Properties of Type Ia Supernovae
From the (intermediate) Palomar Transient Factory

Seméli Papadogiannakis

Academic dissertation for the Degree of Doctor of Philosophy in Physics at Stockholm University to be publicly defended on Friday 24 May 2019 at 13.00 in sal FA32, AlbaNova universitetscentrum, Roslagstullsbacken 21.

Abstract

Type Ia Supernovae (SNe) have been used to discover the accelerated expansion of the universe but many open questions remain unanswered. These include the stellar progenitor, extinction and possible systematic trends in the supernova brightness for different host galaxy environments or cosmic time. In this thesis we attempt to address these open questions by looking at a large homogeneous sample of nearby SNe from the Palomar Transient Factory (2009-2012) and the intermediate Palomar Transient Factory (2013-2017) for which we have 265 well-observed light-curves in the R-band and 2981 spectra from a total of 2060 SNe.

In Paper I we study the global properties of the R-band light-curves, such as rise-time, stretch and intrinsic brightness at different SN phases, to examine if there are multiple populations in any of the parameters suggesting different progenitor channels. We do not find evidence supporting this. We characterize the second maximum in the R-band in Paper II and find a correlation between the time from light-curve maximum, and the “colour-stretch” parameter, a proxy for $^{56}$Ni mass. We also found that the integrated flux under the second maximum, correlates with the transparency timescale, a proxy for total ejecta mass. Using these two relations we find that sub-Chandrasekhar double detonation models can account for the biggest fraction of the PTF/iPTF SNe light-curves properties. In Paper III we present the spectroscopic sample of PTF/iPTF and using automatic machine learning tools to explore spectral features and possible connection to photometric and host galaxy properties.

Paper IV focuses on a small sample of SNe, with multi-wavelength light-curves, to address one of the most important systematic uncertainties in supernova cosmology: extinction by dust in the line-of-sights. We found a diversity in the reddening laws as characterised by the total-to-selective extinction, $R_V$. Finally, Paper V looks at a strongly lensed SNIa at $z=1.4$ to see if there is evolution of its spectral and photometric properties over cosmic time. Both Paper IV and Paper V use the code developed for Paper III to analyse spectra.

Keywords: Type Ia supernovae, cosmology, machine learning.

Stockholm 2019
http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-167380

ISBN 978-91-7797-684-4
ISBN 978-91-7797-685-1

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Seméli Papadogiannakis
To the reader of this thesis, and the ones who helped me write it. You know who you are. I am most grateful.

Thank you.
Accompanying Papers

We include the following papers in the thesis, referred to by their Roman numerals in the text.

*R-band light-curve properties of Type Ia supernovae from the (intermediate) Palomar Transient Factory*  
MNRAS, 483, 5045P, 2019

II Papadogiannakis S., Dhawan S., Morosin R. and Goobar A.  
*Characterising the secondary maximum in the r-band for Type Ia Supernovae: Diagnostic for the ejecta mass*  
MNRAS, 485, 2343P, 2019

III Papadogiannakis S. et al.  
*Spectroscopic properties of type Ia Supernovae from the (intermediate) Palomar Transient Factory*  
In preparation

IV Amanullah, R...[3 authors], Papadogiannakis. S., ...[35 authors].  
*Diversity in extinction laws of Type Ia supernovae measured between 0.2 and Si2μm*  

V Petrushevskaya, T...[5 authors], Papadogiannakis. S.  
*Testing for redshift evolution of Type Ia supernovae using the strongly lensed PS1-10afx at z = 1.4*  
A&A, 603A.136P, 2018
Papers not included on the thesis

These papers are not included in the thesis but the author contributed to them during the time of the PhD. They will be cited as any other paper in the text.

VI Dhawan S...[6 authors], Papadogiannakis. S. 
_iPTF16abc and the population of Type Ia supernovae: Do early time peculiarities manifest at late epochs?_
MNRAS, 480, 1445D, 2018

VII Cao, Yi; Kulkarni, S. R.; Gal-Yam, Avishay; Papadogiannakis, S.; 
Nugent, P. E.; Masci, Frank J.; Bue, Brian D. 
_SN2002es-like Supernovae from Different Viewing Angles_

VIII Goobar, A;...[23 authors], Papadogiannakis. S., ...[9 authors]. 
iPTF16geu: A multiply imaged, gravitationally lensed type Ia supernova 
Science, 356,6335, 2016

IX Goobar A., ...[24 authors], Papadogiannakis S., ...[8 authors] 
_The Rise of SN 2014J in the Nearby Galaxy M82_
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PART II PAPERS

I R-band light-curve properties of Type Ia supernovae from the (intermediate) Palomar Transient Factory ................

II Characterising the secondary maximum in the r-band for Type Ia Supernovae: Diagnostic for the ejecta mass ........

III Spectroscopic properties of type Ia Supernovae from the (intermediate) Palomar Transient Factory ........

IV Diversity in extinction laws of Type Ia supernovae measured between 0.2 and 2μm ........................

V Testing for redshift evolution of Type Ia supernovae using the strongly lensed PS1-10afx at z = 1.4
Preface

This PhD thesis is a thesis consisting of two major parts: introductory chapters comprising a summary of the scientific results and the accompanying papers.

Chapters 1-4, 6 and 8 have been adapted from the licentiate thesis put forward in 2016 (unpublished) with some modifications and updates (to a varying degree depending on the Chapter).

In addition to the papers presented in this thesis I have contributed to a paper about host galaxy properties of the Palomar Transient Factory led by L. Hangard (in prep.), observed and reduced spectra from the P200, NOT and Keck telescopes (either remotely or on site), “scanned” and scheduled follow-up observations for promising transients (98 days), authored 63 Astronomical Telegrams, 18 of which first author, in the effort of looking for transients for the intermediate Palomar Transient Factory (iPTF). In addition I contributed to proposals for telescope time and white papers for the successor survey ZTF.

I also had the opportunity to visit Caltech for 6 weeks during 2015 to work on the photometric pipeline I use in Paper I.


**Contribution to papers**

**Paper I.** I led the analysis and wrote the paper. I was the PI of the proposal that provided the computer cluster time needed for the analysis.

**Paper II.** I jointly developed the idea for this paper, led the analysis and wrote the majority of the paper.

**Paper III.** I led the analysis and the write-up for this paper which is now in preparation. I developed a code, Spextractor to automatically extract spectral features using a model independent method, which previously has mainly been done by hand, to be able to analyse the spectra from the (intermediate) Palomar Transient Factory. I was the PI of the proposal that provided the computer cluster time needed for the analysis.

**Paper IV.** I contributed to the analysis by using the Spextractor code (my spectral analysis code) to calculate velocities and pseudo equivalent widths (shown in table 7 and figure 12 in the paper), and contributed to the writing of section 6.1 of the paper.

**Paper V.** I contributed to the analysis by using the Spextractor code (my spectral analysis code) to calculate velocities and pseudo equivalent widths for the high redshift supernova PS1-10afx, and wrote that section of the paper, section 2.1 and 2.2 including table 1.
Acknowledgments

First of all I want to thank my supervisors Ariel Goobar, Rahman Amanullah and Ulrich Feindt for your guidance and enthusiasm throughout this time. I have learned so much from you and this thesis would not have been possible without you.

I would also like to thank all members of the SNOVA group, past and present: Ana, Christian, Janina, Uli, Mattia, Markus, Tanja, Joel, Raphael, Raphael II, Laura, Toktam, Karl, Nader, Timothy for productive (and unproductive) discussions and help with code and other technical problems. It has been an honour working with you all.

I also am grateful for interesting discussions, fika and laughs I have shared with many of you from the OKC and COPS group which has taught me a lot about life and statistics. Thanks to everyone who played badminton with me, it was a great but a bit painful part of the PhD time experience. Special thanks to Serena and Emily who organised many great events over the years and taught me a lot about social interactions.

I would also like to thank my fellow FysikShow masters (Kess, Mikica, Emma, Jesper, Oleksii, Shreekanth, Jessica, Odd, Tor, Tanja, Daniel and David) and Hollywoodfysik masters (Calle, Thomas and Samuel) for all the fun shows we did together which made my PhD time so much more rewarding. I do apologise for driving into tunnels and ending up at the wrong side of Stockholm all too often.

Thanks also to David who has taught me to code and debug in Python and helped me with practical things when my body did not function within normal parameters. Most importantly for teaching me to \textit{Own the day!} which has been invaluable during the PhD time. I would in addition like to thank all my family and friends who believe in me and have been of great support and without whom I would not be here.

