THE ULTRAVIOLET PROPERTIES OF SUPERNOVAE

A Dissertation in
Astronomy and Astrophysics
by
Peter J. Brown

© 2009 Peter J. Brown

Submitted in Partial Fulfillment
of the Requirements
for the Degree of
Doctor of Philosophy
August 2009
The dissertation of Peter J. Brown was reviewed and approved\textsuperscript{1} by the following:

Peter W. A. Roming  
Senior Research Associate  
Dissertation Adviser  
Chair of Committee

David N. Burrows  
Senior Scientist/Professor of Astronomy and Astrophysics

Robin Ciardullo  
Professor of Astronomy and Astrophysics

Eric Feigelson  
Professor of Astronomy and Astrophysics

Lee Samuel Finn  
Professor of Physics and  
Professor of Astronomy and Astrophysics

Ruth Daly  
Professor of Physics

Larry Ramsey  
Professor of Astronomy and Astrophysics  
Head of the Department of Astronomy and Astrophysics

\textsuperscript{1}Signatures on file in the Graduate School.
Abstract

Ultraviolet (UV) observations of supernovae (SNe) probe an important wavelength region where hot temperatures, extinction, and metallicity have strong effects. In addition, they provide a comparison set against which to compare and better understand rest frame UV observations of high redshift SNe observed in the optical. UV observations, however, are rare due to the need for telescopes above the atmosphere and the difficulty in observing transient objects with space based observatories. Limited observations with space based observatories, primarily the International Ultraviolet Explorer and the Hubble Space Telescope, are reviewed, after which the Ultra-Violet/Optical Telescope (UVOT) on the Swift spacecraft is introduced. With Swift we have observed more SNe than all previous UV missions combined. Case studies of two individual SNe are first presented: SNe 2005am and 2005cs. SN 2005am is the first young SN observed with Swift, and the near-UV (uvw1: central wavelength $\sim 2600$ Å) light curve is consistent with the previous “template” derived from IUE and HST observations of SNe 1990N and 1992A. SN 2005cs is the first plateau-type II (IIP) with a well observed UV light curve. UVOT observations show a dramatic drop in the UV brightness and shift in the spectral energy distribution from blue to red caused by the dropping temperature and resulting line blanketing in the UV. These case studies demonstrate the information available from the UV data for individual SNe. A photometry method for proper accounting of coincidence loss, aperture corrections, and subtraction of the underlying galaxy is detailed. This method is then applied to a large sample of SNe observed with UVOT. We present 25 light curves and compare SNe by type and across types. The SNe Ia, with a few exceptions, are shown to have very similar light curves in the near UV, whereas, the three SNe Ib/c we have observed are very different. The SNe IIP all have rapidly fading UV light curves, though with different decay rates. The usefulness of UV-optical colors in differentiating the different SN types, particularly young SNe II which are blue and the redder SNe I, is then demonstrated. In a study of the absolute magnitudes of SNe Ia, we find that “normal” SNe Ia are standard candles in the near UV ($u$ and uvw1 bands: central wavelengths 3500 and 2600 Å), but the scatter increases dramatically at shorter wavelengths (uvm2 filter: central wavelength 2200 Å). The utility of this UV database of light curves for better understanding local SN events and for the discovery, classification, and understanding of high redshift SNe is discussed.
### TABLE OF CONTENTS

List of Tables ................................................................. vi
List of Figures ................................................................. vii
Preface ................................................................................... x

#### Chapter 1. Introduction .................................................. 1
   1.1 Supernovae ................................................................. 1
      1.1.1 Thermonuclear Type Ia Supernovae ....................... 3
      1.1.2 Stripped Envelope Core Collapse Supernovae Ib/c .... 7
      1.1.3 Hydrogen Rich Type II Supernovae ...................... 10
      1.1.4 Observations at Different Wavelengths ................. 12
   1.2 UV Observations ....................................................... 13
   1.3 Swift UVOT ............................................................... 20

#### Chapter 2. The Type Ia Supernova 2005am ....................... 26
   2.1 Introduction ............................................................ 26
   2.2 Observations and Reductions ....................................... 27
      2.2.1 Photometry ..................................................... 27
      2.2.2 Grism Spectroscopy .......................................... 29
   2.3 Results ...................................................................... 29
      2.3.1 Optical Light Curves .......................................... 29
      2.3.2 Ultraviolet Light Curves ..................................... 32
      2.3.3 Spectra .......................................................... 33
      2.3.4 XRT Data ...................................................... 33
      2.3.5 XMM-Newton EPIC Data ..................................... 33
      2.3.6 X-ray Results ................................................ 35
   2.4 Summary .................................................................... 35

#### Chapter 3. The Type II Supernova 2005cs ......................... 37
   3.1 Introduction ............................................................ 37
   3.2 Observations and Reductions ....................................... 38
      3.2.1 Swift Observations ........................................... 38
      3.2.2 UVOT Photometry ........................................... 39
      3.2.3 UVOT Grism Data ............................................ 40
   3.3 Discussion .................................................................. 40
      3.3.1 Ultraviolet Light Curves ..................................... 40
      3.3.2 UV Spectra ..................................................... 40
      3.3.3 Comparison of the UV Light Curves of SNe II ......... 44
      3.3.4 Comparison with non-LTE model atmospheres ....... 44
   3.4 Summary .................................................................... 50
Chapter 4. UVOT Photometry of Supernovae .......................... 53
  4.1 General Image Processing and Photometry ........................ 53
  4.2 Galaxy Subtraction Method ...................................... 54
  4.3 Examples .................................................................. 57
  4.4 Other Photometry Issues .......................................... 61
  4.5 Summary ................................................................. 63

Chapter 5. Ultraviolet Light Curves of Supernovae .................. 64
  5.1 SNe Ia Light Curves ..................................................... 67
  5.2 SNe Ib/c Light Curves ............................................... 67
  5.3 SNe IIP Light Curves ................................................... 70
  5.4 SN Phototyping with UV-Optical Colors ........................ 70

Chapter 6. Type Ia Supernovae as Standard Candles in the UV .... 75
  6.1 SNe Ia as Standard Candles ......................................... 75
  6.2 Sample ................................................................... 76
  6.3 Analysis .................................................................. 77
    6.3.1 Peak Apparent Magnitudes .................................... 79
    6.3.2 $K$ corrections ...................................................... 79
    6.3.3 Correcting for extinction ....................................... 81
    6.3.4 Determining the distances ..................................... 84
  6.4 Results ................................................................... 88
    6.4.1 Peak Pseudo-colors ............................................... 88
    6.4.2 Absolute Magnitudes ............................................. 91
    6.4.3 Search for Photometric UV Luminosity Indicators ...... 98
  6.5 Discussion ................................................................. 99

Chapter 7. Conclusions and Future Work .............................. 101
  7.1 Conclusions From This Work ....................................... 101
  7.2 Future Work at Low Redshift ..................................... 102
  7.3 High Redshift Application .......................................... 105

Appendix A. Acronyms ......................................................... 109

Appendix B. Image Archive pipeline .................................. 110

Appendix C. Galaxy Subtraction Recipe ............................... 112

Appendix D. Data File ........................................................ 116

Appendix E. Light Curve Plots ........................................... 118

Appendix F. Color Evolution Plots ...................................... 132

Bibliography .................................................................. 137
List of Tables

1.1 Non *Swift* UVOT UV SN Observations ............................................ 13
1.2 *Swift* UVOT Filter Characteristics ................................................. 24
1.3 Common UVOT Modes for SN Observations ......................................... 25

2.1 Optical and Ultraviolet Light Curves of SN2005am ............................. 30
2.2 UVOT Grism Observations of SN 2005am ............................................. 31

3.1 *Swift* UVOT Filter Characteristics ................................................... 39
3.2 *Swift* UVOT Photometry of SN 2005cs ............................................. 41
3.3 *Swift* UVOT Grism Observations of SN 2005cs ................................. 41

5.1 Decay Rates of Early UV Light Curves .............................................. 68

6.1 UVOT Filter Characteristics ............................................................... 77
6.2 Apparent Magnitudes at Maximum Light .............................................. 80
6.3 $K$ corrections for SNe Ia near Maximum Light ................................... 83
6.4 $E(B-V)$ Color Excess Measurements ............................................... 85
6.5 Host Galaxies and Distances ............................................................... 89
6.6 UV-Optical Peak Pseudocolors ............................................................ 96
6.7 Absolute Peak Magnitudes ................................................................. 97
6.8 Mean Absolute Magnitudes and Scatter .............................................. 98

7.1 *Swift* UVOT UV Observations ........................................................... 102
## List of Figures

1.1 HET spectra of SNe of different types. ........................................... 2  
1.2 HET spectra of SNe Ia. ............................................................... 4  
1.3 b and b-v curves of SN 2007af illustrating $\Delta m_{15}(B)$ and the Lira relation. 5  
1.4 HET spectra of SNe Ib/c. ............................................................ 8  
1.5 HET spectra of SNe II. ............................................................... 11  
1.6 IUE spectrophotometry for 21 SNe. .............................................. 17  
1.7 IUE spectrophotometry for SN 1987A. ........................................... 18  
1.8 Bright star contamination regions for UVOT. .................................. 22  
1.9 UVOT filters with the spectra of SNe 2005am and 2005cs. .................... 24  

2.1 Effective area curves of UVOT's six broadband filters on a spectrum of SN2005am. ............................................................ 28  
2.2 Ultraviolet and optical light curves of SN2005am obtained by UVOT. .... 31  
2.3 UVOT Grism Spectra of SN2005am. ................................................. 34  

3.1 Swift images of SN 2005cs and its host galaxy M51. ......................... 38  
3.2 Light curves of SN 2005cs obtained by UVOT in the three UV filters and the V band. ................................................................. 42  
3.3 Grism spectra of SN 2005cs obtained by UVOT). .............................. 43  
3.4 Comparison of SNe II observed by IUE and Swift-UVOT. ....................... 45  
3.5 Comparison between the photometric UVOT, spectroscopic optical observations (CfA) and CMFGEN models for SN 2005cs on 6 June 2006. .... 48  
3.6 Comparison between the photometric UVOT, spectroscopic optical observations and CMFGEN models for SN 2005cs on 5 July 2005. .............. 49  
3.7 Radial variation of the mean intensity over the UV and optical ranges for the June 30th CMFGEN model. ............................................. 51  
3.8 Radial variation of the mean intensity over the UV and optical ranges for the July 5th CMFGEN model. ............................................. 52  

4.1 UVOT images of SN2006X (left) and pre-explosion images of M100 (right). 55  
4.2 Pre and post galaxy subtracted count rates for the source region centered on SN 2006X in b. ......................................................... 56  
4.3 B and V light curves of SN 2005cf. ............................................... 58  
4.4 B light curves of SN 2005hk. ....................................................... 59  
4.5 B light curves of SN 2006X with different aperture sizes. ...................... 60  
4.6 B light curves of SN 2005am. ....................................................... 62  

5.1 UV light curves of SNe detected in at least three epochs by UVOT. ......... 65  
5.2 UVOT light curves of SN2007af, 2007Y, 2006bp. ................................ 65  
5.3 UV light curves of the SNe grouped by type. .................................... 66  
5.4 Histogram of the decay rates of the early UV light curves. .................... 69  
5.5 Color-color plots showing the differentiation of young SNe II from SNe Ia. 72
5.6 UV-optical color evolution of our sample over the first 50 days.
6.1 UVOT filter curves and the SN 1992A spectrum.
6.2 $K$ corrections as a function of redshift for the 6 UVOT filters.
6.3 $K$ corrections in the uvm2 filter as a function of redshift for different values of E(B-V).
6.4 Extinction as a function of $E(B-V)$.
6.5 $A_{\lambda}$ divided by $E(B-V)$ as a function of reddening using the MW (solid) and LMC (dotted) extinction laws.
6.6 UV-$b$ colors of the normal SNe Ia.
6.7 Peak UV-$b$ pseudocolors plotted with respect to their optical decay rate $\Delta m_{15}(B)$.
6.8 UV and optical absolute magnitudes plotted with respect to their optical decay rate $\Delta m_{15}(B)$.
6.9 The uvw1 absolute magnitude and the optical decay rate $\Delta m_{15}(B)$ are plotted with respect to the uvw1 decay rate.
6.10 UV colors plotted with respect to the optical decay rate $\Delta m_{15}(B)$.
7.1 Rest frame UV light sampled by the UVOT UV filters as it corresponds to observed wavelengths as a function of redshift.

E.1 UVOT light curves of SN 2005am.
E.2 UVOT light curves of SN 2005cf.
E.3 UVOT light curves of SN 2005cs.
E.4 UVOT light curves of SN 2005df.
E.5 UVOT light curves of SN 2005hk.
E.6 UVOT light curves of SN 2005ke.
E.7 UVOT light curves of SN 2006E.
E.8 UVOT light curves of SN 2006X.
E.9 UVOT light curves of SN 2006aj.
E.10 UVOT light curves of SN 2006at.
E.11 UVOT light curves of SN 2006bc.
E.12 UVOT light curves of SN 2006bp.
E.13 UVOT light curves of SN 2006dd.
E.14 UVOT light curves of SN 2006dm.
E.15 UVOT light curves of SN 2006ej.
E.16 UVOT light curves of SN 2006jc.
E.17 UVOT light curves of SN 2006mr.
E.18 UVOT light curves of SN 2007S.
E.19 UVOT light curves of SN 2007Y.
E.20 UVOT light curves of SN 2007aa.
E.21 UVOT light curves of SN 2007af.
E.22 UVOT light curves of SN 2007bm.
E.23 UVOT light curves of SN 2007co.
E.24 UVOT light curves of SN 2007cq.
E.25 UVOT light curves of SN 2005am.
F.1  uvw2-uvm2 color evolution. ................................. 132
F.2  uvw2-uvw1 color evolution. ................................. 133
F.3  uvm2-uvw1 color evolution. ................................. 133
F.4  uvm2-u color evolution. .......................... 134
F.5  uvw1-u color evolution. ................................. 134
F.6  uvw1-b color evolution. ................................. 135
F.7  u-b color evolution. ....................................... 135
F.8  u-v color evolution. ....................................... 136
F.9  b-v color evolution. ....................................... 136
Preface

Much of the material presented here has been published as multiple author papers of which the dissertation author is the first author. The chapters noted below have been reproduced in whole or in part from the submitted version with only minor textual changes for consistency in the dissertation and formatting changes to match the dissertation requirements. Other than minor editing or additions to the text, the work and writing was done by the author except as noted. Specifically, Chapter 2 was published as Brown et al. (2005b). Final SN 2005am photometry in the initial study in Section 2.2.1 was performed by Stephen Holland. Grism reduction for SN 2005am in Section 2.2.2 was done by Cynthia James. Chapter 3 was published as Brown et al. (2007). Grism observations of SN 2005cs in Section 3.2.3 were reduced by Wayne Landsman. Figure 3.1 was created by Stefan Immler. The CMFGEN modelling in Section 3.3.4 and the accompanying Figures 3.5, 3.6, 3.7, and 3.8 were done by Luc Dessart. Chapter 5 is excerpted from Brown et al. (2009).
Chapter 1

Introduction

1.1 Supernovae

In ancient times, the appearance of a new star in the sky, or “stella nova” as it was called, was a source of wonder as well as a confrontation to the astronomical theories of the day. Some of these occurred in distant galaxies, even outshining the host, and these extremely energetic explosions were dubbed “supernovae” (SNe). While resembling new stars, they actually signify the death of a star. As they did centuries ago, SNe continue to confront astronomical theories as well as serving as tools to better understand our universe.

The classification of SNe is based primarily on optical spectra (see Filippenko 1997 for a comprehensive review). The optical continuum is mostly thermal, with elements in the SN ejecta causing P-Cygni profiles. P-Cygni profiles result from doppler broadened line emission from the expanding photosphere, some of which is receding from the line of sight and some of which is moving toward the observer. From this emission the blue edge is absorbed by material moving toward the observer. Narrow emission lines originate from interaction of the SN ejecta with circumstellar material (either at rest with respect to the SN or moving away due to a stellar wind), and narrow absorption lines arise from cold intervening material and can be used to estimate the extinction from dust in either the host galaxy or in our own Milky Way.

As the SN ejecta expands and becomes more transparent, photons escape from deeper layers, resulting in a photosphere which is receding in velocity space. Thus the earliest spectra reveal the properties of the outer, fastest-moving layers of the ejecta and a time series of spectra will reveal deeper, slower layers. At the lower velocities, lines are less blended with other lines and easier to identify. Measuring the velocity distribution of individual ions gives a map of their physical distribution. Especially for elements synthesized during the explosion itself, such maps shed insight into the explosion mechanism, the chemical makeup of the progenitor, and extent of explosive nucleosynthesis.

The first separation of SN types, designated I and II, is based on the presence or absence of hydrogen lines. SNe without hydrogen in their spectra are typed SNe I. Further subclassification is based on the presence or absence of other lines, and examples are shown in Figure 1.1. SNe Ia have very prominent SiII absorption. SNe Ib have helium lines, but no hydrogen or silicon. SNe Ic have no hydrogen, helium, or silicon lines. SNe II do have hydrogen lines in their spectra. A more detailed description of the SN types, their spectra and light curves, and their further subclassification is given below. While spectral typing is more definitive, color differences can also be used to distinguish between the SN types. This topic will be addressed in more detail in Section ??.
Fig. 1.1 Spectra of SNe of different types obtained with the Hobby Eberly Telescope (HET). All spectra were obtained using the Low Resolution Spectrograph (LRS) with the g1 grism (300 lines/mm) and a slit width of 1" or 2" resulting in a resolving power of $R \sim 300–600$. They were reduced using standard IRAF procedures (bias subtraction, flat-fielding). Wavelength calibration was done with Cd and Ne arc lamps. Flux calibration has been performed using standard stars observed either the same night or within a couple of weeks. The relative flux calibration is stable, but the absolute flux is generally uncertain due to the variable aperture size of the HET. SNe 2007co and 2007ck (in the same host galaxy) were observed 13 June 2007. SN 2007C was observed 13 January 2007. SN 2005ek was observed 8 October 2005. The defining lines of Si II (Ia), He (Ib), and H (II) are identified in the respective spectrum. As a Ic is classified by a lack of the above lines, the strongest lines of Na I, O I, and Ca II which are visible are labeled.
1.1.1 Thermonuclear Type Ia Supernovae

The spectra of SNe Ia are dominated by intermediate mass elements (O, Mg, S, Si, Ca) with a Si II feature at 6150 Å being the most prominent. Heavier elements also appear in the blue end of the spectrum and become stronger with time. An example spectrum with prominent lines identified is displayed in Figure 1.2.

The SN Ia light curve is powered by the radioactive decay of $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ (Colgate & McKee 1969; van Hise 1974; Rust et al. 1976). The half lives for these two decays are 6.1 and 77.2 days$^2$, respectively. This results in a rapid decay for about one month after maximum light followed by a slower decay. The peak bolometric magnitude is an indicator of how much radioactive nickel was produced in the explosion. An example $b$-band light curve is displayed in Figure 1.3.

While SNe Ia are fairly homogeneous in their absolute magnitudes, the differences in the absolute magnitudes are correlated with the light curve shape in the sense that brighter SNe have broader light curves. This is referred to as the Luminosity-Width Relation (LWR). This feature transforms SNe Ia from decent standard candles to excellent standardizable candles. The intrinsic absolute magnitude can be inferred from some distance independent luminosity indicator, so the distance can be calculated from the observed apparent magnitude. The cosmological use of SNe as standard candles has resulted in a whole cottage industry built around different calibrations. Beginning at least as early as 1977 Pskovskii (1977) noted the absolute magnitude was related to the decay rate. Phillips (1993) used the parameterization $\Delta m_{15}(B)$ which measures the number of magnitudes the $B$ light curve fades in the first 15 days after maximum light. This is graphically depicted in Figure 1.3. The shape of the absolute magnitude versus $\Delta m_{15}(B)$ relation was improved upon with larger samples and a new determination of the reddening based on the late time colors (Phillips et al. 1999). This method of determining the reddening, dubbed the “Lira Relation”, relies on the observed tendency for SNe Ia to have the same color and color slope between one and three months after maximum light. This is shown in the bottom panel of Figure 1.3. Other groups have used this same parameter and found slightly different absolute magnitude relations (Hamuy et al. 1996a; Altavilla et al. 2004; Garnavich et al. 2004). In particular, Garnavich et al. (2004) increased the sample of subluminous SNe Ia and found a steeper slope in the LWR for the rapidly fading SNe, namely the absolute magnitudes drop even faster for larger values of $\Delta m_{15}(B)$. This is actually a result of the B band light curve transitioning from the steep to shallow decay at earlier times so the B light curve does not continue to drop off as rapidly (Hamuy et al. 1996b; Kasliwal et al. 2008).

Goldhaber et al. (2001) introduced the “stretch” parameter, which is a simple multiplicative factor required to match the light curve to a template. The other main light curve fitter in use originated as the light curve shapes (LCS) method (Riess et al. 1995), later becoming the Multicolor Light Curve Shapes method (MLCS; Riess et al. 1996a, and its latest incarnation MLCS2k2 (Jha et al. 2007). In this method the light curves are compared to a training set of light curves to simultaneously determine the

\[^{2}\text{http://www.nndc.bnl.gov/nudat2/}\]
Fig. 1.2 HET spectra of SNe Ia. SN 2007af was observed 15 March 2007. SN 2007S was observed 7 February 2007. SN 2007ax was observed 15 March 2007. SN 2008A was observed 20 January 2008. All SNe Ia are dominated by P-Cygni profiles of intermediate mass elements, in particular a strong Si II line near 6150 Å. Superluminous SNe Ia also show lines from doubly ionized Fe III and Ni III. Subluminous SNe Ia have Ti II absorption which cause them to appear red. SN 2002cx-like objects show some of the same lines as above but with much slower expansion velocities.
Fig. 1.3 top: \( b \) light curve from Swift/UVOT (comparable to ground based \( B \); see Section 1.3) of SN 2007af showing the steep-shallow shape of the early light curve and measurement of \( \Delta m_{15}(B) \).

Bottom: Swift/UVOT \( b - v \) (similar to ground based \( B - V \)) color evolution of SN 2007af compared with the Lira relation. The difference between the observed color and the predicted intrinsic color yields the “color excess” or reddening to the SN.
reddening (and constrain the reddening law), luminosity distance, and the fitting parameter $\Delta$ which is approximately equal to the magnitude difference from the defined “normal” absolute magnitude.

In addition to those listed above, multiple other methods use different filter or color curves at certain epochs which in a similar manner correlate with the absolute magnitudes (Tripp 1998; Guy et al. 2005; Wang et al. 2005a, 2006). There are also spectral features, the strength of which correlate with the absolute magnitude (Nugent et al. 1995; Bongard et al. 2006). Even at late times the relative strengths of lines during the nebular phase (Mazzali et al. 1998) and photometric decay slopes (Wang & Hall 2008) also correlate with absolute magnitude.

SNe Ia lack hydrogen or helium in the spectra, have similar brightness (and thus similar mass/energy), and are detected in old and young stellar systems. With these clues, a white dwarf pushed over the Chandrasekhar limit seemed a natural mechanism to cause the explosion to occur at the same mass and be dominated by intermediate mass elements. A variety of mechanisms have been proposed to push the star over the Chandrasekhar limit. In the single degenerate scenario, the white dwarf has a main sequence or giant companion which loses mass onto the white dwarf. The white dwarf accretes mass until it reaches the Chandrasekhar limit, at which point electron degeneracy can no longer support the mass and the SN compresses further until nuclear reactions again take over and blow the SN apart. This type of explosion is referred to as thermonuclear because it is the energy liberated in the nuclear reactions that disrupts the star. The explosion could take place as a detonation, deflagration, or a deflagration that results in a delayed detonation (Höflich & Stein 2002; Hoeflich et al. 1998). The element abundances suggest a delayed detonation, as some burning must take place even in the outer layers before the disruption of the star.

Another possible progenitor path is the double degenerate scenario, which involves two white dwarfs which eventually inspiral and merge, with the merged mass being above the Chandrasekhar limit and undergoing the collapse, ignition, and explosion described above. This model has been suggested as the cause of so called super-Chandrasekhar SNe (Howell et al. 2006; Hicken et al. 2007) because it naturally allows for the explosion to occur with mass significantly above the Chandrasekhar limit. In reality, both models might be necessary to explain the seemingly bi-modal delay times which indicate a population of SNe Ia which are strongly correlated with recent star formation and a group requiring a delay of about 3 Gigayears (Mannucci et al. 2006).

The Chandrasekhar limit explosion was a logical way to explain how all SNe Ia explode with similar energies, but as SN observations have improved it has become clear that there is intrinsic scatter in the absolute magnitudes above and beyond the measurement error. Having found models to be similar it is now necessary to make those models result in different explosions. Differences in the progenitors, companions, or in the propagation of the explosion might cause these. The year 1991 cemented the non-uniformity of SNe Ia with the prototypical super and sub-luminous SNe 1991T and 1991bg. Though very different, these two SNe represent the extremes of the LWR fit by the absolute magnitude relations. The superluminous (or SN 1991T or 1999aa like) SNe are located at the broad/bright end and have higher photospheric temperatures and Fe III absorption. The subluminous (or SN 1991bg like) objects at the narrow/faint end
are much cooler and have strong Ti II in the blue end of the optical spectrum. Example spectra are displayed in Figure 1.2. While super and sub-luminous refer to the extremes of the LWR, the terms over-luminous and under-luminous are often employed to describe SNe Ia which are too bright or too faint for their decay rate and thus not located on the LWR continuum. Super-Chandrasekhar SNe are an example of the over-luminous ones, while 2000cx-like objects are an example of SNe Ia which are under-luminous for their optical decay rate. The latter have been claimed to be related to SNe Ib/c (Valenti et al. 2009), but some are found in early type galaxies (Foley et al. 2009) and their peculiarity may arise from the explosion mechanism being primarily a deflagration rather than a delayed detonation (Phillips et al. 2007).

1.1.2 Stripped Envelope Core Collapse Supernovae Ib/c

While the spectroscopic naming classification is based on the presence or absence of hydrogen and other elements in the ejecta, a more physical dichotomy would separate SN explosions by the basic explosion mechanism. SNe Ia, as described above, are thermonuclear explosions, where the disruption of the star is driven by runaway reactions (explosive nucleosynthesis). Nearly all other SN explosions result from core-collapse explosions. In the simplest sense, core-collapse is initiated when a massive star exhausts its nuclear fuel. Without the outward radiation pressure to support it, the star collapses in on itself. The core forms a hard surface off of which the supersonically falling outer layers bounce off. This, however, is not sufficient to result in the ejection of the stellar envelope that would be observed as a SN. Additional neutrino-heating or 3-dimensional instabilities are necessary to actually result in a SN explosion rather than a stalled shock (Fryer 2004).

Here we treat SNe Ib and Ic as a single group, as they share many features and the physical distinctions are small. SNe Ib/c, while sharing a common explosion mechanism with SNe II, lack the spectroscopic signatures of a hydrogen envelope. They are differentiated from SNe Ia by the lack of a prominent Si II feature at 6150 Å and from each other by the observed presence of He in the spectrum, with SNe Ib having He and SNe Ic exhibiting no strong He. Under careful review, however, many SNe classified as Ic do in fact show some traces of He which is either weak or transient, though this is not sufficient to require a continuum of progenitor characteristics (mass, radius, mass loss, etc.) (Clocchiatti et al. 1996). The physical cause of the dichotomy is also uncertain, as He may be absent in SNe Ic because the He is physically stripped away from the progenitor star (either through strong stellar winds or interaction with a companion) or that it might just not be excited enough to have a measurable effect on the spectrum (Matheson et al. 2001). The spectra of SNe Ib/c are dominated by strong Ca II as well as O I, C II, Na I, and in the blue Fe II (Branch et al. 2002). Figure 1.4 displays a few examples of SNe Ib/c and their important spectral features.

Among Ic there is a subclass referred to as hypernovae (or simply broad-lined Ic) which have broad absorption lines. These velocity broadened lines result from extremely high expansion velocities (\(\sim 30,000 \text{ km/s}\)) and were not recognized as SNe at first (Nakano et al. 1997). SN 1998bw, associated with GRB980425, was one of the first to be identified (Galama et al. 1998). Some broad-lined SNe were possibly coincident with
Fig. 1.4 HET spectra of SNe Ib/c. SN 2006jc was observed 17 October 2006, a few days after maximum light in the optical. SN 2007uy was observed 29 January 2008, a few days after maximum light in the optical. SN 2005ek was observed 8 October 2005, a week after maximum light in the optical. SN 2006aj (associated with GRB060218) was observed 3 March 2006, two weeks after the inferred explosion date (and GRB detection) and a few days after maximum light in the optical. The most significant lines are identified above. Note the extreme velocities of SN 2006aj which stretch the features out until they are barely recognizable.
a GRB (owing to the poor localizations of GRBs in previous decades) while some were not associated with a detected GRB (e.g., SN 2002ap; though the possibility of earth occultation of gamma ray detectors and off-axis jets means a GRB cannot be completely ruled out). Radio observations put strict limits on the fraction of SNe Ib/c that could have been accompanied by a GRB (Soderberg et al. 2006).

For a few SNe Ib/c there has been observational evidence of the shock breaking out of the stellar surface. This is a brief peak in the light curve shortly after explosion from the surface of the star being shock heated and glowing with a peak in the X-ray/UV bands. The SN surface is small, so the shock cools and fades rapidly, but a brief early fading was seen in the light curves of SN 1999ex (which occurred in the same host galaxy (IC5179) as the regularly monitored 1999ee (Stritzinger et al. 2002), SN 2008D (which occurred serendipitously during Swift observations of SN 2007uy in NGC2770; Soderberg et al. 2008), and two GRBs where observations were triggered by the detection of a GRB: SNe 1998bw/GRB980425 (Galama et al. 1998) and the recent 2006aj/GRB060218 (Campana et al. 2006). For SNe 2006aj and 2008D the peak was actually longer than predicted, but consistent with the shock arising from the surface of a dense stellar wind rather than the actual stellar surface (Campana et al. 2006; Soderberg et al. 2008). The shortness of the peak makes it extremely difficult to detect through normal SN search programs.

Following the shock breakout, SNe Ib/c have light curves that rise and fade similar in shape to SNe Ia, being also powered by radioactive decay. They are, however, redder and in general fainter than SNe Ia, which are intrinsic characteristics as opposed to merely an effect of reddening. The light curves and absolute magnitudes of SNe Ib/c are diverse, with a large range in decay rates and absolute magnitudes (Richardson et al. 2006). The GRB-SNe tend to be more luminous than most SNe Ic, but this may be a selection effect as less luminous SNe would be undetected in the light of the afterglow (Richardson 2009). Most of these are only detected as a red, late-time bump in the light curve of the afterglow, though the number of spectroscopically confirmed GRB-SNe is growing. Under the collapsar model, a massive star implodes to create a new black hole with an accretion disk powering a powerful jet which gives rise to the GRB. It requires low metallicity (stellar winds must carry away the hydrogen envelope but not too much of the stellar mass, though a binary companion might be responsible for stripping away the envelope) and sufficient angular momentum for an accretion disk to form around the black hole.

SNe Ib/c preferentially occur in late-time spirals near star-forming regions, thus indicating a different type of progenitor than the SNe Ia which were also (but not exclusively) found in older stellar populations (Porter & Filippenko 1987). Studies of the location of SN events within galaxies show that in general core-collapse SNe follow the star formation in the galaxy while GRBs are more highly concentrated to the brightest locations within the galaxies where the star formation is highest (Fruchter et al. 2006). Kelly et al. (2008) find that SNe Ic are also more concentrated to regions of active star formation. Adding this to the fact that the small number of GRB-SN spectra have all been SNe Ic, these clues suggests that GRBs are a small subset of SNe Ic. Radio observations which can constrain the presence of an off-axis jet (GRBs that were not
pointed toward Earth) indicate that much less than 10 percent of SNe Ic could have been accompanied by a GRB (Soderberg et al. 2004).

There have also been two observed cases where a nominally “long” GRB (060505 and 060614) was not accompanied by a SN down to very faint limits (Fynbo et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006; Ofek et al. 2007). While these GRBs might be a new class of objects (Gehrels et al. 2006), they could be the first examples of the predicted failed or fall-back SNe which produce or at least eject little radioactive Nickel because most of the material falls into the newly formed black hole (Fryer et al. 2006).

