HOT JUPITER ATMOSPHERES
WITH THE SPITZER SPACE TELESCOPE

A Dissertation in
Astronomy and Astrophysics

by
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Abstract

I analyze Spitzer Space Telescope observations of seven transiting hot Jupiters during the time of secondary eclipse, the portion of the planet’s orbit when it is behind the star from the point of view of a Solar System observer. For six of them, HAT-P-3b, HAT-P-4b, HAT-P-6b, HAT-P-8b, HAT-P-12b and XO-4b, I analyze broadband photometric light curves at 3.6 and 4.5 μm. I compare the resulting eclipse depths, which are a measure of the planets’ dayside emission, to model emergent spectra by Burrows et al. and Fortney et al. The atmosphere of XO-4b has a strong temperature inversion, HAT-P-6b has weak or no temperature inversion, HAT-P-8 has a non-inverted atmosphere. The models are inconclusive about the temperature structure of the atmospheres of HAT-P-3b and HAT-P-4b. I find that HAT-P-3b, HAT-P-4b and HAT-P-8b have relatively inefficient heat transport from their day sides to their night sides. The models suggest moderate to low heat transport for XO-4b and HAT-P-6b. I discuss the physical implications of my results in the context of theoretical and empirical hypotheses on correlations related to the temperature-pressure structures of the atmospheres and the efficiency of energy transfer to the night side of the planet. In particular, I focus on the idea by Knutson et al. that planets with chromospherically active host stars may in general not have a stratosphere-like temperature inversions, while a quiet host star may lead to an inverted atmosphere. Another hypothesis I examine is that by Cowan and Agol and Perna et al. who suggest that the hottest planets have a narrow range of permitted heat redistribution efficiencies and, thus, high day-night contrasts.

The seventh object I study is HD 189733b. I examine the time series spectroscopy during 18 eclipses between wavelengths of 5 and 14 μm. This is the most extensive data set observed for the emission spectrum of any exoplanet to date. Some of these data sets have been analyzed in the past by Grillmair et al., however eight of them are examined here for the first time. I use the latest analysis techniques to remove the systematic effects from the spectral light curves, and measure the secondary eclipse depths as a function of wavelength. I compare the results with three emergent spectrum models I compute using a modified version of a radiative transfer code by Richardson et al., and with the best fit model by Burrows et al. that Grillmair et al. adopt. I exclude isothermal and gray atmospheres with a high degree of confidence and confirm the water feature detected by Grillmair et al. I also comment on the physical implications on HD 189733b’s atmosphere and how the results of the complex Burrows forward model compares with the simpler Richardson models that can be used for retrieval.
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Everything starts somewhere, though many physicists disagree.

–Terry Pratchett
Chapter 1

Introduction

One of the fastest developing fields of science today is the discovery and characterization of exoplanets—planets that orbit stars other than the Sun. There are several well-established methods for the discovery of these planets, such as pulsar timing (e.g., Wolszczan & Frail 1992), time-series measurements of the radial velocity of the host star (e.g., Mayor & Queloz 1995), detection of transits of the planet in front of the star (e.g., Charbonneau et al. 2000), detection of microlensing events (e.g., Bond et al. 2004) and direct imaging (e.g., Marois et al. 2008). These methods have been used to discover about 925 planets\(^*\) (as of July 24, 2013).

1.1 Hot Jupiters

Many of the known short period exoplanets are hot Jupiters—they have masses and radii similar to those of Jupiter, with orbital periods typically between 1 and 10 days and equilibrium temperatures above 1000 K. Hot Jupiters relatively rarely have eccentricities much larger than zero\(^†\). Hot Jupiters are intriguing objects because their formation mechanisms are poorly understood and because they exhibit atmospheres and climates with no Solar System analogues, in terms of temperature and pressure ranges (e.g., Knutson et al. 2007, 2008; Machalek et al. 2009; Todorov et al. 2010; Beerer et al. 2011; Deming et al. 2011; Todorov et al. 2012). In addition, transiting hot Jupiter studies serve as a training ground for observational techniques that could in the future be applied to study the atmospheres of transiting super-Earths and Earth analogues. This could be achieved, provided that next-generation facilities such as the James Webb Space Telescope can supply the sensitivity necessary to study the faint signals produced by rocky worlds (e.g., Deming et al. 2009; Belu et al. 2011; Hedelt et al. 2013).

1.2 Transits and Eclipses

Due to their small semimajor axes, hot Jupiters are likely to transit their host stars and in turn to be eclipsed by them. The transit probability is approximately \(R_*/a_p\), where \(R_*\) is the radius of the host star and \(a_p\) is the semimajor axis of the planet’s orbit (e.g., Borucki & Summers 1984). This makes hot Jupiters ideal targets for detailed atmospheric studies via the transits and eclipses.

Over 270 exoplanets are currently known to transit their host star, of which about 150 are hot Jupiters\(^†\). In this dissertation, I define a “transit” to be the event when a

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\(^*\)Jean Schneider, exoplanet.eu.

\(^†\)The Exoplanet Orbit Database (Wright et al. 2011) at http://exoplanets.org/.
planet crosses in front of its host star from the point of view of an Earth-based observer. On the other hand a “secondary eclipse”, or just “eclipse” occurs when the planet moves behind its host star, as seen from Earth. Transiting hot Jupiters often can produce secondary eclipses, which can be observed as a drop of brightness of the total light from the star-planet system as the planet disappears behind the star. This is not inevitable, since, in theory, a planet that transits may have a combination of high orbital eccentricity and inclination such that it never passes directly behind the star from the point of view of an Earth-bound observer. In practice, due to the hot Jupiters’ typically low orbital eccentricities, such cases should be relatively rare. Secondary eclipse measurements are essential for the study of their atmospheres, since their thermal radiation can be detected in the infrared before and after an eclipse as the drop of brightness of the unresolved star-planet system during eclipse provides a “star only” reference flux measurement.

The drop of brightness as the planet moves behind the star was measured for the first time independently by Charbonneau et al. (2005) and Deming et al. (2005). The depth of the eclipse normalized to the stellar flux varies with wavelength depending on the spectral energy distributions (SED) of the planet and the star. Therefore, if the spectral type of the host star is known, one can measure the planetary eclipse depth at several photometric bands to observe a very low resolution emergent spectrum of the observed planet (e.g., Charbonneau et al. 2008; Knutson et al. 2008; Stevenson et al. 2010; Todorov et al. 2010). Figure 1.1 shows a typical example of three such spectra from Charbonneau et al. (2008), Knutson et al. (2008) and Todorov et al. (2010).

This technique is typically unable to unambiguously detect specific chemical species (Lee et al. 2012; Line et al. 2012, 2013), primarily because of the low spectral resolution, but it can still be used to constrain the overall shape of the planet’s SED. Alternatively, for bright systems, one can observe time-series spectroscopy of the star-planet system during secondary eclipse and measure the drop of brightness as a function of wavelength in the resulting spectra (e.g., Richardson et al. 2007; Grillmair et al. 2008; Swain et al. 2008). The resolution of the SED for this method is better (see Section 1.3 for description of the Spitzer spectroscopic capabilities), but the photons per resolution element are far fewer. Since the depth of the eclipses is typically well below \( \sim 0.5\% \), with current technology the application of this technique is only possible for the brightest systems that provide the highest signal-to-noise ratios, such as HD 189733 and HD 209458. So far, this has been done only with Spitzer (in the mid-infrared), and the Hubble Space Telescope (e.g., Swain et al. 2009a) and some premier ground-based observatories (e.g., Swain et al. 2010) at shorter wavelengths. In all cases, the systematic effects from the instruments and Earth’s atmosphere are very significant and their removal poses a challenge.

Secondary eclipse depth measurements are done predominantly in the infrared, therefore, they probe the planet’s thermal radiation. The infrared is preferred since the ratio between planetary and stellar brightness is maximized there, even though it remains low, often of order \( 10^{-3} \). Due to the low amplitude of the signal, these measurements are extremely difficult to perform, especially from the ground where thermal background radiation from the warm telescope and from the Earth’s atmosphere produce large noise levels. Historically and currently, the facility best suited for this type of observations has been the Spitzer Space Telescope. However, secondary eclipse observations have also
Fig. 1.1 The ratios between the planet and host star brightnesses for three planets: HD 209458b (open squares; Knutson et al. 2008), HAT-P-1b (filled circles; Todorov et al. 2010) and HD 189733b (open triangles; Charbonneau et al. 2008). The eclipse depth points are slightly offset from each other in the plot in order to prevent overlap of their error bars. The secondary eclipse depths of the planets were measured by photometry as a function of wavelength. For these studies, data were available in at least the four wavelengths, corresponding to the four Spitzer/IRAC photometric bands. These results constrain the low-resolution emergent spectrum of the planets since the spectral types of the host stars (and hence their SEDs) are well known. The atmosphere of HD 209458b is likely inverted, indicated by its 4.5 μm eclipse which is significantly deeper than the 3.6 μm eclipse. Conversely, the 3.6 μm eclipse for HD 189733b is deeper than the one at 4.5 μm, suggesting a non-inverted atmosphere. The HAT-P-1b measurements are well represented by a 1500 K black body planet model (hence, with an isothermal atmosphere) and a Kurucz host star spectrum (solid line; Kurucz 1979). An isothermal atmosphere is the border state between an inverted and a non-inverted atmosphere. The eclipses at 5.8 μm and 8 μm are offset from the 4.5 μm eclipses in a similar fashion for all three planets, suggesting that observations at only 3.6 and 4.5 μm could be sufficient to determine the presence or absence of a temperature inversion (e.g., Knutson et al. 2010). For a discussion of temperature inversions, see Section 1.4.
been performed, mostly in the near-infrared, from the ground (e.g., de Mooij & Snellen 2009; Sing & López-Morales 2009; Croll et al. 2010, 2011; Swain et al. 2010; Zhao et al. 2012; Wang et al. 2013) and with other space-based observatories like the Hubble Space Telescope (e.g., Swain et al. 2009a,b) and CoRoT (e.g., Alonso et al. 2009). All of these observatories have significant systematic effects due to background levels or instrument specifics that, unless carefully removed, could cause the data to be misinterpreted. For instance, Gibson et al. (2011) have called into question previous results based on Hubble NICMOS transmission spectroscopy data (time-series spectroscopy as the planet transits the star, appearing to have different radii at different wavelengths due to varying atmospheric opacity) that require similar analysis to eclipse observations. Some ground-based eclipse depth measurements (e.g., Swain et al. 2010; Waldmann et al. 2012) are also controversial (Mandell et al. 2011; Birkby et al. 2013). Spitzer observations are also impacted by systematics, however they are better understood and the signal-to-noise ratio is often much higher than in ground-based studies.

1.3 Overview of the Spitzer Space Telescope

Spitzer is a Ritchey-Chrétien design telescope with an 85 cm aperture. It was launched on August 25, 2003 from Cape Canaveral, Florida, and was delivered to Earth-trailing heliocentric orbit. Spitzer is an infrared telescope and therefore its instruments must be kept as cold as possible. During the cryogenic portion of the mission, before the liquid helium coolant ran out in 2009, there were three main functional instruments on board. The Infrared Array Camera (IRAC, Fazio et al. 2004) was capable of imaging and photometry in broad wavelength bands centered around 3.6, 4.5, 5.8 and 8.0 µm. The InfraRed Spectrograph (IRS, Houck et al. 2004) had four observing modes between 5 and 40 µm, with resolving power, $R = \lambda/\Delta \lambda$, of order 100, where $\lambda$ is the observed wavelength. In addition, the IRS Peakup arrays provided the opportunity for stellar photometry at 16 and 22 µm. The Multiband Imaging Photometer for Spitzer (MIPS, Rieke et al. 2004) could produce photometry and images at 24, 70 and 160 µm, as well as low-resolution spectroscopy between 55 and 95 µm.

In May 2009, Spitzer exhausted the last of its liquid helium cryogen and transitioned into the warm phase of the mission. The telescope temperature went up from $\sim 4$ K to $\sim 29$ K, and it is now cooled by passive radiation. This rendered most of its instruments too warm to operate, however, the 3.6 and 4.5 µm detector arrays of IRAC remained operational. This dissertation uses archival time series spectroscopy data from the IRS and Warm Spitzer IRAC data.

1.4 Hot Jupiter Atmospheres via the Secondary Eclipse Method

Measurements of the eclipse depth of a planet as a function of wavelength can be used to reproduce its SED, which is shaped by the planet’s atmosphere. Therefore, probing eclipse depths allows us to directly probe the atmospheres of exoplanets. Multiband photometry of hot Jupiters has suggested that they have two classes of atmospheres – with or without a temperature inversion (e.g., Knutson et al. 2008; Machalek et al. 2009;
A “temperature inversion” is defined as a layer in the upper atmosphere of a planet where the temperature is similar to or higher than in the layers below, when it is expected to be lower. Planets that are thought to have temperature inversions include HD 209458b, CoRoT-1b, XO-2b, etc., while HD 189733b, TrES-1, WASP-4b, and others appear to have no temperature inversion in their atmospheres. There are also planets that seem to have SEDs compatible with neither inverted, nor non-inverted atmospheres, e.g. CoRoT-2b (Knutson et al. 2010, and references therein).

The reasons for the presence or absence of temperature inversions are not well understood, however, it is generally thought that planets with an inversion have an additional opacity source in the upper layers of their atmospheres, at pressures below \( \sim 0.01 \) bar (Burrows et al. 2008; Fortney et al. 2008). The source of extra opacity absorbs some wavelengths of stellar radiation at high altitudes in the atmosphere. This causes the atmosphere’s upper layers to have higher temperature than the layers below, which may lack this extra absorber, or where it may be shielded by the opaque layers above. The additional opacity may be produced by gas phase TiO (Hubeny et al. 2003; Burrows et al. 2007, 2008; Fortney et al. 2006a, 2008), however, this molecule is expected to form grains on the night sides or in cold traps deep in the atmospheres of some hot Jupiters with inversions like HD 209458b, causing them to rain out of the atmosphere and be depleted in its upper layers (Spiegel et al. 2009). This idea has been examined recently by Parmentier et al. (2013) who find that strong vertical mixing may support TiO in the atmosphere of this object. Additionally, since the temperature and pressure in TrES-3b’s atmosphere are not expected to cross into the condensation region of TiO, this molecule should be abundant in its atmosphere, and yet the planet has no temperature inversion (Fressin et al. 2010). In contrast, XO-1b’s atmosphere should be too cool to maintain gas phase TiO, but it is thought to have a temperature inversion (Machalek et al. 2008).

At least two alternative hypotheses have been put forward to explain the presence or absence of temperature inversions. The cause for opacity in the upper layers of the inverted atmospheres may be sulfur compounds (Zahnle et al. 2009), in at least some hot Jupiters. Another suggestion is that temperature inversions are negatively correlated with the magnetic activity and the accompanying ultraviolet (UV) flux of the host star (Knutson et al. 2010). According to this explanation, the high-altitude absorber that causes inversions is destroyed by the large amounts of UV flux received by planets that orbit active stars.

Climate is another atmospheric property can be studied through secondary eclipse observations. Hot Jupiters are expected to synchronize their rotation period with their orbital periods within \( \sim 1 \) Gyr, assuming zero orbital eccentricity (e.g., Jackson et al. 2008; Correia & Laskar 2010). Therefore, these planets are expected to have a permanent day and night sides. The amount of heat that is transported from the day side to the night side is affected by the wind currents and their strengths. More efficient heat transfer cools the day side, making it dimmer in the thermal infrared. Since during secondary eclipse, we measure the brightness of the day side only, this effect can be measured. The heat transfer efficiency is degenerate with the Bond albedo of the planet’s day side (high albedo would mean higher flux from the day side), but by relating models to observations constraints can be put on the possible combinations of these parameters (Cowan & Agol 2011).
Given sufficiently large spectroscopic resolving power, it is possible to detect molecular features in the light emitted by the day sides of some hot Jupiters during secondary eclipse. Higher spectral resolution dilutes the target’s light density on the detector, and makes longer exposure times necessary. This has made time-series spectroscopy during secondary eclipse impractical for most targets except HD 209458b and HD 189733b, which are hot and orbit bright nearby stars, resulting in relatively deep eclipses and providing enough signal to noise to make an impossible measurement merely very difficult. These two systems have been observed using this technique with the IRS instrument on board Spitzer. Grillmair et al. (2008) claim the detection of a water feature near 6 µm in their data on HD 189733b.

Planetary climate, atmospheric composition and temperature inversions are all deeply related phenomena. Careful modeling can constrain these properties based on the observed quantities, but in order to achieve full understanding of hot Jupiter atmospheres we need as many secondary eclipse measurements of as many planets in as many wavelengths possible. In addition, all time series spectroscopy should be carefully analyzed using the best available understanding of the instrumental effects.

1.5 Goals and Motivation

In this dissertation, I set out to expand the number of hot Jupiters that have their secondary eclipses measured in at the 3.6 and 4.5 µm bands by six – HAT-P-3b, HAT-P-4b, HAT-P-6b, HAT-P-8b, HAT-P-12b and XO-4b. The number of systems with previously measured secondary eclipses at these wavelengths is 27. This growing sample allows us to search for correlations between the shape of the planets’ SEDs and various other properties of their systems. Some of these planets are relatively cool, with equilibrium temperatures below 1500 K, and therefore observations of their eclipses probe an under-explored domain. The properties I adopt for these planets and their host stars are listed in Table 1.1. I use data from the IRAC instrument on Spitzer from the warm phase of the mission. For each planet, I perform photometry in the two available bands, at 3.6 and 4.5 µm. The resulting photometry of each planet’s day side is compared to atmospheric models and constraints are placed on the flux recirculation efficiency and the presence or absence of temperature inversions in each planet’s atmosphere.