\footnote{Translated to: “Own the day!” from Klingon}
# Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN</td>
<td>Supernova</td>
</tr>
<tr>
<td>SNe</td>
<td>Supernovae</td>
</tr>
<tr>
<td>PTF</td>
<td>Palomar Transient Factory</td>
</tr>
<tr>
<td>iPTF</td>
<td>intermediate Palomar Transient Factory</td>
</tr>
<tr>
<td>ZTF</td>
<td>Zwicky Transient Facility</td>
</tr>
<tr>
<td>SD</td>
<td>Single-degenerate</td>
</tr>
<tr>
<td>DD</td>
<td>Double-degenerate</td>
</tr>
<tr>
<td>WD</td>
<td>White dwarf</td>
</tr>
<tr>
<td>SED</td>
<td>Spectal energy distribution</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>pEW</td>
<td>pseudo equivalent width</td>
</tr>
<tr>
<td>P48</td>
<td>Palomar 48-inch Oschin Schmidt Telescope</td>
</tr>
<tr>
<td>ISM</td>
<td>Inter-stellar medium</td>
</tr>
<tr>
<td>IS</td>
<td>Inter-stellar</td>
</tr>
<tr>
<td>CSM</td>
<td>Circum-stellar medium</td>
</tr>
<tr>
<td>CS</td>
<td>Circum-stellar</td>
</tr>
<tr>
<td>PSF</td>
<td>Point spread function</td>
</tr>
<tr>
<td>GP</td>
<td>Gaussian Processes</td>
</tr>
<tr>
<td>LSST</td>
<td>Large synaptic survey telescope</td>
</tr>
<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
</tr>
<tr>
<td>SLNS</td>
<td>Supernovae Legacy Survey</td>
</tr>
<tr>
<td>PanSTARRS1</td>
<td>Panoramic Survey Telescope &amp; Rapid Response System</td>
</tr>
</tbody>
</table>
Astronomical terminology

In this thesis a number of astronomy terms are used, some of which are explained here. What we measure from the supernovae (SNe) is the light that reaches us. There are two main ways of measuring the light coming from e.g.: SNe photometry and spectroscopy. Which of these two depends on the instrument mounted on the telescope. In this thesis the SNe from the Palomar Transient Factory (PTF) and intermediate Palomar Transient Factory (iPTF) found at the P48 telescope at Palomar Observatory are presented. Both photometry from the P48 telescope and a long list of telescopes following up the transients for spectroscopy as described in more detail in the main text is used.

Photometry

Photometry is the measure of the intensity of the electromagnetic radiation coming from the observed source, the flux over a range of wavelengths determined by the photometric band. Usually photometry is commonly measured in units of magnitude.

Photometric bands

We measure photometry in given wavelength bands, photometric filter bands. These bands are determined by the wavelength range and efficiency at the given wavelength range. The efficiency includes both transmission efficiency i.e. how much of the light gets through, the quantum efficiency of the instrument at those wavelengths and an average atmosphere correction.

For very nearby Core-collapse supernovae we can measure neutrinos as well as light, the only example of this is SN1987A.
Spectroscopy
As opposed to photometry in spectroscopy we measure a spectrum, i.e. the flux as a function of wavelength. It is much less efficient than photometry since the light has to go through a slit and the flux at each wavelength bin has to be measured. These bins are much smaller than the photometric bands and thus higher integration times are required for the same signal-to-noise.

Reduction
This is the process of calibrating the raw counts measured on the CCD (charged coupled device), the camera of the telescope, into flux measurements. Included in this calibration is the comparison with standard stars, the measurement of the total light of the source and the background, corrections for atmosphere and instrument used etc. This has to be done for both photometry and spectroscopy.

Redshift
As we will see later, the redshift of a source is a measure on how displaced the observed wavelengths are compared to ones at rest.

Transient
An astronomical transient is a source that appears and disappears within a given timescale in a non-periodic way. For the purpose of this thesis this timescale is from 1 day to a few months. The source behind the transient can be an asteroid, a flaring star, a variety of different types of SNe, tidal disruption events \(^3\) and many other phenomena.

---

\(^3\)Stars being tidally disrupted by a black hole.
Chapter 1

Introduction

In the late 1990’s, the high-z SN search [1] and The supernova cosmology project [2] discovered that the expansion of the universe was accelerating. They used type Ia supernovae, very bright explosions that can be standardised and used as cosmological distance estimators. Later, with larger surveys and data sets this has been confirmed (e.g. SDSS, [3], SNLS [4], Supernova cosmology project (SCP) survey [5], [6], PanSTARRS1 survey, [7]). These larger supernova surveys were in addition able to constraint a number of cosmological parameters, such as the dark energy equation of state and dark energy density (mentioned later in the thesis) with a precision of 5%. The most accurate measurements of the local expansion rate, $H_0$ are at the time of writing from [8], which mainly improves by increasing the sample of Cepheid stars (variable stars) in the same galaxies as type Ia supernovae and thus reducing the uncertainty to 2.4% with this better distance calibration.

In order to attain a more precise cosmology we need to understand the systematic uncertainties that currently dominate this measurement (e.g. [9], [6], [10]) and to answer a number of remaining open questions regarding the nature of Type Ia supernovae. Higher precision is needed to be able to differentiate between different cosmological models, and in particular to find if our universe deviates from the status quo, $\Lambda CDM$ model.

Despite the success of type Ia supernovae as cosmological probes we still do not know their progenitors. Finding the cause of the explosion, the progenitor of the supernova, would be of great astrophysical and cosmological interest.

The Palomar Transient Factory (PTF) and its successor the intermediate Palomar Transient Factory (iPTF) are two surveys dedicated to find, among other things, new and young supernovae. The telescope surveys parts of the sky several times per night, which enables us to build a light-curve of the objects we find, i.e. follow their brightness in time. This strategy means that two different time scales are probed simultaneously: a longer one over the years
Chapter 1. Introduction

the survey runs and a shorter intra-night time-scale. The large field of view of the PTF/iPTF, 7.26 deg², allows us to cover a large part of the sky, see figure (1.1).

![Figure 1.1: This graph shows all the images taken by the PTF and iPTF survey, the more images taken the more yellow the field as is indicated by the colour-bar to the left of the plot from 2009-2014.](image)

The large field of view also means that we discover many new supernovae, ∼ 10 every clear night. In this thesis the type Ia supernovae discovered in PTF and iPTF are presented, to look at the statistical properties of the light-curves and spectra. Due to the telescope’s relatively small size, 1.2 meters we find nearby (low redshift) supernovae which are well suited for studies of the astrophysical processes surrounding them, e.g. their progenitor and environment.

Outline of this thesis

In Chapter 2 a short introduction to cosmology and the relevant observables are presented and the reader is introduced to supernova cosmology and its current challenges and uncertainties. This chapter outlines the motivation to the thesis and provides a broad background to understand the results presented in subsequent chapters.

The thesis work is centred around the large sample of type Ia SNe provided by PTF and iPTF, the survey is presented in Chapter 3. In Chapter 4 and
Chapter 5 the global photometric properties and the SN physics that can be learned from the R-band are discussed. Chapter 6 presents a new method to analyse large number of spectra with different noise levels and resolutions and in Chapter 7 we discuss host galaxy properties of Type Ia SNe. A large focus of this work (especially true for the spectra) has been to automate methods and techniques in order to measure quantities in an unbiased and reproducible manner.

Finally, Chapter 8 discusses what it is possible to do with this type of instrument and survey strategy in terms of SNe Ia cosmology, paving way for future surveys and a research outlook.
Chapter 2
Cosmology with Supernovae

Cosmology provides us with many different possible descriptions of the universe and using various methods, some of which will be outlined in this thesis, we have tried to determine which of the realisations we live in. We will assume that the universe is homogeneous and isotropic in the following calculations, bearing in mind that observations might prove these assumptions insufficient. This assumption is referred to as the cosmological principle, and holds true on larger scales encompassing at least a few galaxy clusters\(^1\).

For a more thorough treatment of cosmology see any of the books in this subject (e.g. [11–14]). Here we mention the most relevant for our subsequent work and state equations and their implications without derivation with the aim to show how measuring distances can give us insight into the cosmological parameters that describe our universe.

2.1 Observables

From Einstein’s gravitational field equation (for full derivation see e.g. [15], [16] and [17]),

\[
G_{\mu\nu} = R_{\mu\nu} - \frac{g_{\mu\nu}R}{2} - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}
\]  

(2.1)

where \(\Lambda\) is the cosmological constant, \(R_{\mu\nu}\) the Riemann tensor, \(T_{\mu\nu}\) the energy tensor and \(g_{\mu\nu}\) measures how a line element behaves under curvature.

Starting with the Friedmann-Lemaître-Robertson-Walker metric,

\[
\text{cd}r^2 = \text{cd}t^2 - R^2(t) \left(\text{dr}^2 + S_k^2(r) d\psi^2\right)
\]  

(2.2)

\(^1\)It should be noted that at the very local universe homogeneity and isotropy does not hold.