More recently, a class of SNe Ib has been identified with He emission (Pastorello et al. 2008). The best observed of these, SN 2006jc, appeared at the location of a faint outburst two years earlier, which has been interpreted as a Luminous Blue Variable (LBV) outburst (Foley et al. 2007; Pastorello et al. 2007). The interaction of the SN ejecta with the helium shell ejected earlier gave rise to the strong He emission. A SN Ibn classification has been suggested to describe both the Helium and the narrow emission lines similar to SNe IIn which exhibit narrow hydrogen emission lines.

1.1.3 Hydrogen Rich Type II Supernovae

Type II SNe are identified by the presence of hydrogen in the spectra. SNe II-Linear and II-Plateau (IIP and IIL) are further distinguished based on the light curve behavior. Spectroscopically both have broad hydrogen emission. Some SNe IIL lack Hα absorption (cf. SNe 1979C and 1980K; Panagia et al. 1980; Barbon et al. 1982), though a more thorough study of the photometric and spectroscopic differences between these two subtypes is greatly needed (Gal-Yam et al. 2007). At early times, SNe II spectra match a blue, hot blackbody. As the photosphere cools, metal lines begin to absorb flux starting at shorter wavelengths and moving redward. The continuum can be used to determine the photospheric temperature and the extinction. The line identifications and their shapes constrain the density profile, ionization structure, and metallicity.

SN IIP light curves are powered by the energy deposited in the hydrogen envelope by the shock. As the SN cools, the hydrogen recombines, providing energy which powers the near constant optical luminosity. The bluer bands such as $U$ and $B$ actually show fading while redder bands such as $I$ actually brighten during the early part of the plateau. The length of the plateau is determined by the energy of the explosion. SNe IIL, on the other hand, reach a maximum several days after explosion and then fade roughly linearly in the optical, by about 3 magnitudes in the 50 days after maximum (Barbon et al. 1979; Doggett & Branch 1985). The decaying light curves of the SNIIL are taken to be evidence of a much smaller hydrogen shell, lost through either binary interaction or strong stellar winds. The envelope size can be inferred from the expansion velocity of the spectral lines if the explosion energy is about the same. The width of the lines is consistent with a IIP-III-1Ib-Ib-Ic progression from greatest to smallest envelope (Matheson et al. 2001).

The absolute magnitudes of the plateau range from $-13 < M_V < -19$. Hamuy & Pinto (2002) found that the absolute magnitudes correlate with the photospheric velocity during the plateau, allowing one to use them as standardizable candles. Physically, both of these parameters are related to the explosion energy (Nadyozhin 2003). This “Standardizable Candle Method” (SCP) has been supported by larger samples of SNe
Fig. 1.5 HET spectra of SNe II. SN 2007od was observed 6 November and 15 December 2007, a few days and about fifty days after explosion. SN 2007pk was observed 13 November 2007, a few days after explosion. The continuum is a nearly featureless black-body with narrow emission lines superimposed. SN 2005ip was observed 29 November 2008 (over a thousand days after explosion). The continuum is very faint while strong emission lines dominate the flux. SN 2008ax was observed 19 March 2008. H is the dominant line in all SNe II. The metal lines in SNe IIP in the blue end of the spectrum grow with time.
IIP (Nugent et al. 2006; Poznanski et al. 2009). SNe IIL are also very heterogeneous with some being among the brightest SNe observed (cf. SN 2008es: Miller et al. 2009; Gezari et al. 2009).

The distances to SNe IIP can also be measured using a variation of the Baade-Wesselink method adapted for SNe called the “Expanding Photosphere Method” (EPM; Kirshner & Kwan 1974; Eastman et al. 1996; Dessart & Hillier 2005). The EPM utilizes early time spectra and photometry to calculate the expanding photospheric angular size which is used as a standard ruler with which to measure distances. The accuracy of the distance measures has increased with better SN models which improve upon the simple dilution factors previously used. Similarly, accurate synthetic spectra and spectrophotometry can be compared to observed spectra and photometry to obtain the distance modulus (Baron et al. 1995).

SNe IIn feature narrow emission lines of hydrogen, indicative of interaction with circumstellar material. Most are believed to result from the explosion of a massive star that interacts with its previously ejected envelope (Gal-Yam et al. 2006). The IIn characteristics can be observed for a variety of underlying explosions, as the narrow lines come from the interaction of any explosion type with a thick shell of material. SNe IIn possibly associated with Ia SNe have been observed (Aldering et al. 2006; Prieto et al. 2007), and SN 1994W has been suggested to have arisen from the interaction of two ejected shells without requiring the explosion of the progenitor star at all (Dessart et al. 2009).

SNe IIb are believed to be transitional objects between II and Ib. They show hydrogen lines at early times, indicative of a small hydrogen shell, but spectroscopically transition to a hydrogen-free helium-rich SN Ib. SNe 1978K and 1993J are considered to be the prototypes of the class. SN 1993J was close enough for extensive observations, and detailed modelling is consistent with the progenitor having had a main sequence mass of 13-16 $M_\odot$ losing its hydrogen envelope due to interaction with a binary companion (Woosley et al. 1994). The progenitors of most SNe IIP, on the other hand, are low to moderate mass red supergiants with masses in the range 8-12 $M_\odot$ based on theoretical modelling and the detection/non-detection of progenitors in deep, high-resolution pre-explosion HST images (Maund et al. 2005; Hendry et al. 2006).

1.1.4 Observations at Different Wavelengths

The last few decades have seen large strides in the understanding of SNe, from the nature of their progenitors, to the explosion mechanisms, and their interactions with the surrounding medium and the host galaxy. Much of this progress has come about because of the expanding baseline of observations, stretching out to longer wavelengths as well as to shorter wavelengths/higher energies including X-rays and even neutrinos.

For a long time, our knowledge of SNe was based solely on the optical properties, measured using ground based telescopes using photographic plates for detectors. Fortuitously, the majority of the bolometric photon luminosity for most SNe over much of its lifetime is emitted in the optical region. Thus the optical light curves give a good indication of the explosion energy. We have already discussed many of the properties seen in the optical spectra.
At longer wavelengths, into the near-infrared (NIR), spectral lines are more spread out. These regions are also less susceptible to the effects of dust extinction, and SN searches in the NIR can find SNe that would be undetected in optical searches (Cresci et al. 2007). The IR regions are also sensitive to dust emission, important for measuring how much of the dust in the universe could have been created in SN explosions.

At very high energies, gamma rays and X-rays can come from the radioactive decay of products of the explosion or from the shocking of highly relativistic particles in a GRB jet. X-rays, and at the other end of the spectrum radio emission, are also produced by the interaction of the SN ejecta with the interstellar medium, and thus are a sensitive probe of the SN environment and mass loss.

Neutrinos, despite carrying away 99% of the energy of the explosion, are the hardest to detect. Neutrino detections from SN 1987A were a confirmation of the core-collapse theory of explosion (Bionta et al. 1987). As evidenced by SN 1987A, the detection of neutrinos is possible for the very nearest SNe (Ikeda et al. 2007; Franckowiak et al. 2007). The detection of gravity waves from SN explosions (again from the nearest events) is also becoming a less distant possibility (Rapagnani 1990; Arnaud et al. 2004).

From the earliest photon signal from a SN during the shock breakout, the UV light from SNe contains many clues about the explosion and the environment, with application to both nearby and high-redshift SNe. The contribution of UV light to the bolometric luminosity can be significant, particularly at the earliest epochs when the high temperature yields a large UV flux. Line blanketing in the UV is dominated by iron peak elements, so the UV brightness is sensitive to the ionization level (cf. Dessart et al. 2008) and differences in metallicity (Nugent et al. 1997; Lentz et al. 2000; Sauer et al. 2008). The large UV extinction observed in most extinction curves also allows UV observations to better constrain the reddening to individual objects (Jeffery et al. 1994). In addition, UV observations of nearby SNe provide a comparison set against which to compare and better understand rest frame UV observations of high redshift SNe observed in the optical.

1.2 UV Observations

The first UV observations of a SN were performed by the Orbiting Astronomical Observatory in 1972, with photometry in filters with effective wavelengths of 4250, 3320, 2980, 2460, and 1910 Å. These observations revealed the UV faintness of a type I SN (Holm et al. 1974), with the flux dropping to shorter wavelengths and being negligible in the 1910 Å filter. The spectral energy distribution resembled that of an early F supergiant. A list of SNe observed in the UV is given in Table 1.1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Instrument</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 1972</td>
<td>Ia</td>
<td>OAO-2</td>
<td>32</td>
</tr>
<tr>
<td>SN 1978G</td>
<td>II</td>
<td>IUE</td>
<td>2</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Instrument</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 1979C</td>
<td>IIL</td>
<td>IUE</td>
<td>19</td>
</tr>
<tr>
<td>SN 1979C</td>
<td>IIL</td>
<td>HST</td>
<td>3</td>
</tr>
<tr>
<td>SN 1979C</td>
<td>IIL</td>
<td>XMM-OM</td>
<td>1</td>
</tr>
<tr>
<td>SN 1980K</td>
<td>IIL</td>
<td>IUE</td>
<td>34</td>
</tr>
<tr>
<td>SN 1980K</td>
<td>IIL</td>
<td>HST</td>
<td>4</td>
</tr>
<tr>
<td>SN 1980N</td>
<td>Ia</td>
<td>IUE</td>
<td>8</td>
</tr>
<tr>
<td>SN 1981B</td>
<td>Ia</td>
<td>IUE</td>
<td>5</td>
</tr>
<tr>
<td>SN 1982B</td>
<td>Ia</td>
<td>IUE</td>
<td>2</td>
</tr>
<tr>
<td>SN 1983G</td>
<td>Ia</td>
<td>IUE</td>
<td>7</td>
</tr>
<tr>
<td>SN 1983N</td>
<td>Ib</td>
<td>IUE</td>
<td>6</td>
</tr>
<tr>
<td>SN 1984J</td>
<td>II</td>
<td>IUE</td>
<td>1</td>
</tr>
<tr>
<td>SN 1985F</td>
<td>Ib</td>
<td>IUE</td>
<td>1</td>
</tr>
<tr>
<td>SN 1985L</td>
<td>II</td>
<td>IUE</td>
<td>2</td>
</tr>
<tr>
<td>SN 1986G</td>
<td>Ia</td>
<td>IUE</td>
<td>6</td>
</tr>
<tr>
<td>SN 1987A</td>
<td>II</td>
<td>IUE</td>
<td>619</td>
</tr>
<tr>
<td>SN 1987A</td>
<td>II</td>
<td>HST</td>
<td>42</td>
</tr>
<tr>
<td>SN 1988Z</td>
<td>IIn</td>
<td>HST</td>
<td>5</td>
</tr>
<tr>
<td>SN 1989B</td>
<td>Ia</td>
<td>IUE</td>
<td>4</td>
</tr>
<tr>
<td>SN 1989M</td>
<td>Ia</td>
<td>IUE</td>
<td>7</td>
</tr>
<tr>
<td>SN 1990B</td>
<td>Ib</td>
<td>IUE</td>
<td>3</td>
</tr>
<tr>
<td>SN 1990M</td>
<td>Ia</td>
<td>IUE</td>
<td>1</td>
</tr>
<tr>
<td>SN 1990N</td>
<td>Ia</td>
<td>IUE</td>
<td>9</td>
</tr>
<tr>
<td>SN 1991T</td>
<td>Ia</td>
<td>IUE</td>
<td>5</td>
</tr>
<tr>
<td>SN 1991bg</td>
<td>Ia</td>
<td>IUE</td>
<td>1</td>
</tr>
<tr>
<td>SN 1992A</td>
<td>Ia</td>
<td>IUE</td>
<td>10</td>
</tr>
<tr>
<td>SN 1992A</td>
<td>Ia</td>
<td>HST</td>
<td>7</td>
</tr>
<tr>
<td>SN 1993J</td>
<td>Iib</td>
<td>IUE</td>
<td>32</td>
</tr>
<tr>
<td>SN 1993J</td>
<td>Iib</td>
<td>HST</td>
<td>16</td>
</tr>
<tr>
<td>SN 1994I</td>
<td>Ic</td>
<td>IUE</td>
<td>7</td>
</tr>
<tr>
<td>SN 1994I</td>
<td>Ic</td>
<td>HST</td>
<td>9</td>
</tr>
<tr>
<td>SN 1994Y</td>
<td>IIn</td>
<td>HST</td>
<td>3</td>
</tr>
<tr>
<td>SN 1995N</td>
<td>II</td>
<td>HST</td>
<td>3</td>
</tr>
<tr>
<td>SN 1998S</td>
<td>IIn</td>
<td>HST</td>
<td>15</td>
</tr>
<tr>
<td>SN 1999em</td>
<td>IIP</td>
<td>HST</td>
<td>9</td>
</tr>
<tr>
<td>SN 2001ay</td>
<td>Ia</td>
<td>HST</td>
<td>4</td>
</tr>
<tr>
<td>SN 2001ba</td>
<td>Ia</td>
<td>HST</td>
<td>3</td>
</tr>
<tr>
<td>SN 2001eh</td>
<td>Ia</td>
<td>HST</td>
<td>9</td>
</tr>
<tr>
<td>SN 2001el</td>
<td>Ia</td>
<td>HST</td>
<td>12</td>
</tr>
<tr>
<td>SN 2001ep</td>
<td>Ia</td>
<td>HST</td>
<td>5</td>
</tr>
<tr>
<td>SN 2001ex</td>
<td>Ia</td>
<td>HST</td>
<td>12</td>
</tr>
<tr>
<td>SN 2001ig</td>
<td>Iib,Ib/c</td>
<td>HST</td>
<td>5</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 1.1 – Continued

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Instrument</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 2002ap</td>
<td>Ic</td>
<td>HST</td>
<td>5</td>
</tr>
<tr>
<td>SN 2004dt</td>
<td>Ia</td>
<td>HST</td>
<td>12</td>
</tr>
<tr>
<td>SN 2004ef</td>
<td>Ia</td>
<td>HST</td>
<td>9</td>
</tr>
<tr>
<td>SN 2005M</td>
<td>Ia</td>
<td>HST</td>
<td>6</td>
</tr>
<tr>
<td>SN 2005ay</td>
<td>IIP</td>
<td>GALEX</td>
<td>5</td>
</tr>
<tr>
<td>SN 2005cf</td>
<td>Ia</td>
<td>HST</td>
<td>12</td>
</tr>
<tr>
<td>SN 2007aa</td>
<td>IIP</td>
<td>GALEX</td>
<td>4</td>
</tr>
<tr>
<td>SN 2007gr</td>
<td>Ic</td>
<td>GALEX</td>
<td>3</td>
</tr>
<tr>
<td>SN 2008ax</td>
<td>Ic</td>
<td>GALEX</td>
<td>1</td>
</tr>
<tr>
<td>SN 2008aw</td>
<td>IIP</td>
<td>GALEX</td>
<td>3</td>
</tr>
<tr>
<td>SN 2009at</td>
<td>IIP</td>
<td>GALEX</td>
<td>3</td>
</tr>
<tr>
<td>SN 2009dd</td>
<td>IIP</td>
<td>GALEX</td>
<td>2</td>
</tr>
</tbody>
</table>

The International Ultraviolet Explorer (IUE) built up a larger sample with UV spectroscopic observations of 25 SNe beginning with the type II SN 1978G (see Panagia 2003 for a review of IUE observations and Benvenuti et al. 1982 and Cappellaro et al. 1995 for the spectra and spectrophotometry). The first well observed object was the type II-Linear SN 1979C (Panagia et al. 1980), with IUE observations beginning just three days after its discovery. The spectra showed a relatively smooth continuum, with a color temperature of 11,000 K, but with excess UV flux shortward of 1600 Å compared to a simple blackbody. The early UV spectra were useful in constraining the low level of extinction to the SN, and the UV contribution at those early epochs was 44% of the bolometric flux. The SN flux faded more rapidly in the UV than the optical, at a rate of about 0.08 magnitudes per day in 100 Å wide bins centered at 3000 and 2400 Å and steeper to shorter wavelengths.

Several SNe Ia were observed by IUE, all with a steep dropoff to shorter wavelengths and only broad features. Branch & Venkatakrishna (1986) modeled the UV spectrum of SN 1981B and found that the features between 2900-3300 Å were not consistent with any of the ions used to fit the optical spectra, but well fit with blends of Fe II and Co II (110 and 21 individual lines respectively), with a ratio consistent with being formed from $^{56}\text{Ni}$ during the explosion 15 days earlier. Analysis of SN 1990N showed that iron peak elements synthesized during the explosion were distributed to the higher velocity outer layers, contrary to popular models (Jeffery et al. 1992). SN 1990N, however, was not the most normal Ia, and its UV spectra are somewhat different than others observed by IUE.

SN 1983N was a Ib well studied by IUE, which showed a light curve shape and UV spectrum similar to SNe Ia, with only 13% of the bolometric luminosity coming shortward of 3400 Å (Panagia 2007). The lack of strong UV emission just a few days after explosion limits the size of the stellar progenitor to $<10^{12}$ cm (Panagia 2007).
The spectrophotometry for the IUE SNe available in Cappellaro et al. (1995) is displayed in Figure 1.6. IUE was limited to the brightest SNe, so only a couple of objects could be observed per year and the light curve evolution of most of the SNe could not be followed more than a few magnitudes below maximum light.

The local group SN 1987A was well observed by three UV observatories, leading to a wealth of information regarding the progenitor, explosion, and interaction with the surrounding medium. The first IUE observation showed it to be very UV bright, and allowed for the estimation of the reddening, temperature, and radius (Kirshner et al. 1987). It faded rapidly, so the UV observations were first able to confirm which star had disappeared, unambiguously identifying the progenitor (Gilmozzi et al. 1987). The rapid decay was caused by the falling temperature and resulting UV opacity from absorption lines in the UV, which together shift the flux distribution to longer wavelengths (Pun et al. 1995). An IUE spectrophotometric light curve from Cappellaro et al. (1995) is displayed in Figure 1.7. The UV flux reached a minimum at about 30 days after the explosion before rising again to a local peak 85 days after explosion. This peak was powered by the decay of radioactive elements formed in the explosion. Another local minimum was reached at day 125, after which the UV flux rose much slower to peak 350 days after explosion (coinciding with the formation of dust in the ejecta) and then steadily faded. A plot of the IUE spectrophotometry of SN 1987A (from Cappellaro et al. 1995) showing these different regimes is displayed in Figure 1.7. Just after SN 1987A had become too faint for IUE, observations with the Hubble Space Telescope (HST) began. These observations followed the light curve to even fainter levels (Pun et al. 1995).

The early IUE data was also supplemented by the Astron Station (Lyubimkov 1990). The Astron near-UV spectroscopy showed similar broad absorption as the IUE spectra, associated with singly ionized iron peak elements. In particular, Lyubimkov (1990) associates the strongest blends with TiII and ascribes their strong increase by day 120 to be the result of Titanium synthesized during the explosion being exposed as the photosphere recedes into deeper layers.

In addition to SN 1987A, HST has added excellent UV spectroscopic or photometric data for another ∼30 SNe (Wang et al. 2005a; see also Panagia 2003 for a review of IUE and HST UV observations up to that time). Much of the Ia photometry is still unpublished, but single epoch spectra spanning the UV-optical regimes have given excellent snapshots to understand the formation of the UV for most SN types.

The IUE-HST synergy continued with SN 1992A. IUE was able to begin observations a few days before maximum light and continue to twenty days after. HST obtained high signal UV-optical spectra and photometry 5 and 45 days after maximum light. Combining IUE spectrophotometry for SN 1990N (which was observed beginning well before optical maximum) with IUE and HST data for SN 1992A led to the first UV template light curve (Kirshner et al. 1993) which has been found to match subsequent observations with Swift (Brown et al. 2005b). The near-maximum light spectrum of SN 1992A is still the best UV spectrum of a SN Ia to date.

Ruiz-Lapuente et al. (1995) extended the SN 1992A observations with photometry and UV spectra 291 days after maximum light. Nebular phase models were unable to reproduce the UV spectrum. Some of the disagreement might come from poorly known collision strength values in the UV. The UV spectrum also shows a lack of circumstellar
Fig. 1.6 IUE spectrophotometry for 21 SNe in the HST F275W band (similar to Swift UVOT’s uvw1 band). SN 1987A is displayed separately in Figure 1.7 due to its large dynamic range and temporal baseline.
Fig. 1.7 IUE spectrophotometry for SN 1987A.
matter interaction, puts strong limits on the small amount of interstellar reddening, and constrains the ionization fractions of iron peak elements.

SN 1994I was labeled “the best observed ‘ordinary’ SN Ic” by Millard et al. (1999), which included an excellent HST spectrum eleven days after maximum light as well as IUE. The spectra were similar to those obtained for SN 1983N with IUE and strengthened the idea that SNe I are weak UV emitters (Panagia 2007). Fitting the HST UV-optical spectrum required Fe II and Ca II in the optical and UV while Mg II and Cr II ions were only strong in the UV. A detailed analysis of the UV was left for future work (Millard et al. 1999).

SN 1999em was a normal IIP observed with HST about ten days after the explosion (Baron et al. 2000; Leonard et al. 2002a). The UV spectrum showed a continuum that stayed bright out to 3000 Å before dropping to shorter wavelengths. The absorption in the blue was dominated by FeII, probably Ni II and the Mg II blend at 2798 Å. The spectrum was slightly brighter near 2000 Å, likely from gaps in absorption rather than emission. Non-local thermodynamic equilibrium (NLTE) models showed strong unobserved lines, raising the possibility of a lower metallicity (Baron et al. 2000).

SN 1993J is the prototypical IIb SN, a transitional object between II and Ib, as it showed hydrogen only at early times. It was observed by both IUE and HST. The early IUE observations showed a strong UV continuum and evidence for an extinction bump near 2200 Å (Wamsteker et al. 1993). The relatively smooth UV continuum showed evidence for circumstellar matter interaction and decayed rapidly (Balonek et al. 1993). The lack of strong absorption features seen in other UV spectra and predicted by models is evidence for circumstellar matter interaction (Jeffery et al. 1994; Baron et al. 1994), consistent with X-ray and radio observations (Pooley & Green 1993).

SN 1998S was the bluest of the SNe observed with HST, with the first HST observation twenty days after explosion showing a strong continuum rising at shorter wavelengths to 2,000 Å before dropping (Lentz et al. 2001). Two weeks later the UV luminosity had dropped dramatically, with the peak flux then occurring at about 4,000 Å. The spectra were reasonably reproduced with a region of circumstellar interaction above the SN photosphere. Late-time observations of the IIn SN1995N also showed strong UV flux, arising primarily from FeII fluorescence and a strong Mg II line (Fransson et al. 2002).

Currently in operation is the XMM-Newton Optical Monitor (OM). While XMM’s primary observations are X-ray, simultaneous OM UV observations of X-ray targeted SNe are often made. One example is the detection late time X-ray, optical, and UV emission from SN 1979C indicating interaction with circumstellar material (Immler et al. 2005a). The Galaxy Evolution Explorer (GALEX) has also observed several SNe IIP in the UV\(^3\). Grism observations of SN 2005ay in the UV show a spectral similarity to other SNe IIP observed with HST and Swift/UVOT (Gal-Yam et al. 2008). The wide field-of-view of GALEX was also useful for the discovery of the shock breakout of two SNe IIP (Gezari et al. 2008; Schawinski et al. 2008). The observations and theoretical simulations show a rapid rise in the UV luminosity that plateaus for the first three days after explosion as the photospheric expansion is balanced by the decreasing

\(^3\)http://www.weizmann.ac.il/home/galyam/galex.html
temperature. HST observations of SNe have continued, with the UV observations of SN 2005cf showing good agreement with the UVOT photometry (Wang et al. 2009b). Rest-frame UV observations of higher redshift SNe observed in the optical from the ground are also now being regularly obtained, primarily of SNe Ia (Astier et al. 2006; Foley et al. 2008a; Ellis et al. 2008), and the detection of rest frame UV from SNe IIn up to a redshift of 2 has recently been announced (J. Cooke, 2009, private communication).

IUE was able to obtain low signal spectra for a large number of SNe near maximum light. HST’s legacy for UV SN is the handful of very high signal to noise spectra of which there is one for almost every major SN type. What was lacking, however, was information on the temporal behavior of the UV flux at early times and well after maximum light for individual SNe. Most objects had only a few epochs of UV observations, with the light curves of a few well observed objects being used to represent the whole class. Also missing were observations of enough SNe of each type to draw meaningful comparisons as to the variation in the UV behavior.

1.3 Swift UVOT

The latest UV observatory is the Swift Ultra-Violet/Optical Telescope (UVOT; Roming et al. 2005). The Swift observatory’s quick response capability and short term scheduling, necessitated by the unpredictable and variable behavior of individual gamma ray bursts (GRB), also allows newly discovered SNe to be observed quickly and with well sampled light curves (Gehrels et al. 2004). Data are available in a matter of hours, and observing times and filter combinations can be changed on a day to day basis depending on what is seen in recent observations. Thus far, Swift has focused mostly on nearby SNe (\(z \lesssim 0.02\)) for which high quality data can be obtained with only a small impact on spacecraft operations and Swift’s primary mission to detect and observe GRBs. SN observations are performed under Swift’s Target of Opportunity (ToO) program \(^4\). A dedicated website\(^5\) has been set up that gives the status of Swift SN observations, images and regularly updated light curves for the benefit of the community.

Swift’s quick response comes in the ability to overlay an “automated target” (AT) over the previously planned schedule during times the AT position does not violate any pointing constraints (minimum distance from the earth, sun, and moon) as calculated by the spacecraft. Thus Swift can discover and localise a new gamma ray burst (GRB) with the Burst Alert Telescope (BAT) and autonomously slew to it to point the narrow field instruments (NFIs; XRT and UVOT) at the position within minutes of the burst detection. In addition to new GRBs, ATs for GRBs discovered by other spacecraft or for other time critical Targets of Opportunity (TOOs) can be observed via uploaded commands. This allows urgent targets to be observed quickly without requiring the observing plan to be redone. Even without ATs, the Swift observing plan is done on a relatively short term basis compared to most space based observatories. Typically a plan is created just 1-3 days before execution, with changes being made and the plan being uploaded to the spacecraft hours before being executed. Necessitated by the variable

\(^4\)http://www.swift.psu.edu/too.html
\(^5\)see http://swift.gsfc.nasa.gov/docs/swift/sne/swift_sn.html
behavior of GRB afterglows, it also allows other targets to be observed very flexibly and on short notice.

The UVOT is a 30 cm telescope with a modified Ritchey-Chretian design. UVOT’s detector uses a photocathode and micro-channel plate intensifiers to produce a cloud of electrons from an incoming photon. A phosphor screen is lit up by the electron cloud and the photons carried via fiber-optics to the detector. The charge coupled device (CCD) has an array of 256 X 256 pixels for data collection which is read out every 11 ms (reading out a smaller area can result in a shorter frame time). In each frame “photon splashes” (from the cloud of electrons hitting the phosphor plate) are centroided to 1/8 of a pixel, resulting in a 2048 x 2048 resolution. This translates to a 0.5″ resolution on the sky and a 17x17 arcminute field of view.

Operating as a photon counter, the UVOT can transmit the locations and times of all these “events” (appropriately enough called event mode) but for telemetry reasons usually uses image mode. In this mode the UVOT collects all of the photons into an image on board—counting individual events and adding the centroided event to a digital image as opposed to accumulating electrons and then reading it out like like a typical CCD. It then sends the whole image down. For telemetry reasons, beginning March 2006 most science images are binned 2x2 on board before transmitting them to the ground. Since the UVOT’s point-spread function (PSF) is about 2″ this does not significantly degrade the image resolution. Images of SN 2006E taken before and after the binning change were part of the calibrations checks that the photometry was not significantly changed by the binning.

The UVOT is centroiding photon splashes, so it cannot distinguish photons which arrive near the same place in the detector during the same 11 ms frame. The splashes of the photons would be centroided and counted only once. This is called coincidence loss, a form of non-linearity similar to what is called “pile-up” for X-ray detectors. Based on the frame time there is a theoretical correction to go from the observed to the incident count rate for a single pixel detector. Since the actual effect occurs over multiple pixels and involves the PSF, an empirical correction has also been calibrated to improve the coincidence loss correction (Poole et al. 2008). The coincidence loss can be corrected up to about 100 counts/s (when every frame has at least one count at the detector position the source is saturated and information is lost). It might be possible to calibrate the wings of the PSF or the brightness of the star halos to estimate the brightness of objects brighter than this, but it is complicated and requires further study. The coincidence loss corrections in Poole et al. (2008) are calibrated for a point source, so extended sources or point sources with a high background (including SNe on top of a bright galaxy) do not follow the same correction (Breeveld et al., 2009, in preparation). For the analysis in Chapter 4 we have found an empirical count rate for the underlying galaxy below which the coincidence loss corrections works and exclude those filters for which the galaxy is too bright. By reading out a smaller portion of the CCD, the read out time can be decreased and the coincidence loss limit increased, resulting in about one more magnitude before the saturation limit is reached.

To avoid excessive degradation of the photocathodes, bright star limits are imposed by the UVOT software. During slews the target region is searched for bright stars and planets within 20' of the requested position. If the catalog brightness and color of a
star predicts too high of a count rate in a given filter the length of the exposure will be cut down or skipped completely. This bright limit is approximately 6th magnitude. To protect against transient bright sources there is a safety circuit which trips if the count rate is too high for a certain number of frames. In addition, if the spacecraft settles too far from the requested position, the UVOT software will move the filter wheel to blocked and place the UVOT in a safe configuration and await further commands before observing again. There is also the potential for contamination from reflected light halos of bright stars. For stars of 8th magnitude or brighter there is a halo of about 140″. A sample image is shown in Figure 1.8.

![Sample Image](image)

Fig. 1.8 Bright star contamination regions for UVOT. Stars brighter than 10th magnitude have a bright core with a radius of 20″. There is also a 10″ radius halo offset from the star. Stars brighter than 8th magnitude also have a large, bright halo of 140″ radius. Sources within these regions near bright stars would be contaminated.

UVOT’s observing sequence is determined by a mode assigned in the pre-planned science timeline (PPST). The PPST is a time series of commands telling the spacecraft when to slew to a target (including the sky coordinates and the spacecraft roll angle) and which instrument modes to use. UVOT modes are hexadecimal numbers corresponding to an observing sequence specifying the filter, binning, frame size to be read out from the CCD, whether to save the data as events or an image, image size to save, and the time or time fraction to spend in that filter. For most multi-filter modes, UVOT takes the given snapshot length and determines the exposure times for each filter. If a preplanned target is interrupted (GRB, uploaded AT, spacecraft problem) the sequence is terminated (and any later exposures in the other filters in the sequence missed). For
targets uploaded as ATs, the observing time is often inaccurately given as the time to the next constraint. If the time for a higher merit PPT occurs during the AT, the filter sequence will be terminated midstream and the later exposures in the other filters skipped. Since the first observation of a SN is often done as an AT, a couple of unscaled modes were created that would observe in each filter for a set amount of time in order to complete the six filter sequence in 1000 or 2000 seconds to increase the likelihood of getting all six filters even if the snapshot lengths are truncated.

SNe chosen for observation by Swift are generally young and nearby \((z < 0.02)\) and should be offset from bright field stars or the host galaxy nucleus by at least 10". Low extinction is also preferred, particularly for more distant SNe, though a few nearby events (notably SNe 2006X, 2006bp, and 2007bm) do suffer from significant extinction. These criteria have been dynamically evolving as a result of experience and are less strictly applied for rarer events. Thus we are not an unbiased sample but strive to observe the range of SN events accessible to UVOT.

UVOT typically observes SNe with three UV and three optical broadband filters. There is also a broad “white” filter which covers the whole detector range \((1600 – 6000 \, \text{Å})\) which is useful for very faint objects, but is not used for nearby SNe because the color information and SED is much more valuable and easily accessible. The typical modes used are listed in Table 1.3. The central wavelengths and widths of these filters are given in Table 1.2 (Poole et al. 2008). The transmission of the filters with respect to SNe spectra is shown in Figure 1.9. UVOT also has low resolution spectroscopic grisms. However, like IUE, UVOT grism spectra are limited to the brightest epochs of the nearest SNe. Here we focus on results from the photometry; spectroscopic results will be presented elsewhere (Bufano et al. 2009). Grism observations are optimally preceded by what is called a “slew in place,” in which a short observation is requested followed by a second. Since the slew is short, the repointing is more accurate, placing the target in a better location where the calibration is better.
Fig. 1.9 UVOT filters with the spectra of SNe 2005am and 2005cs.