The second objective of this dissertation is to examine and analyze uniformly the highest signal-to-noise time series secondary eclipse spectroscopy performed with Spitzer’s IRS instrument. The data cover secondary eclipses of HD 189733b (see Table 1.1 for the adopted properties of this object). There are 22 archival data sets on this planet. The wavelength coverage is mostly between ~ 5 and ~ 14 µm, but there are four data sets taken during HD 189733b eclipses at wavelengths between 21 and 40 µm. Ten of the data sets have never been analyzed. Details on the available data are discussed in Chapter 2. While, as mentioned earlier, there are 27 planets observed via Spitzer photometry at the 3.6 and 4.5 µm bands during eclipse, only two planets have been observed via secondary eclipse time-series spectroscopy with Spitzer – HD 189733b and HD 209458b. This dissertation aims to substantially increase the number of analyzed secondary eclipse

‡The Exoplanet Orbit Database (Wright et al. 2011) at http://exoplanets.org/.
Table 1.1. Adopted Stellar and Planetary Parameters

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<th>XO-4b&lt;sup&gt;a&lt;/sup&gt;</th>
<th>HAT-P-3b&lt;sup&gt;b&lt;/sup&gt;</th>
<th>HAT-P-4b&lt;sup&gt;c&lt;/sup&gt;</th>
<th>HAT-P-6b&lt;sup&gt;d&lt;/sup&gt;</th>
<th>HAT-P-8b&lt;sup&gt;e&lt;/sup&gt;</th>
<th>HAT-P-12b&lt;sup&gt;f&lt;/sup&gt;</th>
<th>HD 189733b&lt;sup&gt;g&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_*$ (M&lt;sub&gt;☉&lt;/sub&gt;)</td>
<td>1.32 ± 0.02</td>
<td>0.917 ± 0.030</td>
<td>1.271&lt;sup&gt;±0.120&lt;/sup&gt;</td>
<td>1.29 ± 0.06</td>
<td>1.28 ± 0.04</td>
<td>0.733 ± 0.018</td>
<td>0.823&lt;sup&gt;±0.022&lt;/sup&gt;</td>
</tr>
<tr>
<td>$R_*$ (R&lt;sub&gt;☉&lt;/sub&gt;)</td>
<td>1.56 ± 0.05</td>
<td>0.799 ± 0.039</td>
<td>1.600&lt;sup&gt;±0.017&lt;/sup&gt;</td>
<td>1.46 ± 0.06</td>
<td>1.58&lt;sup&gt;±0.08&lt;/sup&gt;</td>
<td>0.701&lt;sup&gt;±0.017&lt;/sup&gt;</td>
<td>0.766&lt;sup&gt;±0.007&lt;/sup&gt;</td>
</tr>
<tr>
<td>$K_p$ (mag)&lt;sup&gt;h&lt;/sup&gt;</td>
<td>9.406 ± 0.023</td>
<td>9.448 ± 0.025</td>
<td>9.770 ± 0.020</td>
<td>9.313 ± 0.019</td>
<td>8.953 ± 0.013</td>
<td>10.108 ± 0.016</td>
<td>5.541 ± 0.021</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>6400 ± 70</td>
<td>5185 ± 80</td>
<td>5990</td>
<td>6410</td>
<td>6130</td>
<td>4650</td>
<td>5090</td>
</tr>
<tr>
<td>$b_{\text{impact}}$</td>
<td>0.16 ± 0.08</td>
<td>0.530 ± 0.075</td>
<td>0.084&lt;sup&gt;±0.014&lt;/sup&gt;</td>
<td>0.602 ± 0.030</td>
<td>0.32&lt;sup&gt;±0.09&lt;/sup&gt;</td>
<td>0.211 ± 0.012</td>
<td>0.900&lt;sup&gt;±0.006&lt;/sup&gt;</td>
</tr>
<tr>
<td>$M_p$ (M&lt;sub&gt;J&lt;/sub&gt;)</td>
<td>1.72 ± 0.20</td>
<td>0.591 ± 0.018</td>
<td>0.680&lt;sup&gt;±0.038&lt;/sup&gt;</td>
<td>1.057 ± 0.119</td>
<td>1.52&lt;sup&gt;±0.18&lt;/sup&gt;</td>
<td>0.211&lt;sup&gt;±0.066&lt;/sup&gt;</td>
<td>1.138&lt;sup&gt;±0.022&lt;/sup&gt;</td>
</tr>
<tr>
<td>$R_p$ (R&lt;sub&gt;J&lt;/sub&gt;)</td>
<td>1.34 ± 0.05</td>
<td>0.827 ± 0.055</td>
<td>1.337&lt;sup&gt;±0.036&lt;/sup&gt;</td>
<td>1.330 ± 0.061</td>
<td>1.50&lt;sup&gt;±0.08&lt;/sup&gt;</td>
<td>0.959&lt;sup&gt;±0.021&lt;/sup&gt;</td>
<td>1.178&lt;sup&gt;±0.023&lt;/sup&gt;</td>
</tr>
<tr>
<td>P (days)&lt;sup&gt;i&lt;/sup&gt;</td>
<td>4.1250823±</td>
<td>2.8997382±</td>
<td>3.0565254±</td>
<td>3.8530030±</td>
<td>3.0763402±</td>
<td>3.21305929±</td>
<td>2.21857312</td>
</tr>
<tr>
<td>a&lt;sub&gt;p&lt;/sub&gt; (AU)</td>
<td>0.0000039</td>
<td>0.0000009</td>
<td>0.0000012</td>
<td>0.0000014</td>
<td>0.0000015</td>
<td>0.00000034</td>
<td>0.000000036</td>
</tr>
</tbody>
</table>

<sup>a</sup>Values from McCullough et al. (2008), except the impact parameter, $b_{\text{impact}}$, and $a_p$ (Narita et al. 2010), and the magnitude, $K_p$.

<sup>b</sup>Values from Chan et al. (2011), except for $K_p$, the period, P, and $a_p$ (calculated).

<sup>c</sup>Values from Southworth (2011), except for $K_p$, $T_{\text{eff}}$ (Knutson et al. 2010), the period, P, and $a_p$ (calculated).

<sup>d</sup>Values from Noyes et al. (2008), except for $K_p$, $T_{\text{eff}}$ (Knutson et al. 2010), and the period, P.

<sup>e</sup>Values from Latham et al. (2009), except for $K_p$, $T_{\text{eff}}$ (Knutson et al. 2010), and the period, P.

<sup>f</sup>Values from Hartman et al. (2009), except for $K_p$, $T_{\text{eff}}$ (Knutson et al. 2010), the period, P, and $a_p$ (calculated).

<sup>g</sup>Values from Triaud et al. (2009), except for $K_p$ and $T_{\text{eff}}$ (Knutson et al. 2010).

<sup>h</sup>Two Micron All Sky Survey (2MASS) $K_p$ magnitude of the star (from the Infrared Science Archive: http://irsa.ipac.caltech.edu).

<sup>i</sup>The orbital periods of HAT-P-3b and HAT-P-4b are taken from Sada et al. (2012); the period for HD 189733b is from Triaud et al. (2009); the rest are from updated ephemerides by Todorov et al. (2012, 2013).
spectroscopic data sets available not just for HD 189733b, but for exoplanets in general. Having as complete understanding of the planets’ spectra as possible is a vital key to constraining their atmospheres, therefore analyzing these “forgotten” data sets is a large step toward this goal.

I aim to test and improve the results of previous investigations (Grillmair et al. 2007, 2008). This is necessary, because in the following years since these studies, the understanding of the systematic effects typical for Spitzer and its instruments has improved. I apply a physically motivated correction function for the detector ramp (Agol et al. 2010). In the past various schemes have been employed to correct for the pointing oscillation encountered in long time series observations with Spitzer. This causes the star to move across the slit, resulting in apparent brightness oscillations with period of about an hour. The pointing oscillation has been traced to the operation of a heater, designed to keep a battery within its operating temperature range. For observations made after 10 October 2010, both the amplitude and period of the oscillation were reduced (to $\sim 40$ minutes) to make it easier to remove this effect from the light curves§. Unfortunately, by then the IRS instrument was no longer functional. In this dissertation, I examine the utility of several methods to account for the apparent changes in brightness due to drift of the target star across the spectrograph slit. In addition, many of the available observations have been analyzed by various groups (Grillmair et al. 2007, 2008; Richardson et al. 2007; Swain et al. 2008), and in order to make fair comparisons between their results, a uniform analysis of all data sets is needed. Therefore, I am motivated by the need to present a uniform test and improve on previous investigations.

HD 189733b has the most thoroughly studied exoplanet atmosphere. The results of this thesis almost double the number of analyzed secondary eclipse spectroscopy data sets on it, put our understanding of its structure on firmer footing and test the robustness of previous results. For instance, I compare the planet’s secondary eclipse IRS spectra to relatively trivial atmospheric models like isothermal and gray atmosphere. This is pivotal for exoplanet science – if an isothermal atmosphere cannot be ruled out for the most thoroughly observed exoplanet, then past observational studies claiming to derive the temperature structure of hot Jupiter atmospheres may be in need of a more skeptical review. On the other hand, if the simple models can be ruled out, as I find, it is certain that we have moved on from just detection of exoplanets to the stage of their detailed characterization.

While the spectroscopic analyses focus on the details of the atmosphere of a single planet, the secondary eclipse time-series photometry analyses aim to characterize as many planets as possible, offsetting the lack spectroscopic detail by studying a larger number of objects. I significantly expand the sample size of planets with secondary eclipses measured via Spitzer photometry, and compare theoretical predictions from two different research groups to the resulting eclipse depths. This approach helps test hypotheses about the causes behind general properties of hot Jupiter atmospheres, and also serves as a check for the reliability of the atmospheric temperature-pressure profiles extracted based on a given atmospheric model.

In addition, the data presented here and other similar studies provide us with the tools and understanding required to perform secondary eclipse observations on smaller and cooler transiting planets. These become more and more difficult with decreasing radii and temperatures due to the fainter and fainter signals from the planets. But, in the future, large infrared telescopes, particularly the James Webb Space Telescope, will enable measurements of transiting super-Earth and even exo-Earth SEDs. Therefore, the broader aim of this dissertation is to help the exoplanet community to be able to extract the maximum possible information from secondary eclipse observations of rocky worlds, when they become possible. To do this we must improve our understanding of the required observation and analysis techniques by making effective use of the data available presently.

In order to achieve these objectives, it is vital to reduce the available data self-consistently and in a way that minimizes the impact of the systematic effects inherent to the observatory. I describe the observations I examine in this dissertation and my data reduction algorithms in the next chapter (Chapter 2).
Chapter 2

Data and Data Reduction

This dissertation utilizes infrared time series photometric data on six hot Jupiters during secondary eclipse in two bands each. I also examine archival time series spectroscopy during secondary eclipse in the infrared for one hot Jupiter. All data have been acquired with the Spitzer Space Telescope.

2.1 Photometric Data and Reduction

2.1.1 Photometric Data

I analyze secondary eclipse time series photometry for six hot Jupiters: HAT-P-3b, HAT-P-4b, HAT-P-6b, HAT-P-8b, HAT-P-12b and XO-4b. The observations were performed with the Spitzer IRAC instrument during the warm phase of the mission. Two secondary eclipses were observed for each planet, one in each available photometric band – 3.6 $\mu$m and 4.5 $\mu$m.

HAT-P-3b, HAT-P-6b, HAT-P-8b and XO-4b were observed in subarray mode in both pass-bands. These observations result in $32 \times 32$ pixel ($39'' \times 39''$) images stacked in FITS data cubes of 64 consequent frames each. The effective exposure time per image is 1.92 s in both wavelength bands. HAT-P-3b, HAT-P-6 and HAT-P-8 were observed for $\sim 7$ hr 42 minutes resulting in 13,760 images (215 data cubes) in each photometric channel. Both eclipses of XO-4b were observed for $\sim 7$ hr 52 minutes (220 data cubes per eclipse). No comparison stars are needed for my analysis, and so the small spatial coverage of the images does not present a problem.

The eclipses of HAT-P-4b and HAT-P-12b were observed in IRAC’s full array mode, resulting in individual images with the full available spatial coverage of $256 \times 256$ pixels ($5.2' \times 5.2'$). At both channels, the HAT-P-4 system was observed with effective exposure times of 4.4 s per image, while the HAT-P-12 observations have effective exposure times of 10.4 s. The time series observations for HAT-P-4 during both eclipses lasted 7 hr 38 minutes, resulting in 3871 images per pass-band. HAT-P-12 was observed for 7 h 37 min (2097 images) per pass-band.

Full information about the time-span of the observations is presented in Table 2.1.

2.1.2 Photometry Extraction

I begin the image reduction process with the Basic Calibrated Data (BCD) products of the Spitzer calibration pipeline version S18.18.0. The calibration consists of removing all well-understood instrumental effects from each image, including bias and flat field correction, and dark flux subtraction. The pipeline is described in detail in
<table>
<thead>
<tr>
<th>Photometric band</th>
<th>AOR key&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Observation start (UTC)</th>
<th>Observation end (UTC)</th>
<th>Orbital phase coverage</th>
<th>Image count</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAT-P-3b</td>
<td>3.6 μm</td>
<td>2010 Mar 17, 02:45</td>
<td>2010 Mar 17, 10:28</td>
<td>0.433 – 0.544</td>
<td>13,760</td>
</tr>
<tr>
<td></td>
<td>4.5 μm</td>
<td>2010 Mar 20, 00:04</td>
<td>2010 Mar 20, 07:46</td>
<td>0.428 – 0.539</td>
<td>13,760</td>
</tr>
<tr>
<td>HAT-P-4b</td>
<td>3.6 μm</td>
<td>2010 Apr 12, 02:21</td>
<td>2010 Apr 12, 09:59</td>
<td>0.439 – 0.543</td>
<td>3871</td>
</tr>
<tr>
<td></td>
<td>4.5 μm</td>
<td>2010 Sep 02, 18:49</td>
<td>2010 Sep 03, 02:27</td>
<td>0.448 – 0.552</td>
<td>3871</td>
</tr>
<tr>
<td>HAT-P-6b</td>
<td>3.6 μm</td>
<td>2010 Sep 11, 23:21</td>
<td>2010 Sep 12, 07:02</td>
<td>0.453 – 0.537</td>
<td>13,760</td>
</tr>
<tr>
<td></td>
<td>4.5 μm</td>
<td>2010 Sep 19, 16:14</td>
<td>2010 Sep 19, 23:55</td>
<td>0.453 – 0.536</td>
<td>13,760</td>
</tr>
<tr>
<td>HAT-P-8b</td>
<td>3.6 μm</td>
<td>2010 Jan 14, 16:18</td>
<td>2010 Jan 14, 24:00</td>
<td>0.437 – 0.542</td>
<td>13,760</td>
</tr>
<tr>
<td></td>
<td>4.5 μm</td>
<td>2010 Jan 11, 14:35</td>
<td>2010 Jan 11, 22:17</td>
<td>0.439 – 0.543</td>
<td>13,760</td>
</tr>
<tr>
<td>HAT-P-12b</td>
<td>3.6 μm</td>
<td>2010 Mar 16, 13:58</td>
<td>2010 Mar 16, 21:35</td>
<td>0.445 – 0.544</td>
<td>2097</td>
</tr>
<tr>
<td></td>
<td>4.5 μm</td>
<td>2010 Mar 26, 05:09</td>
<td>2010 Mar 26, 12:47</td>
<td>0.443 – 0.542</td>
<td>2097</td>
</tr>
<tr>
<td>XO-4b</td>
<td>3.6 μm</td>
<td>2009 Dec 15, 07:26</td>
<td>2009 Dec 15, 15:18</td>
<td>0.452 – 0.532</td>
<td>14,080</td>
</tr>
<tr>
<td></td>
<td>4.5 μm</td>
<td>2009 Dec 07, 01:28</td>
<td>2009 Dec 07, 09:21</td>
<td>0.453 – 0.533</td>
<td>14,080</td>
</tr>
</tbody>
</table>

<sup>a</sup>The Astronomical Observation Request (AOR) key that uniquely identifies the observation in the *Spitzer* Heritage Archive (http://sha.ipac.caltech.edu/applications/Spitzer/SHA/).
Chapter 5 of the IRAC Instrument Handbook*. I extract the timing information of each image from the BCD FITS file headers, where it is given in the Coordinated Universal Time (UTC) standard. Following the discussion in Eastman et al. (2010), I convert these times to the Barycentric Dynamic Time (TDB) standard. UTC is based on the International Atomic Time standard that utilizes hyperfine transitions of Cesium-133 (\(^{133}\text{Cs}\)) atoms. However, UTC is also kept within 0.9 seconds of the UT1 standard, which relies on the mean solar day, by introducing leap seconds, sometimes as often as once every 6 months, but typically roughly once a year or less often. This makes UTC discontinuous and confusing. The Terrestrial Time (TT) standard is a continuous alternative of UTC, offset from it by \(32.184 + N\) seconds, where \(N\) is the current number of leap seconds accumulated since the adoption on the standard in 1972. For the observations discussed here, \(N = 34\). TT is further improved with a relativistic correction due to Earth’s gravity well to yield TDB. The size of the relativistic correction is typically several milliseconds (Eastman et al. 2010), which is negligible for the purposes of transit and eclipse timing.

After reading the images, I convert their pixel intensity units from MJy·sr\(^{-1}\) to electron counts. This allows me to estimate the expected Poisson noise levels and compare them with the noise levels in the light curves after I account for the systematic effects. I adopt a spatially constant background radiation level within each frame. The background is estimated by constructing a histogram of all pixel intensities within the frame, excluding those near target star in the subarray mode images. The full-array images have many more pixels, and as a result the histograms cannot be affected by a single star. The histograms are well represented by Gaussian functions. I adopt the centroid of the Gaussian to be the best estimate of the background level in each image and subtract it from all frame pixels. I test the full-array data for spatially variable background by including only pixels within a 30 × 30, 50 × 50 and 100 × 100 pixel boxes centered on the target system in the background histograms. This approach to removing background yields at most 0.7% change in the scatter of the raw photometry around a running boxcar median of width 20, compared to the scatter produced while using the whole array to estimate the background. This change is marginal, and I choose to adopt the background levels based on the whole array in order to maximize their statistical significance.

Energetic particle hits on the detector are removed by comparing the value of each pixel in a given image to a running median with a width of 5 of the values of this pixel through the whole FITS data cube (subarray mode) or all of the images (full-array mode). The values of pixels that are more than 4\(\sigma\) away from the median are replaced with its value. The fractions of pixels corrected in this way are listed in Table 2.2.