Seméli Papadogiannakis, Properties of Type Ia Supernovae from the (intermediate) Palomar Transient Factory, SU 2019
we can derive important relations between observables and cosmological parameters. Here \( d\psi \) is the angular distance between two points on the sky, \( d\tau \) is the proper time, \( r \) is the co-moving distance and \( R \) is the curvature radius. \( S_k(r) \) is defined in equation (2.3) where \( k \) is the spatial curvature, defined to be zero for a flat universe and +1, −1 for a positive respectively negative curvature.

\[
S_k(r) = \begin{cases} 
\sin r & k = +1 \\
\sinh r & k = -1 \\
r & k = 0
\end{cases}
\]

(2.3)

For light propagation we can write and integrate,

\[
r = \int \frac{cdt}{R(t)} \Rightarrow \frac{dt_{\text{emit}}}{dt_{\text{obs}}} = \frac{R(t_{\text{emit}})}{R(t_{\text{obs}})} = \frac{\nu_{\text{obs}}}{\nu_{\text{emit}}}. \]

(2.4)

Now using the definition of redshift, \( z \), below and equation (2.4) we get,

\[
z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = \frac{R(t_{\text{obs}})}{R(t_{\text{emit}})},
\]

(2.5)

which tells us that observing shifts in spectra can give us access to the time at which this light was emitted, a very important result for observational cosmology. The subscripts \( \text{obs} \) and \( \text{emit} \) in equations (2.4) and (2.5) indicate the observed and emitted quantity. Wavelength, \( \lambda \) or frequency, \( \nu \) are the observables and \( c \) is the speed of light. This shift can at small distances be approximated by a radial velocity and thus compared to a relativistic Doppler shift.

Further from the Friedmann equation below,

\[
\dot{R}^2 - \frac{8\pi G \mathcal{G} R^2}{3} = -k c^2
\]

(2.6)

where \( G \) is the gravitational constant, we can get an equation useful for observables. The density, \( \mathcal{G} \) in equation (2.6), contains all contributions including matter, radiation and vacuum. We can now rewrite the Friedmann equation in terms of observables. \( H(t) \) is the so-called Hubble parameter, denoting the expansion rate of the universe at a given time.

\[
H(t)^2 \equiv \frac{\ddot{R}}{R} = \frac{4\pi G}{3} \left( \rho + \frac{3p}{c^2} \right) + \frac{\Lambda c^2}{3}
\]

(2.7)

We need to define a parameter \( w \), called the equation of state parameter,

\[
w \equiv \frac{p}{\rho c^2}
\]

(2.8)
where $p$ is the pressure and $\rho$ the density.

If we now also assume a flat universe ($k = 0$), and the total energy density to be a sum of the energy density of matter, radiation and vacuum energy (or dark energy), $\Omega_{Tot} = \Omega_M + \Omega_\Lambda + \Omega_r$ we get:

$$R_0 dr = \frac{c}{H_0} \left( (1 - \Omega_{Tot})(1 + z)^2 + \Omega_\Lambda + \Omega_M(1 + z)^3 + \Omega_r(1 + z)^4 \right)^{-\frac{1}{2}}$$  \hspace{1cm} (2.9)

The components of the energy density are the cosmological constant (or vacuum energy) ($\Omega_\Lambda$), matter ($\Omega_M$) and radiation ($\Omega_r$), and $H_0$ is defined to be $H(t = 0)$. There are several observational probes for measuring these observables including studying the cosmic microwave background, gravitational lensing of galaxies and type Ia supernovae. In this thesis we focus on the later.

In order to measure the Hubble-Lemaître parameter, $H_0$ with supernovae (see section 2.4) we will need the relation between redshift and distance. Rewriting equation (2.4) in terms of $H(z)$ where

$$\frac{dz}{dt} = -\frac{R_0}{R} \frac{dR}{dt} = -(1 + z)H(z)$$  \hspace{1cm} (2.10)

we get

$$R_0 r = \int \frac{c}{H(z)} dz.$$  \hspace{1cm} (2.11)

Another useful quantity is the luminosity distance, $D_L$ which is defined to be:

$$D_L(z) \equiv (1 + z)c \int_0^z \frac{dz'}{H(z')}$$  \hspace{1cm} (2.12)

### 2.2 Measurements of brightness in astronomy

Due to historical reasons astronomers preferentially measure brightnesses in magnitudes, $m$, defined to be

$$m \equiv -2.5 \log_{10} \left( \frac{F}{F_0} \right)$$  \hspace{1cm} (2.13)

where $F$ and $F_0$ are the observed and reference flux. Luminosity, $L_\nu$, describes how bright something is at a certain frequency, $\nu$,

$$L_\nu = 4\pi r^2 F_\nu$$  \hspace{1cm} (2.14)

at a given distance $r$ and Flux, $F_\nu$ at a certain wavelength $\nu$. In practice astronomers use wavelength bands from which they calculate magnitudes, see

\footnote{Hereafter we assume $k = 0$.}
figure (2.1) for an example. In addition the light coming from e.g. a supernova is seen through our own galaxy, its host galaxy and the material between these two galaxies. This material, including cosmic dust, dims the light and is explained in section (2.3).

Figure 2.1: The wavelength range and transmission of the 3 bands used in the PTF/iPTF survey; g, R and H-alpha (see section (3.1)) and the Bessell B and V filter wavelengths in dashed and dotted lines. The grey band is a spectrum of normal type Ia supernova from our sample.
2.3 Extinction and reddening

Extinction, \( A(\lambda) \) is defined to be the dimming of light due to dust absorption or scattering at a certain wavelength, \( \lambda \); and is defined as:

\[
A(\lambda) = -2.5 \log \left( \frac{F_{\text{obs}}(\lambda)}{F_{\text{intrinsic}}(\lambda)} \right)
\]  

(2.15)

where \( F_{\text{obs}} \) and \( F_{\text{intrinsic}} \) are the observed and intrinsic (to the source and dust free) fluxes. We can thus write \( F_{\text{obs}} \) as,

\[
F_{\text{obs}} = F_{\text{intrinsic}} 10^{-0.4A(\lambda)}
\]  

(2.16)

by rewriting equation (2.15). We can also look at the colour excess \( E(B-V) \),

\[
E(B-V) \equiv (B-V)_{\text{observed}} - (B-V)_{\text{intrinsic}} = A_B - A_V
\]  

(2.17)

where the subscripts \( V \) and \( B \) refer to two different photometric wavelength bands, \( B \) and \( V \) shown in figure (2.1). It is also useful to define the total-to-selective extinction parameter, \( R_V \),

\[
R_V = \frac{A_B - A_V}{A_V} = \frac{E(B-V)}{A_V}
\]  

(2.18)

which is often used when comparing different supernovae. If we want the extinction \( A_X \) for another wavelength band, \( X \), we can use this equation:

\[
A_X = A_V \frac{\lambda_B}{\lambda_X} \left( \frac{\lambda_V - \lambda_X}{\lambda_V - \lambda_B} \right) + A_V\]

(2.19)

To compare objects at different distances astronomers use absolute magnitudes. The absolute magnitude, \( M_\lambda \) is defined to be the brightness in magnitudes an object would have at 10 parsec distance\(^3\) from us and shown in equation (2.20) as a function of the observed magnitude \( m_\lambda \) and the luminosity distance defined in equation (2.12).

\[
M_\lambda = m_\lambda - 5 \log_{10}(D_L) - 5 + A(\lambda) + K_\lambda
\]  

(2.20)

\( K_\lambda \) is a K-correction, i.e. a correction for the changing observed spectral energy distribution at different redshifts and times of the light-curve. Note that \( A(\lambda) \) includes the extinction both due to the host galaxy, our own galaxy, the intergalactic medium and around the supernova itself. When doing SN

---

\(^3\)1 parsec \( \approx \) 3.26 light-years.
cosmology one measures $m_\lambda$, tries to estimate $A(\lambda)$ and $K_\lambda$ using multi-band photometry and spectral templates and then fit for $M_\lambda$ and $D_L$. As we will see later in this thesis measuring the extinction is an important systematic uncertainty which affects the measurement of brightness of e.g. supernovae and is therefore important to study.

### 2.4 Type Ia supernovae

There are a number of ways to measure cosmological distances, all of which require some signal (electromagnetic, gravitational or from particles such as neutrinos) that can propagate through vast distances in space. If we want to trace a source emitting electromagnetic radiation at a large distance from us, it has to be coming from an energetic event. In addition we need to know its intrinsic brightness to be able to infer its distance according to the luminosity-distance relation, see equation (2.12).

**Figure 2.2:** Author’s artist impression of two different type Ia progenitor scenarios, the single degenerate to the left and the double degenerate to the right.