Table 1.2. Swift UVOT Filter Characteristics

<table>
<thead>
<tr>
<th>Filter</th>
<th>(\lambda_{central}) (Å)</th>
<th>FWHM (Å)</th>
<th>Zeropoint(^a) (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>uvw2</td>
<td>1928</td>
<td>657</td>
<td>17.35 ± 0.03</td>
</tr>
<tr>
<td>uvm2</td>
<td>2246</td>
<td>498</td>
<td>16.82 ± 0.03</td>
</tr>
<tr>
<td>uvw1</td>
<td>2600</td>
<td>693</td>
<td>17.49 ± 0.03</td>
</tr>
<tr>
<td>u</td>
<td>3465</td>
<td>785</td>
<td>18.34 ± 0.020</td>
</tr>
<tr>
<td>b</td>
<td>4392</td>
<td>975</td>
<td>19.11 ± 0.016</td>
</tr>
<tr>
<td>v</td>
<td>5468</td>
<td>769</td>
<td>17.89 ± 0.013</td>
</tr>
</tbody>
</table>

\(^a\)The zeropoint is given for conversion from count rates to Vega magnitudes (such that \(m_{\text{Vega}} = 0\) in all filters) as in the equation \(m = -2.5\log(\text{counts/s}) + ZP\) Poole et al. (2008).
Table 1.3. Common UVOT Modes for SN Observations

<table>
<thead>
<tr>
<th>Mode</th>
<th>Filters</th>
<th>Binning</th>
<th>Time(^a) (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x30ed</td>
<td>W1,UU,BB,W2,VV,M2</td>
<td>2</td>
<td>167,83,83,249,83,332</td>
</tr>
<tr>
<td>0x223f</td>
<td>W1,UU,BB,W2,VV,M2</td>
<td>2</td>
<td>105,53,53,265,53,424</td>
</tr>
<tr>
<td>0x2238</td>
<td>W1,UU,BB,VV</td>
<td>2</td>
<td>555,222,111,111</td>
</tr>
<tr>
<td>0x0270</td>
<td>W1,UU,BB,W2,VV,M2</td>
<td>2</td>
<td>160,80,80,320,80,440</td>
</tr>
<tr>
<td>0x122f</td>
<td>UC,W2</td>
<td>1(^d)</td>
<td>910,91</td>
</tr>
<tr>
<td>0x1230</td>
<td>VC,W1</td>
<td>1(^d)</td>
<td>910,91</td>
</tr>
</tbody>
</table>

Note. — The filter abbreviations used here are as follows: W1: uvw1; UU: u; BB: b; W2: uvw2; VV: v; M2: uvm2; UC: UV grism, clocked; VC: V (optical) grism, clocked.

\(^a\)The time is given as would be scaled for a 1000 s snapshot. With the exception of 0x0270, smaller or longer snapshots will have the same fractional exposure in each of the filters.

\(^b\)Popular modes earlier in the mission 0x10ed (which is unbinned) and 0x20ed had the same exposure time weighting but had the uvm2 and uvw2 exposures in event mode.

\(^c\)This mode is unscaled, and snapshots greater than 1000 s will increase the exposure time in the last filter (uvm2). For shorter snapshots the sequence will just be cut short.

\(^d\)The grism exposure is binned 1x1 but the filter exposure is binned 2x2.

\(^e\)Grism observations are typically preceded by a short observation to improve the pointing with an additional short slew. This also protects the grism exposure from contamination by bright earth limb light during the beginning of the observation. A short snapshot in a UV filter follows the grism exposure for protection as the earth angle decreases toward the end of the exposure.
Chapter 2

The Type Ia Supernova 2005am

This chapter discusses the first SN observed by Swift, the type Ia SN 2005am. It was published in Brown et al. 2005, ApJ, 635, 1192. At the time of publication, it was the convention to refer to the UVOT filters in upper case (i.e., UVW2). With the Poole et al. (2008) recalibration the convention was changed to lower case to avoid confusion with the Johnson $UBV$ filters. This chapter retains the older convention, as it was done on the older calibration. The photometry was redone with the new calibration in Chapter 4.

2.1 Introduction

Type Ia supernovae (SNe) are among the brightest of astrophysical events, making them useful as probes of the distant universe. Because Type Ia have similar luminosities at their peak, and a well-established relationship between their peak brightness and rate of decay, they are excellent standardizable candles. The dispersion in absolute magnitudes can be reduced to approximately 15% by calibrating the peak luminosity to other observable parameters such as the $B$-band decline rate $\Delta m_{15}(B)$ (Phillips 1993; Phillips et al. 1999). SNe Ia gave the first evidence that the expansion of the universe is accelerating (Riess et al. 1998), and they are used to constrain certain cosmological parameters (Perlmutter et al. 1999).

UV observations are important for understanding the behaviour of SNe. For local ($z \approx 0$) SNe, observations in the UV can be used to distinguish between different explosion models, as the UV emission probes the metallicity of the progenitor, as well as the degree of mixing of the synthesized $^{56}$Ni (Blinnikov & Sorokina 2000). For SNe observed at high redshifts, the rest-frame UV is redshifted into the optical bands, so understanding the rest-frame UV behaviour of SNe is critical to understanding the nature of more distant SNe Ia.

Unfortunately, observations of local SNe in their rest-frame UV are limited because they require space-based observatories. The International Ultraviolet Explorer (IUE) obtained UV spectroscopy of 12 Type Ia SNe, and the Hubble Space Telescope (HST) continues to obtain valuable UV spectroscopy and photometry (see Panagia 2003 for a review of SN observations in the UV). One of the best observed Ia SN is 1992A which was observed by both IUE and HST (Kirshner et al. 1993). There is also a Cycle 13 HST programme (PI: Filippenko) that has obtained UV observations of SN2004dt, SN2004ef, and SN2005M (Wang et al. 2005a). A larger sample is needed to determine how uniform Type Ia SNe are in the UV.

SN2005am was discovered by Martin et al. (2005) in images from 2005 February 22 and 24 (all dates UT). The reported position was RA =9:16:12.47 and Dec =-16:18:16
(J2000) in NGC 2811 ($z = 0.007899$; Theureau et al. 1998). It was confirmed a week later by K. Itagaki, by which time it had brightened by about 3.5 magnitudes (Martin et al. 2005). Modjaz et al. (2005) classified it from spectra as an early Type Ia SN on 2005 March 3, and the observations with the Swift spacecraft reported here began the next day. In this paper we present UV and optical photometry, grism spectroscopy, and an upper limit to the X-ray luminosity.

2.2 Observations and Reductions

Observations of SN2005am were made with the Swift spacecraft (Gehrels et al. 2004) between 2005 Mar 4 and 2005 May 17.

Swift’s Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005) is a 30 cm telescope equipped with two grisms and six broadband filters. The UV grism produces spectra from approximately 2000 Å to 3400 Å, and the V (optical) grism produces spectra from approximately 3000 Å to 6000 Å. The filters and their corresponding central wavelengths are UVW2 (1800 Å), UVM2 (2200 Å), UVW1 (2600 Å), U (3600 Å), B (4200 Å), and V (5500 Å). To understand where in the spectrum of a SN these filters correspond, Figure 2.1 shows the effective area curves for the six broadband filters superimposed on a combined spectrum of SN2005am using both the UV and optical grisms.

Observations began while the spacecraft was still in its commissioning phase, and some calibrations are still ongoing. Because of this, the photometric zero points used will be explicitly given in the event that future calibrations require an adjustment of those values.

2.2.1 Photometry

SN2005am is located in the outer edge of the visible disc of the host galaxy NGC 2811 and 6′.3 from a foreground star ($V = 14.55 \pm 0.04$). This star, and the diffuse light from the host galaxy, complicate precision photometry. High precision photometry will have to wait until the SN has faded and the underlying diffuse light from NGC 2811 can be subtracted. It is anticipated that UVOT will reobserve NGC 2811 at that time.

We performed aperture photometry in a circular aperture with a radius of 3′.5 centered on the SN. A sky annulus with an inner radius of 20″ and a width of 5″ was used to estimate the local background. We found that these choices minimized contamination from the host galaxy and the nearby bright source while including most of the light from the supernova.

The UVOT is a photon-counting detector, so it suffers from coincidence losses for sources with high count rates. This occurs when the count rate approaches the frame rate and all photons are not counted, and for very high count rates the number of photons missed cannot be calculated. This corresponds to saturation magnitudes of $V_{\text{coinc}} = 12.94$, $B_{\text{coinc}} = 14.23$, $U_{\text{coinc}} = 13.45$, $UVW_1_{\text{coinc}} = 12.93$, $UVW_2_{\text{coinc}} = 12.30$, and $UVW_2_{\text{coinc}} = 12.93$. Coincidence corrections were applied to all of our data, though the nearby star may have caused the coincidence losses to have been underestimated. At the SN’s peak brightness, our observations in the $B$ were above the calculated saturation point and are treated as lower limits to the true $B$-band magnitudes. In addition, the $U$
Fig. 2.1 Effective area curves (in \( cm^2 \)) of UVOT’s six broadband filters superimposed on a spectrum of SN2005am.
and V-band observations near maximum have larger errors (∼ 0.1 magnitudes) due to coincidence losses.

The magnitudes were transformed to Vega magnitudes using Landolt standards for the optical bands (Landolt 1992) and white dwarfs observed by IUE for the UV bands (Wegner & Swanson 1991). The following preliminary flight photometric zero points were applied: $ZP_V = 17.83 \pm 0.09$, $ZP_B = 19.12 \pm 0.08$, $ZP_U = 18.34 \pm 0.16$, $ZP_{UVW1} = 17.82 \pm 0.23$, $ZP_{UV,M2} = 17.19 \pm 0.26$, and $ZP_{UV,W2} = 17.82 \pm 0.27$. Color terms have not been calibrated, so they were not applied to the photometry. The photometry is presented in Table 2.1.

### 2.2.2 Grism Spectroscopy

Table 2.2 lists the grism exposures taken by UVOT. The Epoch column lists the number of days after maximum light in the B band. The spectra of SN2005am (integrated from both the UV and V grism exposures) were extracted using the Swifttools software included in the standard HEASOFT software package. Care was taken to perform the background subtraction of the grism data using clean regions, but this was hard to achieve due to the crowding of the field. Sequence IDs 00030010007 and 00030010011 were particularly affected by this problem. All of the V grism observations suffer from a high background level due to the neighbouring galaxy, but, since both the background and the spectral regions are likewise affected, the one should cancel the other. Contamination of the first order spectra by close and overlapping zeroth order spectra adversely affected the quality of the spectra from sequence IDs 00030010003 and 30010004. In order to circumvent the contamination in these regions, a narrow source width was specified for the spectral extraction from sequence IDs 00030010003 and 00030010007. This may have resulted in some loss of flux.

### 2.3 Results

The light curves are presented in Figure 2.2. For comparison we have overlaid template curves for the B and V bands from SN1992A (Hamuy et al. 1996b) and for the UVW1 band from SNe 1992A and 1990N (Kirshner et al. 1993).

#### 2.3.1 Optical Light Curves

The B band is saturated, so the time of $B_{\text{max}}$ and the value of $\Delta m_{15}(B)$ are not well determined by our data alone. To estimate their values, the SN2005am light curves in the B and V bands were compared to templates from Hamuy et al. (1996b). Due to the scatter, our light curves are consistent with SN1992A ($\Delta m_{15}(B) = 1.47$) or the template of SNe 1992bo/1993H ($\Delta m_{15}(B) = 1.69$). Ground based data confirm an intermediate value for $\Delta m_{15}(B)$ (M. Hamuy, private communication). We estimate that $B_{\text{max}}$ occurred on JD 2453438 ± 1 day (2005 March 8).

We note that our B band data are systematically fainter than the ground-based data presented by Li et al. (2006a) by about 0.15 magnitudes. This difference could be due to the different zeropoints and aperture sizes or unaccounted for by coincidence losses from the nearby star. Our larger aperture and host galaxy contamination could
<table>
<thead>
<tr>
<th>Julian Date</th>
<th>UVW2</th>
<th>UVM2</th>
<th>UVW1</th>
<th>U</th>
<th>B</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2453434.442</td>
<td>17.69</td>
<td>(072)</td>
<td>19.00</td>
<td>237</td>
<td>15.79</td>
<td>(043)</td>
</tr>
<tr>
<td>2453438.186</td>
<td>17.56</td>
<td>(081)</td>
<td>19.06</td>
<td>127</td>
<td>15.93</td>
<td>(024)</td>
</tr>
<tr>
<td>2453438.586</td>
<td>17.63</td>
<td>(038)</td>
<td>18.86</td>
<td>110</td>
<td>15.96</td>
<td>(024)</td>
</tr>
<tr>
<td>2453438.922</td>
<td>17.63</td>
<td>(037)</td>
<td>18.77</td>
<td>103</td>
<td>16.02</td>
<td>(025)</td>
</tr>
<tr>
<td>2453439.257</td>
<td>17.62</td>
<td>(040)</td>
<td>18.75</td>
<td>110</td>
<td>16.06</td>
<td>(026)</td>
</tr>
<tr>
<td>2453439.512</td>
<td>17.71</td>
<td>(040)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2453439.851</td>
<td>17.66</td>
<td>(038)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2453441.527</td>
<td>17.77</td>
<td>(053)</td>
<td>18.71</td>
<td>132</td>
<td>16.35</td>
<td>(037)</td>
</tr>
<tr>
<td>2453441.868</td>
<td>17.85</td>
<td>(042)</td>
<td>19.01</td>
<td>119</td>
<td>16.31</td>
<td>(028)</td>
</tr>
<tr>
<td>2453442.271</td>
<td>17.98</td>
<td>(048)</td>
<td>18.74</td>
<td>109</td>
<td>16.39</td>
<td>(031)</td>
</tr>
<tr>
<td>2453443.463</td>
<td>17.98</td>
<td>(096)</td>
<td>18.81</td>
<td>230</td>
<td>16.55</td>
<td>(067)</td>
</tr>
<tr>
<td>2453443.744</td>
<td>18.12</td>
<td>(048)</td>
<td>18.84</td>
<td>108</td>
<td>16.59</td>
<td>(032)</td>
</tr>
<tr>
<td>2453444.414</td>
<td>18.13</td>
<td>(048)</td>
<td>19.12</td>
<td>129</td>
<td>16.67</td>
<td>(034)</td>
</tr>
<tr>
<td>2453444.959</td>
<td>18.11</td>
<td>(130)</td>
<td>18.45</td>
<td>242</td>
<td>16.73</td>
<td>(095)</td>
</tr>
<tr>
<td>2453445.690</td>
<td>18.31</td>
<td>(061)</td>
<td>19.05</td>
<td>143</td>
<td>16.77</td>
<td>(041)</td>
</tr>
<tr>
<td>2453446.024</td>
<td>18.34</td>
<td>(062)</td>
<td>18.75</td>
<td>120</td>
<td>16.92</td>
<td>(044)</td>
</tr>
<tr>
<td>2453446.224</td>
<td>18.39</td>
<td>(058)</td>
<td>19.01</td>
<td>125</td>
<td>16.86</td>
<td>(039)</td>
</tr>
<tr>
<td>2453446.627</td>
<td>18.39</td>
<td>(059)</td>
<td>18.96</td>
<td>125</td>
<td>16.96</td>
<td>(041)</td>
</tr>
<tr>
<td>2453446.962</td>
<td>18.55</td>
<td>(067)</td>
<td>18.98</td>
<td>133</td>
<td>16.99</td>
<td>(044)</td>
</tr>
<tr>
<td>2453447.428</td>
<td>18.51</td>
<td>(060)</td>
<td>19.25</td>
<td>141</td>
<td>17.08</td>
<td>(042)</td>
</tr>
<tr>
<td>2453447.965</td>
<td>18.58</td>
<td>(060)</td>
<td>19.07</td>
<td>122</td>
<td>17.04</td>
<td>(040)</td>
</tr>
<tr>
<td>2453448.302</td>
<td>18.64</td>
<td>(062)</td>
<td>19.16</td>
<td>131</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2453451.976</td>
<td>19.20</td>
<td>(123)</td>
<td>19.11</td>
<td>179</td>
<td>17.91</td>
<td>(091)</td>
</tr>
<tr>
<td>2453452.044</td>
<td>19.65</td>
<td>(247)</td>
<td>18.16</td>
<td>105</td>
<td>15.99</td>
<td>(039)</td>
</tr>
<tr>
<td>2453452.655</td>
<td>19.23</td>
<td>(132)</td>
<td>19.16</td>
<td>253</td>
<td>17.71</td>
<td>(111)</td>
</tr>
<tr>
<td>2453452.725</td>
<td>19.87</td>
<td>(310)</td>
<td>17.70</td>
<td>088</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2453453.85</td>
<td>19.49</td>
<td>(166)</td>
<td>&gt; 20.13</td>
<td></td>
<td>17.98</td>
<td>(107)</td>
</tr>
<tr>
<td>2453453.918</td>
<td>19.72</td>
<td>(284)</td>
<td>17.81</td>
<td>095</td>
<td>16.24</td>
<td>(050)</td>
</tr>
<tr>
<td>2453454.533</td>
<td>19.29</td>
<td>(011)</td>
<td>19.77</td>
<td>209</td>
<td>18.03</td>
<td>(075)</td>
</tr>
<tr>
<td>2453454.867</td>
<td>19.12</td>
<td>(088)</td>
<td>19.61</td>
<td>183</td>
<td>17.89</td>
<td>(069)</td>
</tr>
<tr>
<td>2453455.999</td>
<td>19.49</td>
<td>(112)</td>
<td>19.96</td>
<td>232</td>
<td>18.24</td>
<td>(085)</td>
</tr>
<tr>
<td>2453456.541</td>
<td>19.46</td>
<td>(133)</td>
<td>20.03</td>
<td>347</td>
<td>18.15</td>
<td>(173)</td>
</tr>
<tr>
<td>2453456.588</td>
<td>19.37</td>
<td>(343)</td>
<td>18.30</td>
<td>163</td>
<td>16.65</td>
<td>(051)</td>
</tr>
<tr>
<td>2453456.6</td>
<td>19.56</td>
<td>(220)</td>
<td>18.22</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2453457.741</td>
<td>19.48</td>
<td>(132)</td>
<td>19.77</td>
<td>343</td>
<td>18.05</td>
<td>(124)</td>
</tr>
<tr>
<td>2453457.806</td>
<td>19.61</td>
<td>(221)</td>
<td>18.29</td>
<td>104</td>
<td>16.72</td>
<td>(053)</td>
</tr>
<tr>
<td>2453464.979</td>
<td>20.14</td>
<td>(147)</td>
<td>20.00</td>
<td>206</td>
<td>19.01</td>
<td>(116)</td>
</tr>
<tr>
<td>2453466.858</td>
<td>20.22</td>
<td>(299)</td>
<td>&gt; 20.17</td>
<td></td>
<td>19.09</td>
<td>(173)</td>
</tr>
<tr>
<td>2453470.597</td>
<td>20.32</td>
<td>(275)</td>
<td>19.04</td>
<td>344</td>
<td>19.35</td>
<td>(236)</td>
</tr>
<tr>
<td>2453470.656</td>
<td>20.43</td>
<td>(240)</td>
<td>20.19</td>
<td>315</td>
<td>19.10</td>
<td>(165)</td>
</tr>
<tr>
<td>2453482.593</td>
<td>20.78</td>
<td>(263)</td>
<td>&gt; 20.71</td>
<td></td>
<td>19.91</td>
<td>(251)</td>
</tr>
<tr>
<td>2453507.639</td>
<td>&gt; 20.75</td>
<td></td>
<td>&gt; 20.37</td>
<td></td>
<td>18.71</td>
<td>(244)</td>
</tr>
</tbody>
</table>

Note. — Errors quoted do not include any systematic error in the zeropoint or errors due to coincidence losses. Lower limits to the brightness due to coincidence saturation and $3\sigma$ upper limits are indicated.
Fig. 2.2 Ultraviolet and optical light curves of SN2005am obtained by UVOT. For visual clarity, the U curve has been shifted by +1 magnitude and the UVW2 curve by +2 magnitudes. Overlaid are B and V templates of SN1992A (Hamuy et al. 1996b) and the *F275W template from SNe 1992A/1990N (for our UVW1 curve; Kirshner et al. 1993).

Table 2.2. UVOT Grism Observations of SN 2005am

<table>
<thead>
<tr>
<th>Sequence ID</th>
<th>Grism Used</th>
<th>Date Time (UT)</th>
<th>Epoch</th>
<th>Exposure Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>00030010003</td>
<td>V</td>
<td>2005-03-08 17:47:10</td>
<td>-1</td>
<td>1812.7</td>
</tr>
<tr>
<td>00030010004</td>
<td>UV</td>
<td>2005-03-07 23:07:34</td>
<td>0</td>
<td>2781.7</td>
</tr>
<tr>
<td>00030010007</td>
<td>UV</td>
<td>2005-03-09 14:29:01</td>
<td>+1</td>
<td>2369.9</td>
</tr>
<tr>
<td>00030010011</td>
<td>V</td>
<td>2005-03-10 14:36:01</td>
<td>+2</td>
<td>2332.4</td>
</tr>
<tr>
<td>00030010024</td>
<td>V</td>
<td>2005-03-15 23:21:01</td>
<td>+7</td>
<td>1828.9</td>
</tr>
<tr>
<td>00030010035</td>
<td>V</td>
<td>2005-03-17 20:21:41</td>
<td>+9</td>
<td>1828.3</td>
</tr>
<tr>
<td>000300100054</td>
<td>V</td>
<td>2005-03-23 01:50:01</td>
<td>+15</td>
<td>1838.5</td>
</tr>
</tbody>
</table>
also explain the difference between our B and V magnitudes and those independently derived by Li et al. (2006a) for some of the late time UVOT observations, as well as our deviation from the templates at late times. Subtracting template images of the host galaxy after the SN has faded will improve the photometry most for these later observations.

### 2.3.2 Ultraviolet Light Curves

The UV photometry presented here is a unique set. The only two other Type Ia SNe with UV photometry available in the literature are SNe 1992A and 1990N. Using those two SNe, Kirshner et al. (1993) composed a template light curve using HST’s F275W filter and the flux extracted from IUE spectra over a similar range, but cut off at 3400 Å. This band, named *F275W in the above paper, covers a similar wavelength range as UVOT’s UVW1 filter, so this template is compared to the UVOT data in Figure 2.2. Our observations agree very well with the template. This is reassuring, since the optical light curves of SNe 2005am and 1992A are similar. SN1990N had a shallower decay in the optical ($\Delta m_{15}(B) = 1.07$; Phillips et al. 1999), and in Figure 3 of Kirshner et al. (1993) appears to be slightly broader, but the observations do not extend past four days after $B_{max}$. UV observations of SNe with a variety of values of $\Delta m_{15}(B)$ using HST, Swift, or other space-based observatories would be valuable in calibrating a peak luminosity-width relationship in the UV which will be useful for cosmology.

Blueward of 2500 Å, only a few data points are available for SN1992A, which marginally matched a U-band template (Kirshner et al. 1993). The UVW2 and UVM2 curves presented here are the first opportunity to see the photometric evolution in this spectral range. One feature is that the decay rate in the UV is actually shallower than in the U and B bands. To quantify this, a subsection of the photometry beginning three days after maximum and extending to day twenty are used to calculate the decay rate in each band. The decay rates (in magnitudes per day) over this period are $D_V = 0.0684 \pm 0.0008$, $D_B = 0.135 \pm 0.001$, $D_U = 0.158 \pm 0.001$, $D_{UVW1} = 0.129 \pm 0.002$, $D_{UVM2} = 0.069 \pm 0.007$, and $D_{UVW2} = 0.114 \pm 0.003$. An interesting feature is that the decay rate in the UVM2 filter is shallower than the decay rate in the other UV filters that overlap with it on both sides. This shallow decay and the general faintness in the UVM2 filter may be a result of interstellar extinction, which has not been corrected for in the magnitudes presented here. The 2175 Å bump present in the extinction curve of the Milky Way (Pei 1992) is nearly centered on the UVM2 filter bandpass.

UV observations of SNe such as these could be useful for interpreting high redshift SNe observed in the optical bands. For example, Kirshner et al. (1993) noted that the light curve of a nearby SNe observed in the *F275W filter would be similar to that of a SN at $z = 0.6$ observed in the $B$ band. The same would be true of UVOT’s UVW1 filter. Similarly, a rest frame SN observed with UVOT’s UVW2 filter should match a $B$ band observation of a SN at a redshift of $z \approx 1.5$. Time dilation would need to be taken into account, as well as $K$ corrections which have not been done in the UV.
2.3.3 Spectra

The grism spectra are presented in Figure 2.3. The optical spectra are typical of Type Ia SNe, featuring P-Cygni line profiles superimposed on a roughly thermal continuum. The UV continuum is suppressed by deep absorption from blends of iron peak elements. Broad peaks on either side of 3000 Å resemble those seen in other SNe observed in the UV (Benvenuti et al. 1982) and identified by Branch & Venkatakrishna (1986) as blended lines of FeII and CoII. A more detailed analysis of these spectra will be performed after better calibrations are available.

2.3.4 XRT Data

All XRT data, from June 30th to September 14, were merged into a single 33.0 ks observation to search for X-ray emission from SN 2005cs. However, a relatively bright (integrated flux between 0.2 and 10 keV, $f_{0.2-10} = [3.3 \pm 0.7] \times 10^{-14} \text{ergs cm}^{-2} \text{s}^{-1}$) and nearby (8′′ offset) X-ray flash source detected in sequence number 00030083011 (Immler et al. 2005a) severely affects an estimate of the amount of emission from SN 2005cs because this source is within the XRT source extraction aperture (18″ half-power diameter at 1.5 keV). We therefore excluded all observations obtained on the day the X-ray flash was observed (2005-07-06, sequence numbers 00030083010/11/12/13) to minimize contamination, leaving 26.8 ks of exposure time in the final merged image used below.

The 26.8 ks observation shows no X-ray source at the position of the X-ray flash, and no source at the position of SN 2005cs. We therefore extracted on-source counts from a circular extraction region with a radius of 10 pixel (23.6′′) and subtracted the background from an annulus centered on the position of SN 2005cs to account for diffuse emission from the galaxy. A 3-sigma upper limit to the 0.2–10 keV count rate of $1.7 \times 10^{-3} \text{cts s}^{-1}$ is obtained, which corresponds to an unabsorbed X-ray flux of $f_{0.2-10} < 9.0 \times 10^{-14} \text{ergs cm}^{-2} \text{s}^{-1}$.

2.3.5 XMM-Newton EPIC Data

SN 2005cs was observed with XMM-Newton on 2005-07-01 (OBS-ID 0212480801) as a Target of Opportunity (PI: Immler) to search for prompt X-ray emission from the SN. Data processing and analysis were performed with SAS 6.5.0¹ and the latest calibration constituents. After screening of the EPIC PN and MOS data for periods with a high background, cleaned exposure times of 28.1 ks for the PN and 33.8 ks for each of the two MOS instruments were obtained.

Inspection of the EPIC images showed that the X-ray “flash” serendipitously observed by Swift XRT during some of the observations (Immler et al. 2005b) is also present in the data obtained near-simultaneously with the XMM-Newton EPIC. Since the offset of this bright X-ray source from the position of SN 2005cs (8′′) is smaller than the point-spread-function of the XRT+EPIC (15″ half energy width), no reliable upper limits to the X-ray flux of SN 2005cs can be established from the XMM-Newton X-ray.

¹http://xmm.vilspa.esa.es/external/xmm_sw_cal/sas.shtml
Fig. 2.3 UVOT Grism Spectra of SN2005am. Each spectrum is labeled with its epoch in days from $B_{\text{max}}$. The vertical scale is given in logarithmic units of ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The spectra have been trimmed from their full size to avoid contamination by other spectral orders.
data. The XMM-Newton EPIC data will therefore not be further used and we will rely on the Swift XRT data to study the X-ray emission from SN 2005cs.

2.3.6 X-ray Results

The upper limit from the merged 26.8 ks XRT observation corresponds to an unabsorbed X-ray flux and luminosity of $f_{0.2-10} < 9.0 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ and $L_{0.2-10} < 8.4 \times 10^{38}$ ergs s$^{-1}$, respectively for an assumed thermal plasma spectrum with a temperature of 10 keV, an absorbing foreground column density of $1.6 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990) and a distance of 8 Mpc. SNe IIP have been detected in X-rays in the past (SN 1999em, Pooley et al. 2002; SN 1999gi, Schlegel 2001; SN2004dj, Pooley & Lewin 2004) but usually at lower flux levels (typically around $10^{38}$ ergs s$^{-1}$) than these upper limits. But these observations do rule out an X-ray bright SN more luminous than SN 1994W ($8 \times 10^{38}$ ergs s$^{-1}$), a IIP with optical evidence for CSM interaction. The typically faint X-ray luminosity is attributed to a low density circumstellar matter (CSM) surrounding the progenitor stars (Schlegel 2001). The presence of X-rays would indicate likely interaction with the CSM which would also affect the UV luminosity. Thus the lack of X-rays is consistent with the photospheric origin of the UV radiation discussed previously.

We calculated the upper limit to the mass-loss rate of the progenitor assuming a shock velocity of 10,000 km s$^{-1}$ and following the description by Immler et al. (2002). A 3-sigma upper limit of $\dot{M} < 1.3 \times 10^{-5}$ M$_\odot$ yr$^{-1}$ ($v_w/10$ km s$^{-1}$), where $v_w$ corresponds to the wind velocity, is obtained for a median date of the XRT observations around 12$ \pm $1 days after the outburst.

2.4 Summary

SN2005am appears to be a normal Type Ia SN. Its light curves resemble those of SN1992A in both the optical and near UV. The UV and optical spectra resemble those of other normal Type Ia SNe.

The observations reported here show the power of Swift’s UVOT for studying the UV behavior of SNe. UVOT can obtain low-resolution grism spectra of bright SNe and follow their light curve decay in three UV passbands. Another of Swift’s unique characteristics is its short term scheduling, allowing observations to be made within days or even hours. This allows UV observations to be made at earlier epochs than with other UV instruments past or present.

This paper presents a unique set of UV light curves for SN2005am which are better sampled in time and cover a wider wavelength range than any previous UV observations of a SN Ia. This SN was also well-observed in the optical and near-infrared wavelength ranges. Comparisons between the combined UV-OPT-NIR light curves of SN 2005am and radiation transport simulations of various theoretical explosion models for type Ia SNe will enhance our understanding of thermonuclear SN events.

Further Swift UV observations of local Type Ia SNe will help us understand the range in the UV properties of SNe Ia and enhance their use as standardizable candles.
This in turn will allow observations of high-redshift SNe Ia to better constrain the cosmological parameters governing the expansion of the universe.
Chapter 3

The Type II Supernova 2005cs

This chapter discusses the Swift observations of SN 2005cs. It was the first core-collapse SN observed by Swift, and the first light curve of a IIP in the UV. It was published in Brown et al. 2007, ApJ, 659, 1488. As in the previous chapter, the UVOT filters are referred to in upper case as was the convention for the older calibration upon which this analysis was based.

3.1 Introduction

Supernova (SN) 2005cs was discovered in the Whirlpool Galaxy (M51, NGC 5194) by W. Kloehr et al. (2005) on 2005 June 28.9 (all dates UT). Pastorello et al. (2006) estimate the explosion occurred June 27.5 (JD 2453549) based on previous non-detections. Modjaz et al. (2005) classified it from a spectrum as a young SN II on June 30.23, and the observations with the Swift spacecraft (Gehrels et al. 2004) reported here began June 30.9. The photometric and spectroscopic evolution of SN 2005cs is consistent with that of a subluminous SN II-Plateau (IIP), with a plateau phase lasting \( \sim 110 \) days and low ejecta velocities (Tsvetkov et al. 2006; Pastorello et al. 2006).