One of the well known systematic effects of Spitzer photometry is a strong correlation of the position of the center of the stellar image, precise to within hundredths of a pixel, with the observed stellar intensity. This effect is caused by a variation in sensitivity over the detecting surface of an individual pixel. This is evident in the time series photometry in Figures 2.1 and 2.2 as an apparent oscillation in intensity on hour timescales as the telescope pointing drifts by a fraction of a pixel. The effect and its

*http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/.
removal are discussed in more detail in Chapter 3. To facilitate the best possible systematics removal, I locate the centroids of the stellar point response function (PRF) using two different techniques. The PRF is just the Spitzer point spread function (PSF), sampled by the detector pixels, with the intrapixel sensitivity variation taken into account. I compare centroiding by fitting a two-dimensional Gaussian to the PRF (Agol et al. 2010) and flux-weighted centroiding (e.g., Charbonneau et al. 2008; Knutson et al. 2008), which is an average position, weighted by the flux in each pixel.

In order to ensure that I extract the aperture photometry with least associated systematic uncertainty, I also compare the results from two approaches. First, I perform standard fixed aperture photometry using the IDL routine aper. I vary the aperture radius between 0.5 and 6.5 pixels in increments of 0.5 pixels. I adopt the photometry with the aperture radius that yields the least true scatter of the raw light curve around a running boxcar median with a width of 20. This scatter is weakly correlated with aperture. I find that there is least amount of scatter with aperture radius of 3.0 pixels for HAT-P-3 and HAT-P-8 at 3.6 μm and 2.5 pixels for all other subarray mode data. In the full array mode data, the scatter is minimized for aperture radii of 4.0 pixels (HAT-P-4, 3.6 μm), 3.0 pixels (HAT-P-4, 4.5 μm), 5.0 pixels (HAT-P-12, 3.6 μm) and 2.5 pixels (HAT-P-12, 4.5 μm).

In parallel, I perform photometry utilizing a relatively new technique, called variable aperture photometry (Mighell 2005; Knutson et al. 2012; Lewis et al. 2013). It is optimized for images with undersampled point spread functions, which is true for data from the Spitzer IRAC 3.6 and 4.5 μm channels. For undersampled PSFs, the number of pixels over which the light of the star is spread may change based on the exact position of the PSF on the detector array. This is illustrated in Figure 2.3.

Following Mighell (2005); Knutson et al. (2012) and Lewis et al. (2013), for each data frame, I calculate the noise-pixel parameter, as defined in the Section 2.2.2 of the Spitzer/IRAC Instrument Handbook as:

\[
\tilde{\beta} = \frac{\left(\sum_i I_i\right)^2}{\sum_i I_i^2},
\]

(2.1)

\[1\]More information on the Spitzer PRF is available at http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/calibrationfiles/psfprf/.
Fig. 2.1 Raw time series photometry for HAT-P-3, HAT-P-4 and HAT-P-12 at 3.6 and 4.5 $\mu$m (black points), as a function of time. Over-plotted are the best fit models I obtain to account for the the systematic effects and the eclipse (discussed in Chapter 3). The time shown along the x-axis has units of phase – the fraction of the planetary orbit elapsed since the middle of primary transit, based on the observation and exposure times of each image and the ephemeris adopted in Table 1.1. All photometric measurements are shown here, including some that I later omit from photometric analyses (black points not covered by a red model). The details of the analysis are discussed in Chapter 3.
Fig. 2.2 Similar to Figure 2.1, but for HAT-P-6, HAT-P-8 and XO-4.

Fig. 2.3 A qualitative view of why variable aperture photometry is often needed for the undersampled PSF case. In the left panel, the PSF (circle) has a radius of 0.5 pixels and fits entirely within a single pixel. Therefore the ideal aperture photometry radius is $\sqrt{2}/2$ pixels to encompass all of the detected stellar intensity. In the right panel, the stellar image has drifted on the detector and the intensity is distributed over four pixels. In order to encompass the same amount of photons as in the left panel, a larger aperture photometry radius of $\sqrt{2}$ pixels is needed.
where $I_i$ is the number of photons observed by the $i^{th}$ pixel. The noise-pixel parameter, scales linearly with the full-width-half-maximum of the PSF (Mighell 2005). Hence, for each image, we can calculate an aperture radius to encompass a constant amount of flux:

$$r = b\sqrt{\beta} + c,$$

(2.2)

where $b$ is a scaling factor and $c$ is a constant. In all images, I estimate the flux needed to calculate $\beta$ by using circular apertures. I vary their radii between 1.0 and 6.5 pixels. Pixels, of which only a fraction falls within this circular radius, are fully included in the $\beta$ calculation. For each of these radii, I vary $b$ and $c$ in steps of 0.05. The photometric light curve produced by each combination of $\beta$, $b$ and $c$ is fit with the model of the systematic effects and the eclipse described in Chapter 3. I adopt the variable aperture parameters which yield the smallest standard deviation of the residuals of the eclipse-and-systematics model and the light curve. The best combinations are detailed in Table 2.3.

I perform photometry on all data sets with fixed and variable apertures, and with Gaussian and flux-weighted centroiding. For each combination, I calculate the best fit model as discussed in Chapter 3 and compare the standard deviation of the residuals after subtracting the flux model from the light curve. I find that HAT-P-3, HAT-P-4, HAT-P-6, HAT-P-12 and XO-4 data in both wavelengths yield best results when I apply variable aperture photometry combined with flux-weighted centroiding. The HAT-P-8 data sets in both channels yield best results for fixed aperture photometry and Gaussian centroiding. For the HAT-P-8b at 4.5\(\mu\)m, this may be because the pointing oscillation is very small, reducing the need of variable aperture. For the 3.6\(\mu\)m light curve, the median variable aperture radius is smallest among all of the data sets, only 1.67 pixels (Table 2.3). This suggests that in this data set the number of pixels used for variable aperture photometry is insufficient to minimize the noise after systematics removal. The raw photometry based on the best available combination of techniques is presented in Figures 2.1 and 2.2, along with the best fit models from Chapter 3.

2.2 Spectroscopic Data and Reduction

2.2.1 Spectroscopic Data

I examine all archival time series spectroscopy taken with Spitzer/IRS during secondary eclipse. The IRS functionality was lost when the warm phase of the mission began in 2009, and so these observations remain unique until another infrared observatory with similar capabilities comes into service. There are no additional proprietary Spitzer IRS time-series data sets (since the IRS is unavailable since 2009, the proprietary period would have expired in 2010). The data cover the secondary eclipses of two hot Jupiters, HD 189733b and HD 209458b, between 5 and 40\(\mu\)m at resolution $R \approx 100$. I summarize these data sets in Table 2.4. In this dissertation, I focus on the observations of HD 189733b, since, once stacked they yield the highest signal-to-noise ratios.
Table 2.3. Adopted Variable Aperture Photometry Parameters

<table>
<thead>
<tr>
<th></th>
<th>$R_1^a$ (pixels)</th>
<th>$b^b$ (pixels)</th>
<th>$c^b$ (pixels)</th>
<th>median r$_{var}^c$ (pixels)</th>
<th>max r$_{var}^c$ (pixels)</th>
<th>min r$_{var}^c$ (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAT-P-3b</td>
<td>3.6 $\mu$m</td>
<td>3.5</td>
<td>0.40</td>
<td>1.30</td>
<td>2.21</td>
<td>2.33</td>
</tr>
<tr>
<td></td>
<td>4.5 $\mu$m</td>
<td>6.5</td>
<td>0.30</td>
<td>1.60</td>
<td>2.33</td>
<td>2.39</td>
</tr>
<tr>
<td>HAT-P-4b</td>
<td>3.6 $\mu$m</td>
<td>4.0</td>
<td>0.85</td>
<td>0.35</td>
<td>2.24</td>
<td>2.47</td>
</tr>
<tr>
<td></td>
<td>4.5 $\mu$m</td>
<td>6.5</td>
<td>0.50</td>
<td>1.05</td>
<td>2.55</td>
<td>2.64</td>
</tr>
<tr>
<td>HAT-P-6b</td>
<td>3.6 $\mu$m</td>
<td>3.0</td>
<td>0.65</td>
<td>0.95</td>
<td>2.49</td>
<td>2.63</td>
</tr>
<tr>
<td></td>
<td>4.5 $\mu$m</td>
<td>10.5</td>
<td>0.20</td>
<td>1.80</td>
<td>2.39</td>
<td>2.45</td>
</tr>
<tr>
<td>HAT-P-8b</td>
<td>3.6 $\mu$m</td>
<td>2.5</td>
<td>0.50</td>
<td>0.50</td>
<td>1.67</td>
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$^a$Radius adopted for calculating the stellar intensity for Equation 2.1.

$^b$Variable aperture photometry parameters adopted, see Equation 2.1.

$^c$Median, maximum and minimum variable aperture radius.
Table 2.4. Spectroscopic Observation Details

<table>
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<tr>
<th>Data set name</th>
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<th>Observation date</th>
<th>Wavelength range (µm)</th>
<th>Exposure time (sec)</th>
<th>Spectra count</th>
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*aThe Astronomical Observation Request (AOR) key that uniquely identifies the observation in the Spitzer Heritage Archive (http://sha.ipac.caltech.edu/applications/Spitzer/SHA/).
2.2.2 Spectroscopy Extraction

Similarly to the photometry extraction process, I begin the spectroscopic data reduction with the BCD fits files produced by version S18.18.0 of the Spitzer calibration software. As with the photometry I convert the UTC-based FITS header time information to the TDB standard. Then read in the spectral images for each data set. For the 7.4 – 14 µm, I clip the first two and the last three pixel rows (the spectra are dispersed along the columns) since they are noisier and may be subject to unknown systematic effects. The 5.0 – 7.5 µm data covers rows only between 1 and 80 out 128. Similarly, I clip the first two and the last seven rows for these spectra. I correct energetic particle hits by following the value of each pixel as a function of time and replacing values that are 4σ away from a running median of width 5 with that median. About 0.8% of the pixels from 5.0 – 7.5 µm data sets are corrected for energetic particle hits, compared to 0.4% for 7.4 – 14 µm data and 0.7% for 14 – 40 µm data.

The Spitzer IRS detectors have suffered damage over time from Solar protons. This has caused some pixels to behave as hot pixels (that always show high intensity when read out) or unstable pixels (that, when exposed multiple times to the same intensity, yield unreliably variable measurements, e.g., Howell 2000). These are referred to as “rogue pixels” in the IRS Instrument Handbook, and their number grew in the years of operation of the IRS‡.

For the IRS images discussed here, it appears that, while most rogue pixels are permanently damaged, some pixels can behave like rogue pixels for the duration of some observations and exhibit normal behavior in other data sets. Therefore, creating a single rogue pixel mask for all data sets is not practical. Instead, for each data set and for each image, I compare each pixel to its two closest neighbors in the positive y-direction (the direction of the light dispersion) and two neighbors in the negative y-direction. If a pixel is more than 4σ away from the median of the 5 pixels being examined, then it is flagged as a possible hot pixel. If a pixel is flagged in more than 25% of the images of a given data set, then it is considered a hot pixel. However, a hot pixel will often be flagged 80% or more of the time in a given data set. In addition, I flag as suspect pixels whose standard deviation throughout the data set is 3σ or higher than the mean standard deviation of its two neighbors on each side in the y-direction. The fractions of pixels I flag as suspect are ∼6% in the 5.0 – 7.5 µm data sets, ∼2.5% in the 7.4 – 14 µm data and ∼3% in the 14 – 40 µm data. Each of these pixels is replaced by the median value of its two neighbors above and below, in each image.

I then use optimal extraction, as described in Horne (1986), to reduce the images to one dimensional spectra. First, for each image, I estimate the background as a function of wavelength by fitting a third order polynomial to each pixel row (perpendicular to the dispersion direction), excluding the flux where the source is located. Then, for each pixel row, I subtract the background and use a Gaussian function to locate the peak detected emission. This allows me to follow any curves or gradual distortions of the dispersed spectrum. For each row, I make an initial estimate of the detected flux by integrating

‡A thorough discussion of the IRS rogue pixels can be found in Section 7.2 of the IRS Instrument Handbook, http://irsa.ipac.caltech.edu/data/SPITZER/docs/irs/irsinstrumenthandbook/.
the intensity over x-position in pixels. The integration is centered on the x-position measured by the Gaussian centroid. The integration range changes with wavelength, since the PSF widths change with wavelength, but it is always $3\sigma$ of the Gaussian centroid in both the positive and negative x-directions. I then use the algorithm from Horne (1986) to iteratively calculate the optimum spectrum in each image. Sample raw spectra between 5 and 7.5 $\mu$m and 7 and 14 $\mu$m are presented in Figure 2.4.

![Sample extracted spectra utilizing the Horne (1986) optimal extraction algorithm.](image)

**Fig. 2.4** Sample extracted spectra utilizing the Horne (1986) optimal extraction algorithm. A sample spectrum from the g14 data sets is shown in the left panel, and one from the g4 data set in the right panel. In my analysis, I follow the brightness at a given wavelength as a function of time.

Sample light curves with the spectra integrated over wavelength are presented in Figures 2.5 and 2.6. I discard the data set acquired on 2006 Oct 21 (designated g1 in Table 2.4), because the telescope was nodded between two positions every 30 exposures (every $\sim 12$ minutes). This was done to facilitate efficient background removal, but in practice it makes effects, such as the ramp of intensity with time and the quasi-periodic sinusoidal variation, difficult to correct reliably. In addition, the g1 data set contains higher levels of white noise than the g2 data set, which is not nodded, despite the identical exposure times. The 14 – 40 $\mu$m data sets have a very low signal-to-noise ratio and are too strongly affected by noise to yield any useful results. Therefore, I choose to reject these data as well, and focus on the g2 – g18 data sets.
Fig. 2.5 To produce the light curves above, the extracted time-series spectra between 5 and 7.5 µm have been integrated over wavelength. The resulting white light intensity as a function of time has been normalized to 1 at the time of eclipse and offset for clarity. The time here is in units of phase, the fraction of the planetary orbit elapsed since the middle of transit. It is calculated based on the FITS file observation and exposure times, converted to the TDB standard, and the ephemeris adopted in Table 1.1. The colored labels are the data set designations from Table 2.4. The apparent oscillation in the flux of the star is caused by the telescope’s pointing jitter. As the pointing shifts, the spectroscope slit drifts across the stellar PSF, causing the apparent brightness of the target to vary. This systematic effect and its removal are discussed in detail in Chapter 3.
Fig. 2.6 Similar to Figure 2.5 but for the time series spectroscopy between 7.4 and 14 μm.
Chapter 3

Analysis and Results

3.1 Photometric Light Curves

3.1.1 Data Preparation

The instrumental effects in Spitzer IRAC light curves are significant, and a secondary eclipse can only be detected after their careful removal. I normalize the intensity of each light curve to unity at the time of secondary eclipse. I remove several points from some of the data sets because their images have relatively high background intensity levels: 13 points for XO-4 at 3.6 $\mu$m, 5 points for XO-4 and HAT-P-3 at 4.5 $\mu$m, 9 for HAT-P-3 at 3.6 $\mu$m, 22 for HAT-P-4 at 3.6 $\mu$m, 42 for HAT-P-4 at 4.5 $\mu$m, 75 for HAT-P-12 at 3.6 $\mu$m and 26 for HAT-P-12 at 4.5 $\mu$m. In addition, in agreement with previous studies (e.g., Harrington et al. 2007; Agol et al. 2010; Deming et al. 2011; Cowan et al. 2012), I find that the 57th frame in each data cube of the subarray mode data sets exhibits elevated background levels (215-220 frames per subarray mode light curve). The photometric points from images with higher background are often not outliers, but they may be subject to unknown systematic effects that I cannot account for. Therefore, I elect to omit them from the analysis.

There are two primary systematic effects known from previous Spitzer IRAC light curve observations that can affect the beginning of a light curve. First, at the start of the observation there is often a period of $\sim 10 - 30$ minutes before the position of the target star stabilizes on the IRAC array (e.g., Anderson et al. 2011). Light sensitivity for IRAC varies not only from pixel to pixel, but also within pixels. For the initial observations, the peak of the stellar PSF often falls on pixel regions with different intrapixel sensitivity variations than for the rest of the observation. This causes the initial observations to appear brighter or dimmer than the rest before the pointing and the observed intensity stabilize.

The second transient systematic effect (e.g., Campo et al. 2011; Deming et al. 2011) is not correlated with the position of the stellar image on the detector array and affects only some of the 3.6 $\mu$m light curves. It causes the observed intensity at the start of the observation to increase (or in some cases decrease) sharply before stabilizing. This is similar to an effect observed for the 5.8 and 8.0 $\mu$m IRAC arrays during the cryogenic phase of the Spitzer observatory. This was believed to be due to charge trapping and building up in the pixels during the continued observations of a bright target. This affects only the illuminated pixels, and the charge trapping rate depends on the level of illumination (e.g., Knutson et al. 2007; Agol et al. 2010). It appears that poorly illuminated pixels that form the background of the image climb the ramp continuously at a much slower rate than the pixels where the stellar image falls.
The only reliable way to eliminate these effects is to clip the beginning of the observations as necessary. Therefore, I drop from the analysis the first 48.7 minutes from the HAT-P-3 data at 3.6 $\mu$m, corresponding to 1423 frames taken before orbital phase of 0.44. Similarly, I reject: the first 1056 points (or, 35.5 minutes of observations), with phase less than 0.445 for HAT-P-8 at 3.6 $\mu$m; the first 1920 photometric points for HAT-P-6 at 3.6 $\mu$m (initial 65 minutes), with phase less than 0.465; and the initial 876 data points for HAT-P-6b at 4.5 $\mu$m, corresponding to 30 minutes of data with phase less than 0.4582. The other data sets do not appear to be affected and therefore I do not discard their initial portions. It is unclear why some data sets are more severely affected than others, although it is likely related to the observations performed with IRAC immediately before the current ones and their flux levels.

The time stamps of the individual time frames are in modified Julian date, which makes the numbers large and difficult to handle. Therefore, I convert them to units of orbital phase using the ephemerides listed in Table 1.1. The orbital phase in this dissertation is defined as the fraction of the planetary orbital period elapsed since the middle of the last primary transit. The central phases of the hot Jupiter eclipses are expected to occur near phase of 0.5.