An example of such an object is the type Ia supernova. They are believed to be thermonuclear explosions of white dwarfs$^4$ due to a binary companion interaction. The exact mechanism is yet unknown but the two main scenarios that are currently considered in the literature is either a white dwarf colliding with another white dwarf (double degenerate scenario) and a white dwarf accumulating mass from a giant companion that has filled its Roche lobe (single degenerate), as shown in figure (2.2).

$^4$White dwarfs are the remnant of a low mass star after it has exhausted its hydrogen and helium in the core, leaving a carbon oxygen object held up by electron degeneracy pressure. See [18] for a book on stellar evolution.
These are referred to as the double-degenerate (DD) and single degenerate (SD) scenario in the literature. See [19] for a review.

### 2.4.1 Hubble-Lemaître diagram

Using the redshift-distance equation (2.11), one can plot a Hubble-Lemaître diagram with the absolute magnitude, $M_\lambda$ in some wavelength, $\lambda$ (or range of wavelengths) against redshift.

![Hubble-Lemaître diagram](image)

**Figure 2.3:** The Hubble-Lemaître diagram as compiled by [20] and the residuals, here the distance modulus ($M_\lambda - m_\lambda$ from equation (2.20)) is plotted against redshift. Note that this is a compilation of a large number of studies.

The magnitude at maximum light is used for this purpose and is deter-
mined by following the supernova in time, i.e. building a light-curve. It is then plotted, as shown in figure (2.3) as a function of redshift. In the lower part of the plot the residuals to the model are shown. Their size give an indication of how good type Ia SNe are as standardizable candles for cosmology. Small residuals enable different cosmological models to be distinguished. This method was used to discover the accelerated expansion of the universe by [2] and [1].

2.5 Measurement uncertainties

Some of the systematic and statistical uncertainties in using SNe Ia as distance measurements are briefly outlined below. For $z < 0.1$ the SNe used come from a variety of surveys thus creating an inhomogeneous and hard to calibrate sample. This low-redshift part of the Hubble-Lemaître diagram needs to be updated since it is very important for the relative distances calculated and to quantify the inter-galactic-medium (IGM) contribution to extinction [21]. Throughout this thesis and in the papers included we attempted to address a number of these, which are also explained in more detail in subsequent chapters. Understanding and characterising these is central to achieve the precision required to be able to distinguish between different theoretical models from SNe observations.

2.5.1 Dust extinction

In the equation (2.20) we showed that dust dims the apparent brightness of the supernova. There is dust in the inter-stellar medium (ISM) in the host galaxy of the SN, dust in our own galaxy and possibly around the supernova itself (called circum-stellar medium dust, CSM). Fully understanding the dimming of light by dust by both the ISM and CSM, which affects different wavelengths in different amounts, would reduce an important systematic uncertainty in the use of SNe Ia as distance estimators. Discussed in Paper I and IV.

2.5.2 K-corrections

When observing supernovae from different redshifts in a certain wavelength band, as often is the case in astronomy, different parts of the spectral energy distribution (SED) are sampled. This introduces an uncertainty since an SED has to be assumed to correct for this. K-corrections are especially a problem for the type Ia’s that have a significantly different SED from the template used to make this correction. A further complication is that the redshift might be poorly defined which introduces a significant uncertainty in the K-correcting
factor. Note that this affects a small amount of supernovae in our survey and whenever possible a spectrum of the host galaxy or the supernova (with host galaxy lines) is used to determine the redshift. Discussed in Paper I.

2.5.3 Malmquist bias

Malmquist bias, first discussed in [22], is introduced when a survey is magnitude limited. Thus at a certain redshift, only the brightest portion of the true distribution of luminosities of SNe Ia are sampled and the mean of the measured distribution becomes biased. Discussed in Paper I.

2.5.4 Redshift determination uncertainty

Any statistical or systematic uncertainty in the redshift measurement will impact the estimated distance. These uncertainties can arise from a number of different reasons. If the redshift is taken from a spectrum this can be noisy which makes the redshift difficult to determine. This uncertainty can also arise from getting the redshift, not from the spectrum of the supernova but from its host galaxy. Especially since correct identification of the host galaxy can sometimes be difficult. Discussed in Paper I and III.

2.5.5 Host galaxy properties

The host galaxy environment has been shown in the literature to be correlated with the colour-corrected magnitude at peak in the bluer optical wavelength bands. While we in this thesis find this not to be the case in the redder bands, the origin of this correlation is not well understood and could be biasing our derived magnitudes at peak. Discussed in Paper I.

2.5.6 Brightness evolution with redshift

There could be an evolution with redshift such that the observed properties of type Ia SN are different at high redshifts compared to lower ones. This effect could be due to differences in the environment of the SN, such as metallicity and star formation of the host galaxy or something (e.g. dust) between us and the host galaxy that does not have a wavelength dependence. If such an evolution is found it would bias our results and could mimic the accelerated expansion of the universe. Discussed in Paper I and V.

5Spectra can be noisy for a variety of reasons generally attributed to poor observing conditions.
2.5.7 Calibration

The calibration of the images and spectra received from the telescope introduce uncertainties. These include insufficient correction for imperfection of the telescope’s charged coupled device (CCD), electronics and optics, the atmosphere, light-pollution and method chosen for extracting the brightness of the source. Discussed in Paper I.

2.5.8 Progenitor system

As mentioned earlier the progenitor of type Ia supernovae remains unknown and an open question in this field. Studying the spectra of SNe Ia could give us clues about the progenitor (as done in Paper III), as well as studying the light-curve long before the explosion to look for signs of interaction between the white dwarf and a giant companion (as in Paper I). If there is an evolution with redshift, as mentioned earlier, knowing the progenitor would be important. Discussed in Paper I, II, III, IV and V, this uncertainty is of great interest both for understanding the underlying physics but also to be able to use type Ia SNe as more precise cosmological tools.
Chapter 3

The PTF and iPTF survey

3.1 Overview

The intermediate Palomar Transient Factory (iPTF) was the successor survey of the Palomar Transient Factory (PTF) and its main goal was to survey the sky and discover new transients. A transient is any object appearing on the sky for a limited amount of time, for example asteroids, novae, supernovae, flaring stars and active galactic nuclei. The survey is performed by the 48-inch (1.2 meters) Oschin Schmidt Telescope (P48) at Palomar mountain, California, U.S.A. with a field of view of 7.26 deg². The survey has been conducted most of the time in the R-band (wavelength range 5800 Å-7300 Å) but also in g-band (wavelength range 3900 Å-5600 Å) and narrow H-α bands during 5 days closest to the full moon. This was chosen as a compromise between the multiple science cases in the collaboration and because the signal-to-noise ratio (SNR) is lower around the full moon due the increased ambient light.

3.2 Survey strategy

PTF and iPTF performed an untargeted search by imaging the sky 1-5 times per night and then comparing them to reference images in order to discover new transients. The same spot was then typically visited again after 1-5 days. The reference images were taken in 2009 and 2012 for PTF and iPTF respectively. In Figure 3.1 we show the cadences for both intra-night and between nights for the observations in Paper I. This is a much denser cadence than the average transient in the survey since the sample was selected for good data quality. An untargeted survey search means that no particular part of the sky was surveyed minimising the bias associated with targeted searches, i.e. finding transients only in well-resolved host galaxies. In addition, since we use data only from
Chapter 3. The PTF and iPTF survey

Figure 3.1: Showing the cadence from the observations of the SNe used in paper I. The most common intra-night cadence is 43 and 63 minutes shown in the lower panel while the most common inter-night cadence was 1 day, shown in the upper panel. The upper panel is a zoomed in version for the cadences up to 31 days.

this telescope and photometric band other systematic effects are minimised.\footnote{Note that iPTF was not completely blind as it followed a Census of the Local Universe catalogue of galaxies within 200 Mpc (Cook et al. in prep) for 8 months during the spring and autumn of 2013.}

After running through an image-subtraction pipeline the images from the survey telescope (P48) are analysed using a machine learning algorithm [23] trained in early data from PTF. This sets a score on the likelihood that each candidate is a real transient, which is used to discard the many false candidates that are found with the pipeline. For the PTF collaboration this was done in a combination of 'Supernova zoo participants' [24] and an effort of the consortium where the top candidates were screened by humans. For the iPTF
3.2 Survey strategy

Data the top candidates were selected solely by people from the consortium. In Figure 3.2 we show an example discovery image of a supernova. This survey strategy and quick follow-up enables discoveries of transients close to the last non-detection limits which has been the focus of a number of single papers from the collaboration. In this work however we make use of the large number of SNe Ia that have been discovered by (i)PTF to look at statistical properties of their light-curves and spectra. In Figure 3.3 we show the spacial distribution on the sky of the data sample used in this thesis.