A young SN discovered in a nearby galaxy as well studied as M51 offers a unique opportunity for detailed investigations. The host galaxy has previously been observed at various wavelengths by many different instruments (see e.g., Calzetti et al. 2005, Dewangan et al. 2005). Examination of pre-explosion images from the Hubble Space Telescope (HST) has identified a \( 7 - 9M_\odot \) red supergiant as a plausible progenitor candidate (Li et al. 2006b; Maund et al. 2005). The position measured using high resolution images from the Canada-France-Hawaii Telescope and HST is R.A. =13:29:52.764 and Dec. =+47:10:36.09 (J2000; Li et al. 2006b).

The quick identification and classification of this SN event allowed for observations by instruments on the ground and in space while the SN was still in its early photospheric phase. This is especially critical in the UV because of the rapid decline in luminosity at short wavelengths as the SN photosphere cools. UV data on SNe are limited, because they require space-based observatories. This is especially difficult for early time observations because of the generally long lead time required for scheduling space-based observatories. While IUE observed several SNe II, none were of the “plateau” subtype despite it being the most common type of SNe II. HST observed the SN IIP 1999em at two epochs, starting about two weeks after the explosion (Baron et al. 2000). The observations presented in this paper fill an important gap by showing the UV evolution of this IIP SN 2005cs during the first few weeks after its explosion.
3.2 Observations and Reductions

3.2.1 Swift Observations

Regular observations of SN 2005cs were made with the Swift spacecraft (Gehrels et al. 2004) between 2005 June 30th and July 23rd with a follow-up observation on September 14, utilizing both the X-ray Telescope (XRT; Burrows et al. 2005) and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005), but only the UVOT results will be reported here. Images from UVOT and XRT of SN 2005cs and its host galaxy M51 are displayed in Figure 3.1. Pertinent calibration details for UVOT\(^1\), including the filter bandpasses and photometric zeropoints, are given in Table 3.1. The first observations were made by uploading the target to the Swift spacecraft as a Target of Opportunity. Typical observations were 2000 s, with the exposure time ratios weighted to the UV with mode 0x10ed (see Table 1.3).

\[\text{Fig. 3.1 Swift UVOT optical (left), UV (middle) and XRT X-ray(right) images of SN 2005cs and its host galaxy M51. The position of SN 2005cs is indicated by a white circle of 8'' radius and the spatial scale, identical for each image, is indicated in the top corner of each panel. The optical image was constructed from the UVOT V (1,815 s exposure time; red), B (1,232 s; green), and U (1,065 s; blue) filters, the UV image from the UVOT UVW1 (3,038 s red), UVM2 (7,189 s; green) and UVW2 (4,703 s; blue) filters obtained on 2005-09-14.97 UT and slightly smoothed for appearance sake with a Gaussian filter of 1.5 pixel (FWHM). The (0.2–10 keV) XRT X-ray image was constructed from the merged 33 ks XRT data and adaptively smoothed using the CIAO command csmooth to achieve a S/N in the range 2.5 to 4.}\]

\(^1\)see \url{http://swift.gsfc.nasa.gov/docs/heasarc/caldb/swift/docs/uvot/} for updated documentation
Table 3.1. Swift UVOT Filter Characteristics

<table>
<thead>
<tr>
<th>Filter</th>
<th>λc (Å)</th>
<th>FWHM (Å)</th>
<th>Zeropoint (mag)</th>
<th>Flux Density (10^{-16} ergs cm^{-2} s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVW2</td>
<td>1880</td>
<td>760</td>
<td>17.77 ± 0.20</td>
<td>6.04 ± 0.42</td>
</tr>
<tr>
<td>UVM2</td>
<td>2170</td>
<td>510</td>
<td>17.29 ± 0.23</td>
<td>6.89 ± 0.96</td>
</tr>
<tr>
<td>UVW1</td>
<td>2510</td>
<td>700</td>
<td>17.69 ± 0.20</td>
<td>3.52 ± 0.07</td>
</tr>
<tr>
<td>U</td>
<td>3450</td>
<td>875</td>
<td>18.38 ± 0.23</td>
<td>1.49 ± 0.06</td>
</tr>
<tr>
<td>B</td>
<td>4390</td>
<td>980</td>
<td>19.16 ± 0.12</td>
<td>1.31 ± 0.14</td>
</tr>
<tr>
<td>V</td>
<td>5440</td>
<td>750</td>
<td>17.88 ± 0.09</td>
<td>2.24 ± 0.12</td>
</tr>
</tbody>
</table>

Note. — λc refers to the central wavelength of the filter’s effective area curve. The Flux Density is a multiplicative conversion from count rate to flux density assuming a Vega spectrum. The zeropoints and flux density factors correspond to a source with a Vega-like spectrum and a count rate of one count per second.

3.2.2 UVOT Photometry

SN 2005cs is located in a spiral arm of M51, which causes the background to be variable over small spatial scales. There is an underlying HII region visible in pre-explosion GALEX UV images (Bianchi et al. 2005). This means that high precision photometry will not be possible until SN 2005cs has faded and the underlying light can be subtracted. It is anticipated that Swift UVOT will reobserve the field of SN 2005cs in 2007 so that late-time template images of the host galaxy can be obtained. At the early times in which we are most interested here, the SN is much brighter and contribution from the HII region or other contamination is small.

We performed aperture photometry using a circular aperture with a radius of 2′′ (UBV) or 4′′ (UV filters) centered on the SN. A background sky region was selected by eye which contained approximately the same structure and light as the region containing the SN. Photometry was done using several background regions selected in this way and all were found to return similar magnitudes. Aperture corrections to the standard UVOT photometry apertures (6′′ for UBV and 12′′ for UVW1, UVM2, and UVW2) were calculated frame by frame in UBV. For the UV filters, a single aperture correction for each filter was computed from a summed frame due to the lack of UV-bright, isolated stars in the field of view. The larger source aperture was chosen to minimize errors due to small orbital variations in the PSF.

The count rates were corrected for coincidence loss using the coincidence loss equation in the Swift UVOT Calibration Database (CalDB)\(^2\). Corrected count rates were transformed to Vega magnitudes using the appropriate photometric zero points in the CalDB. The U and B curves begin near or above the saturation level of UVOT’s photon counting detector and will not be considered here. The photometry in the remaining

\(^2\)available from http://swift.gsfc.nasa.gov/docs/heasarc/caldb/swift/
four UVOT filters, 3 UV filters and the V band, is presented in Table 3.2 and displayed in Figure 3.2. These values have not been corrected for extinction. The errors (given in Table 3.2 or displayed in Figure 3.2) are the 1σ statistical errors only and do not include the systematic errors in the photometric zeropoint calibration (given in Table 3.1).

### 3.2.3 UVOT Grism Data

*Swift* UVOT also observed SN 2005cs several times using its R∼75 spectroscopic grisms. These observations are listed in Table 3.3. The wavelength scale could be shifted by up to 30 Å due to the difficulty of fixing the scale on the saturated zeroth order spectrum especially at early times when the UV flux was greatest. There is also a large uncertainty in the background subtraction due to the bright underlying galaxy.

The extracted spectra were smoothed using a running average of 10 points (∼20Å) to increase the signal to noise ratio and scaled to match contemporaneous UVOT photometry (using the flux conversion factors of Table 3.1). The resulting spectra from four epochs are displayed in Figure 3.3. The first epoch spectrum is a composite of the UV grism and V grism spectra, spliced near 2900 Å, in order to avoid order overlap in the UV grism. The UV grism observation from 6 July contains the zeroth order of another field star near 2450 Å, and the affected region has been removed from the spectrum.

### 3.3 Discussion

#### 3.3.1 Ultraviolet Light Curves

The SN is initially extremely bright in the UV, outshining the nucleus of M51 by over 2 magnitudes. The blue UV-optical colors of SN 2005cs were used to photometrically type SN 2006at (Brown & Immler 2006) and SN 2006bc (Immler & Brown 2006) as young SNe II. The UV faded quickly until falling below the brightness of an underlying HII region about 10 days after the explosion. While the decay slope generally steepens at shorter wavelengths (see Li et al. 2006b, Tsvetkov et al. 2006 or Pastorello et al. 2006 for the optical curves), the decline in UVM2 is actually steeper (0.38 mag/day) than the filters on either side, UVW1 (0.31 mag/day) UVW2 (0.34 mag/day). This is likely caused by the strong FeIII and the strengthening FeII lines concentrated within the UVM2 bandpass.

#### 3.3.2 UV Spectra

The first two UV spectra displayed in Figure 3.3 show strong features also seen in the HST spectra of SN 1999em (Baron et al. 2000). Overlapping absorption lines, particularly of FeIII, FeII and MgII remove much of the UV light (see e.g., Lucy 1987, Mazzali & Lucy 1993, & Branch 1987). Emission features are not lines but regions of reduced line blanketing where more of the continuum escapes. See Figure 3 in Dessart & Hillier (2005) for the opacity contributions of individual species. The later spectra are of lesser quality but show the UV continuum becoming increasing fainter.
Table 3.2. *Swift* UVOT Photometry of SN 2005cs

<table>
<thead>
<tr>
<th>JD</th>
<th>UVW2</th>
<th>UVM2</th>
<th>UVW1</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2453552.4</td>
<td>13.46 ± 0.06</td>
<td>13.01 ± 0.10</td>
<td>12.89 ± 0.02</td>
<td>14.55 ± 0.04</td>
</tr>
<tr>
<td>2453555.1</td>
<td>14.43 ± 0.06</td>
<td>⋮</td>
<td>⋮</td>
<td>14.47 ± 0.10</td>
</tr>
<tr>
<td>2453557.3</td>
<td>15.02 ± 0.06</td>
<td>14.97 ± 0.10</td>
<td>⋮</td>
<td>14.53 ± 0.04</td>
</tr>
<tr>
<td>2453557.9</td>
<td>15.22 ± 0.06</td>
<td>15.20 ± 0.10</td>
<td>14.52 ± 0.03</td>
<td>14.55 ± 0.06</td>
</tr>
<tr>
<td>2453558.8</td>
<td>15.75 ± 0.07</td>
<td>15.62 ± 0.11</td>
<td>14.80 ± 0.03</td>
<td>14.65 ± 0.04</td>
</tr>
<tr>
<td>2453560.0</td>
<td>16.02 ± 0.07</td>
<td>16.04 ± 0.11</td>
<td>15.23 ± 0.03</td>
<td>14.57 ± 0.04</td>
</tr>
<tr>
<td>2453560.6</td>
<td>16.26 ± 0.07</td>
<td>16.14 ± 0.11</td>
<td>15.43 ± 0.04</td>
<td>14.58 ± 0.06</td>
</tr>
<tr>
<td>2453562.0</td>
<td>16.33 ± 0.07</td>
<td>16.26 ± 0.11</td>
<td>15.72 ± 0.04</td>
<td>14.55 ± 0.06</td>
</tr>
<tr>
<td>2453562.8</td>
<td>16.62 ± 0.08</td>
<td>16.22 ± 0.11</td>
<td>15.78 ± 0.05</td>
<td>14.63 ± 0.06</td>
</tr>
<tr>
<td>2453565.0</td>
<td>16.46 ± 0.08</td>
<td>16.36 ± 0.12</td>
<td>15.94 ± 0.06</td>
<td>14.55 ± 0.08</td>
</tr>
<tr>
<td>2453567.0</td>
<td>16.50 ± 0.07</td>
<td>16.24 ± 0.11</td>
<td>15.94 ± 0.04</td>
<td>14.65 ± 0.05</td>
</tr>
<tr>
<td>2453571.0</td>
<td>16.62 ± 0.08</td>
<td>16.49 ± 0.12</td>
<td>16.11 ± 0.05</td>
<td>14.73 ± 0.08</td>
</tr>
<tr>
<td>2453573.5</td>
<td>16.50 ± 0.08</td>
<td>16.32 ± 0.12</td>
<td>16.23 ± 0.06</td>
<td>14.76 ± 0.09</td>
</tr>
<tr>
<td>2453628.5</td>
<td>16.67 ± 0.07</td>
<td>16.39 ± 0.11</td>
<td>16.44 ± 0.04</td>
<td>14.86 ± 0.03</td>
</tr>
</tbody>
</table>

Note. — The observation time is given as the Julian Date (JD) of the middle of the exposure or set of exposures. These values have not been corrected for extinction.

Table 3.3. *Swift* UVOT Grism Observations of SN 2005cs

<table>
<thead>
<tr>
<th>Observation Sequence</th>
<th>Date (UT)</th>
<th>Exposure (Seconds)</th>
<th>Grism</th>
</tr>
</thead>
<tbody>
<tr>
<td>00030083007</td>
<td>3 Jul 2005</td>
<td>2078.1</td>
<td>V</td>
</tr>
<tr>
<td>00030083008</td>
<td>3 Jul 2005</td>
<td>2078.5</td>
<td>UV</td>
</tr>
<tr>
<td>00030083012</td>
<td>6 Jul 2005</td>
<td>2137.9</td>
<td>UV</td>
</tr>
<tr>
<td>00030083017</td>
<td>8 Jul 2005</td>
<td>2017.7</td>
<td>UV</td>
</tr>
<tr>
<td>00030083023</td>
<td>11 Jul 2005</td>
<td>2077.7</td>
<td>UV</td>
</tr>
<tr>
<td>00030083027</td>
<td>13 Jul 2005</td>
<td>1788.3</td>
<td>UV</td>
</tr>
<tr>
<td>00030083035</td>
<td>19 Jul 2005</td>
<td>1955.2</td>
<td>UV</td>
</tr>
</tbody>
</table>
Fig. 3.2 Light curves of SN 2005cs obtained by UVOT in the three UV filters and the V band. For clarity, the UV curves have been shifted by a constant offset given in the legend. The steep decay in the UV levels off as the SN fades below the brightness of the underlying HII region.
Fig. 3.3 Grism spectra of SN 2005cs obtained by UVOT, smoothed and scaled to contemporaneous UVOT photometry. The first spectrum is a composite of UV and V grism spectra and the others from the UV grism.
3.3.3 Comparison of the UV Light Curves of SNe II

We created a new UVW1 light curve for SN 2005cs by assuming that the magnitude in the last epoch (~ 80 days after explosion) corresponds to the underlying background and subtracting that flux from the early UVW1 data. This might overestimate the background caused by a residual contribution from the SN, but this is not expected to be significant because of the continued fading seen in more recent UV observations of SNe II such as SN 2006bp (Immler et al. 2007b). This new UVW1 curve is compared to other UV observations of SNe II in Figure 3.4.

Several SNe II were observed by IUE, including several with multiple epochs (more than four observations: SNe 1979C, 1980K, 1987A & 1993J). For comparison we use the $m_{275}$ magnitudes given by Cappellaro et al. (1995) which are calculated by convolving the HST F275W filter (central wavelength 2770 Å and width 594 Å; Nota et al. 1996) with the IUE spectra and calibrated so Vega would have $m_{275} = 0$. Due to the quantity of data, only an early selection from SN 1987A was used. Any magnitudes from spectra marked as saturated were also left out, as were the later spectra of SN 1993J which were contaminated by sunlight. As the difference in apparent magnitude between the brighter SNe observed by IUE and SN 2005cs is enough to separate their respective curves, so the curves are not shifted as they were in Figure 3.2.

To make sure the comparison of the UV light curve shapes with the UVW1 and $m_{275}$ filters is valid, we performed spectrophotometry on the IUE spectra of SN 1987A (Pun et al. 1995) using the IRAF SBANDS command. A selection of LWP spectra were convolved with the UVW1 effective area curves to simulate how SN 1987A would have appeared in the UVW1 filter. The light curves of the UVW1 spectrophotometry and $m_{275}$ were very similar.

While the fading behavior in the UV is common among these SNe, it is interesting to note how varied the early optical ($V$ band) behavior is for these SNe. SN 1979C (Panagia et al. 1980) and SN 1980K (Buta 1982), both II-Linear SNe, were fading in the optical. SN 1993J (Richmond et al. 1994), a IIb, was caught soon after explosion and showed the UV/optical brightness declining, reaching a local minimum about 8 days before rising again as the photosphere receded to layers influenced by non-thermal excitation due to the unstable isotopes of Nickel and Cobalt. SN 1987A (Pun et al. 1995), a peculiar type II, was mostly rising optically during this period. As shown in Figure 3.2, SN 2005cs had a nearly constant $V$ magnitude during this period, the distinguishing characteristic of a SN II-Plateau. The addition of UV observations of SN 2005cs to this group is important, as IIP SNe are the most common type of SNe II, but their temporal behavior in the UV was previously not well observed.

3.3.4 Comparison with non-LTE model atmospheres

We report on a preliminary quantitative analysis of the UVOT photometric evolution and optical ground-based spectroscopy covering the first two weeks after discovery. Detailed results of this study are reported in (Dessart et al. 2008).

We employ the non-LTE model atmosphere code CMFGEN (Hillier & Miller 1998; Dessart & Hillier 2005) and follow the same approach as Dessart & Hillier (2006) for their analysis of SN 1999em. The version of the code that was used assumes a spherically
Fig. 3.4 Comparison of SNe II observed by IUE and Swift-UVOT. An early UV decay is seen in all these SNe while the optical curves were brightening, fading, or remaining constant.
symmetric (1D), steady-state, chemically homogeneous, homologously expanding ejecta with a density power-law of exponent $n$. A key ingredient of our approach is that we set the inner boundary luminosity of the model (at a Rosseland optical depth of $\sim 50$-100) so that the emergent synthetic flux matches the observed flux. To do this, we require the distance to SN 2005cs, which we take as 8 Mpc, the rough average of various distance estimates to the host galaxy M51 or sources within it. These distance estimates used HII regions (9.6 Mpc; Sandage & Tammann 1974), young stellar associations (6.9±0.6 Mpc; Georgiev et al. 1990), planetary nebulae (8.4±0.6 Mpc, revised to 7.6±0.4 Mpc; Feldmeier et al. 1997; Ciardullo et al. 2002), surface brightness fluctuations (7.7±1.0 Mpc; Tonry et al. 2001), the SN Expanding Atmosphere Method (SEAM) (6.0±1.1 Mpc; Baron et al. 1996), and more recently the Expanding Photosphere Method (EPM) and Standard Candle Method (SCM) using SN 2005cs itself (7.1±1.2 Mpc; Takáts & Vinkó 2006). We reddened the synthetic spectral energy distribution computed by CMFGEN using the law of Cardelli et al. (1988) and $E(B-V)=0.04$, which offers the best fit to the observations, and renormalize them to the observed flux at 6000 Å (the flux offset between synthetic and observed spectra is small and $\sim 10$-20%).

We assume an (homogeneous) ejecta composition that differs somewhat from that of Dessart & Hillier (2006) used for SN1999em. Indeed, OII lines present in the June 30 spectrum at $\sim 4600$ Å required a higher oxygen abundance. We obtain satisfactory fits at all times using H/He= 5, C/He= 0.0004, N/He= 0.0013 and O/He= 0.0016, in agreement with the recent determination of the average surface composition of galactic B-supergiants (Crowther et al. 2006), together with a solar metallicity for the other elements.

To document the early color evolution of the spectral energy distribution of SN 2005cs, we focus on only two dates, June 30th and July 5th, complementing UVOT observations with optical spectra obtained by the CfA SN Group (for June 30th) and Pastorello et al. (2006; for July 5th) - the full time sequence will be shown in the follow-up analysis to this paper. We show in Figures 3.5 and 3.6 a comparison, for these two dates, of the observed UVOT (blue crosses) and optical spectra (black curve) of SN2005cs with reddened synthetic spectra (red curve) computed with CMFGEN. To fit the observations, we vary primarily the base radius/luminosity to modulate the ionization balance of the ejecta. This changes, in a non-linear way, the sources of opacity, modifying line strengths, but also the hardness of the SED at the thermalization layer, where it resembles that of a blackbody. Hence, this modifies the slope of the continuum as well. We also change the density exponent $n$, adopting a very high value of 20 for the June 30th model. This represents an extremely steep density decrease with radius, but is necessary in order to reproduce the very weak optical features. A steep density profile was also required to fit early observations of SN 1993J (Baron et al. 1995). A lower value of ten is used to reproduce the observations of July 5th. We obtain satisfactory fits for a reddening of 0.04, which we adopt for all dates. Discordant flux distributions between quasi-simultaneous observations of Pastorello et al. (2006) and the CfA suggest that the flux is not very accurate below 4000 Å, likely due to the CfA spectra not being taken at the parallactic angle. This is a region where spectra would best constrain the reddening and the ionization/temperature of the ejecta. The corresponding uncertainty in the slope...
suggests that the reddening could be as low as 0, but could not be higher than 0.1 without setting stringent requirements on the spectral modeling. Either way, the reddening is low, with a value equal or lower than that adopted by Pastorello et al. (2006), namely $E(B-V)=0.11$. The Schlegel dust maps give $E(B-V)=0.035$ (Schlegel et al. 1998).

We find that the density distribution flattens considerably in the continuum and line formation region over that week, described here as a change in the density exponent from $n=20$ to $n=10$. This reproduces the changing optical line features, which appear systematically weak in the first spectrum but considerably stronger in the second. Given the numerous constraints on our modeling, only varying the density exponent can lead to the desired reduction of line fluxes in the first epoch. The corresponding flattening of the density profile over the course of one week does not constitute a puzzle. As demonstrated by Dessart & Hillier (2005), line formation in Type II SN is localized to a narrow spatial region above the photosphere and, thus, no sizeable flux emission occurs beyond a few tens of percent beyond the photospheric velocity. On the 5th of July 2005, $\sim90\%$ of the $H\alpha$ flux (the strongest optical line) received from SN2005cs falls within a range of line of sight velocities of $\pm5000\ km\ s^{-1}$, thus well below the photospheric velocity on the 30th of June for which we adopt the steeper density slope. Another point (Woosley, priv. comm.) is that the ejecta swept up by the shock remains in a dynamical phase up to one week after breakout. Homologous expansion is not reached until after about one week. This suggests that interpreting and comparing ejecta velocities inferred spectroscopically during the first week of explosion is not straightforward.

Beside a flattening of the density distribution, we also find that the ionization/temperature changes significantly between these two dates, following cooling through expansion of the ejecta, as well as radiation from the surface layers. We infer a drop of the photospheric temperature from 15750 K down to 8200 K in that period. (We define the photosphere as the ejecta location where the inward integrated optical depth at 5000 Å, including bound-free, free-free, and electron-scattering opacity processes, is equal to two-thirds.) The corresponding constraints from the observations are the fast changing UV flux/magnitude and the strengthening of line blanketing in the UV and, more modestly, in the optical. Line identifications apply here the same way as for SN 1999em (Dessart & Hillier 2006), but with a few alterations. The first spectrum is likely closer to the explosion date (see Dessart et al. 2006), showing much weaker lines and a steeper spectrum than for SN 1999em. The ejecta of SN 2005cs is also slower, so that we not only confirm the presence of NII lines (Dessart & Hillier 2006) but also of OII at 4600 Å. The SiII 6355Å line is also well resolved, while it overlapped with the Hα trough in SN1999em (Dessart & Hillier 2006; Leonard et al. 2002a) or SN 1999gi (Leonard et al. 2002b).

The temporal evolution of the flux distribution reflects first the cooling of the photosphere. At the base of our two CMFGEN models (corresponding to a Rosseland optical depth of 70 and 73, or a radius of $1.6$ and $4.176 \times 10^{14}$ cm for the two selected dates), the electron temperature varies from 40750 K down to 23670 K, and the corresponding flux distributions, which match blackbodies at such depths, peak at 710 Å and 1220 Å. We thus see that the intrinsic photon distribution softens significantly, although it still peaks in the UV. The emergent flux distribution peaks further to the red due to the intervening blocking of light in the UV, between the thermalization layer where the
Fig. 3.5 Comparison between the photometric UVOT (blue crosses), spectroscopic optical observations (CfA) for SN 2005cs on the 6th of June 2006, and a reddened \( E(B-V) = 0.04 \) synthetic spectrum computed with CMFGEN using the procedure followed for the Type IIP SN 1999em and described in Dessart & Hillier (2006). Model parameters are: \( L_* = 2.7 \times 10^8 L_{\odot}, \) \( T_{\text{phot}} = 15750 \text{K}, \) \( R_{\text{phot}} = 2 \times 10^{14} \text{cm}, \) \( v_{\text{phot}} = 6900 \text{ km s}^{-1}, \) \( \rho_{\text{phot}} = 2.5 \times 10^{-13} \text{ g cm}^{-3}, \) and \( n = 20. \) The synthetic flux, 20% lower than observed for an adopted distance of 8 Mpc, is re-normalised at 6000 Å. UVOT fluxes are scaled so that the V-band flux matches the observed flux at 5460 Å.
Fig. 3.6 Same as Figure 3.5 for the observations of SN2005cs on the 5th of July 2005 and a reddened synthetic CMFGEN spectrum, whose corresponding model parameters are: \( L_\star = 1.5 \times 10^8 L_\odot \), \( T_{\text{phot}} = 8200 \text{K} \), \( R_{\text{phot}} = 4.2 \times 10^{14} \text{cm} \), \( v_{\text{phot}} = 5200 \text{km s}^{-1} \), \( \rho_{\text{phot}} = 6.4 \times 10^{-14} \text{g cm}^{-3} \), and \( n = 10 \). The synthetic flux, 10\% lower than observed for an adopted distance of 8 Mpc, is re-normalised at 6000 Å, and the UVOT fluxes scaled to match the V band at 5460 Å. We also overplot the UVW2, UVM2, UVW1, and V filter bandpasses, scaled in proportion to the observed flux. For both epochs, the (weak) UV brightness of the underlying H\textsc{ii} at \( \sim 80 \) days has been subtracted. (See text for discussion)
photon distribution is characterized to layers where it escapes freely. We illustrate this effect in Figures 3.7 and 3.8 by showing the radial variation in the comoving frame (the radiation field appears redshifted with height) of the mean intensity ($J$) normalised to the continuum intensity ($J_c$; bottom panels), for the June 30th and the July 5th models. Here the continuum intensity is computed by solving the radiative transfer equation for the processes associated with the continuum only. At the base, $J/J_c$ is unity but as we cross the photosphere at $\sim 1.4R_0$ (where $R_0$ is the base model radius), this ratio suddenly drops below unity in the UV, while showing the appearance of many lines in the optical. At such early times, optical lines are mostly of $\text{H}\alpha$ and $\text{He}\alpha$, with weaker contributions from $\text{N}\alpha$ and $\text{O}\alpha$. In the top panel, we show the same ratio, at the maximum grid radius, but transformed to the observer’s frame. Hence, we see that line blanketing plays a strong role in the UV, but it operates on a photon distribution that becomes intrinsically more and more depleted in the UV. These two combined effects explain the color evolution of SN2005cs and in particular confirm the “thermal,” photospheric origin of this radiation. Work is underway to interpret quantitatively the absolute flux levels observed, with links to the explosion energy and the ejecta kinematics.

3.4 Summary

SN 2005cs is the first SN IIP with a well observed UV light curve, and is an important addition to the SNe II observed in the UV by IUE and HST. The rapid drop in the UV shows the importance of quick response observations, as the emergent flux is dominated by the UV for only about a week after the explosion. The early UV photometry presented in this paper demonstrates the temporal effects of photospheric cooling and line blanketing which can be reproduced by non-LTE model atmospheres. This effort will be continued by increasing the sample of UV light curves and spectra of SNe II with Swift in order to provide constraints for the spectroscopic modeling of multiple objects.
Fig. 3.7 Radial variation (in the comoving frame) of the mean intensity normalised to the continuum mean intensity over the UV and optical ranges (bottom panels) for the June 30th CMFGEN model. In the top panel, we show the same ratio but in the observer’s frame and at the maximum CMFGEN grid radius.
Fig. 3.8 Same as Figure 3.7, but this time for the July 5th CMFGEN model.
Chapter 4

UVOT Photometry of Supernovae

Having observed a larger sample of SNe with varying amounts of galaxy contamination and with the completion of a revision in the UVOT calibration (Poole et al. 2008), an improved photometric method that would accurately subtract off the underlying galaxy flux was needed. With this new calibration the convention was adopted to refer to the UVOT filters with lower case letters, in particular to distinguish UVOT’s $ubv$ filters from Johnson $UBV$. The differences are small, however, as shown by comparing the UVOT $bv$ photometry with published ground based $BV$ photometry. There are slight differences between UVOT $u$ and ground based $U$ due to the bluer response of UVOT which makes a difference when comparing SNe of different spectral shapes.

4.1 General Image Processing and Photometry

Images were obtained from the Swift archive. For those whose most recent processing occurred prior to 2007, the raw images and event lists were reprocessed, primarily to utilize an improved plate scale for the uvw2 images and corrections to exposure times in the headers. Swift/UVOT software was used for the data analysis\footnote{www.swift.ac.uk/UVOT_swguide_v2.pdf}. Aspect correction was done (or at least attempted) using $uvotaspcorr$ in the pipeline processing, though for some images, mostly in the UV, the aspect correction had to be improved by matching a few stars in each image by hand to their counterpart in the Digitized Sky Survey (DSS) due to the small number of stars that could be automatically matched with the catalogues. The exposures corresponding to a single observation segment are coadded together, with smeared, short, or otherwise problematic exposures being excluded at this step when found. The improvement of the aspect correction and the exclusion of problematic exposures is usually done in an iterative fashion along with photometry of other sources in the field in order to catch problems. The resulting summed images are stacked into a single file (in Flexible Image Transport System or FITS format) for each filter (typically the 6 non-white filters are used for each SN) during the SN’s visible lifetime. A separate template image is made for each filter which is a summation of all exposures before the SN explosion or after it has faded well below detectability. A sample segment of the script used to do this for a single filter is included in Appendix B.

Count rates are determined using $uvotmaghist$ which actually calls $uvotsource$ on each of the images in the file. The coincidence loss corrections and zeropoints are based on the Poole et al. (2008) calibration. 3″ and 5″ apertures have both been used (see details below), and the outputs of $uvotmaghist$ are manipulated in performing the galaxy
subtraction. Within uvotsource, counts within a 5′′ aperture around the SN position were used to compute the coincidence loss correction factor (to be consistent with the calibration), and when necessary an average point spread function (PSF) for each filter was used to compute the aperture correction factor from a 3′′ aperture to the 5′′ for which the zeropoints are calibrated (Poole et al. 2008).

4.2 Galaxy Subtraction Method

It is common to use late template images to subtract the galaxy light by PSF matching and flux scaling the template image and subtracting the images (cf. Alard & Lupton 1998; Gal-Yam et al. 2004a; Barris et al. 2005). The UVOT photon counting detector is non-linear (due to coincidence loss), so removing the background counts in that way would result in the counts in the photometric aperture being smaller and thus the coincidence loss correction underestimated. Performing the subtraction and looking at the resulting image might be helpful in assessing the validity of questionable detections.

In the following analysis, we consider three contributors to the count rate (CR) within the source aperture: source counts ($CR_{SN}$), galaxy counts ($CR_{galaxy}$), and background counts ($CR_{bkg}$; including scattered light, earth limb, etc.).

$$CR_{total} = CR_{SN} + CR_{galaxy} + CR_{bkg}$$

To determine the source count rate, we first subtract off the average background count rate using a clear background region chosen by eye to avoid contribution from stars or galaxies but as close as possible to the source position so that any differences in scattered light, vignetting effects, or non-uniformity in the background will be minimized. The galaxy count rate is measured using the same source and background regions from the template image. An example of these regions is displayed in Fig 4.1. Figure 4.2 shows the coincidence loss corrected, background subtracted light curve of SN 2006X source region, with the first point representing the galaxy brightness and the later points representing the galaxy+SN brightness (i.e., before the galaxy counts were subtracted) as well as the SN brightness after the galaxy counts are subtracted.

We performed photometry using a 3′′ aperture. u votmaghist measures count rates within a 5′′ aperture in order to compute coincidence losses, so we utilize those for photometry as well to compare the effect of different aperture sizes. When using the 3′′ aperture the background and galaxy are subtracted before the aperture correction, which assumes the counts would follow the average PSF for a point source. The script to perform the galaxy subtraction for a single filter is included in Appendix C.