### 3.1.2 Initial Fit and Systematics Correction

In order to estimate the values of the parameters of the eclipse-and-systematics model described below, I assume a given central phase of the eclipse and perform a simultaneous linear regression to the unbinned light curve for all fit parameters. I iterate this procedure for a range of values of the central phase. For each central phase, I record the $\chi^2$ value of the light curve model regression fit and adopt the parameters and central phase that produce the lowest $\chi^2$ value to be the initial fit best parameters. The central phase step size in units of phase is $10^{-5}$ and I cover the phase range from 0.48 to 0.52. I also experiment with larger phase ranges, especially for the cases of HAT-P-12b (both wavelengths) and XO-4 (3.6 $\mu$m), which exhibit very shallow eclipses but this does not improve the fits. Letting the central phase of the eclipse to vary is needed because it depends on several factors. The most important parameter is the orbital eccentricity, which is in these cases close to zero, but not necessarily exactly zero. Even very small eccentricities can cause central eclipse phases to differ by $\sim 0.01$ from the expected value of 0.5. In addition, other parameters, like the system’s light-travel delay (very well known for my data) and the temperature map of the day side of the planet can also cause apparent shifts from the expected central phase of 0.5. The possible offsets are discussed in more detail in Section 3.1.3

The observed central position of the stellar image on the detector array is typically confined within a single pixel, even though there is a quasi-periodic telescope pointing drift with amplitude of about 0.1-0.2 pixels on $\sim 40$ minutes time scales, as discussed in Section 1.5. I find that the X and Y position of the stellar image on sub-pixel scale and the observed stellar intensity are correlated. This appears to be caused by intrapixel sensitivity variation, which is consistent with the findings of other studies that have used the *Spitzer* IRAC instrument (e.g., Knutson et al. 2009; Beerrer et al. 2011; Deming et al. 2011). In order to correct for this correlation, I adopt a quadratic dependence between
the X and Y positions and the intensity:

\[ I(t) = at + b_1 X + b_2 X^2 + c_1 Y + c_2 Y^2 + I_0 + d_1 M, \]  

(3.1)

where \( I(t) \) is the observed stellar intensity as a function of time, \( t \) is time in units of phase, \( X \) and \( Y \) are the positions of the stellar centroid on the pixel in the x and y directions, \( M \) is the secondary eclipse shape model, and \( a, b_1, b_2, c_1, c_2, I_0 \) (the ordinate axis intercept) and the eclipse depth, \( d_1 \), are the free parameters of the model. The eclipse shape model, \( M \), is based on the Mandel & Agol (2002) calculations, but with no limb darkening effects included, because during secondary eclipse the planet is behind the star and stellar limb darkening plays no role in the light curve formation. Planetary limb darkening (or possibly brightening, if the atmosphere is inverted) is an extremely small effect that affects only the ingress and egress portions of the eclipse, but not its depth. The signal-to-noise ratio of our observations is much too low to detect this effect. Therefore, it is not included in the eclipse model. From these parameters, I am interested in \( d_1 \), while the rest are used to correct for instrumental effects. The central phase of the secondary eclipse is included in the computation of \( M \) and it needs to be assumed in advance, thus it is not part of the linear regression fit. Adding the noise pixel parameter, \( \tilde{\beta} \) (Section 2.1.2), as an extra dimension to this fit, does not improve the quality of the regression, and hence I do not include it. Numerous studies in the past have also settled on a quadratic decorrelation function (e.g., Charbonneau et al. 2008; Knutson et al. 2008; Christiansen et al. 2010; Anderson et al. 2011; Cochran et al. 2011; Demory et al. 2011; Désert et al. 2011). Fixing any combination of the parameters of \( a, b_2 \) and \( c_2 \), at zero reduces the number of free parameters and unsurprisingly causes the minimum value of \( \chi^2 \) to increase indicating a worse fit.

However, it is possible that by keeping all parameters free I am “over-fitting” the light curve. Therefore, I experiment with the Bayesian information criterion test (BIC, Schwarz 1978) as a way to determine the optimal number of free parameters for my light curve model. The BIC is a \( \chi^2 \)-like statistic that penalizes the use of numerous parameters.

\[ BIC = \chi^2 + k \ln(N), \]  

(3.2)

where \( k \) is the number of parameters and \( N \) is the number of data points. I calculate the values of the BIC as a function of the number of free parameters. In addition, I check the BIC values resulting from additional higher order terms to Equation 3.1. I find a broad BIC minimum near a quadratic correction function in both X and Y. This choice could not be rigorously defended for each individual data set, however, the totality of the results suggests that setting all parameters in Equation 3.1 free, while not adding additional terms is the optimal choice for removing the effects of the intrapixel sensitivity variation. For the HAT-P-4b at 3.6\( \mu \)m and HAT-P-12b at 4.5\( \mu \)m data sets, the minimum BIC is found by removing the quadratic terms of Equation 3.1, but this leads to red noise with large amplitude in the residuals of the light curves when the best fit models are subtracted. In the case of the HAT-P-4b at 3.6\( \mu \)m data set, this also leads to an unrealistically large eclipse depth value. These problems suggest that the BIC test is not ideally suited for this problem. Therefore, I elect to set all parameters
from Equation 3.1 free consistently for all data sets, but not add any higher order terms to it.

The parameter $a$ from Equation 3.1 governs the slope of a linear function with time. The overall BIC results favor keeping the parameter free. In addition, in the case of HAT-P-6 at 3.6 $\mu$m, a measurable linear ramp with positive slope appears in the residuals if $a$ is fixed at zero. Hence, I elect to keep $a$ as a free parameter in all data sets.

In both wavelengths, the best fit eclipse depths of HAT-P-12b are consistent with zero. To investigate the possible interference from systematic effects that I have not accounted for, I experiment by removing various portions of the data near the start and near the end of the observations from the analysis. The resulting fits have central phases that cover the whole observed range and eclipse depths that take small positive or negative values (the latter are unphysical but allowed by my analysis algorithms). Based on this, I cannot claim a detection of the secondary eclipses of this planet.

### 3.1.3 Best Fits and Uncertainties

After using the initial linear regression fits to determine the best functional form and number of free parameters for the light curve models, I utilize two methods to determine the best fit values of these parameters and their uncertainties – Markov Chain Monte Carlo (MCMC) and prayer-bead Monte Carlo (PBMC). I implement a MCMC algorithm following the recipe suggested by Ford (2005, 2006). I perturb one parameter at a time, choosing randomly which parameter to make a step next. The step size is drawn from a Gaussian distribution. I perform $10^6$ iterations per free parameter, which amounts to $8 \times 10^6$ steps total – there are seven free parameters in Equation 3.1, but for the MCMC I also include the central phase as a formal free parameter. Before running the main chain, I run several shorter chains to optimize the widths of the Gaussian distributions that govern the step sizes of each parameter. These are chosen so that step acceptance rates for every parameter are between 35% and 55%. This probability for the acceptance of a new parameter state is optimal for efficient conversion (Ford 2006, and references therein).

For each data set, I create histograms of the physically interesting parameter values from the MCMC chains, by dropping the initial $10^6$ as copious “burn in” time to ensure the chain’s convergence. These histograms of parameter states approximate Gaussian distributions and I adopt the best fit value of a parameter from the MCMC method to be the median of its histogram. The uncertainties are taken to be standard deviations from this best fit value. I present the eclipse depth histograms in Figures 3.1 and 3.2. Since the MCMC algorithm assumes that the data are dominated by Gaussian white noise, the parameter histograms appear approximately Gaussian even for data sets dominated by red noise.

Both eclipses of HAT-P-12b are below my detection limits and therefore the MCMC fails to converge. Therefore, for these data sets, instead of MCMC uncertainties, I report eclipse depth upper limits derived from the best fit value and uncertainties from a linear regression fit at eclipse central phase of 0.50007. This number refers to an orbit with $e \cos(\omega) = 0$, where $e$ is eccentricity and $\omega$ is the argument of periastron and includes a correction for planetary system light travel delay time. It does not, however,
Fig. 3.1 The histograms that result from the PBMC (black line) and MCMC (red line) fits for HAT-P-3, HAT-P-4 and HAT-P-12 are shown here. There are $7 \times 10^6$ MCMC steps included in the red histogram in each panel, therefore, these histograms are arbitrarily scaled down for clarity. I take the best fit eclipse depth value for each method to be the median eclipse depth from that Monte Carlo run. These best fits are indicated by the vertical solid lines – black for PBMC and red for MCMC. The dashed lines bracket regions centered on the best fit values that cover 68% of the Monte Carlo depth measurements (color coded as before). Since the HAT-P-12b eclipse is not detected, the MCMC does not converge, and hence there is no meaningful histogram for these runs. For this planet’s prayer-bead runs, the eclipse depths are centered at phase 0.50007, as described in the text. The blue solid and dashed lines represent the best fit and 1σ uncertainties from the linear regression used to determine the eclipse depth in the observed light curves. For the final results listed in Table 3.1, I conservatively adopt the larger of the two uncertainty estimates for a given data set.
Fig. 3.2 As in Figure 3.1, I show the histograms that result from the PBMC (black line) and MCMC (red line) fits, but for HAT-P-6, HAT-P-8 and XO-4. The MCMC histograms are arbitrarily scaled down for clarity, since each of them contains $7 \times 10^6$ steps total. Again, I take the best fit eclipse depth for each method to be the median resulting from that Monte Carlo run. The best fits are indicated by the vertical solid lines for PBMC (black) and MCMC (red). The dashed lines bracket regions centered on the best fit values that cover 68% of the Monte Carlo depth measurements (color coded as before). For the final results shown in Table 3.1, I adopt the larger of the two uncertainty estimates for a given observation.
take into account a possible apparent eclipse central phase delay caused by the hottest spot on the face of the planet trailing behind the substellar point as the planet orbits its host star. This delay, if present, is expected to be small – 20 – 30 s (e.g., Knutson et al. 2007; Agol et al. 2010).

The influence of red noise on the parameter uncertainties can be estimated by utilizing a “prayer bead” analysis approach (Gillon et al. 2007a). This technique has been used in the past on Spitzer IRAC data sets (e.g., Désert et al. 2011; Deming et al. 2011). In the PBMC algorithm, I subtract the initial fit from the raw photometry and shift the residuals over to the right (positive in time) by one; I move the last measurement the now vacant first position. Then, I add the shifted residuals back to the best fit initial regression model. In this way, I simulate an artificial but realistic data set with the red noise preserved. I fit the light curve model to the simulated data using the same procedure as for the initial fit (Subsection 3.1.2). For the next iteration, I shift the residuals by two, then three, etc. I repeat these steps as many times as there are photometric data points in the light curve (over $10^4$ in each case), each data set simulation using the residuals based on the regression fit to the observed data. I record the eclipse depth and central phase found for each simulated data set and plot their histograms in Figures 3.1 and 3.2. For data sets where the residuals of the best fit are dominated by white noise, the parameter histograms approach a Gaussian, as expected. For the light curves where red noise in the initial fit residuals is prominent, the histograms are strictly non-Gaussian.

The minimum $\chi^2$ values yielded by the regression fit to the original data indicate a best fit that is necessarily close to the true parameter values only for data sets dominated by white noise, or where the red noise has been efficiently removed. However, in the residuals of the best fits for Spitzer IRAC light curves, red noise is often still evident. This noise is presumably due to instrumental effects that have not been taken fully into account and, therefore, it is unrelated to the astrophysical event being observed. In this sense, each of the data sets simulated by the PBMC could have happened to be the observed one (assuming that the residuals do not include an over- or under-subtracted eclipse). Thus, I report the best fit value based on the PBMC to be the median eclipse depths and central phases from the PBMC histograms. The PBMC uncertainties are based on the histogram region that covers 68% of the values, centered on the PBMC median.

The final results for the eclipse depths and central phases are presented in Table 3.1 and Figures 3.3 and 3.4. Between the MCMC and PBMC best values, I conservatively adopt the results from the method that yields the larger uncertainties. If the photometry data are dominated by white noise, this approach should reduce to adopting the model that yields the minimum $\chi^2$. Since the removal of systematic effects is relatively efficient, the eclipse depths from the initial regression fit are close to the final best values found by PBMC or MCMC: for HAT-P-3b, the initial fit results in depths of 0.108% and 0.096% versus Monte Carlo median eclipses of $0.112^{+0.015}_{-0.013}$ and $0.094^{+0.016}_{-0.009}$, at 3.6 and 4.5 $\mu$m, respectively. In both wavelengths, the difference between the two estimates is about 0.13 $\sigma$. The HAT-P-4b initial fit eclipses are $0.142^{+0.014}_{-0.016}$ and $0.122^{+0.012}_{-0.014}$ from the MC at 3.6 and 4.5 $\mu$m, respectively (differences of 0 and 0.17 $\sigma$, respectively). The initial fit eclipse depths for HAT-P-6b are 0.108%
The HAT-P-8b initial eclipses have depths of $0.131\%$ (3.6 $\mu$m) and $0.111\%$ (4.5 $\mu$m), 0.22 and 0.38 $\sigma$ different, respectively, from the values I adopt as final results. The XO-4b initial fit eclipse depths are $0.050\%$ (3.6 $\mu$m) and $0.130\%$ (4.5 $\mu$m), different by 0.25 and 0.20 $\sigma$, respectively, from the adopted values. Therefore, the exact choice of best fit eclipse depth values has no effect on my conclusions about the atmospheres of these planets.

3.2 Spectroscopic Light Curves

3.2.1 Systematic Effects

There are two systematic effects that dominate the red noise in the Spitzer IRS secondary eclipse observations. The first one is a ramp with time similar to the ones seen in 8 $\mu$m IRAC observations (e.g., Knutson et al. 2008; Agol et al. 2010; Todorov et al. 2010). The physical reasons for this ramp are unclear, but it is hypothesized that it is due to photoelectrons getting trapped in detector defects that act as quantum wells (e.g., Agol et al. 2010). At the start of the observation the electron traps are empty and a fraction of the photoelectrons generated by each exposure are captured instead of read out. As the observations progress, the wells fill and a larger and larger fraction of the photoelectrons from the most recent exposure are read out, leading to an apparent brightening of the observed source with time. When the electron traps are full, essentially all photoelectrons are read out and the apparent brightness of the source asymptotically approaches a constant value (assuming that the astrophysical source is constant, of course). Based on this hypothesis, Agol et al. (2010) suggest a physically motivated toy model to account for the ramp,

$$\frac{F'}{F} = a_0 - a_1 e^{-t/\tau_1} - a_2 e^{-t/\tau_2},$$

(3.3)

where $F'$ is the detected intensity before the correction for the ramp, $F$ is the intensity corrected for the ramp, $a_0$, $a_1$, $a_2$, $\tau_1$ and $\tau_2$ are coefficients and $t$ is time since the start of the observation. The parameters in the two exponential terms in Equation 3.3 are degenerate and strongly correlated, causing convergence problems for the MCMC algorithm I use to determine the best fit eclipse depths and their uncertainties. Therefore, I simplify the Agol et al. (2010) expression by neglecting the second exponential term. This causes a marginal increase of the minimum $\chi^2$ value achieved by the fits, and significantly reduces their BIC value (Schwarz 1978). Therefore, simplifying the expression in this manner is justified.

Another function that has been empirically successful (e.g., Todorov et al. 2010) in removing the ramp is the log-linear,

$$\frac{F'}{F} = a_0 - a_1 t - a_2 \log(t),$$

(3.4)

where the parameters are defined as in Equation 3.3. An advantage of this function is that the coefficients do not appear as exponents and thus the expression can be used
Fig. 3.3 The secondary eclipse time series photometry for HAT-P-3, HAT-P-4 and HAT-P-12 at 3.6 and 4.5 µm after correction for instrumental effects. The bins are 0.0015 wide in units of orbital phase, corresponding to 6 minutes 16 s, 6 minutes 36 s and 6 minutes 56 s for HAT-P-3b, HAT-P-4b and HAT-P-12b respectively. The best fit parameters are used to correct all photometric data, but only the parts of the light curve covered by the best fit model (red line) were used in the fit. I place upper limits on the HAT-P-12b eclipse depth, which in this plot has been set to zero.
Fig. 3.4 Similarly to Figure 3.3 but for HAT-P-6, HAT-P-8 and XO-4, here the secondary eclipse time series photometry at 3.6 and 4.5 μm is displayed after correction for the instrumental effects. The bin widths are again 0.0015 in units of orbital phase, corresponding to 8 minutes 19 s, 6 minutes 39 s and 8 minutes 55 s for HAT-P-6b, HAT-P-8b and XO-4b respectively. Only the parts of the light curve covered by the best fit model (red line) were used in the fit, but I show all of the data with the best fit corrections applied.
Table 3.1. Secondary Eclipse Photometry Results

<table>
<thead>
<tr>
<th></th>
<th>Eclipse Depth (%)</th>
<th>Brightness Temperature (K)(^a)</th>
<th>Eclipse Central Phase</th>
<th>BJD(_{TT})(^b) - 2 450 000</th>
<th>O – C(^c) (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAT-P-3b</td>
<td>3.6 (\mu m) 0.112(^{+0.015}_{-0.030})</td>
<td>1575(^{+75}_{-162})</td>
<td>0.50515(^{+0.00092}_{-0.00110})</td>
<td>5272.82936(^{+0.00264}_{-0.00316})</td>
<td>21.2(^{+3.8}_{-4.6})</td>
</tr>
<tr>
<td></td>
<td>4.5 (\mu m) 0.094(^{+0.016}_{-0.009})</td>
<td>1268(^{+77}_{-45})</td>
<td>0.50084(^{+0.00106}_{-0.00071})</td>
<td>5275.71660(^{+0.00304}_{-0.00203})</td>
<td>3.2(^{+4.4}_{-3.0})</td>
</tr>
<tr>
<td>HAT-P-4b</td>
<td>3.6 (\mu m) 0.142(^{+0.014}_{-0.019})</td>
<td>2194(^{+98}_{-116})</td>
<td>0.49945(^{+0.00091}_{-0.00081})</td>
<td>5298.78653(^{+0.00275}_{-0.00243})</td>
<td>-2.8(^{+4.9}_{-3.5})</td>
</tr>
<tr>
<td></td>
<td>4.5 (\mu m) 0.122(^{+0.014}_{-0.012})</td>
<td>1819(^{+83}_{-100})</td>
<td>0.49960(^{+0.00110}_{-0.00102})</td>
<td>5442.44368(^{+0.00333}_{-0.00309})</td>
<td>-2.1(^{+4.8}_{-4.5})</td>
</tr>
<tr>
<td>HAT-P-6b</td>
<td>3.6 (\mu m) 0.108 (\pm 0.007)</td>
<td>1876(^{+49}_{-51})</td>
<td>0.50018(^{+0.00051}_{-0.00054})</td>
<td>5451.65548(^{+0.00187}_{-0.00208})</td>
<td>0.2(^{+2.8}_{-3.0})</td>
</tr>
<tr>
<td></td>
<td>4.5 (\mu m) 0.099 (\pm 0.010)</td>
<td>1607(^{+69}_{-72})</td>
<td>0.49874(^{+0.00064}_{-0.00079})</td>
<td>5459.35593(^{+0.00240}_{-0.00300})</td>
<td>-7.8(^{+3.5}_{-4.4})</td>
</tr>
<tr>
<td>HAT-P-8b</td>
<td>3.6 (\mu m) 0.130(^{+0.005}_{-0.010})</td>
<td>1924(^{+31}_{-63})</td>
<td>0.49965(^{+0.00030}_{-0.00048})</td>
<td>5211.37506(^{+0.00076}_{-0.00138})</td>
<td>-2.3(^{+1.3}_{-2.1})</td>
</tr>
<tr>
<td></td>
<td>4.5 (\mu m) 0.108(^{+0.008}_{-0.010})</td>
<td>1574(^{+50}_{-63})</td>
<td>0.50032(^{+0.00078}_{-0.00113})</td>
<td>5208.30077(^{+0.00220}_{-0.00345})</td>
<td>0.7(^{+3.5}_{-5.0})</td>
</tr>
<tr>
<td>HAT-P-12b</td>
<td>3.6 (\mu m) &lt; 0.042</td>
<td>&lt; 970</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>4.5 (\mu m) &lt; 0.085</td>
<td>&lt; 980</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>XO-4b</td>
<td>3.6 (\mu m) 0.053(^{+0.007}_{-0.012})</td>
<td>1497(^{+67}_{-123})</td>
<td>0.50230(^{+0.00155}_{-0.00131})</td>
<td>5181.01893(^{+0.00635}_{-0.00536})</td>
<td>12.7(^{+9.2}_{-7.8})</td>
</tr>
<tr>
<td></td>
<td>4.5 (\mu m) 0.128 (\pm 0.010)</td>
<td>1907(^{+71}_{-73})</td>
<td>0.50042(^{+0.00052}_{-0.00045})</td>
<td>5172.76101(^{+0.00203}_{-0.001683})</td>
<td>1.6(^{+3.1}_{-2.6})</td>
</tr>
</tbody>
</table>

\(^a\)The uncertainty of the brightness temperature included here only takes into account the uncertainty of the eclipse depths, but not the uncertainties in the stellar properties and the planetary radius.