Due to weather constraints a larger portion of well-sampled supernovae are from the spring/summer half of the year. The gap in data on the northern hemisphere in Figure 3.3 is from the galactic plane which obscures extragalactic supernovae. The area around the galactic plane is also very crowded, i.e. filled with many stars, and thus harder to perform accurate image subtractions to find transients.

**Figure 3.2:** An example candidate supernova as displayed in the iPTF marshal. The images shown are, from left to right: the new image, the reference, the subtraction and the SDSS RGB image respectively.
Figure 3.3: Ra and dec distribution of the 265 type Ia SNe from the PTF and iPTF survey used in Paper I and II. The grey points show the remainder of the SNe type Ia used in Paper III. We can see fewer points in the left side of the plot due to worse weather conditions in the winter months, the semi-circular gap shows the galactic plane. The Figure is adapted from paper I.
Chapter 4

The R-band light-curve: global properties

In Paper I we discuss the general properties of the R-band light-curves from the sample from PTF and iPTF. In this chapter we will first highlight why PTF and iPTF are particularly well suited for this type of study and then discuss the findings from Paper I and highlight the most important results.

4.1 PTF and iPTF - a unique dataset

(i)PTF was an untargeted survey, meaning that the sky was sampled homogeneously without preference to image galaxies, i.e. avoiding sampling bias. This is a significant advantage since the state-of-the-art cosmological studies with type Ia SNe [20], are currently held back by the limitations in modelling the low redshift SNe. This is mainly due to the fact that low redshift datasets used to date come from many different surveys and telescopes with a variety of discovery and follow-up strategies making calibration and bias containment difficult.

By using the surveying strategy of PTF and iPTF it is possible to get distributions of both light-curve (described in this Chapter) and spectral parameters (see Chapter 6) that are minimally biased with respect to host environment, since SNe in low mass galaxies are not found in targeted surveys. PTF and iPTF also presents the largest spectroscopically confirmed type Ia SN sample from a single telescope and survey. This allows us to look at statistical properties and trends and study the global properties of type Ia SNe, from the light-curve described in this Chapter to the spectra in Chapter 6 and the host galaxy environments in Chapter 7. We can unfortunately not use this sample for cosmology due to the survey strategy employed, of predominantly
observing one wavelength band at a time, but we instead focus on the global statistical properties of the R-band light-curve.

To explore the global properties of the R-band light-curve we select the best sampled 265 type Ia SNe and look at their global properties. We use a non-parametric method, Gaussian Processes (GP) to smoothly model the shape of the light-curve and look at how the scatter changes with epoch. We search to see if there is evidence for multiple populations in the light-curve parameters to indicated different progenitors, we quantify the average extinction and Malmquist bias for our sample and look for pre- and post-explosion flares.

4.2 Gaussian Processes template

4.2.1 Introducing Gaussian Processes

We use Gaussian processes (GP), with the python package [25], to study the light-curve template in the Mould R-band [26] and the light-curves in general as well as study the spectroscopic features, see Chapter 6. The method will be outlined briefly below, for a more thorough review see [27]. This method has been used in statistics, economics and bioinformatics but has not been used extensively in light-curve analysis of supernovae, possibly due to only recently developed accessible tools to perform GP. This however is changing with a number of recent papers (e.g. [28], [29] etc.) using Gaussian processes for supernova (and astronomy in general) research. The advantages of using GP include being able to automatically detect the noise level in a dataset, construct a full Bayesian model of the noise which allows confidence intervals of the latent function and being able to deal with gaps in the data. The latter being a frequent problem in astronomy.

Gaussian processes is a machine learning algorithm for non-parametric regression, i.e. it allows reconstruction of a function without assuming parametrisation or functional form. The aim is to find the latent function \( f(t) \) that maximises the likelihood of producing the observed data under the assumption of independent Gaussian noise. Gaussian Processes approximates the latent function (or true function) as

\[
GP(m(t), k(t, t')) \approx f(t),
\]

(4.1)
given the expected mean, \( m(t) \), and a covariance function or kernel, \( k(t, t') \), defined to be:

\[
m(t) = \mathbb{E}[f(t)] \tag{4.2}
\]

\[
k(t, t') = \mathbb{E}[(f(t) - m(t))(f(t') - m(t'))] \tag{4.3}
\]
where $E$ denotes the expectation value.

A kernel, $k$, is defined as the distance between two functions $f$ and $g$ and is measuring how similar the 2 points are:

$$d(f, g) = \langle f | k | g \rangle = \int f(t)k(t, t')g(t')dt dt'.$$  \hfill (4.4)

It is possible to choose from a wide variety of different kernels or use a linear combination of these which is what we do in Paper I and II. We also use heteroscedastic GP since the simplest formulation of GP assumes that every data point has an equal Gaussian noise, the magnitude of which is derived from the data itself. Heteroscedastic GP uses the errorbar from each datapoint.

In Papers III, IV and V we use the simpler version of GP assuming a Gaussian noise due to the computationally expensive nature of GP which scales in time as $O(N^3)$ and because the error of the individual data point at many times were unknown. For the GP template described in 4.2.2 we do however find that it is important to incorporate the individual error of each data-point meaning that we needed to run our code on a computer cluster using up 2TB of RAM. The large RAM usage is due to the step of inverting a large square matrix $11960 \times 11960$ in our case, since the size is proportional to the number of data points.

**4.2.2 GP template**

To look at how the light-curve behaves in different epochs we constructed a Gaussian Processes template of the best sampled light-curves from -20 to +75 days with respect to peak. Before this was done the light-curves have passed quality cuts, were K-corrected using equation 2 from [30] and the Hsiao templates [31], stretch corrected and corrected for galactic extinction and aligned (more details in Paper I). Stretch is a measure of the light-curve width. The finished template is shown in Figure 4.1.

This method allows us to study and characterize the intrinsic scatter of the type Ia light-curve changes over a wide epoch range and provide a model-independent template of the shape of the R-band light-curve for type Ia SNe, see section 4.3. We find the scatter to be quite homogeneous over epoch and be $\sigma_R = 0.186 \pm 0.033$ mag for the redshift range $0.05 < z < 0.1$ without the correction of colour for individual SNe. This correction which is an important systematic uncertainty in SN cosmology cannot be accounted for due to the data being observed in a single band.
Figure 4.1: The Gaussian Processes template of the 265 best sampled type Ia SNe in the PTF and iPTF sample. This plot comes from paper I. The upper panel show the flux vs. time in days with respect to maximum light (epoch) and the lower panel shows the residuals to the GP template.

4.3 Searching for multiple populations

Using our template we can search for multiple populations in the scatter around the template as well as in stretch, a measure of the width of the light-curve. If multiple populations were to be found it could point to diversity in the SNe physics, suggesting different progenitors or explosion mechanisms that create variations in the shape of the light-curve.

We start looking for multiple populations in the scatter around the GP template for a variety of epochs, by dividing the data into bins of 9 days\(^1\). We then fit the distribution of each bin using Gaussians Mixture models, GMM in order to see if one or several Gaussians best describe the observed distribution. To determine how many Gaussians best describe the distribution without over-fitting we use the Bayesian information criteria (BIC) from [32]:

\[
BIC \equiv -2 \ln \mathcal{L} + k \ln N
\]  

\(^1\)The particular choice of binning had no effect on the results.
4.3 Searching for multiple populations

**Figure 4.2:** The left panel shows the combined Gaussian mixture model (GMM) in a solid line and two components in dashed lines, together with the histogram of the stretch distribution. The right panel shows the information criteria (IC): AIC and BIC for different number of Gaussian components. The Gaussian Mixture model fit of the stretch distribution, where we see that both BIC, in the solid line, and AIC, in dashed line, favours two components over one with a $\Delta BIC = 2$. This plot is adapted from Paper I.

Where $\mathcal{L}$ is the maximum likelihood, $k$ the number of parameters in the model and $N$ the number of data points in the fit. We choose BIC because it tends to favour models with fewer parameters than the Akaike information criteria (AIC) [33], this way we err on the side of caution. We pick the best model by looking at the lowest value of BIC and we consider that a particular model is statistically significantly better than another if $\Delta BIC > 6$, [34]. In addition we require a $3\sigma$ difference in the mean of the distributions.

In the case of the scatter around the template we find that all but one bin is best fitted with one Gaussian. The exception is the bin around the secondary maximum of the light-curve at epochs 25-34 days with respect to peak, where we find that 3 Gaussians better fit the data. This range is further discussed in Chapter 5.

We used the GMM method to search for multiple populations in the light-curve stretch distribution. We show the fit of the stretch distribution in Figure 4.2 where we see that 2 Gaussians fit better than one. However $\Delta BIC = 2$, so this is not statistically significant evidence for multiple populations. In the literature there are several examples of both asymmetry and populations in
stretch and colour, e.g. [35–41].