The 3′ photometry procedure is summarized as follows:

- raw count rates are coincidence loss corrected (using 5′′ source region for consistency with the calibration)
- count rate in 3′′ aperture is background subtracted
- 3% error added in quadrature to source rate error to account for differences in large and small scale sensitivity (Poole et al. 2008)
- galaxy count rate (in 3′′ aperture) is subtracted
Fig. 4.1 Left: Images of M100 with SN2006X Right: Pre-explosion images of M100. The top panels shows the source and background regions used in both the SN and template images. The lower panels shows a close up of the 5″ radius source region around the SN.
Fig. 4.2 SN + galaxy count rates and galaxy subtracted SN count rates for the source region centered on SN 2006X in the UVOT b band.
• galaxy count rate error propagated into total error
• aperture correction applied to galaxy subtracted count rate (because aperture correction assumes the counts would follow the average psf for a point source)
• count rate error scaled by aperture correction (keeps fractional error the same)
• convert to magnitudes using the zeropoints of (Poole et al. 2008)

The 5′′ photometry is done as follows:
• raw count rates are coincidence loss corrected (using 5′′ source region)
• count rate in 5′′ aperture is background subtracted
• 3% error added in quadrature to source rate error to account for differences in large and small scale sensitivity (Poole et al. 2008)
• galaxy count rate (in 5′′ aperture) is subtracted
• galaxy count rate error propagated in
• convert to magnitudes using the zeropoints of (Poole et al. 2008)

Both aperture sizes result in accurate magnitudes. Propagation of the galaxy count rate error into the final magnitudes results in errors that are much larger for the 5′′ photometry. Thus less galaxy “noise” is included in the 3′′ photometry, so it has a higher signal to noise ratio. The error bars adequately account for the observed scatter (see examples below). Therefore, the 3′′ photometry has been adopted for our final photometry in the following chapters. The smaller aperture is even more important if no template image is available to better estimate the galaxy count rate in the source aperture.

4.3 Examples

The problem with developing and testing a method for background subtraction is the lack of transient standards stars. Thus the objects under study are required to check the method by comparison with ground based optical observations and their well tested image subtraction methods. Good comparison SNe are relatively rare, however, because most SNe are either very red or become very red with time. Thus at the time when Swift observations are usually discontinued the SN is near or even below the brightness of the underlying galaxy in the UV while in the optical where these comparisons can be made the SN is still much brighter than the underlying galaxy.

Below we compare UVOT $bv$ photometry with published $BV$ photometry for the following SNe: 2005cf, 2005hk, 2006X, and in a later section 2005am. They are displayed in Figures 4.3 – 4.6, with details in the figure captions.
Fig. 4.3 SN 2005cf was a bright, well isolated SN and serves as a good check on the generic photometry methods, coincidence loss and aperture corrections near the bright limit for UVOT. UVOT b photometry is compared with ground based $B$ photometry from (Pastorello et al. 2007). The UVOT data has been analyzed using 3$''$ and 5$''$ apertures (with an aperture correction for the former) with and without galaxy subtraction. Due to the isolation of the SN the aperture size and galaxy subtraction make no significant difference (and are indistinguishable in this plot) and there is excellent agreement with the ground based photometry.
Fig. 4.4 SN 2005hk was somewhat separated from its host galaxy but not uncontaminated. The 5″ shows the effects of contamination as the SN gets fainter, while the 3″ aperture and the galaxy subtracted UVOT b curves are in excellent agreement with the ground based data from CSP, KAIT, and CTIO (Phillips et al. 2007).
Fig. 4.5 Our most contaminated test case with available ground based photometry is SN2006X, a highly extinguished SN Ia in the nearby galaxy M100, which had been observed previous to the explosion of SN2006X. It is a good check on image subtraction due to its location near a spiral arm and the presence of a $V \sim 17$ star 9 arcseconds away. The 5″ (not shown) and 3″ both show an excess contribution from the galaxy while the galaxy subtracted UVOT b curves using either 5″ or 3″ both agree with the ground based image subtracted $B$ photometry from Wang et al. (2008).
4.4 Other Photometry Issues

Beyond galaxy contamination there are a few more photometry issues of which one should be aware. Many of these are properly accounted for in this analysis, but are mentioned here for the benefit of those doing their own analysis.

Coincidence Losses: coincidence loss is generally understood and correctable for isolated point sources based on observations of standard stars of varying brightness (Poole et al. 2008). Problems arise, however, when the source is near another bright source or located on a bright background. SN 2005am was close to a star of comparable brightness, so the actual coincidence loss is hard to determine. As shown in Figure, the UVOT b magnitudes are systematically fainter than the KAIT photometry (Li et al. 2006a) at early times. Complications also occur for SNe with a bright galaxy background, as the effect of coincidence loss from an extended source will differ from that of a point source. Based on comparisons with ground based BV data, the error in the coincidence loss correction is negligible at 4.4 counts/s (SN 2006X b data compared to Wang et al. 2008 in Figure 4.5), increasing to 0.1 mag at 7.8 counts/s (SN 2005cs v data compared to ground based data in Dessart et al. 2008). For this study, we set a limit of 6 counts/s above which we do not report the data here pending further analysis. Five SNe in our sample have optical count rates higher than this–SN 2005cs, 2006bc, 2006dd, 2006mr, and 2007bm. In addition the presence of a nearby star interferes with the coincidence loss correction for the optical data of SN 2005am which is also excluded here. In most cases the UV count rates are a factor of ~10 lower and are not affected.

Spacecraft Drift: Early uvw2 sky images often showed little tails, as the spacecraft was settling during those images. But they were usually taken in event mode, so reprocessed data have reconstructed the sky images to correct for that. At other times the spacecraft may drift if the star tracker has lost lock, resulting in smeared images (very noticeable in recent images of SN 2008aw). In image mode (almost always in recent years due to telemetry) these cannot be fixed. When noticed, these images are excluded from the data when I coadd the individual epochs.

Exposure Times: Analysis of GRB050603 revealed a software problem in which some data was being thrown out without an appropriate exposure time correction (Brown et al. 2005a). This affected some SN frames, but affected frames have been reprocessed with corrected exposure times.

Frame Times: Some exposures of SNe 2006dd/nr and 2006jc were taken while UVOT was using a smaller hardware window, resulting in a shorter frame time (because the smaller window can be read out faster) and a larger dead time correction. The change in the dead time is negligible, but for brighter sources the frame time needs to be taken into account in correcting for coincidence losses. uvotsource takes into account the frame time in computing coincidence losses, but other methods of correcting for coincidence loss (e.g., Li et al. 2006a) will need to account for the difference. Since the frames can be read out faster, reducing the amount of lost counts, smaller hardware windows will probably be used more in the future for sources that would otherwise be saturated.

\(^2\)http://heasarc.gsfc.nasa.gov/docs/swift/analysis/uvot_digest.html#fixtimes
Fig. 4.6 SN 2005am had issues due to a neighboring star. This figure compares the UVOT b data with the KAIT B data and UVOT B data from Li et al. (2006a).
4.5 Summary

For bright isolated SNe, aperture size is not an issue. The zeropoints, coincidence loss, and aperture corrections from the UVOT calibration files appear to work fine. For faint and/or contaminated sources there is a clear advantage to using a smaller aperture to minimize the galaxy contamination and maximize the signal to noise ratio for the source.

The galaxy subtracted magnitudes show good agreement with the ground based observations, and there are no systematic differences between the 5′′ and 3′′ magnitudes after the galaxy subtraction. The 5′′ galaxy subtracted photometry does have larger error bars due to the larger galaxy count rate errors, which is more significant for more heavily contaminated observations and seems to overestimate the true errors. Thus the 3′′ photometry has been adopted. The agreement with ground based observations gives one confidence in the reduction of the data and its application to astrophysical questions.
Chapter 5

Ultraviolet Light Curves of Supernovae

Having developed a new photometry method to subtract the flux of the underlying galaxy, we have applied the method to a large sample of SNe, including a revision of the photometry for the two SNe (2005am and 2005cs) discussed in the previous chapters. The section below is excerpted from Brown et al. 2009, AJ, 137, 4517.

Swift UVOT observed 45 SNe (21 Ia, 13 Ib/c, and 11 II) between March 2005 (Brown et al. 2005b) and August 2007. From these observations, the light curves of 25 SNe (17 Ia, 3 Ib/c, and 5 II) with at least 3 UV detections above 3 sigma (accounting for Poisson errors in the SN and galaxy count rates) are displayed on a continuous timeline in Figure 5.1. Figure 5.1 illustrates the dynamic range and frequency of Swift SN observations. The bright limit, above which coincidence losses are hard to correct, is approximately 12th magnitude in the UV. In practice this saturation limit from a bright SN or a SN on a bright galaxy background has affected the optical light curves of some of these SNe but not the UV light curves. The faint limit can be as deep as 21 mag (depending on the depth of the SN and template observations) but observations are typically terminated once the galaxy light dominates within the aperture.

In order to easily contrast the light curves of the different SN types, Figure 5.2 shows the UVOT light curves of a well observed example of each type, with light curves of the individual SNe displayed in Appendix E. For easy comparison, the time and magnitude axis are the same scale for the three SNe in Figure 5.2 and the magnitudes are unshifted to show the relative colors.

The temporal behavior of the UV light varies with SN type. Figure shows the UV lightcurves for the SNe grouped by type and shifted in magnitude for comparison of the early shapes. To determine the explosion date we have assumed a rise time of 18 days to the maximum light in the V band for SNe Ia/b/c (Garg et al. 2007) except for SN 2006aj for which we use the GRB trigger time from Campana et al. (2006). For the SNe II we use the explosion times determined by Dessart et al. (2008) for SNe 2005cs and 2006bp and estimate the others based on discovery and non-detection times in the discovery announcements. The light curves will be discussed in more detail by SN type below.

For a simple parameterization of the light curve shape for comparison within and between SN types, we have chosen to measure the early decay rates (over the first 10-20 days) and report it in magnitudes per 100 days, corresponding to the parameter $\beta$ in Pskovskii (1967). Multiple values of the early decay slope were measured from different ranges of early data points. In Table 5.1 we report the midpoint between the upper and lower values and the range of magnitudes above and below the central value corresponding to flatter or steeper slopes. The range about the central decay rate is given, as using different subsections of the data can give steeper or shallower results.
Fig. 5.1 UV light curves of SNe detected in at least three epochs by UVOT. SNe Ia are displayed in red, SNe Ib/c in green, and SNe II in blue.

Fig. 5.2 UVOT light curves of SN2007af, 2007Y, 2006bp. The time axis begins with the estimated explosion dates for SNe 2007af and 2007Y assuming a rise time of 18 days to the maximum light in the V band for SNe Ia/b/c (Garg et al. 2007; Stritzinger et al. 2002), while SN 2006bp uses the explosion date determined by Dessart et al. (2008). Individual plots for each of the SNe are displayed in Appendix E.
Fig. 5.3 UV light curves of the SNe grouped by type, with SNe Ia in the left column, SNe Ib/c in the middle, and SNe II in the right column. The time axis is determined by the estimated explosion date and the magnitudes shifted by subtracting the measured or estimated maximum magnitude. For SN 2006aj (middle column in black) we have done the scaling based on the peak of the radioactively powered portion of the SN light curve (rather than the bright, early shock) since that is the part of the light curve observed for the other Ib/c cases. The deepest uvm2 upper limit for SN 2006aj is marked with a downward triangle. The error bars are not displayed for a clearer comparison of the light curve shapes.
depending on the quality of the data and the shape of the light curve, which is not necessarily linear. Histograms of these slopes are shown in Figure 5.4.

### 5.1 SNe Ia Light Curves

SNe Ia rise to a maximum in the UV peaking just before the optical. As seen in Figures 5.2 and 5.3 and similar to the optical, the UV brightness decays first steeply and then shallower due to radioactive decay of Nickel and Cobalt. The uvw2 and uvw1 lightcurves of SNe Ia are fairly uniform, and the uvw1 curves match well with the HST/IUE spectrophotometry of SN 1992A in the comparable F275W band (Kirshner et al. 1993; Brown et al. 2005b; Milne et al. 2007). The uvm2 photometry is much fainter than the other bands, so the points have larger errors, but the light curves seem to exhibit different behavior—both in the time of the uvm2 maximum and the shape of the light curve decay. This is also reflected in the histograms in Figure 5.4, which reinforces this idea that the uvw1 light curves of SNe Ia occupy a narrow range of decay rates compared to the other filters. The later shallow decay, $\gamma$ in Pskovskii (1967), is only measurable for a few SNe Ia, notably SN 2006E which had a decay rate of about 2.2, 3.9, and 3.2 mags/100 days in uvw1, uvm2, and uvw2, respectively. More details on the lightcurves of SNe Ia and generation of UV lightcurve templates will be presented in Milne et al. (in preparation).

From a sample of light curves one can begin to discern what is normal and what is peculiar behavior. Two SNe Ia that stand out are SNe 2005hk and 2005ke. SN 2005hk was bluer than other SNe Ia and already fading in the UV when Swift observations began, nearly 10 days before the optical maximum. SN 2005ke followed the typical Ia decay until about 15 days after maximum light when the UV brightness remained nearly constant for $\sim$20 days before fading again. In conjunction with a marginal X-ray detection, this plateau in the UV light curves has been attributed to interaction with the circumstellar material (Immler et al. 2006), though other causes such as reduced line blanketing have been suggested (Kasliwal et al. 2008). SNe 2007ax (Kasliwal et al. 2008) and 2006mr show hints of extended emission at late times and this may be common behavior for subluminous SNe Ia.

### 5.2 SNe Ib/c Light Curves

For SNe Ib/c, the sample of well observed SNe is much smaller, with 3 light curves in our sample, but they appear to be as diverse in the UV as they are in the optical (see Figure 5.3). Other SNe Ib/c were also observed but for only a single epoch or were not well detected (see Holland et al. 2007 for additional SNe Ib/c observed during Swift’s first two years). It is hard to define a generic UV behavior, so instead we briefly describe each well sampled SN.

SN 2006aj, a Ic SN, was discovered following Swift BAT trigger on GRB060218 (Campana et al. 2006). The UV initially rose rapidly reaching a bright peak about half a day after the trigger. This first peak has been attributed to the shock breakout from a dense stellar wind (Campana et al. 2006; Blustin 2007; Waxman et al. 2007) or self-absorbed synchrotron radiation (Ghisellini et al. 2007). This faded rapidly in the UV,
Table 5.1. Decay Rates of Early UV Light Curves

<table>
<thead>
<tr>
<th>SN Name</th>
<th>Type</th>
<th>uvw1 range</th>
<th>uvm2 range</th>
<th>uvw2 range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN2005am</td>
<td>Ia</td>
<td>12.2</td>
<td>0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>SN2005cf</td>
<td>Ia</td>
<td>12.2</td>
<td>1.3</td>
<td>4.1</td>
</tr>
<tr>
<td>SN2005cs</td>
<td>II</td>
<td>39.8</td>
<td>4.1</td>
<td>54.1</td>
</tr>
<tr>
<td>SN2005df</td>
<td>Ia</td>
<td>9.5</td>
<td>1.2</td>
<td>5.6</td>
</tr>
<tr>
<td>SN2005hk</td>
<td>Ia</td>
<td>16.4</td>
<td>1.3</td>
<td>14.6</td>
</tr>
<tr>
<td>SN2005ke</td>
<td>Ia</td>
<td>12.6</td>
<td>1.8</td>
<td>14.9</td>
</tr>
<tr>
<td>SN2006E</td>
<td>Ia</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>SN2006X</td>
<td>Ia</td>
<td>6.3</td>
<td>1.3</td>
<td>...</td>
</tr>
<tr>
<td>SN2006aj</td>
<td>Ic</td>
<td>14.1</td>
<td>4.0</td>
<td>...</td>
</tr>
<tr>
<td>SN2006at</td>
<td>II</td>
<td>20.0</td>
<td>2.4</td>
<td>20.8</td>
</tr>
<tr>
<td>SN2006bc</td>
<td>II</td>
<td>17.3</td>
<td>2.1</td>
<td>26.5</td>
</tr>
<tr>
<td>SN2006bp</td>
<td>II</td>
<td>16.4</td>
<td>2.9</td>
<td>23.8</td>
</tr>
<tr>
<td>SN2006dd</td>
<td>Ia</td>
<td>13.6</td>
<td>0.8</td>
<td>13.0</td>
</tr>
<tr>
<td>SN2006dm</td>
<td>Ia</td>
<td>12.7</td>
<td>0.3</td>
<td>...</td>
</tr>
<tr>
<td>SN2006ej</td>
<td>Ia</td>
<td>12.3</td>
<td>0.7</td>
<td>15.4</td>
</tr>
<tr>
<td>SN2006jc</td>
<td>Ib</td>
<td>9.9</td>
<td>1.0</td>
<td>10.2</td>
</tr>
<tr>
<td>SN2006mr</td>
<td>Ia</td>
<td>16.0</td>
<td>2.9</td>
<td>...</td>
</tr>
<tr>
<td>SN2007S</td>
<td>Ia</td>
<td>6.7</td>
<td>0.5</td>
<td>...</td>
</tr>
<tr>
<td>SN2007Y</td>
<td>Ib</td>
<td>20.0</td>
<td>1.7</td>
<td>...</td>
</tr>
<tr>
<td>SN2007aa</td>
<td>II</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>SN2007af</td>
<td>Ia</td>
<td>11.7</td>
<td>1.5</td>
<td>11.0</td>
</tr>
<tr>
<td>SN2007bm</td>
<td>Ia</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>SN2007co</td>
<td>Ia</td>
<td>13.2</td>
<td>0.3</td>
<td>...</td>
</tr>
<tr>
<td>SN2007cq</td>
<td>Ia</td>
<td>12.2</td>
<td>0.5</td>
<td>14.9</td>
</tr>
<tr>
<td>SN2007cv</td>
<td>Ia</td>
<td>12.0</td>
<td>1.0</td>
<td>...</td>
</tr>
</tbody>
</table>

Note. — Decay rates for the different filters are given in units of magnitudes per 100 days. Upper and lower values of the early decay slope were measured from different ranges of early data points. Here we report the midpoint and the range of magnitudes above and below the central value corresponding to flatter or steeper slopes.
Fig. 5.4 Histogram of the decay rates of the early UV light curves. SNe Ia have very similar decay slopes, particularly in uvw1. SNe II decay much faster than SNe Ia and Ib/c, with SN 2005cs decaying twice as fast as the other SNe II.
plateauing briefly from 4–10 days after the explosion in uvw2 and uvw1, after the trigger as the radioactive decay powered a supernova light curve, and then faded again. In uvm2 the SN was undetected at least 5 magnitudes fainter than the earlier peak, showing the contrast between the UV bright shock and the UV faint SN component. The optical curves are consistent with a SN Ic of intermediate luminosity between normal SNe Ic and previous GRB-associated, overluminous SNe Ic (cf. Pian et al. 2006 and Modjaz et al. 2006).

SN 2006jc was a peculiarly bright and blue SN Ib (Foley et al. 2008a), and the UVOT grism spectra show an indication of MgII emission (Immler et al. 2008). Discovered near maximum light, the UV and optical light curves all fade steeply and then shallower and then steeper again.

SN 2007Y, a peculiar Ib with spectral similarities to SN 2005bf (Folatelli et al. 2007), behaved more like a Ia in shape and color with the UV brightness rising with the optical, peaking a little sooner and fading slightly quicker. It will be analyzed in detail in Stritzinger et al. (2009, in preparation).

5.3 SNe IIP Light Curves

SNe IIP start off very bright and blue. Brightening to a maximum just a few days after explosion, the UV magnitudes then fade rather linearly, with SN 2005cs fading about twice as fast, as visible in either the right panels of Figure 5.3 or the histogram of the decay rates in Figure 5.4. The rapid drop in the UV brightness of SNe II is driven by the cooling photosphere and the resulting line blanketing of heavy elements (cf. Brown et al. 2007), so the different decay rates could reflect the different cooling rates of the SN photospheres. Dessart et al. (2008) compare the UVOT photometry of SNe II 2005cs and 2006bp with model spectra and demonstrate the usefulness of UV photometry in constraining the extinction and the temporal change in temperature and ionization. The optical brightness remains constant, resulting in a steady reddening with time. The main SN subtypes not included in this sample are SNe III, IIn, and Ib. Fortuitously, examples of these classes— SNe 1979C (Panagia et al. 1980), 1998S (Fransson et al. 2005), and 1993J (Jeffery et al. 1994), along with the peculiar SN II 1987A (Kirshner et al. 1987; Pun et al. 1995) – were well observed with IUE and/or HST, making these sets complementary. More recent Swift observations now include these subtypes as well – SNe 2008es (Miller et al. 2009; Gezari et al. 2009), 2006jd (Immler et al. 2007a), and 2008aq (Brown et al. 2008).

5.4 SN Phototyping with UV-Optical Colors

This large sample of SNe can be used to compare the color evolution of SNe of different types. It can also be used to examine their usefulness in determining the SN type using photometry rather than the spectroscopic methods discussed in Section 1. In addition to physical properties like temperature and extinction, UV and UV-optical colors are also useful in differentiating SN types. The use of optical colors to distinguish SNe of different types has been explored by multiple authors (Vanden Berk et al. 2001; Poznanski et al. 2002; Gal-Yam et al. 2004b; Sullivan et al. 2006; Kuznetsova & Connolly
These techniques are of primary importance for large and deep surveys and searches for which the SN candidates are either too faint or too numerous for spectroscopic classification of all candidates. The upcoming Pan-STARRS could discover on the order of 10,000 SNe/year\(^1\) and the Large Synoptic Survey Telescope 250,000 SNe/year.\(^2\) Thus photometric measures of the SNe will be critical to classifying SNe, as well as determining photometric redshifts. Rest frame UV observations can greatly improve the accuracy of such determinations. The clear difference between the UV-bright SNe II and the UV-faint SNe Ia was noticed after a few IUE observations of SNe Ia and II (Panagia 1982, see also Panagia 2003). This “UV deficit” is caused by the very red Ia spectrum between \(\sim 2500\) and \(4000\) Å (cf. Kirshner et al. 1993), and was exploited by Riess et al. (2004b) to identify SNe Ia in the Hubble Deep Field.

Figure 5.5 compares the color-color location of all appropriate SNe Ia and II data in our sample in 5 colors (using neighboring filter combinations) available from the UVOT observations. In order to focus on the brighter epochs at which SNe are most likely to be discovered, we have trimmed the data to only include photometry within three magnitudes of the observed or inferred peak for that given filter. For SNe Ia this includes about forty days after maximum light, but only the first \(\sim 15\) days after explosion for a SN II. The UV data for SN 2005cs is supplemented by ground-based \(BV\) data from Dessart et al. (2008).

Extinction is a complicated issue in the UV, as the effects are strong and varied. The exact extinction vector appropriate for a particular SN would depend on the extinction law, spectral shape (particularly for uvw2 and uvw1 which have red tails), and total extinction (since the UV reddening becomes non-linear with respect to the optical reddening). To give the general effect of extinction, vectors corresponding to a color excess \(E(B-V)=0.1\) and the Milky Way extinction law (Cardelli et al. 1989) evaluated at the central wavelengths of the UVOT filters, are plotted in each color-color plot. The SN colors themselves have not been corrected for extinction.

As the UVOT \(ubv\) magnitudes are similar to the Johnson \(UBV\), the bottom right panel is comparable to Figure 3 in Poznanski et al. (2002). In those colors there is still a lot of overlap between SNe Ia and II, though SNe II peak 0.5 magnitudes bluer than SNe Ia. With the addition of the \(uvw1-u\) color in the bottom left panel, the bluer SNe II are spread out even more, showing the advantage of rest-frame UV observations. This effect is maximized when a UV filter is combined with an optical filter to sample the spectra slope where SNe II and Ia are most different. There are, however, diminishing returns for colors from neighboring UV filters, as one loses the contrast with the optical light. The best color-color separation (restricting the wavelength range to three consecutive filters) is achieved with \(u-b\) and \(uvw1-u\), with young SNe II having colors \(uvw1-u < 1\) and \(u-b < -0.5\). Skipping \(u\) to form a \(uvw1-b\) color also differentiates well by itself. In the upper left panel, SNe Ia are actually bluer than SNe II in the \(uvw2-uvm2\) color, but this is likely due to the intrinsic faintness of SNe Ia in the \(uvm2\) filter and a combination of the red SN Ia spectral shape and the red tail of the uvw2 filter.

\(^{1}\)http://pan-starrs.ifa.hawaii.edu/project/reviews/PreCoDR/documents/scienceproposals/sne.pdf

\(^{2}\)http://www.lsst.org/Science/fs_transient.shtml
Fig. 5.5 Color-color plots showing the differentiation of young SNe II from SNe Ia. All available colors from all SNe are shown, but the data is trimmed to include only data within 3 magnitudes of the peak in each filter. The ability to differentiate the two increases when the UV and optical regions are sampled, due to the steep red continuum of SNe Ia. The arrows are extinction vectors corresponding to E(B-V)=0.1 computed using the MW extinction relations of Cardelli et al. (1989) evaluated at the central wavelength of the UVOT filters. Note that MW extinction actually causes bluer uvw2-uvm2 colors, rather than the typical “reddening” effect of extinction, due to the uvm2 filter coinciding with the 2200 Å bump in the MW extinction curve.
While red UV-optical colors differentiate well between young SNe II and Ia, they are not conclusive, as SNe II become redder with time. In Figure 5.6 we display the uvw1−b color evolution of these same SNe. At early times, there is a 3 magnitude difference between the uvw1−b color of SNe Ia and II, and a color of uvw1−b < 1 includes all of our SNe II less than two weeks old while excluding all Ia data except the earliest epochs of the peculiar SN 2005hk. However, this large difference does not persist as the SN II temperature and corresponding UV flux drops with time creating a redder spectrum similar to SNe Ia (whose red colors evolve rather slowly) around day 15. Fransson et al. (1987) noticed this rapid reddening in SN 1987A and cautioned against using the UV alone to distinguish SNe I from II. Even a rough determination of the SN epoch, through either the light curve behavior or even the cadence of the SN search observations can help make the distinction. Reddening is a further degeneracy which can make a young II look older (by about 5 days per additional $E(B - V) \sim 0.2$) or more similar to SNe Ia. This can also be broken by monitoring the color evolution, as reddening would cause a shift in the colors at a given epoch but not mask the differing slopes of the color evolution.

To the color evolution plot we have added the colors of our three SNe Ib/c, spanning the range of colors seen in SNe Ia and II, complicating their differentiation. The similarities of SN 2006jc with SNe IIn (Pastorello et al. 2008) explains the blue UV-optical colors. SN 2006aj had a bright blue peak and then became very red during the SN bump as was SN 2007Y. SNe Ib/c typically have low effective temperatures and the subsequent UV line blanketing make their colors more similar to SNe Ia. The contamination of SNe Ib/c from cosmological samples of SNe Ia, as discussed in Riess et al. (2004a), is reduced because the SNe Ib/c are less common and usually much fainter than SNe Ia.

Understanding the UV color differences within and across types is especially important for classifying high redshift SNe. Some UV information is being incorporated into such phototyping (cf. Riess et al. 2004b; Johnson & Crotts 2006) but in the past has been limited due to the limited epochs at which UV information is available. The addition of this UV photometry should help improve the understanding of the diversity and temporal change of the UV flux to allow SNe to be better identified at larger redshifts. Other high redshift applications are discussed in Chapter 7.
Fig. 5.6 UV-optical color evolution of our sample over the first 50 days. The symbols are the same as used in the above color-color plots. The dramatic color difference at early times vanishes by about 15 days after the explosion. The evolution of other colors are displayed in Appendix F.
Chapter 6

Type Ia Supernovae as Standard Candles in the UV

6.1 SNe Ia as Standard Candles

SNe Ia are among the brightest of astrophysical events, making them useful as probes of the distant universe. SNe Ia gave the first evidence that the expansion of the universe is accelerating (Riess et al. 1998, Perlmutter et al. 1999), and they are used to constrain cosmological parameters such as $\Omega$ and $\Lambda$ (Barris et al. 2004; Astier et al. 2006) and the nature and evolution of dark energy (Riess et al. 2004a; Wood-Vasey et al. 2007b).

This is possible because SNe Ia have a well-established relationship between their optical peak brightness and rate of decay, making them excellent standardizable candles (see Branch & Tammann 1992, Branch 1998, and Leibundgut 2001 for reviews on the subject). This standardizing is done by calibrating the peak luminosity with other distance-independent, observable parameters such as the light curve shape. One common measure of the shape is the number of magnitudes the $B$-band declines in the 15 days after maximum light, $\Delta m_{15}(B)$ (Phillips 1993; Hamuy et al. 1996a; Phillips et al. 1999; Garnavich et al. 2004). The light curve shape can also be described by how much the light curve must be stretched to match a template in one or more filters (Riess et al. 1996a; Goldhaber et al. 2001). The importance of distance independent luminosity indicators is evidenced by the large number of photometric and spectroscopic methods that have been developed (in addition to the above methods and their updated versions, see also Nugent et al. 1995; Tripp 1998; Mazzali et al. 1998; Wang et al. 2005b; Guy et al. 2005; Wang et al. 2006; Bongard et al. 2006). The observed trend that brighter SNe have broader light curves will be referred to here generically as the Luminosity-Width Relation (LWR). The underlying cause of the LWR is believed to be the amount of Ni formed and the resulting change in the temperature/ionization evolution (Nugent et al. 1995; Hoeflich et al. 1996; Mazzali et al. 2001; Kasen & Woosley 2007). There is scatter about this relation and a few outliers have been found (e.g., SNe 2000cx, Li et al. 2001; 2002cx, Li et al. 2003; 2003fg, Howell et al. 2006).

More recent studies have expanded the standard candle utility beyond optical wavelengths. Meikle (2000) and Krisciunas et al. (2004) have reported that SNe Ia might be standard candles in the NIR ($JHK$ bands) at the 0.2 magnitude level without a clear dependence on the decay slope. Recent observations by Wood-Vasey et al. (2007a) strengthen this claim. There is also evidence, however, that the SNe which are subluminous in the optical are also subluminous in the NIR (Garnavich et al. 2004). The U band brightness has recently been shown to be standardizable in a similar way to the optical (Jha et al. 2006), though with increased scatter with respect to the B and V bands, and can also be used in the determination of extinction and distances (Jha
et al. 2007). Here we take the next step to shorter wavelengths, reaching beyond the
atmospheric cutoff to compare the absolute magnitudes of SNe in the UV.

The redshifting of the light from distant SNe leads to two approaches. One can
follow the well understood rest-frame optical light by observing at longer wavelengths or
seek a better understanding of the rest-frame UV light which would then be redshifted
and observable in the optical bands. For moderate redshift SNe, both approaches can
be taken, resulting in more information on the flux and colors with which to constrain
the reddening and distances. At higher redshifts, however, fewer rest-frame optical
bands are observable, especially from the ground. Thus rest-frame UV observations will
be crucial to get the color information for classifying and determining reddening and
distances to high redshift SNe. The utility of rest-frame UV observations have been
discussed by Aldering et al. (2007) and Wamsteker et al. (2006). Its fast turn-around
time for observations, flexible scheduling, and UV capability make the Ultraviolet Optical
Telescope (UVOT; Roming et al. 2005) on board the Swift spacecraft (Gehrels et al. 2004)
well suited to probe the UV photometric behavior in greater detail than ever before. In
addition, Swift has been used to monitor SN spectra in the UV, including the best UV
spectral sequence of a SN Ia ever (SN 2005cf; Bufano et al. 2009).