\(^b\)Time of secondary eclipse central phase, in Barycentric Julian Date (BJD) based on Terrestrial Time (TT). For these observations, TT \(\approx\) UTC + 66.184 s.

\(^c\)The measured offset in minutes from the expected central phase for \(e \cos(\omega) = 0\) of 0.5, adjusted for light travel delay.
for linear regression fits. The two functions produce very similar $\chi^2$ values, but the log-linear function yields slightly higher results. Therefore, I choose to adopt the single exponential function for my analysis.

The second systematic effect is caused by the telescope pointing oscillation described in Section 1.5. While in photometric data, the change in apparent brightness is caused by variable sensitivity across the surface of a single pixel, here it is caused by the fact that the spectrograph slit moves across the PSF of the target. The slit is 3.6
d wide*, compared to the telescope’s angular resolution of 1.5” to 4.2” in the 5 – 14$\mu$m range. Thus, as the pointing oscillates, brighter or fainter sections of the PSF are sampled, causing the oscillation in intensity evident in Figures 2.5 and 2.6. Since the PSF width is proportional to wavelength, while the slit size is independent of it, the amplitude of the apparent intensity variation with time is also wavelength dependent, with higher amplitudes toward shorter wavelengths, for a given pointing oscillation amplitude. For brevity, I refer to this systematic effect as “sawtooth” effect due to the correction function for it chosen by Grillmair et al. (2008). They use an asymmetric sawtooth function with constant amplitude of each tooth to account for the intensity variation, however, Figures 2.5 and 2.6 show that the amplitude and shape of the sawtooth can change within a single observation. Therefore, I explore other options for the removal of this effect.

The best way to remove the effect would be to have precise pointing information from the observatory itself and thus be able to reconstruct the sawtooth. The image file headers have keywords related to pointing but they indicate a complete compliance of the pointing with the desired direction, and show no evidence of the pointing oscillation. Therefore, I contacted the Spitzer help desk and asked for the raw telemetry from the telescope during the time of the observations, which they graciously provided. However, it appears that as the temperature of the heater that causes the pointing oscillation varies, the Spitzer star trackers begin to lose and then regain their alignment with the telescope’s boresight. Thus, the recorded pointings of the telescope are perfectly centered on the target star, despite the change in the pointing of the main mirror. The readings from the observatory gyroscopes also do not provide any useful information.

Since there are multiple observations of HD 189733b in both wavelength ranges, it is possible to stack the resulting light curves. Since the amplitude and phase of the sawtooth change from one observation to the next, in the stacked light curves, the sawtooths nearly cancel one another. This is expected since the pointing oscillation is due to the cycling of a heater, as discussed in Section 1.5, and it is, therefore, not correlated with the orientation of the telescope. Stacking the white light curves from Figures 2.5 and 2.6, but excluding the g6, g7 and g10 data sets due to their very high amplitude sawtooths, results in high signal-to-noise observations of the broadband 5 – 7$\mu$m and 7 – 14$\mu$m secondary eclipses (Figure 3.5). Their depths can be measured very precisely, even if the sawtooth is ignored and only the ramp is taken into account. The broadband eclipses and ramps can then be subtracted from the individual white light curves shown in Figures 2.5 and 2.6, resulting, after smoothing, in sawtooth correction functions for each data set. Since the pointing oscillation is independent of wavelength, only the amplitude

*http://irsa.ipac.caltech.edu/data/SPITZER/docs/irs/irsinstrumenthandbook/4/.
of the sawtooth is wavelength-dependent, not its shape. Hence, the sawtooth correction functions can be multiplied by a factor and applied to the individual narrow-band light curves. I elect to utilize this sawtooth correction approach, since it is feasible and makes no assumptions on the shape of the sawtooth. The precise sawtooth correction algorithm is described below. A caveat of this approach is that any variability of the secondary eclipse depths will be lost. However, Agol et al. (2010) place a $1\sigma$ upper limit of 2.7% on the variability of the HD 189733b day side at 8 $\mu$m, and so it is unlikely that planetary flux variability exists in the infrared at levels that are detectable in the IRS data.

3.2.2 Fitting Procedure

In order to determine the sawtooth correction functions for each data set, I need to first measure the eclipse depths and central phases of the two stacked white light curves shown in Figure 3.5. To stack the eclipse observations, I convert the times of observation to units of orbital phase using the ephemeris listed in Table 1.1 (Triaud et al. 2009) and normalize each white light curve so that the intensity within eclipse is unity. Next, I simply combine all of the measurements in a single data set ordered by orbital phase. Since the $g2$ data set (Table 2.4) has exposure times about four times shorter than the other spectra, I bin these data only by four. I then fit the eclipse and ramp using a MCMC algorithm very similar to the one used in the time-series photometry analysis presented in Section 3.1.3. For this fit, I ignore the sawtooths, since they have mostly canceled one another, and adopt the following expression as the model:

$$I(t) = a_0 - a_1 e^{-t/\tau_1} + d_1 M.$$  (3.5)

The free parameters I define here are the eclipse depth, $d_1$, the central phase and $a_0$, $a_1$ and $\tau_1$ from Equation 3.3 and $I(t)$ is the model intensity as a function of time. As in Section 3.1.2, the secondary eclipse shape is based on the Mandel & Agol (2002) model, but without the limb darkening effects. Since each eclipse observation started at a slightly different phase, the steep sections of their ramps occur at different phases. This makes the stacked light curves noisy and unreliable at phases below \(\sim 0.47\). Not all data sets have observed after phases larger than \(\sim 0.54\), making these portions of the stacked light curves more vulnerable to non-canceled sawtooth variations (Figure 3.5). Therefore, I only use the data between phases 0.47 and 0.54 for the MCMC fit and for all fits on stacked light curves from now on. As with the MCMC runs for the IRAC photometry, I first run several short chains to optimize the widths of the Gaussian distributions from which the step sizes of each parameter are drawn. Again, I pick these such that the step acceptance rates are between 35% and 55%, which are optimal for efficient conversion (Ford 2006, and references therein). I perform $6 \times 10^6$ MCMC steps per light curve and drop the first $10^6$ steps to allow plenty of “burn-in” time for the chain to converge. Since the histograms of the parameter runs closely resemble Gaussian functions, I adopt the mean eclipse depths and central phases from the MCMC parameter runs as the best fit stacked white light eclipse parameters. I find that in the $5 - 7 \mu$m data, the best fit eclipse depth is 0.216% with central phase of 0.50014, while for the $7 - 14 \mu$m data these values are 0.370% and 0.50060, respectively. Assuming \(e \cos(\omega) = 0\) (Agol et al. 2010), the expected eclipse central phase is 0.50016, just due to light travel delay. However,
broadband IRAC observations at 8 µm (Agol et al. 2010) find an additional central phase delay of 38 ± 11 s (0.00020 ± 0.00005 in units of phase). Agol et al. (2010) interpret this as evidence that the hottest point on the day side of the planet lags along the orbit with respect to the substellar point. Thus, my central phase measurements are consistent with previous high signal-to-noise results.

In order to estimate the sawtooth correction function in each wavelength, I take the individual white light curves and, using the same MCMC algorithm, fit them with a ramp (without sawtooth), again using Equation 3.5 as a fitting model. This time, for a given data set, I hold the eclipse depth and central phase constant at their best values from the stacked white light curve fit. I subtract the resulting eclipse-and-ramp model from the white light curve. The residuals represent the sawtooth correction curve and the photon noise. In order to estimate just the sawtooth, I bin the residuals by six, which smooths the curve. This binning factor was chosen through experimentation and represents a sweet spot – larger factors smooth the curve too much and degrade the quality of the measured shape of the function, while smaller factors retain large amounts of noise. I then use the IDL routine *spline* to perform a cubic spline interpolation between the binned points to estimate the value of the sawtooth correction at the phases that correspond to the observed data. A sample of the results obtained from this operation are presented in Figure 3.6.

The light curves derived from a single pixel row in the spectral images have very low signal-to-noise ratio. In order to improve this, I first bin the light curves in wavelength by three, so that each binned channel is derived from three pixel rows, instead of one. Thus, I examine 24 channels between 5 and 7 µm and 42 channels between 7 and 14 µm. In addition, I stack all light curves in a given channel together, similarly to the way the white light curves are stacked – I combine all of the intensity measurements in that channel from all data sets into a single light curve. Again, the light curves from the g2 data sets are binned by four in time, in order to make all data sets have equal exposure times per data point. I do not bin the resulting light curve in time. For each of the data sets, I have estimated the value of the sawtooth correction function for every observation as a function time. Since I have elected to stack the individual channel light curves, I need to combine the sawtooth correction functions as well. I do this, again, by simply combining them without binning or smoothing, since each individual spectrum image has a unique sawtooth correction value associated with it. The amplitude of the sawtooth correction function is dependent on wavelength and so I multiply the stacked sawtooth correction by a new free parameter, ζ, for each stacked light curve for a given wavelength channel. This assumes that ζ is independent of time, and the same value of ζ at a given wavelength applies to all data sets. Because of the relatively low signal-to-noise levels in the non-stacked single-channel light curves, this assumption is difficult to test in practice. However, it is reasonable, since the size of the PSF, which determines the sawtooth amplitude for a given shift in pointing, is stable with time and is only dependent on wavelength. *Spitzer* is on an Earth-trailing orbit around the Sun that is much more thermally stable than, e.g., the Hubble Space Telescope’s low-Earth orbit. Thus, not surprisingly, I see no significant changes in the focus of *Spitzer* throughout the observations that may be due to temperature changes over time.
Fig. 3.5 In order to cancel out the effects of the sawtooth, I stack the white light curves shown in Figures 2.5 and 2.6 into two high signal-to-noise broadband light curves (black points) covering the wavelength ranges between $5 - 7 \mu m$ (top) and $7 - 14 \mu m$ (bottom). The stacked white light curves are normalized to unity at the time of secondary eclipse and offset for clarity. The red line represents the function from Equation 3.5 (eclipse and ramp, but no sawtooth) with the best fit MCMC parameters. The red line phase coverage indicates the region of the light curves that was used for the fits.
Fig. 3.6 The residuals of the white light curve of the g15 data set with the ramp-and-eclipse model removed (black points). For this fit, the eclipse and central phase were held fixed at 0.216% and 0.50014, respectively (the best fit eclipse depth and central phase of the stacked white light curve for the 5 – 7 µm range data). The red diamonds represent the residuals binned by 6. The red line is the cubic spline interpolation between these. I adopt this line as the sawtooth correction function for all g15 narrow-band light curves.
For each wavelength channel, like for the photometric light curves, I perform both MCMC and PBMC fits. The MCMC fits utilize the same algorithm used for the white light curves above, but with the sawtooth included, giving the light curve model equation the form,

\[ I(t) = a_0 - a_1 e^{-t/\tau_1} + \zeta S_s + d_1 M, \]  

(3.6)

where \( S_s \) is the stacked sawtooth correction function. The free parameters here are \( a_0, a_1, \tau_1, \zeta \) and \( d_1 \). The eclipse central phase is held fixed at the best fit value for the stacked white light curve, since it is approximately independent of wavelength\(^\dagger\). For the eclipse central phases, I adopt the values from the stacked white light curves in their respective wavelength ranges, since these fits have much higher signal-to-noise ratios than the single channel measurements. For each channel, I use the recorded MCMC parameter runs to create a histogram of the eclipse depth values accepted by the algorithm. These histograms are close to Gaussian, and so I fit Gaussian functions to them. I adopt the mean of the Gaussian as the best fit eclipse depth for this channel and the Gaussian width as its uncertainty. Sample raw and corrected light curves in two channels are shown in Figures 3.7 and 3.8, along with their best fit models from the MCMC.

Because of possible incompleteness of the sawtooth correction or additional systematic effects for which I have not accounted, there could be residual red noise in the data. To assess its significance, I perform a PBMC fit on the light curves of every channel. My approach is similar to the one I used for the photometric PBMC, but here I adopt the MCMC realization with the smallest \( \chi^2 \) as the best fit model. In addition, shifting the residuals between the best fit model and the stacked light curve is inappropriate in this case, since each observation has its own red noise associated with it, independently of the other observed light curves. Therefore, I shift by a random amount the residuals of each individual light curve at a given channel with the best fit subtracted. I then add the shifted residuals back to the best fit, for each light curve, and combine the shifted light curves as before. Performing a MCMC fit on the thus simulated stacked light curves a statistically significant number of times is prohibitively computationally expensive. Instead, I fit the model light curve using the IDL \texttt{mpfit} package, designed for non-linear least squares fitting (Markwardt 2009). The free parameters in the fits are the same as for the MCMC fits. I simulate 10,000 stacked light curves, which allows me to examine the cumulative effect of the red noise in the individual eclipse observations on the stacked light curves. As in the photometric PBMC runs, I record the eclipse depths during a run, and take the best fit depth to be their median. The 1\( \sigma \) uncertainties are determined as the region of the histogram of a given PBMC depths run that cover 68\% of the values of that run, centered on the median eclipse depth.

I compare the eclipse depths and uncertainties resulting from the MCMC and PBMC fits and find that the PBMC yields larger uncertainties for all wavelengths. The

\[^\dagger\]The central phase may actually be weakly dependent on wavelength. If the hot spot of HD 189733b is shifted from the substellar point as Knutson et al. (2007) and Agol et al. (2010) suggest, then this spatial shift may be different at different atmospheric depths. A hot spot lagging behind the planetary disc center will cause the ingress and egress to appear to occur slightly later than anticipated, causing a delayed eclipse central phase. Since different wavelengths probe different atmospheric levels, this delay may be different for each wavelength. However, this effect is likely subtle and can be safely ignored here.
Fig. 3.7 The stacked uncorrected light curve at 11.38\(\mu\)m (top panel) for all data sets covering this wavelength (black points). The best fit light curve model (red line) includes the ramp, sawtooth correction and the eclipse. The middle panel shows the same light curve, but with the sawtooth and ramp removed. The bottom panel shows the corrected light curve again, but this time binned in phase. Each bin contains about 12 data points and spans 0.0005 in units of phase (2 minutes). The y-axis scaling in the bottom panel is different than in the panels above to emphasize the eclipse which is clearly visible in the binned photometry. The red lines in the middle and lower panels show the best fit eclipse curve. As discussed in Section 3.2.2, the intensity measurements at orbital phases less than 0.47 or greater than 0.54 are dropped, since some of these regions are not covered by all data sets and the ramps do not stack reliably at below phases of 0.47.
Fig. 3.8 Similar to Figure 3.7 but for the light curve at 6.58 µm. Here, even though each bin still covers 0.0005 in units of phase (2 minutes), this corresponds to only about 10 data points per bin, since there are one fewer secondary eclipse light curves in the 5 – 7 µm range than in the 7 – 14 µm range.
PBMC eclipse depths are always within 1σ of the MCMC best fit values. Therefore, in order to be conservative, I adopt the PBMC best fit depths and uncertainties. Technically, the wavelength range of the 7−14 µm IRS spectra extends a little beyond 15µm. However, the intensities detected at wavelengths longer that ∼13.5 µ are subject to the well-documented “teardrop” effect (named like this because in the spectral images, the shape of the spectrum trace becomes lumpy, like a teardrop, at these wavelengths). This effect is due to light leakage, detector or optics defects, and there is no reliable way to correct for it. To ensure that this effect does not impact my results, I remove all eclipse depths at wavelengths longer than 13.5 µ from my results. The final eclipse depth results and their uncertainties are summarized in Table 3.2. The horizontal line in this table between the 7.51 and the 7.53 µm depths indicates the border between the results from the 5−7 µm and the 7−14 µm data sets. The physical implications of the resulting planetary eclipse depth spectrum are discussed in the next chapter.

