high number of lunar impact craters, including some of the largest, were gouged out nearly all at once. The clear inference was that moon had suffered a massive bombardment by asteroids. And if the moon did, so did Earth.

Indeed, Earth must have had it worse, because it is a larger body and has a stronger gravitational pull. This cataclysm became known as the Late Heavy Bombardment—“late” because it occurred well after the planets had already taken shape and the rate of impact should have long since subsided. By some estimates, it was like having the equivalent of a dinosaur-killing impact once every few millennia, or even more frequently. The largest impacts would have turned most of the Earth’s surface into a sea of hot magma, and probably boiled off any water that had accumulated on the planet. No lifeform could have survived that. These events substantially narrowed the window over which life as we know it could have arisen: It couldn’t have gained a foothold before 3.9 billion years ago, but the isotopic and fossil records suggest it was already active by 3.8 billion years ago. On a geological time scale, genesis was
practically instantaneous.

Many scientists were unconvinced. The samples represented only a small fraction of the moon’s surface, after all. Though collected from different locations, they might be ejecta from a single large impact, explaining their common ages. But a powerful argument in favor of the bombardment emerged in the early 2000s. Planetary scientists came to realize that the planets probably did not form in their current orbits, but migrated toward or away from the sun. An influential model of these perambulations, developed a decade ago by a team based in Nice, France, was able to reproduce the current positions of the planets. Along the way, the planets stirred up asteroids and flicked huge numbers of them into the inner solar system, creating exactly the bombardment the moon rocks indicated. Many doubters were finally persuaded by this elegant and well-justified model, and the Late Heavy Bombardment became textbook science.

This past September, Patrick Boehnke and T. Mark Harrison of UCLA published a paper that struck at the foundation of the bombardment scenario: the ages of the Apollo samples. They began with the fact that the argon isotope abundances used to date the Apollo samples are very sensitive to temperature. Even modest temperature increases of a few hundred kelvins can cause argon to diffuse out of the rock, effectively resetting the argon clock near the surface of the rock, at least partially. Such temperatures could be achieved by small, nearby meteoritic impacts that did not melt the rocks. They showed that multiple partial resettings could lead to the appearance of total resetting, making the samples appear much younger than they truly are. In that case, the measured isotope ratios in the Apollo samples no longer require a massive bombardment to make sense.

Boehnke and Harrison also did computer simulations of different possible impact histories for the moon to see whether the argon measurements truly required a Late Heavy Bombardment. They found that a smoothly declining impact rate would explain the isotope abundances just as well. In short, they argued that the original analyses of crater ages from the Apollo rocks overstated the case for a bombardment. Since these analyses formed the basis of the Late Heavy Bombardment hypothesis, Boehnke and Harrison’s new analysis suggested that the bombardment may not have occurred at all.

Other researchers have been studying the asteroid belt, since the asteroids would have been as much the victims as the perpetrators of the Late Heavy Bombardment.
The evidence is equivocal. A key puzzle piece is Vesta, the second largest asteroid and the only one that has been conclusively linked to meteorites that have fallen to Earth. Julia A. Cartwright of Arizona State University and her colleagues have examined some of the Vestan meteorites. Embedded in these rocks are previously melted pebbles known as clasts, which the team dated to a narrow range of ages from 3.4 to 3.7 billion years ago. That suggests a cluster of impacts, in keeping with a Late Heavy Bombardment.

On the other hand, NASA’s Dawn mission visited Vesta in 2011 and 2012. Based on images of its surface, Simona Pirani of Lund University in Sweden and Diego Turrini of the Italian National Astrophysics Institute concluded that Vesta shows little indication of a bombardment. Few craters on the surface seem to date to this period; most are more recent, and Vesta has no atmosphere, oceans, or plate tectonics to wipe away evidence of previous impacts. Indeed, the supposed bombardment was so heavy that it should have ejected Vesta from the asteroid belt altogether, so the asteroid’s very existence seems to argue against such a cataclysm.

Meanwhile, many geologists and microbiologists have questioned whether the Late Heavy Bombardment, even if it really happened, would have been all that bad. Yuhito Shibaike and Shigeru Ida of the Tokyo Institute of Technology and Takanori Sasaki of Kyoto University have argued that the bombardment would have melted, at most, 70 percent of Earth’s surface. That is still a lot of surface, but it would have left refuges for life. A study by Norman Sleep of Stanford University and his colleagues argued that if life began on or spread to the ocean floor, then the primary concern would be the vaporization of the oceans. They showed that the canonical Late Heavy Bombardment impacts likely lacked the energy to boil that much water, and so would not have been able to sterilize the planet.

Further hints come from the ancient zircon crystals. Zircons require liquid water to form, so they, too, suggest the bombardment could not have completely remelted Earth’s surface and boiled off all surface water. So regardless of whether the earliest life clung to the land or hid beneath the waves, the bombardment may not provide a good limit on the starting point of life.

These findings have shocked some of us who work in astronomy, but as we talk to our geologist and microbiologist colleagues, we find that the findings merely reinforce the earlier misgivings about the bombardment. If Boehmke and Harrison are correct, where would this leave us in trying to understand the history of life on Earth?
If the early Earth did not go through a Late Heavy Bombardment, but instead suffered a slowly decreasing bombardment rate from its formation, it might have been hospitable to life much earlier than we had assumed—as long ago as 4.4 billion years. If life goes back 3.8 billion years, it may have taken hundreds of millions of years to arise, and that would imply life may be much rarer than we had thought.

But other evidence suggests that life is older than geologists and biologists previously recognized. In a separate study from their moon-rock takedown, Boehnke and Harrison, along with their colleagues, have argued that zircons show direct evidence of life 4.1 billion years ago. If so, we would be left with much the same conclusion as before: that life arose almost instantly on a geologic timescale. Since nature rarely gets things right on the first try, that implies that life spawns easily in the right environment and is probably common.

For now, though, the main result of the findings is to introduce new uncertainty into the science of astrobiology. For decades, the Late Heavy Bombardment has provided an important benchmark in our understanding of how, when, and where life formed and of how the solar system evolved from a chaotic swarm of planets and planetesimals to its current orderly configuration. If Boehnke and Harrison are correct, modelers of planetary evolution have fewer constraints within which to work.

The answers will help to determine how we conduct searches for extraterrestrial intelligence. If life forms quickly in favorable environments, then almost every planet or moon we discover in its star’s habitable zone has the potential to host life. On average, every star in the galaxy has one planet, so almost every star in the sky would be a search target. On the other hand, if the origin of life is a rare event, we should be focusing our limited telescope time on the oldest stars, where life would have had the most time to arise.

With so much in the balance, it’s clear that scientists need to take another look at the Apollo samples and figure out what they really tell us. Boehnke and Harrison suggest a series of steps: more quantitative analyses to construct a temperature chronology of the rock samples; in situ argon isotope dating of rocks by future lunar missions; careful selection of samples to ensure that they are truly representative of their surroundings; and more research into the properties of the impactors that created the lunar basins, to better understand how much material has struck the moon in total.

Until we do these things, the answer to when life began on Earth will remain
further out of reach than we thought. Reevaluating foundational theories in science can be unsettling, but it ultimately strengthens our grasp of the universe.

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