6.2 Sample

We selected for this study 14 SNe Ia from Brown et al. (2009) and Milne et al.
(2009, in preparation) with low extinction and well sampled light curves in at least one
UV filter. Observations of these began at or before maximum light in the B band ($B_{max}$)
and continued for at least two weeks. The underlying galaxy light has been subtracted
(Brown et al. 2009) and the magnitudes are calibrated to the Vega system (Poole et al.
2008). Detailed analysis of the light curve shapes and colors will be presented in Milne
et al. (in preparation) while here we focus on the peak magnitudes derived therein.
Some UVOT filter characteristics are listed in Table 6.1. Sometimes the UVOT data is
supplemented by ground based data. To avoid confusion, we report only UVOT $u$ band
measurements, due to the bluer transmission curve than observed from the ground.
Thus similar trends should be seen as observed from the ground in the U band (cf.
Jha et al. 2007), but absolute magnitudes and light curve shapes may not be directly
comparable. We do consider UVOT $b$ and $v$ to be interchangeable with Johnson $B$
and $V$ (Li et al. 2006a; Poole et al. 2008) even without color terms or s corrections

While the UV filters have the bulk of their transmission in the near-UV, the red
tails of the uvw1 and uvw2 filters combined with the very red SN Ia spectral shape result
in a redder distribution of received photons compared to the transmission curves. The
uvw2 filter has a sharper transmission cutoff at the red end than the other UV filters.
To visualize the photons UVOT would detect from a SN Ia, we multiplied the SN 1992A
UV-optical spectrum from HST (Kirshner et al. 1993) with the effective area curves of
the UVOT filters (Poole et al. 2008). The resulting photon distributions are displayed in

---

1S corrections account for differences in filter shapes (Stritzinger et al. 2002). Wang et al.
(2009b) show the s-corrections for SN 2005cf from UVOT $bv$ to $BV$ to be 0.02 mag or less near
maximum light.
Fig. 6.6. The photon weighted effective wavelengths (where an equal number of observed photons are longer and shorter than the given wavelength) are listed in Table 6.1.

Table 6.1. UVOT Filter Characteristics

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\lambda_{central}$ (Å)</th>
<th>FWHM (Å)</th>
<th>$\lambda_{SNeff}$ (Å)</th>
<th>$R_{1,\lambda}$ (mag)</th>
<th>$R_{2,\lambda}$ (mag)</th>
<th>$R_{3,\lambda}$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>uvw2</td>
<td>1928</td>
<td>657</td>
<td>3064</td>
<td>6.09</td>
<td>-1.29</td>
<td>0.23</td>
</tr>
<tr>
<td>uvm2</td>
<td>2246</td>
<td>498</td>
<td>2452</td>
<td>8.09</td>
<td>-0.99</td>
<td>0.14</td>
</tr>
<tr>
<td>uvw1</td>
<td>2600</td>
<td>693</td>
<td>3267</td>
<td>5.47</td>
<td>-0.40</td>
<td>-0.01</td>
</tr>
<tr>
<td>u</td>
<td>3465</td>
<td>785</td>
<td>3561</td>
<td>4.90</td>
<td>-0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>b</td>
<td>4392</td>
<td>975</td>
<td>4344</td>
<td>4.16</td>
<td>-0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>v</td>
<td>5468</td>
<td>769</td>
<td>5516</td>
<td>3.16</td>
<td>-0.01</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Note. — $\lambda_{SNeff}$ refers to the photon weighted effective wavelength of the SN photons after passing through the filter. $R_{1,\lambda}$, $R_{2,\lambda}$, and $R_{3,\lambda}$ are the extinction coefficients such that $A_{\lambda} = R_{1,\lambda}E(B-V) + R_{2,\lambda}E(B-V)^2 + R_{3,\lambda}E(B-V)^3$. They were calculated using the SN 1992A spectrum and the MW extinction law and should not be used to calculate the extinction to arbitrary sources observed with UVOT.

6.3 Analysis

In order to determine whether SNe Ia are standard candles in the UV, we must be able to compare their absolute magnitudes ($M_{\lambda}$). This requires measurement of the apparent magnitude ($m_{\lambda}$) at maximum, a $K$ correction (to account for different flux being received for sources at different redshifts; Oke & Sandage 1968), subtraction of the distance modulus ($\mu$), and subtraction of the line of sight extinction from both the host galaxy and our own Milky Way. This is expressed in the basic equation below. The errors for the individual components are added in quadrature to give the error in the absolute magnitude.

$$M_{\lambda} = m_{\lambda} - K_{\lambda} - A_{MW,\lambda} - A_{host,\lambda} - \mu$$

We use the $\lambda$ subscript to indicate that the magnitudes and extinctions are wavelength dependent. The magnitudes and extinctions we give actually refer to the filters rather than the values at any specific wavelength.
Fig. 6.1 In the top panel, the HST spectrum of SN 1992A (Kirshner et al. 1993) is plotted with respect to the six UVOT filters on a logarithmic scale to reveal the structure in the low flux UV region. The 6 lower panels show the distribution of photons resulting from the SN 1992A spectrum passing through the 6 UVOT filters.
6.3.1 Peak Apparent Magnitudes

The apparent magnitudes at maximum ($m_{\lambda}$) for our sample were derived in Milne et al. (2009, in preparation) from fitting the data near peak with a Gaussian rise and decay, or for less well observed SNe fitting a mean template light curve for that filter derived from other SNe Ia. More details on the generation of the UVOT templates and the fitting techniques are given in Milne et al. (2009 in preparation). The apparent magnitudes at maximum light in the three UV filters and $uvb$ are given in Table 6.2. When there are no UVOT optical data or the ground based optical data is more precise than the UVOT data, the $BV$ magnitudes from the ground-based observations are given. The values of $\Delta m_{15}(B)$ from UVOT or the literature are also given in Table 6.2.

6.3.2 $K$ corrections

Despite the low redshift range of our sample, $K$ corrections (Oke & Sandage 1968) are non-negligible due to the sharp drop in flux to shorter wavelengths. Thus even a small shift of the spectrum to shorter wavelengths results in less flux being transmitted through the UV filters. Extinction also has a non-negligible effect on the $K$ correction because it affects the spectral shape, especially in the UV. To estimate the effect of the $K$ correction, we have used the SN 1992A HST UV/optical spectrum (Kirshner et al. 1993). For each SN in our sample, we reddened the rest frame SN 1992A spectrum using the Cardelli et al. (1989) reddening law with $R_V=3.1$ and $E(B-V) = E(B-V)_{host}$. We also reddened the spectrum for MW reddening using the Cardelli et al. (1989) reddening law (blueshifted into the rest frame of the SN based on the host galaxy redshift) with $R_V=3.1$ and $E(B-V) = E(B-V)_{MW}$ from the reddening maps of Schlegel et al. (1998). From this reddened rest-frame spectrum, synthetic photometry in the UVOT filters was performed. The reddened spectrum was then redshifted by the host galaxy redshift, and the synthetic photometry repeated. The $K$ correction is then the difference between the observed magnitude of the redshifted spectrum and the observed magnitude of the rest-frame spectrum plus the flux dilution factor $2.5 \log(1+z)$ (Oke & Sandage 1968) so that

$$k_\lambda(z) = 2.5 \log(1+z) + 2.5 \log \int S(\lambda, E(B-V)) \, d\lambda - 2.5 \log \int S(\lambda(1+z), E(B-V)) \, d\lambda$$

and $m_{\lambda,z=0} = m_{\lambda,z} - k_\lambda(z)$. The $K$ corrections for each SN and each filter (with a 20% error) are listed in Table 6.3. The $K$ corrections in $b$ and $v$ are small as previously determined by (Hamuy et al. 1993; Nugent et al. 2002). The $K$ corrections are strongest in the uvw1 and $u$ bands (see Jha et al. (2006) for a discussion of ground based $U$ $K$ corrections). The effect of extinction on the $K$ corrections is strongest in the uvm2 band where even a small redshift moves the 2200 Å bump in the MW curve from an intrinsic dip in the rest frame spectrum to a peak, increasing the effect of extinction.

The $K$ corrections were estimated using the SN 1992A spectrum because it is the only Ia UV spectrum near maximum light that covers the whole range of the UVOT filters. Comparisons with UVOT grism observations of SN 2005cf (Bufano et al. 2009) and IUE observations of SN 1992A show that the change in $K$ corrections for uvw1 and $u$ do not change significantly between a few days before the time of maximum light in
Table 6.2. Apparent Magnitudes at Maximum Light

<table>
<thead>
<tr>
<th>Name</th>
<th>$\Delta m_{15}(B)$ (mag)</th>
<th>uvw2&lt;sup&gt;a&lt;/sup&gt; (mag)</th>
<th>uvm2 (mag)</th>
<th>uvw1 (mag)</th>
<th>u (mag)</th>
<th>b (mag)</th>
<th>v (mag)</th>
<th>ref&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN2005am</td>
<td>1.52 ± 0.04</td>
<td>16.95 ± 0.08</td>
<td>18.26 ± 0.13</td>
<td>15.35 ± 0.06</td>
<td>⋮</td>
<td>13.90 ± 0.04</td>
<td>13.75 ± 0.03</td>
<td>1</td>
</tr>
<tr>
<td>SN2005cf</td>
<td>1.07 ± 0.03</td>
<td>16.83 ± 0.08</td>
<td>18.32 ± 0.19</td>
<td>15.11 ± 0.07</td>
<td>13.41 ± 0.05</td>
<td>13.54 ± 0.02</td>
<td>13.53 ± 0.02</td>
<td>2</td>
</tr>
<tr>
<td>SN2005df</td>
<td>1.21 ± 0.05</td>
<td>15.61 ± 0.07</td>
<td>16.85 ± 0.09</td>
<td>13.90 ± 0.07</td>
<td>⋮</td>
<td>12.50 ± 0.10</td>
<td>12.40 ± 0.10</td>
<td>3</td>
</tr>
<tr>
<td>SN2005ke</td>
<td>1.77 ± 0.01</td>
<td>18.41 ± 0.11</td>
<td>18.87 ± 0.15</td>
<td>17.09 ± 0.09</td>
<td>15.52 ± 0.07</td>
<td>14.92 ± 0.05</td>
<td>14.22 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>SN2006dm</td>
<td>1.54 ± 0.06</td>
<td>18.93 ± 0.13</td>
<td>⋮</td>
<td>17.63 ± 0.09</td>
<td>15.99 ± 0.07</td>
<td>16.17 ± 0.05</td>
<td>16.13 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>SN2006ej</td>
<td>1.39 ± 0.11</td>
<td>18.73 ± 0.13</td>
<td>18.46 ± 0.14</td>
<td>17.00 ± 0.08</td>
<td>15.47 ± 0.06</td>
<td>15.93 ± 0.05</td>
<td>15.80 ± 0.10</td>
<td>3</td>
</tr>
<tr>
<td>SN2007S</td>
<td>0.92 ± 0.08</td>
<td>⋮</td>
<td>⋮</td>
<td>17.80 ± 0.14</td>
<td>15.86 ± 0.07</td>
<td>15.94 ± 0.05</td>
<td>15.53 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>SN2007af</td>
<td>1.22 ± 0.05</td>
<td>16.50 ± 0.09</td>
<td>17.12 ± 0.15</td>
<td>14.77 ± 0.07</td>
<td>13.16 ± 0.07</td>
<td>13.39 ± 0.05</td>
<td>13.25 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>SN2007co</td>
<td>1.09 ± 0.02</td>
<td>20.11 ± 0.20</td>
<td>⋮</td>
<td>18.80 ± 0.15</td>
<td>16.99 ± 0.07</td>
<td>16.86 ± 0.05</td>
<td>16.69 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>SN2007eq</td>
<td>1.04 ± 0.03</td>
<td>18.61 ± 0.13</td>
<td>18.53 ± 0.19</td>
<td>17.53 ± 0.11</td>
<td>⋮</td>
<td>16.27 ± 0.05</td>
<td>16.17 ± 0.10</td>
<td>3</td>
</tr>
<tr>
<td>SN2007cv</td>
<td>1.33 ± 0.05</td>
<td>18.47 ± 0.13</td>
<td>19.60 ± 0.22</td>
<td>16.83 ± 0.09</td>
<td>15.08 ± 0.06</td>
<td>15.30 ± 0.05</td>
<td>15.15 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>SN2007on</td>
<td>1.89 ± 0.05</td>
<td>15.65 ± 0.05</td>
<td>15.78 ± 0.05</td>
<td>14.36 ± 0.05</td>
<td>12.93 ± 0.05</td>
<td>13.14 ± 0.05</td>
<td>13.06 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>SN2008Q</td>
<td>1.40 ± 0.05</td>
<td>16.42 ± 0.05</td>
<td>17.09 ± 0.08</td>
<td>14.84 ± 0.05</td>
<td>13.39 ± 0.05</td>
<td>13.85 ± 0.05</td>
<td>13.80 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>SN2008ec</td>
<td>1.08 ± 0.05</td>
<td>18.86 ± 0.17</td>
<td>⋮</td>
<td>17.30 ± 0.11</td>
<td>15.62 ± 0.07</td>
<td>15.83 ± 0.05</td>
<td>15.70 ± 0.05</td>
<td>3</td>
</tr>
</tbody>
</table>

<sup>a</sup>1σ errors

<sup>b</sup>References are given for the bv and $\Delta m_{15}(B)$ data while the UV maxima are all from UVOT.

References. — (1) Li et al. 2006 (2) Pastorello et al. 2007 (3) Milne et al. in preparation
B (when the UV curves typically peak) and 5 days after maximum when the HST UV spectrum of SN 1992A was taken. The $K$ corrections using the SNe 1992A and 2005cf spectra and the extinction and redshift values of SN 2005co (our extreme case) do differ by 0.05 mag in uvw1 and u (for $K$ corrections of 0.23 and 0.15), so we have adopted a 20% error on the $K$ corrections. More multi-epoch UV spectra of a range of SNe Ia are needed to better understand the UV photometry (including $K$ corrections) and how much they vary with time and from object to object.

![Image of graph showing $K$ corrections as a function of redshift for the 6 UVOT filters. These are measured from the SN 1992A spectrum with no reddening applied.](image)

**Fig. 6.2** $K$ corrections as a function of redshift for the 6 UVOT filters. These are measured from the SN 1992A spectrum with no reddening applied.

### 6.3.3 Correcting for extinction

The line of sight extinction can be determined because most SNe Ia have a similar post-maximum color evolution and standardizable colors at peak (Phillips et al. 1999; Garnavich et al. 2004). The observed colors can be compared with the expected colors to produce the observed color excess $E(B - V)_{tail}$ and $E(B - V)_{peak}$. $E(B - V)_{true}$, the color excess corresponding to the actual line of sight extinction, is computed from these (Phillips et al. 1999). These estimates are listed in Table 6.4. The Phillips et al. (1999) color relation only applies to the range $0.9 < \Delta m_{15}(B) < 1.6$, so for the rapidly
Fig. 6.3 $K$ corrections in the uvem2 filter as a function of redshift for different values of E(B-V).
Table 6.3. $K$ corrections for SNe Ia near Maximum Light

<table>
<thead>
<tr>
<th>Name</th>
<th>$k_{uvw2}$ (mag)</th>
<th>$k_{uvm2}$ (mag)</th>
<th>$k_{uvw1}$ (mag)</th>
<th>$k_u$ (mag)</th>
<th>$k_b$ (mag)</th>
<th>$k_v$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN2005am</td>
<td>0.03 ± 0.01</td>
<td>0.04 ± 0.01</td>
<td>0.06 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2005cf</td>
<td>0.03 ± 0.01</td>
<td>0.04 ± 0.01</td>
<td>0.05 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2005df</td>
<td>0.02 ± 0.00</td>
<td>0.02 ± 0.00</td>
<td>0.04 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2005ke</td>
<td>0.03 ± 0.01</td>
<td>0.03 ± 0.01</td>
<td>0.04 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2006km</td>
<td>0.10 ± 0.02</td>
<td>0.10 ± 0.02</td>
<td>0.16 ± 0.03</td>
<td>-0.01 ± -0.00</td>
<td>0.01 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2006ej</td>
<td>0.09 ± 0.02</td>
<td>0.09 ± 0.02</td>
<td>0.15 ± 0.03</td>
<td>-0.02 ± -0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2007S</td>
<td>0.08 ± 0.02</td>
<td>0.15 ± 0.03</td>
<td>0.11 ± 0.02</td>
<td>0.01 ± 0.00</td>
<td>0.02 ± 0.00</td>
<td>0.02 ± 0.00</td>
</tr>
<tr>
<td>SN2007af</td>
<td>0.03 ± 0.01</td>
<td>0.04 ± 0.01</td>
<td>0.05 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2007co</td>
<td>0.14 ± 0.03</td>
<td>0.20 ± 0.04</td>
<td>0.23 ± 0.05</td>
<td>0.02 ± 0.00</td>
<td>0.03 ± 0.01</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>SN2007cq</td>
<td>0.13 ± 0.03</td>
<td>0.16 ± 0.03</td>
<td>0.21 ± 0.04</td>
<td>0.00 ± 0.00</td>
<td>0.02 ± 0.00</td>
<td>0.02 ± 0.00</td>
</tr>
<tr>
<td>SN2007cv</td>
<td>0.03 ± 0.01</td>
<td>0.05 ± 0.01</td>
<td>0.07 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.01 ± 0.00</td>
<td>0.01 ± 0.00</td>
</tr>
<tr>
<td>SN2007on</td>
<td>0.02 ± 0.00</td>
<td>0.03 ± 0.01</td>
<td>0.05 ± 0.01</td>
<td>-0.01 ± -0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2008Q</td>
<td>0.03 ± 0.01</td>
<td>0.03 ± 0.01</td>
<td>0.06 ± 0.01</td>
<td>-0.01 ± -0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>SN2008ec</td>
<td>0.08 ± 0.02</td>
<td>0.11 ± 0.02</td>
<td>0.14 ± 0.03</td>
<td>0.00 ± 0.00</td>
<td>0.01 ± 0.00</td>
<td>0.01 ± 0.00</td>
</tr>
</tbody>
</table>

Declining SNe 2005ke and 2007on ($\Delta m_{15}(B)$ equal to 1.77 and 1.89, respectively) we use the relationship in Garnavich et al. (2004). Both of these SNe appear to have peculiar colors, however. SN 2005ke is very red at peak, which could be interpreted as a significant reddening of $E(B-V) \sim 0.4$, but the later tail colors and MLCS2k2 fitting (see below) imply a very small host reddening and no interstellar absorption from the host is detectable in high resolution spectra (Foley 2008, private communication). SN 2007on appears very blue at peak, which results in a negative extinction correction when compared with the nominal colors for SNe of similar decay rates. So we set the host reddening to be equal to zero. Li et al. (2001) caution that not all SNe follow the same color relations at later times and such should be used with caution for individual events. The MLCS2k2 (an updated version of the original Multi Light Curve Shape method; Riess et al. 1996a; Jha et al. 2007) uses multi-filter light curves to measure the light curve shape and determine the reddening and distance. Hicken et al. (2009b) give MLCS2k2 reddening values for most of our sample (we use those parameterized with $R_V = 3.1$). Other light curve fitters (cf. SIFTO, SALT, SALT2; Conley et al. 2008; Guy et al. 2007) empirically correct for intrinsic colors and reddening without separating the two.

From the total reddening toward the SN determined by the SN colors using the above methods, the contribution from the Milky Way along the line of sight in the Schlegel et al. (1998) reddening maps is subtracted to determine the host reddening. The optical decay rate is also affected by extinction (Phillips et al. 1999), so wherever we use $\Delta m_{15}(B)$, the extinction corrected decay rate $\Delta m_{15}(B)_{true}$ is implied (though this affects the SNe in our sample by at most 0.05 magnitudes).
The wavelength dependence of the extinction curves toward SNe are not completely understood, though several well-studied, highly extinguished SNe Ia have been found to have non-MW-like extinction (e.g., Elias-Rosa et al. 2006; Wang et al. 2008), and many samples have shown SNe to have systematically lower values of $R_V$ than the canonical Milky Way value of 3.1 (Riess et al. 1996b; Jha et al. 2007; Hicken et al. 2009b; Nobili & Goobar 2008). Whether the UV extinction follows the Cardelli et al. (1989) parameterization according to $R_V$ is also uncertain, and the intrinsic reddening law of circumstellar material might be modified by geometric effects (Wang 2005; Goobar 2008).

With that in mind we will start with the extinction laws observed in the Local Group.

To calculate the extinction coefficients, we took the HST UV-optical spectrum of SN1992A (Kirshner et al. 1993) and extinguished it with the Cardelli et al. (1989) MW extinction law (with $R_V = 3.1$) over a range of reddening values and calculated the resulting extinction in each filter by comparing synthetic photometry using the UVOT filters. For comparison we follow the same steps for SMC extinction using a power-law fit to the data from Prevot et al. (1984). This method is preferred to using a single wavelength (e.g. central, peak, or effective wavelength) to represent the entire filter as that wavelength is not necessarily representative of the integrated photon distribution.

Usually the extinction coefficients $R_\lambda$ (representing the ratio of the total extinction for the given filter divided by the selective extinction) can be expressed in the form $A_\lambda = R_\lambda E(B - V)$. We find, however, that the UV extinction is not a linear function of the optical reddening. This is displayed in Figure 6.5 where we display the extinction divided by the optical color excess for both extinction laws. In the optical $ubv$ filters this ratio is nearly constant to a reddening of $E(B - V) = 2$. In the UV, however, the extinction is clearly non-linear, with the increase in extinction decreasing for higher reddening values. This can be understood in terms of the flux distribution—reddening selectively extinguishes the bluer photons causing a redder photon distribution so that additional reddening causes a fractionally smaller amount of extinction. In other words, the effective wavelength is shifted redward where the extinction is smaller. Surprisingly, the difference between the MW and SMC curves is smaller in the UV than in the optical. In the analysis below we will use the MW curve, since the MLCS31 reddening and distance values are calculated for a MW extinction term. The coefficients for a cubic fit for $A_\lambda$ in terms of $E(B - V)$, such that $A_\lambda = R_{1,\lambda} E(B - V) + R_{2,\lambda} E(B - V)^2 + R_{3,\lambda} E(B - V)^3$, for the MW extinction curve are given in Table 6.1. As evidenced by those coefficients and Figure 6.5, the quadratic term is unnecessary in the optical but important in the UV. At higher values of $E(B - V)$ an additional term is necessary in $uvw2$ and $uvw1$ as high extinction preferentially suppresses the blue peak seen in Figure 6.6 and the resulting photon distribution actually becomes redder than for the filters with redder peak filter transmission due to the red tails in the $uvw2$ and $uvw1$ filters.

### 6.3.4 Determining the distances

The most universally available distances are calculated from the recessional velocities of the host galaxies by assuming a Hubble law expansion and a value for the Hubble constant. We obtain the local infall corrected recessional velocity which uses the recessional velocity of the host galaxy, shifts it into the rest frame of the cosmic microwave
Table 6.4. \( E(B - V) \) Color Excess Measurements

<table>
<thead>
<tr>
<th>Name</th>
<th>Peak(^{a,b})</th>
<th>Tail(^c)</th>
<th>MLCS31(^d)</th>
<th>MW(^e)</th>
<th>Host(^f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN2005am</td>
<td>0.17 ± 0.06</td>
<td>0.07 ± 0.05</td>
<td>0.12 ± 0.03</td>
<td>0.05 ± 0.01</td>
<td>0.06 ± 0.03</td>
</tr>
<tr>
<td>SN2005cf</td>
<td>0.08 ± 0.05</td>
<td>0.26 ± 0.04</td>
<td>0.19 ± 0.04</td>
<td>0.10 ± 0.02</td>
<td>0.09 ± 0.04</td>
</tr>
<tr>
<td>SN2005df</td>
<td>0.16 ± 0.15</td>
<td>0.05 ± 0.10</td>
<td>0.06 ± 0.03</td>
<td>0.03 ± 0.01</td>
<td>0.03 ± 0.03</td>
</tr>
<tr>
<td>SN2005ke</td>
<td>0.46 ± 0.08</td>
<td>0.06 ± 0.03</td>
<td>0.10 ± 0.03</td>
<td>0.02 ± 0.01</td>
<td>0.08 ± 0.03</td>
</tr>
<tr>
<td>SN2006dm</td>
<td>0.08 ± 0.08</td>
<td>0.01 ± 0.14</td>
<td>...</td>
<td>0.04 ± 0.01</td>
<td>0.04 ± 0.08</td>
</tr>
<tr>
<td>SN2006ej</td>
<td>0.19 ± 0.12</td>
<td>0.35 ± 0.19</td>
<td>0.07 ± 0.02</td>
<td>0.04 ± 0.01</td>
<td>0.03 ± 0.02</td>
</tr>
<tr>
<td>SN2007S</td>
<td>...</td>
<td>0.41 ± 0.05</td>
<td>0.44 ± 0.03</td>
<td>0.03 ± 0.01</td>
<td>0.41 ± 0.03</td>
</tr>
<tr>
<td>SN2007af</td>
<td>0.20 ± 0.08</td>
<td>0.13 ± 0.05</td>
<td>0.17 ± 0.03</td>
<td>0.04 ± 0.01</td>
<td>0.13 ± 0.03</td>
</tr>
<tr>
<td>SN2007co</td>
<td>0.25 ± 0.08</td>
<td>...</td>
<td>0.30 ± 0.04</td>
<td>0.11 ± 0.02</td>
<td>0.19 ± 0.04</td>
</tr>
<tr>
<td>SN2007cq</td>
<td>0.20 ± 0.12</td>
<td>...</td>
<td>0.16 ± 0.04</td>
<td>0.11 ± 0.02</td>
<td>0.06 ± 0.04</td>
</tr>
<tr>
<td>SN2007cv</td>
<td>0.20 ± 0.08</td>
<td>...</td>
<td>...</td>
<td>0.07 ± 0.01</td>
<td>0.14 ± 0.08</td>
</tr>
<tr>
<td>SN2007on</td>
<td>-0.44 ± 0.08</td>
<td>-0.10 ± 0.08</td>
<td>...</td>
<td>0.01 ± 0.01</td>
<td>0.00 ± 0.01</td>
</tr>
<tr>
<td>SN2008Q</td>
<td>0.10 ± 0.08</td>
<td>...</td>
<td>...</td>
<td>0.08 ± 0.01</td>
<td>0.01 ± 0.08</td>
</tr>
<tr>
<td>SN2008ec</td>
<td>0.21 ± 0.08</td>
<td>...</td>
<td>...</td>
<td>0.07 ± 0.01</td>
<td>0.15 ± 0.08</td>
</tr>
</tbody>
</table>

\(^a\)Total \( E(B - V) \) determined from the peak magnitudes (Phillips et al. 1999)

\(^b\)1 σ errors

\(^c\)Total \( E(B - V) \) determined using the Lira relation and the \( B - V \) colors 30-60 days after maximum light (Phillips et al. 1999)

\(^d\)Total \( E(B - V) \) derived from MLCS2k2 fitting (Jha et al. 2007) using \( R_V = 3.1 \) (denoted by MLCS31; Hicken et al. 2009b). For consistency with the other measures of total extinction, we have taken the \( A_V \) values for the host extinction from MLCS31, converted them into \( E(B - V) \), and added the Milky Way reddening.

\(^e\)Milky Way \( E(B - V) \) from Schlegel et al. (1998)

\(^f\)adopted host \( E(B - V) \), from MLCS31 if available, or subtracting the MW \( E(B - V) \) from \( E(B - V)_{\text{peak}} \)
Fig. 6.4 Extinction $A_\lambda$ measured in the SN 1992A spectrum measured as a function of applied $E(B-V)$ reddening using the MW (solid) and LMC (dotted) extinction laws.
Fig. 6.5 $A_{\lambda}$ divided by $E(B - V)$ as a function of $E(B - V)$ for the 6 UVOT filters. The MW values are plotted as straight lines and the SMC values as dotted lines.
background (CMB), corrects for the local velocity flow from the Virgo cluster, Great Attractor, and Shapley supercluster according to the model of Mould et al. (2000) from NED\(^3\). We then compute a Hubble flow distance adopting \( H_0 = 72 \pm 5 \) km/sec/Mpc from the Hubble Key Project (Freedman et al. 2001) and an uncertainty in the recessional velocity of 300 km/sec to account for peculiar motions. These distance moduli are noted in Table 6.5 as \( \mu_z \). Most of these SNe are very nearby and not in the Hubble flow, distances using the Hubble law do have large errors due to possible peculiar motions being a large fraction of the recessional velocity.

We also searched for distances to the host galaxies or group members measured using various independent distance indicators. Five of our SNe have independent distances to the host galaxy or cluster: There is a Surface Brightness Fluctuation distance measurement (SBF; Tonry et al. 2001) to NGC524, the host of SN 2008Q. There are also SBF distances to group members of the host of SN 2005ke (Tonry et al. 2001), and to NGC3311 in the Hydra cluster of which the host of SN 2007cv is a member (Jensen et al. 2001; see also Mieske et al. 2005 and references therein for other measurements of the Hydra distance). The Tonry et al. (2001) SBF distances are decreased by 0.16 magnitudes to correspond to the new IR calibration in Jensen et al. (2003). These independent distances are given in Table 6.5 as \( \mu_I \). The Hubble flow distance to the host of SN 2007co is consistent with that measured via the SNII Standard Candle method (Hamuy 2005) to SN 2007ck using the UVOT v measurements and a spectrum from the Hobby-Eberly Telescope if a modest amount of host reddening is assumed \(( E(B-V) \sim 0.1) \). Since the reddening is not independently known we do not list the SNII distance in Table 6.5 or use it in later sections.

We can also check the distances to the SNe by exploiting the fact that they are standardizable candles in the optical. In Table 6.5 we give the distances obtained using MLCS31 (Hicken et al. 2009b). The SN-derived distances are generally consistent with the best independent distances, with SN 2005ke being the biggest outlier.

### 6.4 Results

#### 6.4.1 Peak Pseudo-colors

A comparison of the UV-\( b \) pseudocolors (referred to as pseudocolors since they are not colors at a specific epoch but a color made by subtracting the peak magnitude in one band from the peak magnitude in a second band regardless of when they occurred) before and after extinction correction is displayed in Fig. 6.6. With the exception of the red SN 2005ke the colors are relatively flat (and this is true also if the SMC extinction law is used). A larger sample of moderately extinguished SNe are needed to evaluate which reddening law fits the data best, if a single law fits at all. Wang et al. (2009a) have found that SNe Ia with velocity features seem to favor a different value of \( R_V \) than normal SNe, though this could also result from a color difference in the SNe rather than the conversion from color to extinction.

---

\(^3\)http://nedwww.ipac.caltech.edu/index.html
Table 6.5. Host Galaxies and Distances

<table>
<thead>
<tr>
<th>Name</th>
<th>Host Galaxy</th>
<th>Redshift</th>
<th>$\mu_z^b$ (mag)</th>
<th>$\mu_I^c$ (mag)</th>
<th>$\mu_{MLCS31}^d$ (mag)</th>
<th>Ref$^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN2005am</td>
<td>NGC2811</td>
<td>0.0079</td>
<td>32.67 ± 0.31</td>
<td>...</td>
<td>32.54 ± 0.10</td>
<td>1</td>
</tr>
<tr>
<td>SN2005cf</td>
<td>MCG-01-39-003</td>
<td>0.0065</td>
<td>32.59 ± 0.31</td>
<td>...</td>
<td>32.58 ± 0.10</td>
<td>2</td>
</tr>
<tr>
<td>SN2005df</td>
<td>NGC1559</td>
<td>0.0044</td>
<td>31.04 ± 0.58</td>
<td>30.91 ± 0.31</td>
<td>31.72 ± 0.20</td>
<td>3,4</td>
</tr>
<tr>
<td>SN2005ke</td>
<td>NGC1371</td>
<td>0.0049</td>
<td>30.91 ± 0.62</td>
<td>31.70 ± 0.15</td>
<td>32.00 ± 0.08</td>
<td>3,5</td>
</tr>
<tr>
<td>SN2006dm</td>
<td>Arp295A</td>
<td>0.0220</td>
<td>34.70 ± 0.18</td>
<td>...</td>
<td>...</td>
<td>1</td>
</tr>
<tr>
<td>SN2006ej</td>
<td>NGC191A</td>
<td>0.0204</td>
<td>34.51 ± 0.19</td>
<td>...</td>
<td>34.97 ± 0.10</td>
<td>6</td>
</tr>
<tr>
<td>SN2007S</td>
<td>UGC5378</td>
<td>0.0139</td>
<td>33.89 ± 0.21</td>
<td>...</td>
<td>33.84 ± 0.10</td>
<td>7</td>
</tr>
<tr>
<td>SN2007af</td>
<td>NGC5584</td>
<td>0.0055</td>
<td>32.31 ± 0.35</td>
<td>...</td>
<td>32.29 ± 0.10</td>
<td>3</td>
</tr>
<tr>
<td>SN2007co</td>
<td>MCG+05-43-016</td>
<td>0.0270</td>
<td>35.30 ± 0.17</td>
<td>...</td>
<td>35.38 ± 0.10</td>
<td>8</td>
</tr>
<tr>
<td>SN2007cq</td>
<td>22144070$^f$</td>
<td>0.0250</td>
<td>35.09 ± 0.17</td>
<td>...</td>
<td>35.16 ± 0.12</td>
<td>9</td>
</tr>
<tr>
<td>SN2007cv</td>
<td>IC2597</td>
<td>0.0076</td>
<td>32.50 ± 0.32</td>
<td>33.70 ± 0.08</td>
<td>...</td>
<td>10,5</td>
</tr>
<tr>
<td>SN2007on</td>
<td>NGC1404</td>
<td>0.0065</td>
<td>32.09 ± 0.38</td>
<td>31.45 ± 0.19</td>
<td>...</td>
<td>11,12</td>
</tr>
<tr>
<td>SN2008Q</td>
<td>NGC524</td>
<td>0.0079</td>
<td>32.54 ± 0.32</td>
<td>31.74 ± 0.20</td>
<td>...</td>
<td>13,12</td>
</tr>
<tr>
<td>SN2008ec</td>
<td>NGC7469</td>
<td>0.0163</td>
<td>34.16 ± 0.20</td>
<td>...</td>
<td>...</td>
<td>14</td>
</tr>
</tbody>
</table>

$^a$Hubble Flow distance includes a local velocity flow correction and calculates a distance assuming $H_0 = 72$ km/sec/Mpc.