‡http://irsa.ipac.caltech.edu/data/SPITZER/docs/irs/features/#8_SL1_14u_Teardrop.
### Table 3.2. Secondary Eclipse Spectroscopy Results

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Eclipse Depth (%)</th>
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<tr>
<td>5.46</td>
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<tr>
<td>5.55</td>
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<td>5.65</td>
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<td>5.74</td>
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<td>5.83</td>
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<td>Wavelength (µm)</td>
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Chapter 4

Physical Implications

4.1 Photometric Light Curves

4.1.1 Comparison to Models

I use planetary emergent flux models from Burrows et al. (2007, 2008), based on the chemical equilibrium and opacity studies by Burrows & Sharp (1999); Sharp & Burrows (2007), and Fortney et al. (2005, 2006a,b, 2008) to examine the physical meaning of the measured broad band eclipse depths at 3.6 and 4.5 $\mu$m. These models can shed light on the likely thermal structures and heat transport efficiencies of the observed planets. In the Burrows models, there are two important parameters that control these. $\kappa_{abs}$ (in units of cm$^2$g$^{-1}$) is the absorption coefficient for the unknown high-altitude absorber presumed to cause temperature inversions. $P_n$ is a parameter that describes the efficiency with which heat is transported from the day side to the night side of the planet. $P_n$ is defined such that $P_n = 0$ represents no energy transport to the night side, while $P_n = 0.5$ is complete redistribution, where 50% of the energy absorbed on the day side is redistributed to the night side.

In the Fortney models, the opacity of the absorber is determined by the presence or absence of TiO and VO in the planet’s atmosphere, which is a Boolean parameter. The only truly free parameter is $f$, the heat redistribution efficiency. It is defined such that for $f = 0.25$ (the minimum value of the parameter) the stellar energy is evenly redistributed over the whole planet. For $f = 0.5$ the heat is evenly spread out on the day side, but no heat leaks to the night side. $f = 0.67$ (the maximum parameter value), represents a situation where no heat flows laterally on the planet, even within the day side of the planet, causing a prominent hot spot near the substellar point to form.

Since both types of models rely on input from multiple sources other than the “free parameters” discussed above, such as chemical opacities and abundances, it makes little sense to mathematically fit the models to two photometric data points. The best current approach is to compute a set of models for each planet for a range of combinations of the free parameters and manually select the ones that bear resemblance to the data after visual examination after considering the errors.

Both the Fortney and the Burrows models neglect the effects from clouds or chemical disequilibrium chemistry that have been suggested to play a role on the atmospheres of some planets (e.g., Pont et al. 2008; Stevenson et al. 2010). All models discussed here adopt a solar composition atmosphere, except for the $f = 0.6$ Fortney model for HAT-P-12b (Figure 4.1), which has 30× solar metallicity and the Fortney $f = 0.5$ non-inverted temperature profile model (without TiO and VO) for HAT-P-8b, which has metallicity 10× the solar value (Figure 4.2). A caveat of these models is that if the atmospheric composition is significantly different from the one adopted, or if clouds play a large role
in the formation of the emission spectrum, the temperature pressure profiles derived here may be inaccurate.

### 4.1.2 HAT-P-3b

The corrected light curves of HAT-P-3 in both wavelengths show some residual red noise, seen in Figures 3.3. This could be explained by the star’s slightly elevated levels of chromospheric activity with Ca II H&K activity index, $\log(R'_{HK}) = -4.904$ (Knutson et al. 2010). However, since this is close to the solar value of $\log(R'_{HK}) = -4.9$ (Noyes et al. 1984), residual systematic effects that have not been accounted for during the analysis are a more likely explanation.

For the atmosphere of HAT-P-3b I adopt a Burrows model with $\kappa_{abs} = 0.1 \text{ cm}^2 \text{ g}^{-1}$ and $P_n = 0.1$. This suggests a temperature inversion and a modest heat redistribution efficiency. The Fortney models also suggest low redistribution efficiency with $f = 0.6$, but the planet is sufficiently cool that the presence or absence of TiO and VO in the atmosphere has minimal effect on the shape of the spectra. Therefore, the Fortney models cannot be used to differentiate between an inverted and non-inverted atmosphere for this object and the HAT-P-3b eclipse depths are matched equally well with both inverted and non-inverted Fortney models. Both the adopted Burrows and Fortney models for HAT-P-3b are shown in Figure 4.1 along with models with radically different parameters in order to illustrate the level of differentiation between models.

The suggestion from both sets of models that the heat redistribution efficiency to the night side of the planet is low seems to be in contradiction with the prediction of Perna et al. (2012) that hot Jupiters with irradiation temperature, $T_{\text{irr}} \lesssim 2400 \text{ K}$ have efficient flux redistribution. Perna et al. (2012) define $T_{\text{irr}} = T_{\text{eff}}(R/\alpha)^{1/2}$, where $T_{\text{eff}}$ is the effective temperature of the star, $R$ is the radius of the star and $\alpha$ is the semimajor axis of the planet’s orbit. For HAT-P-3b, $T_{\text{irr}} = 1610 \text{ K}$. On the other hand, Cowan & Agol (2011) predict that a wide range of redistribution efficiencies are possible for planets with $T_{\epsilon=0} \lesssim 2400 \text{ K}$, while the choice of allowed redistribution efficiencies is significantly narrowed above this threshold. In their notation, $T_{\epsilon=0}$ is the effective temperature of the planet’s day side assuming no redistribution and zero Bond albedo. Since for HAT-P-3b $T_{\epsilon=0} = 1300 \text{ K}$, our results do not contradict, nor do they support this hypothesis.

A common way to parametrize the transport of heat to the night side of a planet is based on the balance between the time scale for a packet of gas to be transported to the night side by winds, $t_{\text{trans}}$, versus the time scale for it to reach thermal equilibrium with its surroundings, $t_{\text{rad}}$. It is often thought that gas packets on planets with inefficient heat redistribution re-radiate their excess heat to space before they have a chance to reach the night side (e.g., Cooper & Showman 2005; Rauscher & Menou 2010; Cowan & Agol 2011; Perna et al. 2012). How these time scales compare depends on many factors, including the value of the time scales themselves (Perez-Becker & Showman 2013), but, as Cowan & Agol (2011) hypothesize, the outcome could vary for cooler planets, while $t_{\text{rad}} < t_{\text{trans}}$ for hotter planets. A very recent theoretical study by Perez-Becker & Showman (2013) suggests that another time scale that may be important – the time scale for the propagation of a pressure wave across the planet’s surface. These
authors argue that local convection or irradiation differences can cause pressure gradients between locations of equal altitude in the atmosphere, resulting in pressure waves, which can then transport energy horizontally. The pressure wave propagation speeds for hot Jupiters are unknown, thus Perez-Becker & Showman (2013) do not make a prediction about the redistribution efficiencies at given planetary effective temperatures.

Knutson et al. (2010) hypothesize that the chromospheric activity of the host star may be correlated with the presence of absence of a temperature inversion. However, for HAT-P-3b the value of $\log(R''_{\text{HK}})$ lies close to the suggested border between stars that host hot Jupiters with inverted versus non-inverted atmospheres, as seen in Figure 4.3. Thus, predictions about what thermal structure the atmosphere of HAT-P-3b should have, according to this idea, are difficult. This, combined with the uncertain outcome from the models, makes using HAT-P-3b to test the Knutson et al. (2010) hypothesis virtually impossible without further measurements in other wavelengths.

4.1.3 HAT-P-4b

I find very little residual red noise in the light curves for HAT-P-4. This is consistent with the star’s low chromospheric Ca II H&K activity index $\log(R''_{\text{HK}}) = -5.082$ (Knutson et al. 2010). The host star of HAT-P-4b is more luminous than HAT-P-3, but the planet is also hotter than HAT-P-3b, leading to slightly deeper eclipses, and smaller error bars in the measurements of their depth.

The preferred Burrows model for HAT-P-4b is based on $\kappa_{\text{abs}} = 0.2 \text{ cm}^2 \text{ g}^{-1}$ and $P_n = 0.1$. This suggests an inversion of the temperature pressure profile of the atmosphere and inefficient transport of heat to the planet’s night side. Both the inverted and non-inverted Fortney models with $f = 0.5$ resemble the observations, even though they are not ideal matches. This implies little redistribution of heat from the day side to the night side. Thus, as in the case of HAT-P-3b, it is difficult to claim the detection of a temperature inversion, although both sets of models agree that efficient heat transfer to the night side of the planet is unlikely. A comparison of the adopted and rejected Burrows and Fortney models for HAT-P-4b is presented in Figure 4.1.

In the Perna et al. convention, for HAT-P-4b, $T_{\text{irr}} = 2440 \text{ K}$. According to Perna et al. (2012), planets with $T_{\text{irr}}$ higher than approximately 2200 to 2400 K are expected to have a low heat redistribution efficiency due to short time scales for re-radiation of heat to space compared to the time needed to transport the hot day side gases to the night side. This makes my result consistent with their hypothesis. For this planet, $T_{c=0} = 2000 \text{ K}$, which is still not high enough to test the hypothesis of Cowan & Agol (2011) that the range of redistribution efficiencies is narrow for $T_{c=0} \gtrsim 2400 \text{ K}$.

Similarly to HAT-P-3, the HAT-P-4 host star lies in the border region between stars whose chromospheric activity causes temperature inversions versus those that do not (Figure 4.3, Knutson et al. 2010). In combination with the ambiguous pressure-temperature structure of the atmospheres from the Burrows and Fortney models, the HAT-P-4b planet is also a poor test of the Knutson et al. (2010) hypothesis.
4.1.4 HAT-P-6b

For HAT-P-6b’s atmosphere I adopt a Burrows model with $\kappa_{\text{abs}} = 0.1 \text{ cm}^2 \text{ g}^{-1}$ and $P_n = 0.3$, suggesting a modest temperature inversion with moderate heat recirculation efficiency. The Fortney model I select has $f = 0.63$ and no TiO/VO in the upper layers of the atmosphere. This implies inefficient heat transport to the night side of the planet and no temperature inversion. The combined results from the models are inconclusive, but they seem to rule out strong temperature inversion and high-efficiency heat transport to the night side.

One measurement of the Ca II H&K activity index of the planet’s host star is $\log(R'_{\text{HK}}) = -5.03 \pm 0.10$ (Hébrard et al. 2011). However, Knutson et al. (2010) find $\log(R'_{\text{HK}}) = -4.799$. This discrepancy is possibly due to the relative weakness of the Ca II H&K lines compared to the continuum for hotter stars. This is the reason why the activity index is not calibrated for stars with $T_{\text{eff}} \gtrsim 6200$ K (Noyes et al. 1984). For HAT-P-6b, $T_{\text{eff}} = 6410$ K (Knutson et al. 2010). This, combined with the ambiguous implications of the Burrows and Fortney models regarding the planet’s atmospheric temperature inversion, makes this system unsuitable for testing of the Knutson et al. (2010) hypothesis, as indicated in Figure 4.3.

For HAT-P-6b, $T_{\text{irr}} = 2310$ K, which is very similar to XO-4b’s value of $T_{\text{irr}}$ (see Subsection 4.1.7). The moderate-to-low heat redistribution efficiency suggested by the models for HAT-P-6b appears to be consistent with the Perna et al. (2012) predictions for a planet whose irradiation temperature is in the $2200 - 2400$ K range, their proposed limit between efficient and inefficient atmospheric heat redistribution. In the notation of Cowan & Agol (2011), $T_{\epsilon=0} = 2090$ K, similar to HAT-P-4b and XO-4b. This is well below the $2400$ K threshold needed to test their hypothesized narrow distribution of recirculation efficiencies above that limit.

4.1.5 HAT-P-8b

The Burrows model that describes the HAT-P-8b results well has $\kappa_{\text{abs}} = 0 \text{ cm}^2 \text{ g}^{-1}$ and $P_n = 0.1$, implying very low heat redistribution efficiency and no inversion of the pressure-temperature profile of the atmosphere. The Fortney model I select has $f = 0.5$, and also no temperature inversion, with adopted metallicity of $10 \times$ that of the Sun. HAT-P-8b is currently the only planet in the published literature that has a host star hotter than $6000$ K and has an unambiguous lack of temperature inversion based on Spitzer data.

The Ca II H&K activity index of the host star is $\log(R'_{\text{HK}}) = -4.985$ and its effective temperature is, $T_{\text{eff}} = 6130$ K (Knutson et al. 2010). This temperature is very close to the Noyes et al. (1984) limit of $6200$ K above which the chromospheric activity index is not calibrated. Even so, HAT-P-8b appears to be in the border region in stellar chromospheric activity space between inverted and non-inverted planetary atmospheres. Therefore, despite the agreement in the models that the planet has a non-inverted atmosphere, the HAT-P-8b measurements neither support, nor contradict the Knutson et al. (2010) hypothesis that non-inverted planets orbit chromospherically active stars (Figure 4.3).
The irradiation temperature of HAT-P-8b is $T_{\text{irr}} = 2480$ K, similar to that of HAT-P-4b. The inefficient heat transport from the day side to the night side of the planet suggested by the Burrows and Fortney models is consistent with the Perna et al. (2012) idea that planets with $T_{\text{irr}} \gtrsim 2200 - 2400$ K are expected to have a low heat redistribution efficiency. The effective temperature of the planet’s day side assuming no redistribution and zero Bond albedo is, $T_{e=0} = 2240$ K. This is less than the suggested $2400$ K limit above which Cowan & Agol (2011) expect a narrow range of redistribution efficiencies. Thus, this planet can neither support, nor undermine their hypothesis.

4.1.6 HAT-P-12b

We do not detect the HAT-P-12b secondary eclipses and we are only able to place upper limits on their depth. It is possible that, due to sufficiently high orbital eccentricity, the eclipses occur at orbital phases removed from the $0.45 - 0.55$ range on which the available data are centered. In their HAT-P-12b discovery paper Hartman et al. (2009) fix the eccentricity of the planet’s orbit at zero for their final fit. For their initial parameter fit they find $|e \cos \omega| = 0.052 \pm 0.025$, which is not a significant detection of eccentricity. Therefore, I have adopted a circular orbit for the determination of the upper limits of the eclipse depths. The observed phase range, within which I would have detected an eclipse, corresponds to $|e \cos \omega| < 0.08$. This upper limit is only $\sim 1\sigma$ away from the initial fit result in Hartman et al. (2009). Based on the Exoplanet Orbit Database*, only about 12% of known transiting exoplanets with orbital periods below 10 days have eccentricities above 0.08. Therefore, an eccentric orbit is a possible explanation for the non-detection of eclipses, but eclipses that are too shallow to be detected is a more likely explanation.

In the HAT-P-12b light curve at 4.5 $\mu$m it appears to the eye that there may be an eclipse, despite the formal non-detection (Figure 3.3). To test this, I allow for a quadratic light curve variation out of eclipse. This can be caused by phase brightness variations, as a larger and larger portion of the planet’s day side is visible to the observer before eclipse, and starts to diminish after eclipse. This variation can also be caused by stellar spots or other stellar variability. Under these conditions, I find a non-zero eclipse depth of $\sim 0.049\% \pm 0.021\%$. This is a 2.5$\sigma$ result and still does not constitute a formal detection. This result is well within the $3\sigma$ upper limit on the eclipse depth calculated without the quadratic phase curve variation, and it is also within $1\sigma$ of the “best fit” result without a quadratic phase curve variation shown in Figure 3.3.

The measurement with a variable out-of-eclipse light curve is statistically tenuous. In addition, there are several problems related to the usage of a quadratic light curve baseline. Fitting the data with a quadratic curve peaking near mid-eclipse will naturally cause any eclipse to appear deeper, since the baseline from which the depth is measured will be above a flat out-of-eclipse baseline for the duration of the eclipse. In addition to this, none of the other examined data sets required a variable out-of-eclipse baseline. All other planets in my sample are hotter than HAT-P-12b, so a phase curve variation due to increasing visibility of the day side as the planet approaches secondary eclipse should

*http://exoplanets.org; (Wright et al. 2011).
have had a higher amplitude for them than for HAT-P-12b. Also, the chromospheric Ca II H&K activity index of the HAT-P-12 host star is $\log(R'_{HK}) = -5.104$ (Knutson et al. 2010), implying that star spots are unlikely to play a significant role in this star’s atmosphere, certainly less than in, e.g., the Sun, which has $\log(R'_{HK}) = -4.9$ (Noyes et al. 1984). This suggests that the apparent eclipse and out-of-eclipse variation may be artifacts of correlated instrumental noise.

Even though I can only place upper limits on the eclipse depths of HAT-P-12b at 3.6 and 4.5 $\mu$m, I can still compare these limits to the Burrows and Fortney models and place constraints on the physical structure of the atmosphere. HAT-P-12b is the coolest planet in my sample ($T_\text{e} = 1120$ K). Therefore, as in the case of HAT-P-3b, the Fortney models with and without TiO/VO are indistinguishable. The Fortney models closest to the eclipse upper limits have $f = 0.5$ and $f = 0.6$ (the latter with 30× Solar metallicity. Both of these models, however, are poor matches to the upper limits. The inverted Burrows model with $\kappa_{\text{abs}} = 0.1 \text{ cm}^2 \text{ g}^{-1}$ and $P_n = 0.3$ also provides a poor match. However, the non-inverted Burrows model ($\kappa_{\text{abs}} = 0 \text{ cm}^2 \text{ g}^{-1}$, $P_n = 0.3$) appears close to the observational 3$\sigma$ upper limits. A comparison of the adopted and rejected Burrows and Fortney models for HAT-P-4b is shown in Figure 4.1.

Possible explanations of the non-detections of the HAT-P-12b eclipses are that the planet has very efficient heat transport to its night side or that its albedo is high, leaving the planet cooler (and so with less thermal radiation) than expected. However, since none of the models provides a truly good fit for the results, it is difficult to claim any of these suggestions with any certainty. For this planet, $T_{\text{irr}} = 1350$ K, so the possible efficient heat redistribution seems to provide support for the Perna et al. (2012) hypothesis that this is true for planets with $T_{\text{irr}} \lesssim 2200 - 2400$ K. However, I note that Perna et al. (2012) assume surface gravity of $10 \text{ m s}^{-2}$ for their models, while the HAT-P-12b surface gravity is $\sim 5.7 \text{ m s}^{-2}$. This difference may be an important factor in global circulation patterns, and so it is difficult to say that these observations are consistent with the Perna et al. (2012) hypothesis.