4.4 The Hubble-Lemaître diagram

Using the template as described in section 4.2.2 we get the time of maximum length in the R-band for our sample with a typical accuracy of $\sim 1$ day. We then calculate the maximum magnitude using equation 2.20, using weighted means (we used here the typical error in our sample of the redshift of 0.005). The magnitude at maximum light is then plotted against redshift in a so-called Hubble-Lemaître diagram, shown in Figure 4.3. The data points are scaled in size by the log of how many data points are in their light-curves. The errors in redshift are, as mentioned in Chapter 6, 50% and determined in a variety of methods. The uncertainty in the apparent magnitude at maximum is found by Monte Carlo simulations. The solid line shows the concordance $\Lambda$CDM model and in the lower panel of Figure 4.3 we show the residuals from this model.

The root-mean-square of the Hubble-Lemaître residuals is 0.35 mag for all redshifts after stretch corrections. Since there is considerable extinction making the distribution asymmetrical, see section 4.5, a large portion of the rms is driven by the fainter tail. We find the average absolute magnitude to be $M_R = -19.02 \pm 0.02 + 5 \log(H_0[km \cdot s^{-1}Mpc^{-1}]/70)$.

4.5 Malmquist bias

In order to determine where the Malmquist bias is significant we first need to estimate the underlying distribution of Hubble-Lemaître residuals. This number is important when planning for future surveys, such as ZTF (see section 8.3) to know which transients to devote valuable follow-up telescope time to. In this case we used the information from Paper I to plan the survey strategy of ZTF.

We adapt a function; the convolution of two functions, an exponential and a Gaussian, in the form presented in [42]. This function, seen in equation 4.6, was originally used [42] to fit $(B - V)_{Bmax} - (B - V)_{Bmax,0}$ or $E(B - V)$. Since we do not have multi-band data we cannot measure the same quantities. If we assume the cosmological parameters are known, and set them to $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$, we know the expected brightness of the supernovae. We saw in equation 2.17 that colour excess, $E(B - V)$ is directly related to $A_V$ and that this quantity in turn is related to $A_R$ (see equation 2.3 where X is replaced with R).
Figure 4.3: The Hubble-Lemaître diagram and residuals for the PTF and iPTF best 265 type Ia SNe. The Malmquist bias, at $z=0.13$ is marked with a dashed line. The colours and size of each data-point reflect how many light-curve points each SN had. This plot was adapted from Paper I.
Figure 4.4: The median of the Hubble-Lemaître residuals in each redshift bin is plotted, the error-bars show the standard estimated error. At low redshifts the peculiar velocities drive the median of the Hubble-Lemaître residuals to higher values. Due to low number statistics the first bin is larger than the rest. At the redshift bin of \( z=0.13 \) we see that the Malmquist bias exceeds 3\( \sigma \).
While $c$, $\sigma_c$, and $\tau$ in equation 4.6 stand for the $(B - V)_{B_{\text{max}}}$, the width of the fitted Gaussian and the colour excess from extinction in [42]; we use instead the observed Hubble-Lemaître residuals and its faint tail (from extinction) for $c$ and $\tau$. We fit equation 4.6 to the histogram of Hubble-Lemaître residuals between the redshifts $z = 0.05 - 0.1$ since the sample is most complete at those redshifts. In Figure 4.4 we show the median of the Hubble-Lemaître residuals at different redshift bins. We used this to plan the subsequent survey ZTF (see Chapter 8).

### 4.6 Average extinction

Calculating the extinction for each individual SN requires multiband photometry, something the PTF and iPTF survey lacks. However we can still find the average extinction by studying the Hubble-Lemaître residual distribution and comparing it to simulations. We use the SuperNova Observation Calculator, $SNOC$, described in [43], to create simulated supernova samples with different amounts of extinction. We use the code to generate samples of 2000 type Ia SNe using the same redshift distribution we have from our iPTF and PTF sample.

For each iteration we change two parameters: the intrinsic scatter (characterised by the width of the Gaussian part in fitting equation 4.6) and the mean free path for host galaxy dust extinction. We allow the values to vary from $0.1 - 0.30$ mag and $1 \times 10^{-3} - 1 \times 10^{-2}$ Mpc for intrinsic scatter and host dust extinction respectively. We then compare the Hubble-Lemaître residual distribution from each $SNOC$ iteration with our own sample distribution using a double-sided Kolmogorov-Smirnov test. We determine the average extinction of the sample by finding the minimum of the mean free path, and find it to be at 1 kpc$^2$ corresponding to a mean $E(B - V)$ of $\approx 0.05(2)$ magnitude $^3$ or an $A_R \approx 0.11$ magnitude, assuming $R_V = 3.1$.

$^1$1 kpc is approximately 1/8th the distance from us the Galactic centre.

$^3$The number in parenthesis denotes one standard deviation from the mean.
4.7 Pre- and post- explosion limits

Taking advantage of the long duration of the (i)PTF survey we search for pre- and post-explosion flares around the light-curves, using data from $-2500 < t < 2000$ days around peak. Similar searches have been done for type IIn SNe [44] also from PTF. We look at the history of all SNe light-curves excluding the points between $-30 < t < +200$ days and find no significant perturbations pre- or post- explosion. We require 3 consecutive detections since artefacts in the photometry such as CCD ghosts, variable cloud coverage, unknown asteroids and photometric noise can cause singular points with SNR > 5. Such flares are not expected for type Ia SNe and with our depth of 21.5 magnitudes we are only able to detect flares as bright as the brightest novae. The deepest limits come from the most nearby SN, iPTF14jj also known as SN2014J with a redshift $z = 0.000677$, and suggests that these type of searches are best made either with nearby SNe or deeper surveys.
Chapter 5

Physics of the r-band light-curve

Figure 5.1 shows an example of SN light-curve in different photometric bands. As described in chapter 3 the PTF and iPTF survey mainly observed in the Mould R-band [45] which is what we focus on here.

![Figure 5.1: Adapted from [19] this Figure shows typical SN Ia light-curves in different bands. Note that the r band shown here is not the same as the one used for the PTF and iPTF sample.](image)

In this chapter we discuss the properties of the r-band light-curve that are linked to the SN physics. This is the main theme of paper II in which we explored the secondary maximum in the r-band and is discussed in section 5.1. In section 5.2 we discuss how the rise-time of type Ia SNe are linked with the progenitor channel, which was presented in paper I. It is important to note...
that the Mould R-band and the more commonly used r-band are not covering the exact same wavelengths and are therefore denoted differently. This is not important in the work from Paper I where only photometry from PTF and iPTF are considered, but becomes important in the work from Paper II where we also used data from other surveys.

The origin of the r-band secondary maximum is not known but has been theorised to be due to the same mechanism as the secondary maximum in the redder bands, see Figure 5.1, such as the i-band [46].

5.1 The secondary maximum in r-band

In Figure 5.1 we see example light-curves of type Ia SNe at different wavelength bands, and the morphology post maximum changes as you go to longer wavelengths starting with the r-band from one to two maxima. This secondary maximum is believed to be due to the ionisation transition of the Fe-group elements from singly to doubly ionised [47,48]. While many papers have studied the secondary maximum in near IR bands, there is a lack of observational studies of this in the r-band as discussed in e.g. [46]. In paper II we attempt to characterise the properties of the secondary maximum in the r-band and to study how this correlates with properties such as the total $^{56}$Ni mass, the total ejecta mass, $M_{ej}$ and the transparency timescale, $t_{\text{transparency}}$ all of which are linked to the physics of the type Ia SN explosion. We also noted in paper I that the dispersion around the secondary maximum of the R-band light-curve was larger than other epochs when studying the dispersion around the GP template.

In Paper II we use the datasets from the Carnegie Supernova Project (CSP-I) [49,50] and F. L. Whipple Observatory of the Harvard-Smithsonian Center for Astrophysics supernova program [51] (CfA) to derive relations relating the properties of the secondary maximum in the r-band and then apply the results to the PTF and iPTF sample, which is a much larger dataset.