$^b$Errors are 1 $\sigma$

$^c$Independent distances

$^d$Distance modulus calculated based on MLCS31 fitting

$^e$The first reference is for the redshift measurement (obtained from NED), and the second reference is for the independent distance if given.

$^f$2MASS22144070+0504435

Fig. 6.6 UV-b colors of the normal SNe Ia without extinction correction and after correction for MW and host extinction (host extinction corrected with MW extinction law). The same horizontal and vertical scales are used to compare the relative amount of scatter in the different colors. There does not appear to be any bias in the extinction corrected colors, and a similar result is found when the host extinction is corrected with the SMC extinction law.
The uncertainty in the total extinction is a large source of error, as a modest uncertainty in $E(B - V)$ of 0.05 (the dispersion in the Lira relation; Phillips et al. 1999) propagates into an uncertainty of $\sim 0.4$ magnitudes in $A_{m2}$. The propagated error could also be reduced by reparameterizing the UV extinction using a longer baseline color excess such as $E(V - K)$ (Krisciunas et al. 2007). The large increase in extinction for a given reddening value may prove to be a helpfully large lever arm with which to check the reddening determined from the optical and NIR data. Extending the wavelength coverage into the NIR has already been shown to greatly increase the accuracy of the extinction corrections (Elias-Rosa et al. 2006; Krisciunas et al. 2007). Extending our understanding of the line of sight extinction toward SNe to shorter wavelengths is important to reducing possible systematic errors in using SNe Ia as cosmological distance indicators. In particular, the effect on the reddening law from circumstellar absorption is different in the UV and optical (Goobar 2008).

The correlation of the peak magnitudes in the UV with the standardizable optical bands without the added uncertainty of the distance measurement is illustrated by the UV-optical peak pseudocolors in Figure 6.7 with respect to the optical decay rate. The colors are generally flat or slightly redder with increasing $\Delta m_{15}(B)$. SN 2005ke appears as an outlier with very red in most colors though not uvm2-b. The $u - b$ colors of the normal SNe Ia do not show the same reddening trend with steeper decay rates seen in ground based $U - B$ in Jha et al. (2006). These observations with a broader $u$ filter might show a combination of that reddening effect and the bluer slope with increasing $\Delta m_{15}(B)$ seen at shorter wavelengths by Foley et al. (2008b).

The average colors with respect to the standardizable B filter and dispersions of those colors for the SNe with $\Delta m_{15}(B) < 1.6$ (thus excluding our rapid decliners SNe 2005ke and 2007on with peculiar colors) after applying the extinction corrections are listed in Table 6.6. A small scatter in the $u - B$ and uvw1$-B$ bands is present of 0.14 and 0.20 mags respectively and a large jump in the scatter to 0.94 for the uvm2$-b$ scatter. The scatter is smaller again for uvw2, but because its photon distribution is spread over redder wavelengths, making it difficult to compare with high redshift observations, we will postpone conclusions about its behavior until the optical light can be appropriately subtracted.

### 6.4.2 Absolute Magnitudes

Our nominal absolute magnitudes are computed using the MLCS31 values for the reddening, if available, or computed from the peak optical colors and the color relation in Phillips et al. (1999). We use independent distances when available and or the Hubble flow distances. Table 6.7 contains the absolute magnitudes in the UVOT filters. These absolute magnitudes are plotted with respect to the extinction corrected optical decay rate $\Delta m_{15}(B)$ from either UVOT or ground based observations (also listed in Table 6.7 for easier identification) in Fig. 6.8.

The absolute magnitudes in the optical and UV are relatively flat for low values of $\Delta m_{15}(B)$. Within the range (0.9 < $\Delta m_{15}(B)$ < 1.6), $v,b,u$, and uvw1 absolute magnitudes have a scatter of about 0.4-0.5 magnitudes listed in Table 6.8. The uvm2 absolute magnitudes have a larger dispersion of about 1 mag, and the uvw2 an intermediate value
Fig. 6.7 Peak UV-\(b\) pseudocolors plotted with respect to their optical decay rate \(\Delta m_{15}(B)\). The colors have been corrected for MW and host reddening using the MW extinction law. The same horizontal and vertical scales are used to compare the relative amount of scatter in the different colors. SN 2005ke is much redder than the other SNe in \(u - b\), uvw1-\(b\), and uvw2-\(b\) but not so different in uvm2-\(b\).
Fig. 6.8 UV and optical absolute magnitudes, calibrated with independent or Hubble flow distances, plotted with respect to their optical decay rate $\Delta m_{15}(B)$. The same horizontal and vertical scales are used to compare the relative changes in absolute magnitude and the scatter. Similar to the optical, the absolute magnitudes in the u, uvw1, and uvw2 bands for the SNe with $0.9 \leq \Delta m_{15}(B) \leq 1.6$ are relatively constant (the average given by a red line). The absolute magnitudes in the uvm2 filter, which has the purest UV transmission, show considerably more scatter and do not obviously vary systematically with $\Delta m_{15}(B)$. SN 2005ke is even fainter in the optical and near-UV filters than one would expect based on its $\Delta m_{15}(B)$, but SN 2007on is brighter. The grey lines represent the Garnavich et al. (2004) absolute magnitudes in B and V with the dispersion of 0.2 magnitudes represented by the width of the line. The B relation is shifted by the mean color to compare the shape of the curve with the absolute magnitudes in the bluer filters.
Fig. 6.9 The uvw1 absolute magnitude and the optical decay rate $\Delta m_{15}(B)$ are plotted with respect to the uvw1 decay rate. There is no strong correlation of either parameter with the uvw1 decay rate, which occupies a narrower range than its optical counterpart.
Fig. 6.10 UV colors plotted with respect to the optical decay rate $\Delta m_{15}(B)$. While subluminous SNe Ia can be identified in the optical by their very red colors, the UV colors of both SNe 2005ke (which is very red in $b - v$ and $u - b$) and 2007on are similar to normal SNe Ia. The same horizontal and vertical scales are used to compare the relative amount of scatter in the different colors.
Table 6.6. UV-Optical Peak Pseudocolors

<table>
<thead>
<tr>
<th>Color</th>
<th>Average (mag)</th>
<th>RMS$_{av}$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w2-B</td>
<td>2.60</td>
<td>0.30</td>
</tr>
<tr>
<td>m2-B</td>
<td>3.12</td>
<td>0.94</td>
</tr>
<tr>
<td>w1-B</td>
<td>1.12</td>
<td>0.20</td>
</tr>
<tr>
<td>u-B</td>
<td>-0.44</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Note. — Average UV-B colors and the RMS scatter for the SNe with $\Delta m_{15}(B) < 1.6$. Excluding SNe 2005df and 2008Q the scatter reduces to 0.3 mags in the optical and uvw1. One major concern is that the scatter we see in the optical is larger than seen in most studies of the absolute magnitudes of SNe (typically $\sim 0.2$ mags; Hamuy et al. 1996a; Phillips et al. 1999; Altavilla et al. 2004; Garnavich et al. 2004). While the Swift SN sample as a whole has a higher than average peculiarity rate (due to the desire to understand the UV and X-ray behavior of the rarer events), none of the SNe in this sample were targeted because of any known peculiarity at the time of observation. The scatter could be due to peculiarity of some of the SNe or errors in the reddening or distance estimates. One can solve for the distance and reddening values which would force the $BV$ data to match the absolute magnitude relations. For unusually blue SNe like SNe 2007on and 2008Q, however, this would result in negative extinction values. Nevertheless, the experiment has been performed and the scatter is significantly reduced in the $u$ and uvw1, but there is no significant reduction in the scatter for uvm2 or uvw2. Thus the same trend is seen—the near UV absolute magnitudes ($u$ and uvw1) for normal SNe ($0.9 < \Delta m_{15}(B) < 1.6$) show a small scatter and thus are likely standard candles with a scatter not much larger than in the optical. The mid UV absolute magnitudes, though, still have a large intrinsic scatter.

Our two rapid declining SNe are much harder to interpret. Figure 6.8 shows the Garnavich et al. (2004) relation for the B band shifted by the mean color for the normal SNe Ia to compare the trend with $\Delta m_{15}(B)$ in the B band to the UV filters. SNe 2005ke is significantly fainter in the UV filters as well as the optical (and is actually fainter than other subluminous SNe with the same decay rate compared to Garnavich et al. 2004). SN 2007on, also a rapid decliner, is less than a magnitude fainter than the average in all filters but about 1-2 mag brighter than would be predicted by the Garnavich et al. (2004) absolute magnitude relation for subluminous SNe Ia. Since both subluminous SNe have
Table 6.7. Absolute Peak Magnitudes

<table>
<thead>
<tr>
<th>Name</th>
<th>$\Delta m_{15}(B)$</th>
<th>$uvw_2$</th>
<th>$uvm_2$</th>
<th>$uvw_1$</th>
<th>$u$</th>
<th>$b$</th>
<th>$v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN2005am</td>
<td>1.52</td>
<td>-16.47 ± 0.38</td>
<td>-15.39 ± 0.43</td>
<td>-18.02 ± 0.36</td>
<td>⋯</td>
<td>-19.26 ± 0.34</td>
<td>-19.29 ± 0.33</td>
</tr>
<tr>
<td>SN2005cf</td>
<td>1.07</td>
<td>-16.89 ± 0.41</td>
<td>-15.83 ± 0.49</td>
<td>-18.57 ± 0.39</td>
<td>-20.17 ± 0.37</td>
<td>-19.85 ± 0.35</td>
<td>-19.67 ± 0.34</td>
</tr>
<tr>
<td>SN2005df</td>
<td>1.21</td>
<td>-15.70 ± 0.38</td>
<td>-14.58 ± 0.42</td>
<td>-17.39 ± 0.37</td>
<td>⋯</td>
<td>-18.67 ± 0.35</td>
<td>-18.71 ± 0.34</td>
</tr>
<tr>
<td>SN2005ke</td>
<td>1.77</td>
<td>-13.95 ± 0.28</td>
<td>-13.68 ± 0.34</td>
<td>-15.21 ± 0.25</td>
<td>-16.72 ± 0.23</td>
<td>-17.21 ± 0.21</td>
<td>-17.81 ± 0.19</td>
</tr>
<tr>
<td>SN2006dm</td>
<td>1.54</td>
<td>-16.37 ± 0.55</td>
<td>⋯</td>
<td>-17.67 ± 0.49</td>
<td>-19.22 ± 0.44</td>
<td>-18.86 ± 0.39</td>
<td>-18.84 ± 0.32</td>
</tr>
<tr>
<td>SN2006ej</td>
<td>1.39</td>
<td>-16.28 ± 0.27</td>
<td>-16.67 ± 0.30</td>
<td>-18.02 ± 0.25</td>
<td>-19.50 ± 0.23</td>
<td>-18.84 ± 0.22</td>
<td>-18.92 ± 0.23</td>
</tr>
<tr>
<td>SN2007S</td>
<td>0.92</td>
<td>⋯</td>
<td>⋯</td>
<td>-18.53 ± 0.31</td>
<td>-20.29 ± 0.28</td>
<td>-19.78 ± 0.26</td>
<td>-19.77 ± 0.24</td>
</tr>
<tr>
<td>SN2007af</td>
<td>1.22</td>
<td>-16.84 ± 0.41</td>
<td>-16.55 ± 0.46</td>
<td>-18.49 ± 0.40</td>
<td>-20.01 ± 0.39</td>
<td>-19.61 ± 0.38</td>
<td>-19.58 ± 0.37</td>
</tr>
<tr>
<td>SN2007co</td>
<td>1.09</td>
<td>-17.11 ± 0.37</td>
<td>⋯</td>
<td>-18.34 ± 0.32</td>
<td>-19.91 ± 0.27</td>
<td>-19.69 ± 0.24</td>
<td>-19.58 ± 0.22</td>
</tr>
<tr>
<td>SN2007cq</td>
<td>1.04</td>
<td>-17.61 ± 0.33</td>
<td>-18.03 ± 0.41</td>
<td>-18.66 ± 0.30</td>
<td>⋯</td>
<td>-19.50 ± 0.24</td>
<td>-19.46 ± 0.24</td>
</tr>
<tr>
<td>SN2007cv</td>
<td>1.33</td>
<td>-16.51 ± 0.53</td>
<td>-15.79 ± 0.70</td>
<td>-18.06 ± 0.46</td>
<td>-19.69 ± 0.41</td>
<td>-19.26 ± 0.35</td>
<td>-19.21 ± 0.27</td>
</tr>
<tr>
<td>SN2007on</td>
<td>1.89</td>
<td>-15.89 ± 0.22</td>
<td>-15.79 ± 0.23</td>
<td>-17.20 ± 0.21</td>
<td>-18.62 ± 0.21</td>
<td>-18.35 ± 0.21</td>
<td>-18.42 ± 0.20</td>
</tr>
<tr>
<td>SN2008Q</td>
<td>1.40</td>
<td>-15.94 ± 0.55</td>
<td>-15.46 ± 0.69</td>
<td>-17.49 ± 0.49</td>
<td>-18.88 ± 0.45</td>
<td>-18.28 ± 0.40</td>
<td>-18.25 ± 0.33</td>
</tr>
<tr>
<td>SN2008ec</td>
<td>1.08</td>
<td>-16.68 ± 0.57</td>
<td>⋯</td>
<td>-18.17 ± 0.50</td>
<td>-19.70 ± 0.45</td>
<td>-19.22 ± 0.40</td>
<td>-19.15 ± 0.33</td>
</tr>
</tbody>
</table>

Note. — These absolute magnitudes assume a MW extinction law for the MW extinction and a SMC extinction law for the host extinction. Hubble flow distances are used unless an independent distance is known (and listed in Table 6.5). The extinction corrected $\Delta m_{15}(B)$ is given for easier identification of individual SNe in the absolute magnitude plots.
their own peculiarities, we do not actually fit them or attempt to draw conclusions based on them.

Tables 6.1, 6.4, and 6.5 give the different extinction coefficients, reddening estimates and distances. From these the absolute magnitudes could be constructed according to different preferences, though the differences are small.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Mean Abs Mag (mag)</th>
<th>RMS$_{\text{avg}}$ (mag)</th>
<th>$\chi^2/\text{DOF}$</th>
<th>$\sigma_{\text{int}}^a$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>uvw2</td>
<td>-16.63</td>
<td>0.54</td>
<td>21.16/(11-1)</td>
<td>0.35</td>
</tr>
<tr>
<td>uvm2</td>
<td>-16.21</td>
<td>1.04</td>
<td>43.45/(8-1)</td>
<td>0.89</td>
</tr>
<tr>
<td>uvw1</td>
<td>-18.18</td>
<td>0.43</td>
<td>14.03/(12-1)</td>
<td>0.15</td>
</tr>
<tr>
<td>u</td>
<td>-19.77</td>
<td>0.45</td>
<td>12.00/(9-1)</td>
<td>0.20</td>
</tr>
<tr>
<td>b</td>
<td>-19.29</td>
<td>0.49</td>
<td>25.24/(12-1)</td>
<td>0.32</td>
</tr>
<tr>
<td>v</td>
<td>-19.25</td>
<td>0.45</td>
<td>25.50/(12-1)</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Note. — The weighted mean absolute magnitudes and RMS scatter exclude SNe 2005ke and 2007on.

$^a$ $\sigma_{\text{int}}$ is the intrinsic scatter required for the reduced $\chi^2$ to be equal to one.

### 6.4.3 Search for Photometric UV Luminosity Indicators

The optical light of the highest redshift SNe will be hard to observe, so it would be valuable to have a distance independent luminosity indicator observable in the UV data to calibrate the magnitudes in the place of $\Delta m_{15}(B)$. Analogous to $\Delta m_{15}(B)$, Milne et al. (2009, in preparation) similarly parameterized the UV light curve shapes by the amount the light curve fades in the 15 days after maximum light in that filter. The uvw1 light curve shapes are very similar, and $\Delta m_{15}(w1)$ has a small range of 0.5 magnitudes compared to the 1 magnitude difference between slow and fast decliners in the optical. Within that small range there is no correlation between $\Delta m_{15}(w1)$ and either $\Delta m_{15}(B)$ or the uvw1 absolute magnitude, displayed in Figure 6.9. The range of decay rates increases again in the uvw2 and uvm2 bands but do not show a correlation with the absolute magnitudes or the optical decay rate. Plots of those values are shown in Milne et al. (2009, in preparation). Thus a UV light curve parameter analogous to $\Delta m_{15}(B)$ is not useful.
Foley et al. (2008b) have reported a possible luminosity indicator in the near-UV spectra of 6 SNe. For SNe observed by Swift the grism observations usually do not have a strong enough signal at those wavelengths to measure the necessary ratio (Bufano et al. 2009). Foley et al. (2008b) suggested some UVOT colors that might show the same trend as their UV spectral ratio. UV colors at maximum would be most useful, as the highest redshift SNe will not likely have well sampled light curves much past maximum or high quality spectra. The UV colors in our small sample, however, do not show a strong correlation between the UV colors and $\Delta m_{15}(B)$, displayed in Fig. 6.10, like there is in the optical. As suggested by Foley et al. (2008b) the red tail of the uvw1 filter may dilute the effect they found, and the effect of small errors in extinction is much larger when comparing broad and separated filters than the closely spaced wavelengths they compare. One would also have to use multiple colors to break any degeneracies between luminosity and extinction.

The absolute UV magnitudes of normal SNe, $0.9 < \Delta m_{15}(B) < 1.6$, do not show a strong correlation with the decay rate, making normal SNe Ia standard candles with varying degrees of scatter. One only needs to identify and exclude SNe at the subluminous end. One well observed subluminous Ia, SN 2005ke, showed a plateau in the light curve $\sim 15$ days after maximum light (Immler et al. 2006) and a very different color evolution (Milne et al. 2009, in preparation). Other subluminous examples show hints of similar behavior (cf. SN 2007ax; Kasliwal et al. 2008). SN 2007on, however, showed no such plateau and evolved in color more like SNe Ia. Milne et al. (2009, in preparation) find a correlation between the optical decay rate and the time that the light curve breaks from its steep to shallow decay, a correlation which is stronger in uvw1 than in the optical. Further observations of this subclass are needed to determine what the normal behavior is and how to identify them by their rest frame UV light curves or colors. Subluminous SNe would be biased against in magnitude limited surveys, and they have yet to be observed in high redshift samples (Foley et al. 2008a).

6.5 Discussion

The UV absolute magnitudes of these SNe Ia seem to show two regimes. The absolute magnitudes in the near UV (2700-4000 Å, representing UVOT $uvw1$ and $u$ and ground based $U$; Jha et al. 2006), show a small amount of scatter, comparable to that in the optical for our sample. *The near UV could be useful for measuring luminosity distances.* This would be most valuable at higher redshift when fewer optical bands are available, to put multicolor constraints on the reddening and distance. While larger samples are now available in $U$ (Jha et al. 2006; Hicken et al. 2009a), the space based UV sample is still relatively small–comparable to the 9 objects used by Phillips (1993) which first suggested a luminosity width relation in the optical. Just as the optical absolute magnitude relations have been refined with larger samples–a larger sample is needed in the UV to better determine the intrinsic scatter and explore observed features that might correlate with the absolute magnitudes. The origin and wavelength dependence of extinction, the uncertainty in $K$ corrections due to intrinsic differences in the UV spectra, and a better understanding of the effects of the red tails of the uvw1 filter are needed to improve the utility of the uvw1 absolute magnitudes.
The absolute magnitudes in the mid-UV (2000 Å–2500 Å, the UVOT uvm2 band) exhibit a large scatter and therefore would not be useful for distance measurements. Studying the cause of that scatter in nearby events, however, might also prove useful in improving the utility of SNe Ia as distance indicators if they can be used to evaluate the optical differences for SNe with varying UV behavior.

Metallicity differences have been suggested as a possible second parameter that would result in luminosity differences between SNe with the same $\Delta m_{15}(B)$ in the optical (Mazzali & Podsiadlowski 2006). A metallicity-dependent component to the absolute magnitudes could result in an evolutionary bias as we go to higher redshift SNe with likely different metallicities. A concern already for the optical, this could be even more critical in the UV where the metallicity plays a strong role in the reverse-fluorescence emission (Mazzali 2000; Sauer et al. 2008) as well as the line blanketing (cf. Lentz et al. 2000; Domínguez et al. 2001). An additional concern is that in addition to systematically changing the absolute maximum in the $B$ band and anything bluer, the metallicity would also bias extinction determinations based on the observed $B-V$ color (Domínguez et al. 2001). A better understanding could be reached through detailed studies of the host galaxies’ ages and metallicities (Gallagher et al. 2008) of SNe observed in the UV and further study of the effects of metallicity on the UV luminosity and colors (Sauer et al. 2008), particularly for the UVOT bands. If correlations can be determined between the UV luminosity and the metallicity inferred for the progenitor, then the UV data might provide leverage in probing the metallicity dependence on the optical brightness and its evolution with redshift, thus making SNe Ia even better standardized candles in the optical. There is disagreement as to whether metallicities have already been found to affect optical measurements (Gallagher et al. 2008; Howell et al. 2009).

The measurement of absolute luminosities of SNe Ia in the UV is hindered by the low UV flux caused by metal line blanketing and being strongly effected by extinction. Yet these difficulties also make them strongly sensitive to metallicity and extinction effects, two sources of systematic uncertainties in the use of SNe Ia as standard candles in the optical. So while they may not be ideal standard candles for cosmological distance measurements, the understanding gleaned from UV data of local events will shed light on the important effects of extinction and metallicity. Comparison with rest frame UV data of high redshift events also has the potential of revealing evolution in the SN Ia progenitors.
Chapter 7

Conclusions and Future Work

7.1 Conclusions From This Work

*Swift/UVOT* proves to be an excellent observatory for UV observations of SNe. *Presented here is the largest collection of UV light curves obtained by any single instrument. This data set has allowed the study of individual objects as well as comparisons within and across SN types.* As shown in Chapter 4, the UVOT calibration and photometry tools, with the subtraction of the host galaxy flux from template images, is shown to agree very well with ground based observations (Brown et al. 2009). Wang et al. (2009b) demonstrated “the great improvements recently achieved in Swift UVOT calibrations.”

UVOT observations of SN 2005am (Brown et al. 2005b) in Chapter 2 revealed a light curve similar to SN 1992A in the optical as well as the near-UV template from IUE and HST observations of SNe 1990N and 1992A (Kirshner et al. 1993). Subsequent observations have shown that most SNe Ia have very similar light curves in the *uvw*1 with the exceptions of SNe 2005ke (Immler et al. 2006) and 2007on (Milne et al. 2009 in preparation). UVOT observations triggered by the GRB detection of GRB060218 revealed the shock breakout of SN 2006aj (Campana et al. 2006), a feature also seen (but not as well due to sparser observations and intrinsic reddening) in the normal SN Ib 2008D serendipitously observed by Swift during the explosion (Soderberg et al. 2008).

In Chapter 3 we showed the usefulness of UV data for SN 2005cs in constraining the temperature and extinction and validating theoretical modelling of SNe II. This was expanded to SN 2006bp in Dessart et al. (2008).

The large sample of SNe compared in Chapter 5 show a great homogeneity in the *uvw*1 light curves of SNe Ia, but more diversity in the bluer filters. The UV light curves of SNe Ib/c are varied, and the SNe II, while consistently fading do show a diversity in decay rates with SN 2005cs fading about twice as fast as the others. *The UV-colors discriminate well between SNe Ia and II, particularly at early times when the SNe Ia are very red and the SNe II very blue.*

We used peak magnitudes from our SNe Ia to study the absolute magnitudes in Chapter 6. Our sample of 14 objects is small compared to optical studies but the largest available in the UV. *The absolute magnitudes in the near-UV bands (u and *uvw*1) have a scatter comparable to that in the optical BV bands. Thus they could be used as a standard candle to measure cosmological distances with an intrinsic dispersion estimated to be 0.2 mag.* The dispersion in this small sample is strongly effected by the inclusion or exclusion of a few objects, but in all cases the scatter in the near-UV is comparable to that of the optical. A careful subtraction of the red tails of the *uvw*1 filter is needed to better assess the scatter in the UV portion and provide a better comparison for what
might be observed at higher redshift. Also, the location of these filters on the steep spectral slope make the \( k \) corrections large and uncertain due to the small number of UV spectra from which to estimate what the \( K \) corrections are and how much they might vary from SN to SN. We have also shown that the extinction corrections become non-linear in the UV. At this point the near-UV should not be targeted for cosmological distance measurements, but near-UV observations might still be useful for constraining extinction and distances in combination with optical filters.

In the mid-UV the uvm2 magnitudes exhibit a large (\( \sim 0.9 \) mag) intrinsic scatter. Thus, rest wavelengths shortward of 2500 Å cannot be used as reliable distance indicators. They might still be useful for constraining metallicity and put important constraints on evolution.

### 7.2 Future Work at Low Redshift

Swift UVOT has continued to observe many SNe. The total sample has nearly doubled since the study performed in Chapter 5. A list updated through April 2009 is given in Table 7.1. Such a sample allows one to examine the diversity of UV behavior within types rather than just accepting the behavior of single objects as representative. The increased sample also includes many previously unobserved subtypes (IIb, IIL, IIn) which can be added into the color comparisons. In particular, the IIL SN 2008es was found to be incredibly bright in the UV (Miller et al. 2009; Gezari et al. 2009), while a couple of SNe IIn observed with the UVOT have been found to emit strongly in the UV for years.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Instrument</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 2005am</td>
<td>Ia</td>
<td>UVOT</td>
<td>76</td>
</tr>
<tr>
<td>SN 2005bc</td>
<td>Ia</td>
<td>UVOT</td>
<td>1</td>
</tr>
<tr>
<td>SN 2005bf</td>
<td>Ib/c</td>
<td>UVOT</td>
<td>1</td>
</tr>
<tr>
<td>SN 2005cf</td>
<td>Ia</td>
<td>UVOT</td>
<td>60</td>
</tr>
<tr>
<td>SN 2005cs</td>
<td>II</td>
<td>UVOT</td>
<td>38</td>
</tr>
<tr>
<td>SN 2005da</td>
<td>Ic</td>
<td>UVOT</td>
<td>29</td>
</tr>
<tr>
<td>SN 2005df</td>
<td>Ia</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2005ek</td>
<td>Ic</td>
<td>UVOT</td>
<td>9</td>
</tr>
<tr>
<td>SN 2005hk</td>
<td>Ia</td>
<td>UVOT</td>
<td>17</td>
</tr>
<tr>
<td>SN 2005ip</td>
<td>IIn</td>
<td>UVOT</td>
<td>3</td>
</tr>
<tr>
<td>SN 2005gj</td>
<td>Ia</td>
<td>UVOT</td>
<td>1</td>
</tr>
<tr>
<td>SN 2005kd</td>
<td>IIn</td>
<td>UVOT</td>
<td>1</td>
</tr>
<tr>
<td>SN 2005ke</td>
<td>Ia</td>
<td>UVOT</td>
<td>35</td>
</tr>
<tr>
<td>SN 2005nz</td>
<td>Ia</td>
<td>UVOT</td>
<td>3</td>
</tr>
<tr>
<td>SN 2006E</td>
<td>Ia</td>
<td>UVOT</td>
<td>11</td>
</tr>
<tr>
<td>SN 2006X</td>
<td>Ia</td>
<td>UVOT</td>
<td>22</td>
</tr>
</tbody>
</table>

Continued on Next Page...
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Instrument</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 2006T</td>
<td>IIb</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2006aj</td>
<td>Ic</td>
<td>UVOT</td>
<td>52</td>
</tr>
<tr>
<td>SN 2006at</td>
<td>IIP</td>
<td>UVOT</td>
<td>18</td>
</tr>
<tr>
<td>SN 2006bc</td>
<td>II</td>
<td>UVOT</td>
<td>9</td>
</tr>
<tr>
<td>SN 2006bp</td>
<td>IIP</td>
<td>UVOT</td>
<td>35</td>
</tr>
<tr>
<td>SN 2006bv</td>
<td>IIn</td>
<td>UVOT</td>
<td>13</td>
</tr>
<tr>
<td>SN 2006dd</td>
<td>Ia</td>
<td>UVOT</td>
<td>23</td>
</tr>
<tr>
<td>SN 2006dm</td>
<td>Ia</td>
<td>UVOT</td>
<td>19</td>
</tr>
<tr>
<td>SN 2006dn</td>
<td>Ic</td>
<td>UVOT</td>
<td>18</td>
</tr>
<tr>
<td>SN 2006ej</td>
<td>Ia</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2006gy</td>
<td>IIn</td>
<td>UVOT</td>
<td>1</td>
</tr>
<tr>
<td>SN 2006jc</td>
<td>Ib</td>
<td>UVOT</td>
<td>58</td>
</tr>
<tr>
<td>SN 2006jd</td>
<td>IIn</td>
<td>UVOT</td>
<td>13</td>
</tr>
<tr>
<td>SN 2006ic</td>
<td>Ib/c</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2006it</td>
<td>Ib</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2006mr</td>
<td>Ia</td>
<td>UVOT</td>
<td>15</td>
</tr>
<tr>
<td>SN 2007C</td>
<td>Ib</td>
<td>UVOT</td>
<td>3</td>
</tr>
<tr>
<td>SN 2007D</td>
<td>Ib</td>
<td>UVOT</td>
<td>4</td>
</tr>
<tr>
<td>SN 2007I</td>
<td>Ic</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2007S</td>
<td>Ia</td>
<td>UVOT</td>
<td>33</td>
</tr>
<tr>
<td>SN 2007Y</td>
<td>Ib</td>
<td>UVOT</td>
<td>20</td>
</tr>
<tr>
<td>SN 2007aa</td>
<td>IIP</td>
<td>UVOT</td>
<td>7</td>
</tr>
<tr>
<td>SN 2007af</td>
<td>Ia</td>
<td>UVOT</td>
<td>56</td>
</tr>
<tr>
<td>SN 2007ax</td>
<td>Ia</td>
<td>UVOT</td>
<td>12</td>
</tr>
<tr>
<td>SN 2007bb</td>
<td>II</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2007bg</td>
<td>Ic</td>
<td>UVOT</td>
<td>4</td>
</tr>
<tr>
<td>SN 2007bm</td>
<td>Ia</td>
<td>UVOT</td>
<td>4</td>
</tr>
<tr>
<td>SN 2007ch</td>
<td>IIP</td>
<td>UVOT</td>
<td>1</td>
</tr>
<tr>
<td>SN 2007ck</td>
<td>IIP</td>
<td>UVOT</td>
<td>11</td>
</tr>
<tr>
<td>SN 2007co</td>
<td>Ia</td>
<td>UVOT</td>
<td>11</td>
</tr>
<tr>
<td>SN 2007cq</td>
<td>Ia</td>
<td>UVOT</td>
<td>13</td>
</tr>
<tr>
<td>SN 2007cu</td>
<td>Ic</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2007cv</td>
<td>Ia</td>
<td>UVOT</td>
<td>21</td>
</tr>
<tr>
<td>SN 2007fo</td>
<td>Ib</td>
<td>UVOT</td>
<td>3</td>
</tr>
<tr>
<td>SN 2007gi</td>
<td>Ia</td>
<td>UVOT</td>
<td>5</td>
</tr>
<tr>
<td>SN 2007od</td>
<td>IIP</td>
<td>UVOT</td>
<td>12</td>
</tr>
<tr>
<td>SN 2007on</td>
<td>Ia</td>
<td>UVOT</td>
<td>25</td>
</tr>
<tr>
<td>SN 2007pk</td>
<td>IIn</td>
<td>UVOT</td>
<td>16</td>
</tr>
<tr>
<td>SN 2007sr</td>
<td>Ia</td>
<td>UVOT</td>
<td>37</td>
</tr>
<tr>
<td>SN 2007uy</td>
<td>Ib</td>
<td>UVOT</td>
<td>41</td>
</tr>
<tr>
<td>SN 2008A</td>
<td>Ia</td>
<td>UVOT</td>
<td>17</td>
</tr>
</tbody>
</table>