I search the literature and I find two planets with relatively cool, low mass planets observed with Spitzer at 3.6 and 4.5 $\mu$m – GJ 436b (Butler et al. 2004; Gillon et al. 2007; Stevenson et al. 2010) and WASP-29b (Hellier et al. 2010; Hardin et al. 2012). These two objects and HAT-P-12b are the three coolest planets observed during secondary eclipse with Spitzer, with equilibrium temperatures, assuming complete redistribution of heat across the whole surface of the planet and no albedo, of $\sim 600$ K (GJ 436b), $\sim 980$ K (WASP-29b) and $\sim 950$ K (HAT-P-12b). The corresponding equilibrium temperatures with zero albedo and no heat redistribution ($T_{e=0}$) are $\sim 700$ K, $\sim 1110$ K and $\sim 1120$ K, respectively. I calculate these values assuming that the planet is always at distance of one semi-major axis away from the host star. This assumption is valid for planets with orbital eccentricities close to zero, like WASP-29b and HAT-P-12b, but for GJ 436b, $e = 0.16$, so the equilibrium temperature given here is only an approximation.

The host star GJ 436 is a M2.5 V red dwarf with $T_{\text{eff}} = 3350 \pm 300$ K (Maness et al. 2007) and metallicity $[M/H] = -0.32 \pm 0.12$ (Bean et al. 2006). HAT-P-12 and WASP-29 are both K4 dwarfs with $T_{\text{eff}} = 4650 \pm 60$ K and $4800 \pm 150$ K, respectively. For HAT-P-12, $[Fe/H] = -0.29 \pm 0.05$ (the same as for GJ 436) and for WASP-29,
\[ \frac{[Fe/H]}{[H]} = 0.11 \pm 0.014 \] (Hartman et al. 2009; Hellier et al. 2010). Exoplanet WASP-29b has mass \(0.244 M_J \pm 0.02 M_J\) (Hellier et al. 2010), which is similar to HAT-P-12b’s (and to Saturn’s) mass. GJ 436b on the other hand is a Neptune-mass planet \((0.0737 M_J \pm 0.0052 M_J\), Southworth 2010).

The 4.5 \(\mu\)m eclipse depth of GJ 436b was below the detection limit of Spitzer, however the 3.6, 5.8, 8.0, 16 and 24\(\mu\)m eclipses were measured. This gave Stevenson et al. (2010) enough information to suggest that the planet’s atmosphere is non-inverted and is out of chemical equilibrium, with high content of CO at the expense of CH\(_4\). In their view, the lack of 4.5\(\mu\)m planetary emission could be caused by strong CO absorption, while the lack of CH\(_4\) absorption could be the cause for the strong 3.6\(\mu\)m emission. However, for pressures of about 1 bar, solar metallicity and temperatures below \(\sim 1100\) K, CH\(_4\) is expected to overtake the abundance of CO and become the dominant carbon bearing molecule (e.g., Lodders & Fegley 2002; Fortney et al. 2008). According to Stevenson et al. (2010), this implies that the atmosphere of the planet is not in thermochemical equilibrium. However, a new study by Moses et al. (2013) suggests that the depletion of CH\(_4\) relative to CO may be a natural result of extremely high metallicity \((\sim 1000\times\) solar\) of the atmosphere. The only available eclipse depth measurements for WASP-29b are at 3.6 (detection) and 4.5\(\mu\)m (non-detection). Hardin et al. (2012) have suggested that the mechanisms behind this could be similar to the ones valid for GJ 436b.

Given that WASP-29b and HAT-P-12b have similar masses and orbit similar stars at similar orbital separations, it would be reasonable to expect that the two planets may have similar atmospheres. Therefore, the non-detection of the secondary eclipses at both 3.6\(\mu\)m and 4.5\(\mu\)m for HAT-P-12b is a surprise, which remains unexplained. I suggest that additional modeling and observations are urgently needed for gas giants with equilibrium temperatures below \(\sim 1000\) K in order to gain understanding of the behavior of their atmospheres. In particular, relatively accessible observations of these planets in the near infrared, where there are multiple methane and CO spectral bands, would be very valuable.

### 4.1.7 XO-4b

The Burrows model that I adopt for XO-4b has \(P_n = 0.35\) and \(\kappa_{\text{abs}} = 0.4 \text{ cm}^2 \text{ g}^{-1}\). This suggests that there is a moderate amount of heat redistribution from the day side to the night side of this planet, combined with a strong inversion of the pressure-temperature profile of its atmosphere. These suggestions are supported by the Fortney model I adopt, with \(f = 0.5\) and TiO/VO absorption in the upper layer of the atmosphere.

The Ca II H&K activity index for the star XO-4 is \(\log(R'_{\text{HK}}) = -5.292\) (Knutson et al. 2010). This places the planet in a stellar activity regime that, according to the hypothesis of Knutson et al. (2010), would correctly predict a temperature inversion. Unfortunately, the activity index measurement is very uncertain because the effective temperature of the host star is \(6400\) K \(\pm 70\) K (McCullough et al. 2008), and the Ca II H&K activity index is not calibrated for stellar effective temperatures above 6200 K or under 4200 K. Therefore, it is difficult to claim with certainty whether XO-4b truly
supports the Knutson et al. (2010) hypothesis of a relationship between stellar chromospheric activity and temperature inversions, as shown in Figure 4.3.

For XO-4b, $T_{\text{irr}} = 2320$, similar to the value for HAT-P-6b. According to the Perna et al. (2012), this irradiation temperature is within the transition region from efficient (lower temperatures) to inefficient (higher temperatures) heat redistribution. This is not inconsistent with the moderate efficiency values suggested by the adopted models. In the notation of Cowan & Agol (2011), $T_{\text{e}=0} = 2080$ K, well below the 2400 K threshold above which they hypothesize a narrow range of heat transport efficiencies for hot Jupiters.

4.2 Spectroscopic Light Curves

4.2.1 Emergent Spectrum Models

I compare the measured emission spectrum of HD 189733b with several model spectra. I am particularly interested in investigating the temperature-pressure (T-P) profile of the atmosphere. Therefore, I utilize a relatively simple radiative transfer code developed by Richardson et al. (2003) and recently updated by D. Deming, which is fast enough to facilitate the retrieval of basic information about the atmosphere. The radiative transfer code includes collision induced absorption from H$_2$-H$_2$ (e.g., Borysow & Frommhold 1990; Borysow 2002) and H$_2$-He (Jørgensen et al. 2000). The planetary atmospheric composition is adopted to be solar, but with all elements except H, He, C and O neglected. The code includes line opacities due to CO, CH$_4$ and H$_2$O. The mixing ratios of these molecules are calculated following Burrows & Sharp (1999). The water lines’ wavelengths and strengths (in units of $cm^2 \cdot s^{-1} \cdot \text{molecule}^{-1}$) are adopted from Partridge & Schwenke (1997). The line opacity is calculated using a Voigt profile for the line shape with pressure broadening coefficient of 0.01 $cm^{-1}$ per atmosphere of pressure. There are hundreds of millions of water lines, many of them overlapping at a given wavelength. This causes the emergent spectrum calculations to be too slow for spectrum retrieval purposes. To mitigate this issue, the water lines are binned to reduce the number of them that need to be included for a given wavelength. Since each line at a given wavelength has a different lower state energy, the binned wavelength strength is dependent on temperature. Therefore, the binning is performed for a range of temperatures in advance. In order to get the combined line strength at the temperature of the current atmospheric layer, the software uses quadratic interpolation between the logarithm of the line strength values for the calculated temperatures. The CO and CH$_4$ lines are not binned, since there are fewer of them than water lines.

The code does not include the effects of clouds or hazes. These appear to play a role in the formation of the planetary transmission spectrum at wavelengths below $\sim 2.5 \mu m$ (e.g., Pont et al. 2008; Gibson et al. 2012) near the terminator of HD 189733b. The Rayleigh-scattering haze suggested by Gibson et al. (2012) is expected to become transparent at longer wavelengths, and has not been observed in the day side spectrum of the planet via secondary eclipses. In addition, the emergent spectrum measured via secondary eclipses involves relatively short, near-vertical light paths through the atmosphere. This is not the case for transmission spectroscopy where the light paths...
Fig. 4.1 The measured eclipse depths (filled circles) compared to the Burrows (left panels; Burrows et al. 2007, 2008) and Fortney (right panels; Fortney et al. 2005, 2006a,b, 2008) models. The upper limits on the HAT-P-12b eclipse depths are represented by downward arrows in the lower panels. The black lines represent the best fit black body planet with a Kurucz-spectrum star (Kurucz 1979). The red lines represent models with a temperature inversion, while the blue lines are models with non-inverted temperature-pressure profiles, except in the cases of the Fortney models of HAT-P-3b and HAT-P-12b, which are relatively cool and TiO and VO have no impact of their spectra. There, the red and blue lines differentiate Fortney models with varying values of $f$. The relevant model parameters are labeled in each panel with the respective colors of the models they refer to. The ratios of the theoretical planetary and stellar fluxes, integrated over the Spitzer IRAC 3.6 and 4.5 $\mu$m pass-bands are shown as diamonds (inverted models) and triangles (non-inverted models).
Fig. 4.2 Similar to Figure 4.1, but for HAT-P-6b, HAT-P-8b and XO-4b. For HAT-P-6b, I adopt an inverted Burrows model with moderate heat redistribution efficiency and a non-inverted Fortney model inefficient heat transport. Both the Burrows and Fortney HAT-P-8b models I select are non-inverted and with relatively inefficient heat redistribution efficiency. Conversely, both the adopted Burrows and Fortney XO-4b models are inverted, although while the Burrows models favor a moderate heat transport efficiency, the Fortney models suggest $f = 0.5$, i.e. strong redistribution throughout the day side, but very little heat flow to the night side. In each panel, I also show less favored models with different values for the parameters. As in Figure 4.1, the labeled parameters are color coded with the spectral models they refer to.
Fig. 4.3 Knutson et al. (2010) hypothesize that there is a correlation between the chromospheric activity of the host star and the presence or absence of a temperature inversion in the atmosphere of a hot Jupiter. Here, the chromospheric activity is represented by the Ca II H&K activity index, $\log(R'_{HK})$ (Noyes et al. 1984), on the y-axis. Chromospherically more active stars (up in this plot) appear to be more likely to host hot Jupiters with non-inverted pressure-temperature profiles (blue stars). This may be because the higher UV and X-ray fluxes from these stars destroy the high altitude absorption layers of the planet’s atmospheres that would otherwise cause an inversion. Planets with less chromospheric activity seem to host planets with a temperature inversion (red circles). In addition, there are planets whose measurements so far are consistent with both inverted and non-inverted atmospheres (gray squares). The activity index is not calibrated for stars hotter than 6200 K (shaded region) or cooler than 4200 K (Noyes et al. 1984). This figure was first published by Knutson et al. (2010) and has been updated here with the objects examined in this dissertation (filled symbols).
have long slanted paths tangential to the planet’s “surface”. Thus, small amounts of haze opacity will have much smaller cumulative effect in secondary eclipse spectroscopy than in transmission spectroscopy. Therefore I do not expect the lack of cloud support of the model to be an important drawback.

In order to calculate the model eclipse depths based on the emergent spectrum of the planet I use a Kurucz model for the HD 189733 host star (Kurucz 1979). Then, I divide the planetary emission model by the Kurucz stellar model, which gives me a prediction for the observed eclipse depths.

The most important free input of the updated Richardson et al. (2003) planetary emergent spectrum model is the T-P profile. I calculate the model output for several different T-P functions in order to investigate the level of atmospheric complexity that can be retrieved from the observations.

I compare the results from these models to the results from the time series spectroscopy from this dissertation. I also examine how the models relate to the eclipse depths from time-series broad-band photometry from Charbonneau et al. (2008) at 3.6, 4.5, 5.8, 8.0 and 16 μm (Spitzer IRAC and MIPS) and at 8 μm (IRAC) from Agol et al. (2010).

4.2.1.1 Isothermal Atmosphere

The simplest T-P profile that can be assumed is an isothermal atmosphere. An isothermal atmosphere should emit black body flux, and therefore in this case, a radiative transfer code is not even necessary. This is an important test, since if the measured planetary eclipses are consistent with black body radiation, it is impossible to claim anything about the structure or composition of the atmosphere of this planet.

The results of this test shown in Figure 4.4 indicate that while at wavelengths λ \gtrsim 8 μm the eclipse depths are consistent with an isothermal atmosphere, the “bump”-like spectral feature in the data around 6.3 μm is not present in the black body spectrum. In addition, the 3.6 μm Spitzer IRAC secondary eclipse depth measurement by Charbonneau et al. (2008) is also inconsistent with an isothermal model. The isothermal spectrum at long wavelengths is in agreement with the findings of a model retrieval method by Lee et al. (2012). This study suggests that the atmosphere at pressures of 0.001 – 0.1 bar (where the 9 – 16 μm emergent spectrum is formed) is isothermal with temperature of about 1100 K. A possible reason for this is the effect of superrotating jets that play a role in heat redistribution from the day side and the night side of the planet and could help maintain a hotter upper atmosphere (Showman & Guillot 2002; Knutson et al. 2007; Lee et al. 2012).

4.2.1.2 Gray Atmosphere

A slightly more realistic T-P profile than an isothermal atmosphere is the T-P profile of a gray atmosphere – in other words an atmosphere which has the same opacity for all wavelengths for a given temperature. In order to calculate the run of temperature
Fig. 4.4 A comparison between the observed spectrum of HD 189733b (filled red circles) with an isothermal atmospheric model (black line), or, in other words, a black body planet. I have also plotted the broad band eclipse depths measured by Charbonneau et al. (2008, filled green squares) with the Spitzer IRAC and MIPS instruments. An average of 6 eclipses at 8 µm measured by Agol et al. (2010) is also indicated (open green square). The band integrated contrasts are plotted for the black body model (blue stars) and the Charbonneau et al. (2008) and Agol et al. (2010) measurements (green stars). The dotted lines represent the Spitzer IRAC and MIPS bandpass transmission functions for the respective broad band measurements, scaled arbitrarily for clarity.
with pressure, I use the following expression (e.g., Rutten 2003):

\[ T(\tau) = T_{\text{eff}} \left( \frac{3}{4} \tau + \frac{1}{2} \right)^{1/4}, \]  

(4.1)

where \( T(\tau) \) is the temperature as a function of \( \tau \), the optical depth, and \( T_{\text{eff}} \) is the temperature of the planets atmosphere at \( \tau = 2/3 \). This expression is a classic result in radiative transfer theory. It is an analytic solution for the temperature structure of a gray atmosphere, based on the Milne-Eddington approximation and an assumption of local thermostatic equilibrium. I begin the emergent flux calculation with a run of pressure values between \( 3 \times 10^2 \) and \( 2 \times 10^8 \text{ dyn cm}^{-2} \) (\( 3 \times 10^{-4} \) to \( 2 \times 10^2 \text{ bar} \)). Thus, to use this expression, I need to calculate the optical depth, \( \tau \), for each point in pressure (starting at the top of the atmosphere, looking down). This is a gray atmosphere approximation, therefore I adopt the Rosseland mean opacities (\( \kappa_R \)) given by Freedman et al. (2008) for ultracool brown dwarfs and exoplanets. The Rosseland mean opacity of a gas depends on temperature, pressure and gas composition. I adopt the Freedman et al. (2008) table of \( \kappa_R \) values for a solar metallicity, which has temperatures in the range between 75 and 4000 K and pressures between \( 3 \times 10^2 \) and \( 3 \times 10^8 \text{ dyn cm}^{-2} \). The change in optical depth can be easily computed from the \( \kappa_R \) using the expression (e.g., Rutten 2003):

\[ d\tau = -\kappa_R \rho dz, \]  

(4.2)

where \( \rho \) is the gas mass density and \( dz \) is the change in altitude between two layers in pressure (positive upward). The equation of hydrostatic equilibrium in stellar structure theory is often written as

\[ \frac{dP}{dr} = -\frac{Gm}{r^2} \rho, \]  

(4.3)

where \( dP \) is change in pressure, \( G \) is the gravitational constant, \( r \) is the distance to the center of the star and \( m \) is the mass within this radius (e.g., Kippenhahn & Weigert 1994). This equation applies to gas giant planets as well. At the surface, where the atmosphere is, we can replace \( m \) with the mass of the planet, \( m_p \), \( r \) with the radius of the planet, \( r_p \), and \( dr \) with \( dz \). Then, \( \frac{Gm_p}{r_p^2} = g \), the surface gravity. Rearranging and substituting \( dz \) in Equation 4.2 yields

\[ d\tau = \frac{\kappa_R dP}{g}. \]  

(4.4)

The equation is easily integrated to yield \( \tau \) as a function of pressure. Now, I can use Equation 4.1 to calculate \( T(\tau) \) and hence, \( T(P) \), the T-P profile.

Since \( \kappa_R \) is temperature dependent, I begin with an “initial guess” T-P profile: isothermal atmosphere, whose temperature becomes the effective temperature of the day side of the planet, \( T_{\text{eff}} \), at \( \tau = 2/3 \) in the final T-P profile (as evident in Equation 4.1). I use the initial guess T-P profile to estimate which values of the Rosseland mean opacity from the Freedman et al. (2008) table I need to use. From these I calculate the optical depth, \( \tau \), as a function of pressure and use Equation 4.1 to calculate the temperature as a function of pressure. I take the resulting T-P profile as the new best guess and I
iterate these steps until the best guess T-P profile converges with the previous estimate. I experiment with a range of values for $T_{eff}$ for the planet and find that the model emergent spectrum with $T_{eff} = 1300$ K is closest in intensity to the measured eclipses, based on $\chi^2$ minimization. The resulting temperature-pressure profile is presented in Figure 4.5.

I use the calculated gray T-P profile as an input for the Richardson et al. (2003) radiative transfer model described in Subsection 4.2.1. Even though the temperature as a function of pressure input assumes a gray atmosphere, the model does not. The resulting planetary emergent spectrum compared to the measured eclipse depths is presented in Figure 4.6.