5.1.1 Determining $t_{r_2}$ and $\mathcal{F}_{r_2}$

Two parameters are measured in Paper II in order to observationally characterise the secondary maximum in the r-band, the time of the secondary maximum, $t_{r_2}$ and the area underneath it, $\mathcal{F}_{r_2}$ as shown in Figure 5.2. We first fit a GP template on each light-curve that has at least 4 data-points between +10 to +40 days with respect to peak and then differentiate the latent function, $l$, to get the gradient, $\frac{dl}{dt}$ shown in the lower panel of Figure 5.2.
Figure 5.2: This is an example of the fit of $t_{r_2}$ and $\mathcal{F}_{r_2}$ from paper II. The time of the secondary maximum, $t_{r_2}$, is determined by the derivative shown in the lower panel and the integrated flux, $\mathcal{F}_{r_2}$, is the shaded region between days $+13$ and $+40$ with respect to peak of the light-curve. The light-curve has been fitted with Gaussian processes; the latent function is show in the black line and the 1σ confidence interval.
Chapter 5. Physics of the r-band light-curve

5.1.2 Transparency timescale and $s_{BV}$

We first look at the ordering parameter $s_{BV}$ [52] which has been shown in [53] to correlate with the peak bolometric luminosity of type Ia SNe. We find a correlation between $t_{r_2}$ and $s_{BV}$ suggesting that there is a link between the timing of the secondary maximum and the bolometric luminosity of type Ia SNe at peak, i.e. that brighter SNe have a secondary maximum in the r-band that is later than fainter ones. This already tells us that measuring the properties of the secondary maximum in the r-band can provide us with clues of their physical origin.

Next we turn our attention to the correlation between $F_{r_2}$ and the transparency timescale, $t_{\text{transparency}}$. Previous studies [54, 55] have shown that the time at which the SN ejecta becomes optically thin, otherwise known as the transparency timescale $t_{\text{transparency}}$, can be related to the $M_{\text{ej}}$ as follows:

$$t_{\text{transparency}} = \left(\frac{M_{\text{ej}} \kappa q}{8 \pi} \right)^{0.5} \frac{1}{\nu_e}$$  \hspace{1cm} (5.1)

where $\kappa$ is the mean opacity of $\gamma$-rays and $\nu_e$ the e-folding velocity for an exponentially decaying density model. This means that there is a direct relation between $t_{\text{transparency}}$ and $M_{\text{ej}}$. We measure $t_{\text{transparency}}$ by fitting a radioactive decay energy (RDE) model to the bolometric light-curves at late times (after peak) of the SNe from the CSP-I and CfA datasets. We find a linear correlation between the measured $t_{\text{transparency}}$ and $F_{r_2}$ which can be used to infer values of $t_{\text{transparency}}$ for the much larger dataset of PTF and iPTF.

5.1.3 Testing explosion models

There are 2 main classes of explosion scenarios, Chandrasekhar and Sub-Chandrasekhar models in the context of both the Single-degenerate (SD) and Double-degenerate (DD) scenario introduced in Chapter 2.1. The main difference between the models is the mass of the white dwarf that explodes; with the Chandrasekhar models having a white dwarf at the Chandrasekhar mass, $M_{\text{ch}} = 1.4$, and the Sub-Chandrasekhar models a mass smaller than that, typically around 1 solar mass ($M_{\odot}$), and the explosion mechanism: detonation and deflagration (supersonic or subsonic shock wave) or a combination of the two.

In Paper II we test five models from the Heidelberg Supernova Model Archive (HESMA) [56], which are explained in brief below and represented in Figure 5.3.

- Chandrasekhar delayed detonation (ddt) [57]: A C-O WD gathers material from non-degenerate companion star and the burning is first a de-
Figure 5.3: This plot, adapted from [56], shows slices of the mean atomic number from the HESMA Archive at the end of the simulations. The top row shows the Chandrasekhar explosion models: deflagration (not used in this work), delayed detonation (ddt) and gravitationally confined detonation (gcd) from left to right. At the bottom row we have Sub-Chandrasekhar explosion models: violent merger (merger), pure detonation (det) and double detonation (doubledet) from left to right.
flagration allowing the WD to expand before the final detonation. This happens as the C-O WD reaches the $M_{Ch}$.

- Sub-Chandrasekhar detonation (det) [58]: A 1 $M_\odot$ exploded by pure detonation.

- Sub-Chandrasekhar double detonation (doubledet) [59]: Here a sub-$M_{Ch}$ C-O WD accretes He from a He-WD or other companion onto a layer until the right conditions are met at which a detonation in the He layer is followed by a second detonation in the C-O WD.

- Gravitationally confined detonation (gcd) [60]: A $M_{Ch}$ C-O WD exploding first with an off-centre deflagration followed by a containment due to gravity leading to the ejecta enveloping the WD. At that point a detonation occurs.

- Violent merger (merger) [61,62]: Merger of two WD that in total exceed the $M_{Ch}$.

The results of the inferred distribution are shown in Figure 5.4 together with the theoretical predictions of different explosion models explained in the next section. We found that none of the models cover the entire range of observed $t_{\text{transparency}}$. This calls for new models in order to explain the observations. The model covering the largest distribution of $t_{\text{transparency}}$ was the Sub-Chandrasekhar double detonation model, covering 77% of the observed distribution.

Because of the relation shown in Equation 5.1 we can compare the results from the CSP sample to radiative transfer models from [63]. The grid of 4500 models tested, have a wide range of different physical parameters associated with the explosion of type Ia SNe such as mass, kinetic energy, $^{56}\text{Ni}$ etc. to simulate different types of explosions. Due to an assumption of local thermodynamic equilibrium (LTE) to save computer time the strength of the secondary bump in the r-band is enhanced compared to observations. In Figure 5.5 we show the total mass of the models for different kinetic energies vs. $\mathcal{F}_{r_2}$ and the CSP extrapolated values for the total mass. We do see a qualitative trend in both our data and the models that are in agreement. Since the two parameters $\nu_e$ and $q$ can range a large number of values we cannot obtain a firm relation
between $F_{r_2}$ and total mass, but we can assert that they are correlated, something that is confirmed by the radiative transfer models. The value of this relation comes when looking at samples without IR coverage, such as PTF and iPTF, but also for large future samples at higher redshifts where it would be possible to probe $M_{r_2}$ to further distance than with i-band.

### 5.2 Rise-times of SNe

The PTF and iPTF dataset also has the advantage of having data at earlier phases compared to other low redshift SNe samples, as shown in Figure 5.6 where we compare with the JLA sample [64] which allows the early lightcurve to be explored. Early studies [65–67] of the early SN light-curve show correlations between the rise-time and the brightness at peak, where the longer the rise-time the brighter the SN. As the samples grew in size but also in
Figure 5.5: This plot from Paper II shows the inferred total mass vs $\mathcal{F}_{r_2}$ of the CSP sample in black squares, and the best fit slope in solid black line. Also shown are the radiative transfer models from [63] for different kinetic energies colour-coded. The best fit slope on the data is also shown superimposed in grey over the models.

...cadence further parametrisation of the rise was possible and the shape of this early light-curves was explored, [68–73]. These types of studies are interesting due to the model prediction [74] of excess flux at early times in 10% of the type Ia SNe given they arise from a single-degenerate scenario. No evidence of this has been found in large samples such as [70, 71] with sizes of 108 and 61 SNe respectively, however in individual nearby SNe this has possibly been detected [75].

In order to study the early light-curve and compare our results to literature values we fit our SNe light-curves with the analytical equation from [76] shown in equation 5.2:

$$L = A \left[ \frac{t - t_0}{t_b} \right]^\alpha \left[ 1 + \left( \frac{t - t_0}{t_b} \right)^\alpha \right]^\frac{\alpha+2}{2}$$  \hspace{1cm} (5.2)
5.2 Rise-times of SNe

![Diagram of SN rise times](image)

**Figure 5.6:** The type Ia SNe from PTF/iPTF compared to the JLA sample from [64]. The figure is adapted from Paper I.

This expression is derived from the assumption that all emission is photospheric and is less sensitive than other methods [73] of where the data is, since it fits for a larger part of the light-curve. Equation 5.2 shows how the flux, \( L \) depends on the normalising factor \( A' \), the explosion time \( t_0 \), the break time \( t_b \), two free parameters determining the shape of the light-curve, \( \alpha_r \), \( \alpha_d \) and a smoothing parameter \( s \).

Our best fit values are \( t_0 = -16.8^{+0.5}_{-0.6} \) days, \( \alpha_d = 1.97^{+0.05}_{-0.07} \) and \( \alpha_r = 2.36^{+0.05}_{-0.07} \). We find that our measured value of \( \alpha_r \) is compatible with literature which reports values between \( \approx 1 - 3 \) e.g. [71, 73, 76–78]. The simplest theoretical model, the fireball model of homogeneous expansion predicts \( \alpha_r = 2 \).
Figure 5.7: This Figure adapted from Paper I, shows three panels with the best fit values of equation 5.2 to 207 SNe with early-time light-curves. The different panels show the contours for one of the parameters fixed, since \( t_0 \) (in days), \( \alpha_d \) and \( \alpha_r \) are degenerate. The contour lines show 1, 2 and 3 \( \sigma \) confidence intervals.
Chapter 6

Spectroscopic properties of type Ia supernovae

In this Chapter we will first discuss the origin of the type Ia spectrum and then present the spectroscopic sample of PTF and iPTF in section 6.3. We then present an automatic code to compute spectroscopic properties in a robust and reproducible way presented in Paper III. After which we discuss spectroscopic subtypes of type Ia SN in section 6.3 which we exemplify by discussing the spectroscopic properties of a few individual supernovae (section 6.6) which are the focus of the author’s contribution to Paper IV and V.