Continued on Next Page...
Table 7.1 – Continued

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Instrument</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 2008D</td>
<td>Ib</td>
<td>UVOT</td>
<td>40</td>
</tr>
<tr>
<td>SN 2008M</td>
<td>II</td>
<td>UVOT</td>
<td>6</td>
</tr>
<tr>
<td>SN 2008Q</td>
<td>Ia</td>
<td>UVOT</td>
<td>16</td>
</tr>
<tr>
<td>SN 2008S</td>
<td>II?</td>
<td>UVOT</td>
<td>4</td>
</tr>
<tr>
<td>SN 2008ae</td>
<td>Ia</td>
<td>UVOT</td>
<td>6</td>
</tr>
<tr>
<td>SN 2008am</td>
<td>II</td>
<td>UVOT</td>
<td>6</td>
</tr>
<tr>
<td>SN 2008aq</td>
<td>IIb</td>
<td>UVOT</td>
<td>7</td>
</tr>
<tr>
<td>SN 2008aw</td>
<td>II</td>
<td>UVOT</td>
<td>9</td>
</tr>
<tr>
<td>SN 2008ax</td>
<td>II</td>
<td>UVOT</td>
<td>20</td>
</tr>
<tr>
<td>SN 2008bo</td>
<td>Ib</td>
<td>UVOT</td>
<td>46</td>
</tr>
<tr>
<td>SN 2008cg</td>
<td>II</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SNF080514-02</td>
<td>Ia</td>
<td>UVOT</td>
<td>14</td>
</tr>
<tr>
<td>SN 2008dq</td>
<td>Ic</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2008dx</td>
<td>Ia</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2008eb</td>
<td>Ic</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2008ec</td>
<td>Ia</td>
<td>UVOT</td>
<td>20</td>
</tr>
<tr>
<td>SN 2008es</td>
<td>II</td>
<td>UVOT</td>
<td>22</td>
</tr>
<tr>
<td>SN 2008fz</td>
<td>Ic</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2008ge</td>
<td>Ia</td>
<td>UVOT</td>
<td>4</td>
</tr>
<tr>
<td>SN 2008ha</td>
<td>Ia</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2008hs</td>
<td>Ia</td>
<td>UVOT</td>
<td>21</td>
</tr>
<tr>
<td>SN 2008hv</td>
<td>Ia</td>
<td>UVOT</td>
<td>23</td>
</tr>
<tr>
<td>SN 2008ij</td>
<td>IIP</td>
<td>UVOT</td>
<td>17</td>
</tr>
<tr>
<td>SN 2008in</td>
<td>IIP</td>
<td>UVOT</td>
<td>8</td>
</tr>
<tr>
<td>SN 2009N</td>
<td>IIP</td>
<td>UVOT</td>
<td>6</td>
</tr>
<tr>
<td>SN 2009Y</td>
<td>Ia</td>
<td>UVOT</td>
<td>36</td>
</tr>
<tr>
<td>SN 2009aj</td>
<td>II</td>
<td>UVOT</td>
<td>1</td>
</tr>
<tr>
<td>SN 2009an</td>
<td>Ia</td>
<td>UVOT</td>
<td>13</td>
</tr>
<tr>
<td>SN 2009at</td>
<td>II</td>
<td>UVOT</td>
<td>3</td>
</tr>
<tr>
<td>SN 2009au</td>
<td>II</td>
<td>UVOT</td>
<td>1</td>
</tr>
<tr>
<td>SN 2009ay</td>
<td>II</td>
<td>UVOT</td>
<td>2</td>
</tr>
<tr>
<td>SN 2009bb</td>
<td>II</td>
<td>UVOT</td>
<td>6</td>
</tr>
<tr>
<td>SN 2009bw</td>
<td>II</td>
<td>UVOT</td>
<td>6</td>
</tr>
<tr>
<td>SN 2009cz</td>
<td>Ia</td>
<td>UVOT</td>
<td>11</td>
</tr>
<tr>
<td>SN 2009dc</td>
<td>Ia</td>
<td>UVOT</td>
<td>4</td>
</tr>
<tr>
<td>SN 2009dd</td>
<td>II</td>
<td>UVOT</td>
<td>5</td>
</tr>
</tbody>
</table>

The large and growing sample of SNe Ia will allow for studies impacting the greatest sources of potential systematic errors in SN Ia cosmology—extinction and evolution. Having many low extinction SNe with which to compare, it would now be useful to also
target moderately reddened SNe to study the shape of the reddening law in the UV to put constraints on the origin of the extinction and how to correct for it in the UV and optical. The UV colors, by comparison with detailed spectral modeling (Sauer et al. 2008), can measure the metallicity of the SNe and determine whether the metallicity evolution expected for SN progenitors is of concern for high redshift studies.

In addition to the absolute magnitudes of SNe Ia which are of interest for cosmological measurements, the UV absolute magnitudes of other SN types will give useful constraints on the total energy output. We are also combining our UV data with optical and near-infrared observations to construct bolometric lightcurves that encompass more of the spectrum for individual objects and refining bolometric corrections used in constructing bolometric curves from optical data alone (cf. Contardo et al. 2000). Despite the observation of extragalactic SNe for decades, the last few years have included the discovery of some of the brightest (SNe 2006gy, 2005ap, 2008es) and faintest SNe (2007ax, 2008ha) ever observed, many of which were observed with the *Swift* UVOT. The long predicted shock breakout of SNe has now been observed twice with Swift, GRB060218/SN 2006aj (discussed earlier) and the normal Ib 2008D (Soderberg et al. 2008).

Additionally, UV observations can also probe other astrophysical phenomena that effect the SN or how we observe it. UV observations of the host galaxies are sensitive to recent star formation, helpful in untangling the timescale of SN progenitors. The UV colors and absolute magnitudes of the SNe can give constraints on the wavelength dependence of reddening, important for not only extinction corrections but to better understand the origin, diversity, and possible evolution of the reddening sources.

Many UV studies, particularly of the intervening matter (Wamsteker et al. 2006), require high resolution UV spectra. While *Swift* UVOT cannot perform the necessary observations, the data presented here will be very helpful in planning the capabilities needed in order for future observatories to carry out such studies. In particular, the brightness of SNe in the UV and the evolution of their light curves can guide the appropriate trigger criteria, exposure times, and cadences. Near term future UV observatories, including a refurbished HST, TAUVEX (Safonova et al. 2008), and WSO-UV (Pagano et al. 2008) will be the first to benefit.

### 7.3 High Redshift Application

In addition to nearby SN observations by UV satellites, deep optical observations can observe the rest-frame UV light from higher redshift SNe. Figure 7.1 displays the rest frame UV light sampled by the UVOT UV filters as it corresponds to observed wavelengths as a function of redshift, highlighting regions where the UV filters correspond well with commonly used optical and infrared filters. To highlight the regions where the overlap between the filters is greatest, the bands are centered on the central wavelength and extend one quarter of the full width half max of the filter transmission in both directions (Poole et al. 2008; Fukugita et al. 1996; Hewett et al. 2006). This graphically depicts useful regions of overlap. For example, the photons corresponding with the rest-frame uvw1 begins to be redshifted into the optical u’ band (e.g. SDSS-II SN survey; Sako et al. 2008; and LSST) for objects at a redshift of $z \sim 0.4$ and the g’ band (e.g.
SNLS; Astier et al. 2006) at \( z \sim 0.8 \), where the \( u' - g' \) colors also correspond well with our \( uvw2 - uvw1 \) colors. While chasing the optical light to high redshifts will require observing into the infrared, the use of rest frame UV light can be done with optical and near-IR observations possible with current and planned large ground based telescopes. While we have discussed the utility of the absolute magnitudes of SNe Ia, the absolute magnitudes of other types, in particular the UV bright SNe II that can be seen to extremely high redshifts is also important. Already SNe II at redshifts of up to 2 are being discovered by their rest frame UV light (J. Cooke 2009, private communication) and the data being provided by the UVOT are the only local UV data for the temporal behavior of the UV flux.

Aldering et al. (2007) discuss many uses for rest-frame UV observations of these high redshift SNe in the context of SNAP, and this local sample should allow a comparison looking for evolutionary effects. Since SNAP is planned to have logarithmically spaced filters beginning at 4000 Å, they will cover the restframe UV observed by the UVOT filters for redshifts beyond \( z \sim 0.8 \). More generally, any deep SN search optimized for finding and following high redshift SNe in the optical will likely also detect the rest-frame UV light of SNe (preferentially SNe II due to their brighter UV luminosities) at the high end of their target redshift and beyond.

The Joint Dark Energy Mission reference mission (JDEM RM), with a wavelength range 4500 - 17000 Å (Gehrels et al. 2009), would observe the rest frame \( BV \) bands out to a redshift of about 1.8. This means that rest frame UV is not critical to cosmological distance measurements in the region where dark energy has the most influence (Aldering et al. 2007). Between redshifts of 0.6-1.8 rest-frame UV measurements will be made along with rest frame optical measurements from which distance measurements. This will increase the sample of rest-frame UV absolute magnitudes with which to access their stand alone utility as standard candles and also guard against systematic changes in metallicity or extinction properties. While the effects of metallicity are strongest in the UV bands, the optical colors (and thus reddening estimates) would also be affected. Thus the UV observations will improve the utility of optical distance measurements.

Coincidentally, at a redshift of 1.8 above which \( V \) begins to be redshifted out of the JDEM RM range, the rest wavelengths covered by the Swift/UVOT detector 1600-6000 are redshifted to the observed wavelength range of the JDEM RM. While the dark energy constraints are weaker, for that reason higher redshifts are ideal for putting constraints on evolution (Riess & Livio 2006). Comparisons of our local UV data with rest frame UV data at high redshift will be useful in putting constraints on evolutionary changes. Ironically the current difficulty in making this comparison is not due to the lack of high redshift SN data but rather a lack of low redshift UV data Sullivan et al. 2009.

The light curve shapes and colors of our large sample should also help in the classification of SNe, particularly at these higher redshifts when spectra are unobtainable and fewer rest-frame optical bands are observable. Thus even if not used in the measurement of the cosmological distances, the rest frame UV will help identify which of the many detected transients are the cosmologically useful SNe Ia. Detections of other SN types at higher redshifts can be used as proxies for star formation rates. Making full use of these data will require a better understanding of the UV light best obtained for nearby
SNe for which multi-wavelength photometry and spectroscopy over a larger portion of the light curve is possible. Rest-frame UV observations of a local sample of SNe have the further advantage of being a comparison sample with which to understand the high redshift SNe, look for evolutionary differences (see e.g. Foley et al. 2008a; Ellis et al. 2008), and further constrain photometric redshifts, extinction, and luminosity distances.
Fig. 7.1 Rest frame UV light sampled by the UVOT UV filters as it corresponds to observed wavelengths as a function of redshift. The observed wavelength ranges for commonly used filter sets (optical–SDSS (Fukugita et al. 1996) and infrared–UKIRT set (Hewett et al. 2006)) are also highlighted (and labeled on the right side).
Appendix A

Acronyms

AT – automated target
BAT – Burst Alert Telescope
CCD – Charge Coupled Device
CMP – Cosmic Microwave Background
DSS – Digitized Sky Survey
EPM – Expanding Photosphere Method
FITS – Flexible Image Transport System
GALEX – Galaxy Evolution Explorer
GRB – Gamma Ray Burst
GTI – Good Time Interval
HST – Hubble Space Telescope
IUE – International Ultraviolet Explorer
JDEM – Joint Dark Energy Mission
LTE – Local Thermodynamic Equilibrium
MLCS – Multicolor Light Curve Shapes
NFI – Narrow Field Instruments on Swift (ie XRT and UVOT)
NIR – Near Infrared
NLTE – Non Local Thermodynamic Equilibrium
PNLF – Planetary Nebulae Luminosity Function
PPST – pre-planned science timeline
PPT – pre-planned target
PSF – Point Spread Function
RM – Reference Mission
SAA – South Atlantic Anomaly
SBF – Surface Brightness Fluctuations
SCM – Standard Candle Method
SEAM – Spectral Expanding Atmosphere Method
SN – Supernova
TF – Tully Fisher
TLA – Three Letter Acronym
UVOT – UV/Optical Telescope
XRT – X-ray Telescope
Appendix B

Image Archive pipeline

Below are the commands used to process the images for SN 2007b. The data is retrievable from the Swift archive from the command line. The observations (which are typically broken up into several snapshots) are coadded by epoch for each filter. These are appended onto a single fits file upon which the UVOT photometry routine uvotsource will operate in the next section. Similar command files are generated for each SN and then edited by hand, as individual images often need to be excluded or fixed because of no aspect solution or smearing from star tracker loss of lock episodes.

```bash
uvotimsum 00030923001/uvot/image/sw00030923001uw2_sk.img.gz 00030923001/uvot/image/sw00030923001uw2_sk_sum.fits exclude=None
uvotimsum 00030923002/uvot/image/sw00030923002uw2_sk.img.gz 00030923002/uvot/image/sw00030923002uw2_sk_sum.fits exclude=None
uvotimsum 00030923003/uvot/image/sw00030923003uw2_sk.img.gz 00030923003/uvot/image/sw00030923003uw2_sk_sum.fits exclude=None
uvotimsum 00030923004/uvot/image/sw00030923004uw2_sk.img.gz 00030923004/uvot/image/sw00030923004uw2_sk_sum.fits exclude=None
fcopy 00030923001/uvot/image/sw00030923001uw2_sk_sum.fits SN2007bm_w2.img
fappend 00030923002/uvot/image/sw00030923002uw2_sk_sum.fits SN2007bm_w2.img
fappend 00030923003/uvot/image/sw00030923003uw2_sk_sum.fits SN2007bm_w2.img
fappend 00030923004/uvot/image/sw00030923004uw2_sk_sum.fits SN2007bm_w2.img
```
uvotimsum 00037768001/uvot/image/sw00037768001uw2_sk.img
00037768001/uvot/image/sw00037768001uw2_sk_sum.fits exclude=none
fcopy 00037768001/uvot/image/sw00037768001uw2_sk_sum.fits
SN2007bm_w2tempsum.img
Galaxy Subtraction Recipe

This script uses the images compiled in Appendix B and performs photometry using source regions given. The galaxy count rate is subtracted as described in Chapter 4.

```bash
### uvotmaghist and galaxy subtraction summary
### replace "SN2007bm" with the SN name
### replace YYYY.YY,YYY.YY below with the SN position and center of background region
echo "writing SN region file"
echo "# SN region file" > SN2007bm_3.reg
echo 'global color=green font="helvetica 10 normal" select=1 edit=1 move=1
delete=1 include=1 fixed=0 source' >> SN2007bm_3.reg
echo 'fk5;circle(171.2597,-9.7983464,3")' >> SN2007bm_3.reg
echo "writing background region file"
echo "# SN background region file" > SN2007bm_bkgclear.reg
echo 'global color=green font="helvetica 10 normal" select=1 edit=1 move=1
delete=1 include=1 fixed=0 source' >> SN2007bm_bkgclear.reg
echo 'fk5;circle(171.23169,-9.7395007,65")' >> SN2007bm_bkgclear.reg
### runs uvotmaghist once and computes photometry using the 3" aperture and the standard 5" aperture
### galaxy count rates come from the template image
echo "running uvotmaghist on the template images"
uvotmaghist SN2007bm_w2tempsum.img srcreg=SN2007bm_3.reg
bkgreg=SN2007bm_bkgclear.reg outfile=SN2007bm_w2_3_cleartempsum.fits
plotfile=SN2007bm_w2_3_cleartempsum.gif coinfie=caldb zerofile=caldb
exclude=none chatter=0 clobber=yes logtime=no
psffile=caldb apercorr=curveofgrowth
echo "running uvotmaghist on the SN images"
uvotmaghist SN2007bm_w2.img srcreg=SN2007bm_3.reg
bkgreg=SN2007bm_bkgclear.reg outfile=SN2007bm_w2_3_clear.fits
plotfile=SN2007bm_w2_3_clear.gif coinfie=caldb zerofile=caldb
exclude=none chatter=0 clobber=yes logtime=no psffile=caldb
apercorr=curveofgrowth
display SN2007bm_w2_3_clear.gif &
echo "copy fits files in case they get deleted by an error
you don't have to rerun uvotmaghist"
rm SN2007bm_*phot.fits
```
fcopy SN2007bm_w2_3_clear.fits SN2007bm_w2_phot.fits
rm SN2007bm_w2_phottempsum.fits
fcopy SN2007bm_w2_3_cleartempsum.fits SN2007bm_w2_phottempsum.fits
### just rename COI_SRC_RATE to S3BCR
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits
clobber=yes clname="S3BCR" tform=1E expr="COI_SRC_RATE"
fcalc SN2007bm_w2_phottempsum.fits SN2007bm_w2_phottempsum.fits
clobber=yes clname="S3BCR" tform=1E expr="COI_SRC_RATE"
echo " add 3% error on count rate in quadrature to poisson error"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
cname="S3BCRe" tform=1E
expr="sqrt((COI_SRC_RATE_ERR)^2+(COI_SRC_RATE*0.03)^2)"
fcalc SN2007bm_w2_phottempsum.fits SN2007bm_w2_phottempsum.fits clobber=yes
clname="S3BCRe" tform=1E expr="sqrt((COI_SRC_RATE_ERR)^2+(COI_SRC_RATE*0.03)^2)"
echo " pull out the count rates from the template images"
#### if you have multiple templates you could pull out the mean
#### and standard deviation
echo " Beware of galaxy count rates above 0.1 due to co-i issues"
fstatistic SN2007bm_w2_phottempsum.fits clname=S3BCR rows=1
outfile=w2_3templatecountrate.txt clobber=yes
set G3BCR='pget fstatistic mean'
fthedit SN2007bm_w2_phot.fits G3BCR operation=add value=$G3BCR
fstatistic SN2007bm_w2_phottempsum.fits clname=S3BCRe rows=1
outfile=w2_3templatecountrate.txt clobber=yes
set G3BCRe='pget fstatistic mean'
fthedit SN2007bm_w2_phot.fits G3BCRe operation=add value=$G3BCRe
echo "w2 count rate is $G3BCR"
# #### zeropoints
fparkey 17.35 SN2007bm_w2_phot.fits ZPT add=yes
fparkey 0.03 SN2007bm_w2_phot.fits ZPTe add=yes
echo " subtract galaxy, propagate error"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S3BCGR" tform=1E expr="(S3BCR-G3BCR)"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S3BCGRe" tform=1E expr="sqrt((S3BCRe)^2+(G3BCRe)^2)"
### apply aperture correction
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S3BCGAR" tform=1E expr="S3BCGAR*AP_FACTOR"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S3BCGARE" tform=1E expr="S3BCGARE*AP_FACTOR_ERR"
### determine significance/3 sigma upper limit
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S3BCGARs" tform=1E expr="S3BCGAR/S3BCGARE"
clname="S3BCGAMl" tform=1E expr="(-2.5*log10(3*S3BCGAR))+ZPT"
echo " convert rate,err to magnitudes"
ftcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
column="S3BCGAM" tform=1E
expression="S3BCGARs>3?-2.5*log10(S3BCGAR)+ZPT:#null"
ftcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
column="S3BCGAME" tform=1E
expression="S3BCGARs>3?(2.5/log(10))*((S3BCGAR/s3BCGAR)):s3BCGAMl"
### add convenient time columns
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="TMID" expr="(TSTOP-TSTART)/2+TSTART"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="JD" expr="T MID/60/60/24+2451910.5"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="JDshort" tform=1E expr="JD-24500000"
ftthedit SN2007bm_w2_phot.fits TDISP78 add f7.2
ftthedit SN2007bm_w2_phot.fits TDISP74 add f5.2
ftthedit SN2007bm_w2_phot.fits TDISP75 add f5.2
echo "create data files for each filter"
ftlist SN2007bm_w2_phot.fits option=t outfile=SN2007bm_w2_mags3.dat
columns="JDshort, S3BCGAM, S3BCGAME" clobber=yes rownum=no colheader=no
echo " now for 5 arcsec aperture photometry using the standard aperture if you want to compare"
### apply co-i correction to std rate
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S5CR" tform=1E expr="(RAW_STD_RATE*COI_STD_FACTOR)"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S5CRe" tform=1E expr="(RAW_STD_RATE_ERR*COI_STD_FACTOR)"
fcalc SN2007bm_w2_phottempsum.fits SN2007bm_w2_phottempsum.fits
clobber=yes clname="S5CR" tform=1E
expr="(RAW_STD_RATE*COI_STD_FACTOR)"
fcalc SN2007bm_w2_phottempsum.fits SN2007bm_w2_phottempsum.fits
clobber=yes clname="S5CRe" tform=1E
expr="(RAW_STD_RATE_ERR*COI_STD_FACTOR)"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S5BCR" tform=1E
expr="((RAW_STD_RATE*COI_STD_FACTOR)-(COI_BKG_RATE*STD_AREA))"
fcalc SN2007bm_w2_phottempsum.fits SN2007bm_w2_phottempsum.fits
clobber=yes clname="S5BCR" tform=1E
expr="((RAW_STD_RATE*COI_STD_FACTOR)-(COI_BKG_RATE*STD_AREA))"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S5BCRe" tform=1E
expr="sqrt((S5CRe)^2+(S5CR*0.03)^2+(COI_BKG_RATE_ERR*STD_AREA)^2)"
fcalc SN2007bm_w2_phottempsum.fits SN2007bm_w2_phottempsum.fits
clobber=yes clname="S5BCRe" tform=1E
eq"sqrt((S5CRe)^2+(S5CR*0.03)^2+(COI_BKG_RATE_ERR*STD_AREA)^2)"
set G5BCR=0
set G5BCRe=0
fstatistic SN2007bm_w2_phottempsum.fits colname=S5BCR rows=1
outfile=/tmp/junk.txt clobber=yes
set G5BCR='pget fstatistic mean'
fthedit SN2007bm_w2_phot.fits G5BCR operation=add value=$G5BCR
fstatistic SN2007bm_w2_phottempsum.fits colname=S5BCRe rows=1
outfile=/tmp/junk.txt clobber=yes
set G5BCRe='pget fstatistic mean'
fthedit SN2007bm_w2_phot.fits G5BCRe operation=add value=$G5BCRe
echo "Beware of galaxy count rates > ~ 0.1"
echo "w2 count rate is $G5BCR"
echo 'Galaxy count rates in 5" aperture' > SN2007bm_galaxyrates.txt
echo "w2 $G5BCR $G5BCRe " >> SN2007bm_galaxyrates.txt
echo " subtract backgrounds, propagate error"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S5BCGR" tform=1E expr="(S5BCR-G5BCR)"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S5BCGRe" tform=1E expr="sqrt((S5BCRe)^2+(G5BCRe)^2)"
## determine significance
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S5BCGRs" tform=1E expr="S5BCGR/S5BCGRe"
fcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
clname="S5BCGMl" tform=1E expr="(-2.5*log10(3*S5BCGRe))+ZPT"
ftcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
column="S5BCGM" tform=1E
expression="S5BCGRs>3?(-2.5*log10(S5BCGR)+ZPT):#null"
ftcalc SN2007bm_w2_phot.fits SN2007bm_w2_phot.fits clobber=yes
column="S5BCGMe" tform=1E
expression="S5BCGRs>3?(2.5/log(10))*((S5BCGRe/S5BCGR)):S5BCGMl"
ftedit SN2007bm_w2_phot.fits TDISP87 add f5.2
ftedit SN2007bm_w2_phot.fits TDISP88 add f5.2
ftlist SN2007bm_w2_phot.fits option=t outfile=SN2007bm_w2_mags5.dat
columns="JDshort, S5BCGM, S5BCGMe" clobber=yes rownum=no colheader=no
# copy photometry files to data and plotting files
This is the final data file that is generated for each SN.

```plaintext
# SN2007bm magnitudes from Swift UVOT
# generated Mon Dec 8 14:53:53 EST 2008
# by Peter Brown, Grad student at Penn State < pbrown@astro.psu.edu >
# If using this data in a publication,
#
# Data comes from newly (2008) reprocessed data from the Swift Data Center
# A 5 arcsec aperture is used to measure the counts for the
# coincidence loss correction, a 3 arcsec aperture was used for
# the photometry, subtracting off the galaxy light
# in a template image with the same aperture,
# and applying an aperture correction (based on average psf in Swift CALDB)
# to put the magnitudes on the UVOT photometric system described in that paper.
#
# b and v data are excluded due to high galaxy count rates
#
# JD(-2450000) Mag MagErr (non detections JD \nodata 3SigMagLimit)
#
# uvw2
4217.31  18.69  0.11
4221.12  18.27  0.08
4223.60  18.21  0.08
4228.91  18.52  0.09
#
# uvm2
4217.32  \nodata  20.01
4221.12  \nodata  20.03
4223.61  19.86  0.33
4228.91  \nodata  20.09
#
# uvw1
4217.31  17.03  0.06
4221.11  16.68  0.06
```
<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>4223.60</td>
<td>16.71</td>
<td>0.06</td>
</tr>
<tr>
<td>4228.91</td>
<td>17.11</td>
<td>0.06</td>
</tr>
</tbody>
</table>

# uvot u
<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>4217.31</td>
<td>15.15</td>
<td>0.05</td>
</tr>
<tr>
<td>4221.11</td>
<td>14.82</td>
<td>0.05</td>
</tr>
<tr>
<td>4223.60</td>
<td>14.81</td>
<td>0.05</td>
</tr>
<tr>
<td>4228.91</td>
<td>15.24</td>
<td>0.05</td>
</tr>
</tbody>
</table>

#
Appendix E

Light Curve Plots

These are the light curves for the 25 SNe studied in Chapter 5. They are published in the electronic version of Brown et al. (2009).

SN2005am
UVOT Light Curves

Fig. E.1 UVOT light curves of SN 2005am.
Fig. E.2 UVOT light curves of SN 2005cf.

Fig. E.3 UVOT light curves of SN 2005cs.
Fig. E.4 UVOT light curves of SN 2005df.

Fig. E.5 UVOT light curves of SN 2005hk.
Fig. E.6 UVOT light curves of SN 2005ke.

Fig. E.7 UVOT light curves of SN 2006E.
Fig. E.8 UVOT light curves of SN 2006X.

Fig. E.9 UVOT light curves of SN 2006aj.
Fig. E.10 UVOT light curves of SN 2006at.

Fig. E.11 UVOT light curves of SN 2006bc.
Fig. E.12 UVOT light curves of SN 2006bp.
Fig. E.13 UVOT light curves of SN 2006dd.

SN2006dm UVOT Light Curves

Fig. E.14 UVOT light curves of SN 2006dm.
Fig. E.15 UVOT light curves of SN 2006ej.

Fig. E.16 UVOT light curves of SN 2006jc.
Fig. E.17 UVOT light curves of SN 2006mr.

Fig. E.18 UVOT light curves of SN 2007S.
Fig. E.19 UVOT light curves of SN 2007Y.

Fig. E.20 UVOT light curves of SN 2007aa.
Fig. E.21 UVOT light curves of SN 2007af.

Fig. E.22 UVOT light curves of SN 2007bm.
Fig. E.23 UVOT light curves of SN 2007co.

Fig. E.24 UVOT light curves of SN 2007cq.
Fig. E.25 UVOT light curves of SN 2007cv.
Appendix F

Color Evolution Plots

These are additional color evolution plots similar to the $uvw1 - b$ plots used in Section 5.4 to differentiate SNe based on their colors. Only colors from neighboring filters or separated by one filter are shown. For visual comparison the x and y axis are on the same scale.

Fig. F.1 $uvw2 - uvm2$ color evolution.
Fig. F.2 uvw2-uvw1 color evolution.

Fig. F.3 uvm2-uvw1 color evolution.
Fig. F.4 uvm2-u color evolution.

Fig. F.5 uvw1-u color evolution.
Fig. F.6 uvw1-b color evolution.

Fig. F.7 u-b color evolution.
Fig. F.8 u-v color evolution.

Fig. F.9 b-v color evolution.
Bibliography


Balonek, T., Sonneborn, G., Rodriguez, P. M., Wamsteker, W., Fransson, C., & Kirshner, R. P. 1993, IAU Circ., 5754, 1


Blustin, A. J. 2007, Royal Society of London Philosophical Transactions Series A, 365, 1263


—. 1998, ARAA, 36, 17


Branch, D. & Tammann, G. A. 1992, ARAA, 30, 359


Brown, P. J. & Immler, S. 2006, The Astronomer’s Telegram, 761, 1
Brown, P. J., Immler, S., & The Swift Satellite Team. 2008, The Astronomer’s Telegram, 1403, 1


Bu, R. J. 1982, PASP, 94, 578


Filippenko, A. V. 1997, ARAA, 35, 309
Folatelli, G., Morrell, N., Phillips, M., & Hamuy, M. 2007, Central Bureau Electronic Telegrams, 862, 1


Foley, R. J., Filippenko, A. V., & Jha, S. W. 2008b, ArXiv e-prints, 803


Garg, A., Stubbs, C. W., Challis, P., Wood-Vasey, W. M., Blondin, S., Huber, M. E., Cook, K., Nikolaev, S., Rest, A., Smith, R. C., Olsen, K., Suntzeff, N. B., Aguilera,


Immler, S. & Brown, P. J. 2006, The Astronomer’s Telegram, 776, 1

Immler, S., Brown, P. J., Filippenko, A. V., & Pooley, D. 2007a, The Astronomer’s Telegram, 1290, 1


Kloehr, W., Muendlein, R., Li, W., Yamaoka, H., & Itagaki, K. 2005, IAU Circ.irc, 8553, 1


Leibundgut, B. 2001, ARAA, 39, 67


Lyubimkov, L. S. 1990, Soviet Astronomy, 34, 239


Martin, R., Yamaoka, H., & Itagaki, K. 2005, IAU Circ.irc, 8490, 1


Pooley, D. & Lewin, W. H. G. 2004, IAU Circ.irc, 8390, 1


Pskovskii, I. P. 1977, Soviet Astronomy, 21, 675

Pskovskii, Y. P. 1967, Soviet Astronomy, 11, 63


Richardson, D., Branch, D., & Baron, E. 2006, AJ, 131, 2233


Safonova, M., Sivaram, C., & Murthy, J. 2008, APSS, 318, 1


Wamsteker, W., Rodriguez, P. M., Gonzalez, R., Sonneborn, G., & Kirshner, R. 1993, IAU Circ., 5738, 1


Vita
Peter Johnson Brown

Education

Ph.D. in Astronomy & Astrophysics, August 2009
Area of Specialization: UV observations of Supernovae

*Brigham Young University* Provo, UT 1997–2004
B.S. in Physics and Astronomy

Awards and Honors

NASA Group Achievement Award 2007

Research Experience

Thesis Advisor: Peter W. A. Roming
  Dissertation Title: “The Ultraviolet Properties of Supernovae”

*Undergraduate Research* Brigham Young University 2002–2004
  Senior Thesis Title: “Observing Gamma Ray Burst Afterglows with BYU’s Orson Pratt Observatory”

*Teaching Assistant* The Pennsylvania State University 2004
Independently taught and graded an Astronomy lab class.

*Teaching Assistant* Brigham Young University 2002–2004
Taught constellation labs with the planetarium and night sky, supervised telescope use