### 4.2.1.3 The Burrows Model

The study by Grillmair et al. (2008) that examines 10 of the 18 spectroscopic light curves discussed here also compares their resulting eclipse depths as a function of wavelength with a model of the emergent flux of the atmosphere. The models Grillmair et al. (2008) utilized are the same the Burrows models I adopt to investigate the Spitzer IRAC photometry. They were developed by Burrows et al. (2007, 2008) and rely on the chemical equilibrium and opacities derived by Burrows & Sharp (1999) and Sharp & Burrows (2007). These are fully non-gray models that solve the equations of hydrostatic equilibrium, conservation of radiated flux and chemical equilibrium, except for the addition of a parametrized generic high-altitude absorber and the parametrized redistribution of energy to the night side of the planet. In order to test the validity of the Grillmair et al. (2008) results, I compare the Burrows model that matches best with the Grillmair et al. (2008) depths to the depths derived in this dissertation. In addition, I use the T-P profile adopted in this model as input for the Richardson et al. (2003) code and calculate a model emergent spectrum based on the simpler chemical composition assumed in it. The Burrows model adopted by Grillmair et al. (2008) as a good match to their results has a heat redistribution parameter, $P_n = 0.15$ and an absorption coefficient of the high altitude absorber, $\kappa_{abs} = 0.035 \text{ cm}^2 \text{ g}^{-1}$. The meanings of these parameters are the same as discussed in Subsection 4.1.1 on the models applied to the photometric light curve eclipse depths. The Burrows T-P profile is shown in Figure 4.7. The Burrows model and the Richardson model based on the Burrows T-P profile are compared to the eclipse depths in Figure 4.8.

### 4.2.2 Implications for the Atmosphere of HD 189733b

The eclipse depths measured via time series spectroscopy here appear to be systematically shallower (lower on the graph) than those measured by Charbonneau et al. (2008) and Agol et al. (2010) via broad band time series photometry. Grillmair et al. (2008) also find systematically deeper IRS eclipses than this dissertation, especially at wavelengths below $\sim 7.5 \mu\text{m}$.

The discrepancy in the eclipse depths measured here and in Grillmair et al. (2008) and Charbonneau et al. (2008) could also be due to the variability of the host star. The eclipse depth, as defined in this dissertation is the ratio between the flux of the planet and the flux of the star. It is possible that the observations presented in Grillmair et al.
Fig. 4.5 The calculated temperature versus pressure (lower panel) and versus optical depth (upper panel) for a gray atmosphere. The dashed line marks the temperature at $\tau = 2/3$, the effective temperature of the planet.
Fig. 4.6 Similar to Figure 4.4, but here I show a comparison between the observed spectrum of HD 189733b (filled red circles) and the gray atmosphere model discussed in Subsection 4.2.1.2 (black line). As before, I have plotted the Spitzer IRAC and MIPS broad band eclipse depths measured by Charbonneau et al. (2008, filled green squares) and Agol et al. (2010, open green square). The band integrated contrasts are plotted for the gray atmosphere model (blue stars) and the Charbonneau et al. (2008) and Agol et al. (2010) measurements (green stars). The dotted lines represent the Spitzer IRAC and MIPS bandpass transmission functions scaled arbitrarily.
Fig. 4.7 The calculated temperature versus pressure (lower panel) and and optical depth (upper panel) for the Burrows model atmosphere for HD 189733b taken from Grillmair et al. (2008). For this model, $P_n = 0.15$ and $\kappa_{abs} = 0.035 \text{cm}^2 \text{g}^{-1}$. Even though the absorption from the unknown absorber in the upper layers is small, it causes a small temperature inversion near 0.01 bar. Compared to the inversion inferred by Burrows et al. (2007) for HD 209458b, where the dip in temperature below the absorbing layer has amplitude of over 600 K, the temperature inversion here is almost negligible. In addition, newer models of HD 189733b have found no evidence of any inversion (Madhusudhan & Seager 2009; Swain et al. 2009b). Hence, HD 189733b is usually considered to have non-inverted atmosphere (e.g., Knutson et al. 2010). The dashed line marks the temperature at $\tau = 2/3$, the effective temperature of the planet.
Fig. 4.8 A comparison between the observed spectrum of HD 189733b (filled red circles) and the Burrows atmosphere model (Grillmair et al. 2008), discussed in Subsection 4.2.1.3 (purple line). The black line is the Richardson et al. (2003) model using the Burrows T-P profile as input. As in Figures 4.4 and 4.6, I have plotted the Spitzer IRAC and MIPS broad band eclipse depths measured by Charbonneau et al. (2008, filled green squares) and Agol et al. (2010, open green square). The band integrated contrasts are plotted for the Richardson et al. (2003) atmosphere model (blue stars) and the Charbonneau et al. (2008) and Agol et al. (2010) measurements (green stars). The dotted lines represent the Spitzer IRAC and MIPS bandpass transmission functions scaled arbitrarily.
(2008) and Charbonneau et al. (2008) were performed near stellar flux minima, causing relatively deep secondary eclipses, while the data analyzed here in addition to the ones from Grillmair et al. (2008) may have been observed near stellar flux maximum, leading to shallower eclipses. HD 189733 is variable in the visible at the \( \sim 1 - 2\% \) level due to (changing) large starspots coming in and out of view with the rotation of the star (Winn et al. 2007). The temperature of the starspots is roughly 1000 K cooler than the rest of the photosphere (Pont et al. 2007) and they cover \( \sim 1 - 2\% \) of the stellar surface (Henry & Winn 2008). Assuming black body flux for the spots and the photosphere, a stellar variability of 1.5% at 0.5 \( \mu m \) translates approximately in variability of about 0.4 – 0.6% in the infrared between 3.6 and 16 \( \mu m \), decreasing towards longer wavelengths. Therefore, I expect that the change in eclipse depth due to stellar variability to be in the 0.4 – 0.6% range, which is insufficient to account for the discrepancy between my measurements and the Grillmair et al. (2008) and Charbonneau et al. (2008) results.

Instead, this discrepancy is likely due to the way I estimate the white light eclipse depth and remove the sawtooth effect, as discussed in Chapter 3. This is not problematic since the possible offset in eclipse depth is relatively small and the shape of the spectrum should be preserved. Because of this, it is difficult to draw conclusions about the heat redistribution efficiency of HD 189733b based on the time series spectroscopy, since it determines the effective temperature of the day side and hence overall flux levels of thermal radiation. However, I can examine the shape of the T-P profile, based on the shape of the observed emergent spectrum.

In their study, Grillmair et al. (2008) notice a “bump” in the observed spectrum of HD 189733b near 6 \( \mu m \). They attribute this feature to water absorption bands seen on either side of the bump, causing an apparent increase of planetary flux between them. Grillmair et al. (2008) also note a very tentative emission peak at 5.9 \( \mu m \), that is not caused by water and is not replicated by their models. These features are also evident in the observations presented here, as seen in, Figure 4.9. However, even though the planetary flux near 5.9 \( \mu m \) appears to be slightly higher than its neighbors in my results, the uncertainties are too high to claim even a tentative detection. In order to test the robustness of the 6 \( \mu m \) water feature, I examine the planet-star contrast between 5.9 \( \mu m \) and 7.0 \( \mu m \). I fit a Gaussian function added to a line to the water bump and measure its amplitude to be 0.00058 (in units of contrast), its mean: 6.28 \( \mu m \), and its width, \( \sigma \): 0.15 \( \mu m \). I simulate 10,000 spectra by drawing random numbers from Gaussian distributions with means equal to the fitted line without the Gaussian (as if the spectral bump was not real) and widths corresponding to the observed uncertainties. I fit each of these simulated data sets in the same way as the true eclipse depths spectrum. I find that about \( \sim 3\% \) of the simulated data sets have peaks similar to the one detected in the observed spectrum – with amplitudes greater than 0.0001 and widths between 0.1 \( \mu m \) and 0.2 \( \mu m \).

The observed spectrum appears less noisy than the large uncertainties suggest. I perform a simple test on the plausibility of the error estimates. I assume that for a relatively smooth planetary spectrum, two eclipse depths at adjacent wavelengths should be close to equal. Then, for independent random errors, their difference should be about equal to the square root of the sum of their squared uncertainties. I then compare these values with the observed differences between neighboring best estimate depths and
Fig. 4.9 A part of the eclipse depth spectrum of HD 189733b around the 6 µm water feature. I overplot a Gaussian added to a linear function to guide the eye. The Gaussian is centered on 6.28 µm and has width, \( \sigma = 0.15 \) µm. I have also indicated the location of the very tentative and unidentified 5.9 µm peak also seen by Grillmair et al. (2008).
find that the uncertainties in the $5 - 7 \mu m$ range are about 63% larger than statistically expected. The uncertainties between $7.5 - 13.5 \mu m$ are about 54% larger than expected. If I reduce the observed uncertainties by this amount, and simulate evaluate the likelihood of the bump to occur randomly in the data again, as before, the number of simulated data sets that produce a bump similar to the one in the data drops to about 2.5%. This is a strong indication that the water feature is real and not an artifact of random noise.

Thus, the isothermal model can be ruled out at the $\sim 97\%$ level based solely on the IRS data and the $6 \mu m$ water feature is detected with the same certainty. I do not attempt to estimate the abundance of water because it is strongly degenerate with temperature, in particular at 0.3 bar (Lee et al. 2012). My analysis is in agreement with Grillmair et al. (2008) who rule out a straight line spectrum model at 95%. The photometric measurements from Charbonneau et al. (2008) could be fit with an isothermal atmosphere curve, albeit at higher temperature, except the $3.6 \mu m$ measurement. The latter is in strong disagreement with the predictions of emission from a black body planet at any temperature. Therefore, the combination of spectroscopy and photometry enables us to reject the isothermal model for the atmosphere.

Similar conclusions can be drawn from the Richardson et al. (2003) model with a T-P profile of a gray atmosphere. The shape of this model spectrum is similar to that of the isothermal model, especially when binned to the spectral resolution of the Spitzer IRS and IRAC eclipse depth measurements. The $6.3 \mu m$ water feature is seen in the model, but it is too weak to cause a significant perturbation in the band-integrated model spectrum (Figure 4.6). As in the case of the isothermal atmosphere, the gray T-P profile atmosphere can be rejected with the help of the Charbonneau et al. (2008) $3.6 \mu m$ IRAC eclipse depth, which has a higher amplitude that the $4.5 \mu m$ eclipse, compared to the gray T-P profile prediction that it should be lower.

The Richardson model with the Burrows T-P profile from Grillmair et al. (2008) and the Burrows model itself (Figure 4.8) provide the best matches to the shape of the spectrum I measure, particularly around the $6.3 \mu m$ water feature. However, both of these predict deeper eclipses than the ones I observe. This highlights an important discrepancy between the eclipse depths presented here and the results in Grillmair et al. (2008) – the eclipse depths between 5 and $7.5 \mu m$ I find are systematically shallower by about 20% than the Grillmair et al. eclipses. This effect becomes marginal for the data sets at wavelengths longer than $7.5 \mu m$; the Burrows model in Grillmair et al. (2008) slightly but systematically overpredicts the IRS eclipse depths, just as it does with the depths I find here. The reasons for this discrepancy are likely rooted in the fact that I determine the sawtooth decorrelation function in a different way than Grillmair et al. (2008). Any bias or offset in the white light eclipse depth between 5 and $7.5 \mu m$, as described in Chapter 3, would lead to a part of the eclipse being subtracted (or added) to the light curves in the individual wavelengths. But, since the sawtooth function is the same in all light curves at a given wavelength range, and so the bias in eclipse depth is the same, the shape of the spectrum should not be affected. The shape of the planetary spectrum observed here is consistent with the Grillmair et al. (2008) results.

The Burrows model describes the shape of the IRS and Charbonneau et al. (2008) IRAC observations better than the isothermal and gray T-P models, even though the $3.6 \mu m$ eclipse depth is still not perfectly matched. For completeness, I compare the
\( \chi^2 \) statistic for the three models. For the isothermal model, \( \chi^2 = 31.1 \). This is larger than for the gray atmosphere mode, where \( \chi^2 = 29.9 \), but smaller than the values for the Burrows T-P profile. Since the Burrows T-P profile is hotter and results in deeper eclipses than what I observe, I simply add an offset to the Burrows contrasts until I the \( \chi^2 \) is minimized. This is only an approximation, since for a much cooler planet, the shape of the spectrum will change. Still, this test will provide a sense of the necessity of the heavy Burrows machinery versus the lighter Richardson model with a gray atmosphere or even a black body. The Burrows T-P profile combined with the Richardson atmospheric model, yields \( \chi^2 = 59.2 \), and with the Burrows radiative transfer model – \( \chi^2 = 41.5 \). For these calculations, I exclude the broadband IRAC eclipses. At first glance, it seems that the data favor simpler models. However, the 6\( \mu \)m water feature is very poorly matched by both the isothermal and gray atmosphere models. It is much better matched by the models based on the Burrows T-P, with the more complex Burrows model providing a much better match to the data at long wavelengths. Therefore, these models appear to be more difficult to reject than the simpler models and the spectrum is best explained by model families with a T-P profiles more complex than the one assuming a gray atmosphere, and similar to the one from Burrows, shown in Figure 4.7.
Chapter 5

Conclusions

In this dissertation, I analyze Spitzer secondary eclipse time series photometry on six hot Jupiters – HAT-P-3b, HAT-P-4b, HAT-P-6b, HAT-P-8b, HAT-P-12b and XO-4b – at 3.6 and 4.5 µm. Based on the eclipse depths I find, I conclude that the atmosphere of XO-4b has a strong temperature inversion. HAT-P-6b has weak or no temperature inversion, HAT-P-8b’s atmosphere has no inversion. HAT-P-8b is the only planet in the published literature that has an unequivocally non-inverted atmosphere based on the Spitzer secondary eclipse measurements and a host star with effective temperature higher than 6000 K. The models are ambiguous about the temperature structure of the atmospheres of HAT-P-3b and HAT-P-4b. I find that HAT-P-3b, HAT-P-4b and HAT-P-8b have relatively inefficient heat transport from their day sides to their night sides, while for XO-4b and HAT-P-6b the models suggest moderate to low heat transport. These findings are not inconsistent with the hypothesis that planets orbiting chromospherically active stars have no temperature inversion, while planets around chromospherically quiet stars have an inversion (Knutson et al. 2010). However, the ambiguity of the temperature inversion of HAT-P-4b suggests that there are additional layers of complexity governing the temperature pressure profiles of planets besides the chromospheric activity of their host stars. Of the examined planets, the low heat redistribution efficiency of HAT-P-3b appears to be in contradiction with the Perna et al. (2012) idea that relatively cool hot Jupiters should have efficient heat redistribution.

I do not detect the eclipses of relatively cool, Saturn-mass planet HAT-P-12b. The non-detections are a surprise, considering the results of Stevenson et al. (2010) and Hardin et al. (2012) on low-mass transiting planets GJ 436b and WASP-29b, which are in the same temperature regime as HAT-P-12b. This hint of diversity underscores the urgent need for additional observational and theoretical investigations into the atmospheres of planets with equilibrium temperatures below ~1200 K as well as with masses below roughly Saturn’s. These regimes are currently under-explored, mostly due to the fact that the observations are expected to have much lower signal-to-noise ratios than those of hotter planets with larger radii. However, our understanding of the way Spitzer IRAC systematics affect the light curves has significantly improved, and we are at a point, where, as shown here, even non-detections could place meaningful constraints on the physical properties of “warm Satuurns,” after suitable modeling of their atmospheres.

The fact that for three of the six planets examined here the Burrows and Fortney models yield ambiguous, contradicting or no explanations is an important warning sign. In many cases, extreme caution should be exercised when claiming presence of absence of temperature inversion based on just the two warm Spitzer band-passes. This underscores the necessity for additional observational and theoretical work in order to fully understand the atmospheres of hot Jupiters.
In addition, I examine all Spitzer IRS time series spectroscopy during secondary eclipse of HD 189733b, a total of 18 eclipses, eight of which are analyzed here for the first time. This comprises the most complete emergent spectrum observed in the infrared for any planet. I confirm the detection of a water feature (Grillmair et al. 2008) and compare the results with several models of the emergent spectrum. A combination of spectroscopic and broad band photometric observations can place constraints on the thermal structure of the atmosphere of a hot Jupiter. However, in the case of HD 189733b the rejection of simplistic models such as an isothermal or gray atmosphere hinge on the 3.6 µm IRAC eclipse depth and the water feature at 6 µm. On the other hand, the exclusion of the simplest temperature-pressure models structures for the atmosphere with a high degree of certainty is exciting and places the study of hot Jupiter atmospheres on firm observational grounds.

My spectral results are consistent with the findings of Lee et al. (2012) who find that in order to extract the precise temperature-pressure structure and molecular abundances one needs data in a wide spectral range in order to break various degeneracies. This is in agreement with a similar studies on model retrieval by Line et al. (2012) and Line et al. (2013). Even a spectrum as complete as the Spitzer IRS HD 189733b data set complemented by the Charbonneau et al. (2008) IRAC eclipse depth measurements is insufficient to fully constrain the T-P profile and the chemical structure of the planet. Therefore, studies that cover smaller wavelength ranges, or have a lower spectral resolution, need to be extremely conservative with respect to the atmospheric properties and uncertainties they derive.

While the study of the emission spectra of hot Jupiters has advanced significantly in the past several years, and the understanding of the systematic effects in the time series has really improved, a lot of uncertainty still remains in our ability to extract physical information from the observations. This is illustrated by the often contradictory implications of the two types of models with which I compare the secondary eclipse depths of HAT-P-3b, HAT-P-4b, HAT-P-6b, HAT-P-8b, HAT-P-12b and XO-4b, but also by the ambiguities and degeneracies in the models for the much more complete spectrum of HD 189733b.

Finally, many open questions remain about the atmospheres of “warm” Jupiter- and Saturn-sized planets like HAT-P-12b, GJ 436b and WASP-29b. This class of objects has been observed rarely so far, especially during secondary eclipse, despite the almost entirely unknown spectral behavior of the planets. The “warm” gas giants are important objects in the transition zone between hot Jupiters and super-Earths and it is vital to study them, not only in their own right, but also as test beds for observational techniques and models to be applied to smaller and cooler planets when their observation becomes feasible.
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• Studies of exoplanet atmospheres via time series photometry and spectroscopy.
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RESEARCH EXPERIENCE

Graduate Research Assistant, Astronomy and Astrophysics Department, Penn State 2009 – present
• Ph.D. thesis: Eclipse depth measurements during secondary eclipse on hot Jupiters in different wavelengths, using Spitzer time-series photometry and spectroscopy. Research performed at NASA GSFC and Astronomy Department, University of Maryland – College Park.
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TEACHING EXPERIENCE

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