6.1 The type Ia SN spectrum

As discussed in Chapter 5 we do not have a complete understanding on the progenitor and explosion mechanism of type Ia SNe. However the observed features of the spectrum are so distinct for type Ia SNe compared to other transients that they are easily distinguished and used for classification. Broadly speaking the spectrum can be understood as several gas layers of different densities. The deepest layer we can see, the photosphere emits a black-body spectrum which gets absorbed and re-emitted by the surrounding less dense material. Due to the fast expansion wide absorption features are created (overlapping with one another, known as P-Cygni profiles) which form the characteristic type Ia spectrum. At early epochs the different absorption lines are a blend of several elements but their main contribution is attributed to singly ionised or neutral intermediate mass elements (IME) such as O, Mg, Si, S, Ca and Fe. In later epochs, the ejecta expands and cools which increases the contributions of higher ionised elements, especially of the Fe group. As the ejecta cools further only the nebular phase emission lines are visible. See [79,80] for
Figure 6.1: Adapted from [81] we show a simplified graphic on how type Ia SNe spectra are formed. Top left: The solid and dashed lines show black-body spectra created from the thermalised photons on the photosphere at different temperatures. Top right: At particular wavelengths photons get absorbed from outside the photosphere. Bottom left: Due to the difference in expansion direction of the absorbing material and Doppler shift we get elements at different angles causing a wider absorption feature. P-Cygni profiles are also created here (not shown in Figure). Bottom right: Here absorption of multiple elements are added and the spectrum is starting to look more like a type Ia. For comparison the thin line shows a typical Ia spectrum from [31].

6.2 Supernova Subtypes

Many attempts have been made to classify type Ia SNe into subcategories based on their photometric and spectroscopic properties in order to make them more standardized candles for cosmology. As we saw in Figure 4.2 the light-
curves have a distribution of broadness and similarly their peak magnitudes vary. This can also be seen in Figure 6.2 where the peak magnitude is plotted against $\Delta m_{15}$, the difference in brightness between the day of peak and 15 days after peak in the B-band. The solid black line in Figure 6.2 shows the relation from [66] between the peak luminosity and $\Delta m_{15}$. While we do not discuss the Ca-rich transients, Fast decliners, SNe Iax and SNe Ia-CSM further they are examples of an ever-growing sub-classification of thermonuclear explosions.

Spectroscopically, we look at line velocities, see section 6.4.1, and the pseudo equivalent widths, see section 6.4.2, to determine which subclass the type Ia SN belongs to. As shown in Figure 6.2 the different spectroscopic classes also have different maximum brightnesses which means spectral class could be used as a way to minimise the Hubble-Lemaître residuals.

We can use several different schemes to spectroscopically type SN Ia. [82], devised a classification scheme based on pseudo equivalent widths (see section 6.4.2) of the prominent Si II absorption lines, which was later refined by e.g. [83].

- **Core normal**: Spectroscopically and photometrically normal supernovae.
- **Broad line**: Similar to Core normal but with deeper pseudo equivalent width (pEW) at Si II 6355 Å. Also classified as spectroscopically normal.
- **Cool**: These SNe typically have lower luminosity at maximum. They are called “cool” due to the signature line at $\approx 4000$ Å caused by the Ti II line, shown by [84] to be caused by lower temperatures in the line forming region.
- **Shallow silicon**: While all SNe in this group have a more shallow pEW feature the group is very heterogeneous and includes normal to brighter-than-normal supernovae (at maximum light).

Other schemes use the line velocity of the same line Si II 6355 Å, e.g. [85] to divide the type Ia supernovae into subclasses corresponding to different photometric properties. These schemes are compared by e.g. [83].

We use a supernova typing tool, **SNID**, described in [86] to classify each SN in addition to the above mentioned classification schemes. **SNID** was originally written to get the redshift of a given supernova spectra (adapting the method by [87]) and then expanded to also determining the type of transient and its age given a spectrum. We have used this tool to determine the redshifts of many supernovae in our sample and in addition to sub-classify the type Ia SNe. **SNID** classifies type Ia SNe into 5 groups: Ia-normal, Ia-91T-like, Ia-91bg-like, Ia-csm, Ia-peculiar.
We used the provided quality cut by SNID to choose the best fitted templates to determine both type and redshift in an automated code. When possible the galaxy lines of the host galaxy or the SDSS spectral redshift were used to determine the redshift, otherwise the best SNID fit was used.

Figure 6.2: Showing the peak brightness in B-band against broadness of the light-curve, $\Delta m_{15}$ and the SN types, the Phillips relation from [66] in the black line. The different sub-types are shown in shaded regions and explained further in the text. This Figure is taken from [88].
6.3 Spectroscopic sample

From PTF and iPTF we have 2981 spectra of 2002\textsuperscript{1} type Ia supernovae from a variety of telescopes and instruments, shown in Table 6.1. Since these spectra come from 33 different instruments and almost as many telescopes the reduction and calibration varies; however it follows these general steps. First the raw spectra were reduced using standard packages in IDL and IRAF in a custom made pipeline corresponding to a specific instrument and telescope. The spectra are then bias, flat field corrected and wavelength calibrated using the arc lamp exposures. To reduce the effects of the dispersion from the atmosphere most spectra are taken aligned to the parallactic angle, [89].

All the above steps vary slightly from telescope to telescope and the errors in the flux calibration are usually not included in the data files. It should also be noted that we do not know (at the time of writing) to what precision we can measure the absolute flux. For this reason it was not possible to use the spectra to correct the Hubble-Lemaître diagram in Figure 4.3 for colour. On the other hand our measured spectral quantities described in section 6.4.1 and 6.4.2 are to a large degree not affected by flux calibration enabling us to use the spectra despite their uneven reduction and calibration. Part of these spectra and data analysis were published in [90].

6.4 Spextractor code: measuring spectral properties

In order to study this large number of spectra from different telescopes and instruments with resolutions ranging from $R=100$ to $R=110000$, we needed a tool that was automatic, robust and that could deal with a large discrepancy in noise levels and resolution. We outline the procedure below and in Figure 6.3.

The code, Spextractor, takes the spectrum and redshift, loads it and then performs an outlier clipping if that has been pre-selected. We choose to do this step for all our spectra, since the reduction, i.e. the processing of the spectra after observation, is quite uneven. What the outlier clipping does is to first downsample the data, i.e. take every $n$ data-points (in this case $n = 20$) before smoothing the spectra using a GP model. Since most of the spectra from PTF and iPTF do not have error-bars, we use homoscedastic GP for the smoothing model. All data-points lying $3\sigma$ above the noise level of the smoothed spectra (which depends on the noise level of the spectrum itself) are then removed to

\textsuperscript{1}The remaining SNe were spectroscopically typed from other surveys.
Table 6.1: A table showing the 2981 spectra of 2002 SNe Ia from PTF/iPTF used in our analysis, the instrument, number of spectra, telescope, wavelength range and typical resolution is noted. Chip gaps in spectra.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Number of spectra</th>
<th>Telescope</th>
<th>λ_{min}</th>
<th>λ_{max}</th>
<th>Typical Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBSP 818</td>
<td>1000</td>
<td>Palomar 5.1m Hale</td>
<td>3405</td>
<td>10077</td>
<td>100-10000</td>
</tr>
<tr>
<td>LRIS 600</td>
<td>946</td>
<td>Keck I 10m</td>
<td>3233</td>
<td>10013</td>
<td>300-5000</td>
</tr>
<tr>
<td>ISIS 274</td>
<td>3382</td>
<td>WHT 4.2m</td>
<td>9460</td>
<td>&lt;10000</td>
<td></td>
</tr>
<tr>
<td>KAST 209</td>
<td>3475</td>
<td>Lick 3-m</td>
<td>9998</td>
<td>500-3000</td>
<td>700-1700</td>
</tr>
<tr>
<td>RC Spec 144</td>
<td>3510</td>
<td>Kitt Peak 4m</td>
<td>8360</td>
<td>270-6000</td>
<td></td>
</tr>
<tr>
<td>DEIMOS 211</td>
<td>4715</td>
<td>Keck II 10m</td>
<td>9605</td>
<td>up to 6000</td>
<td></td>
</tr>
<tr>
<td>SEDM 147</td>
<td>3646</td>
<td>Palomar 1.5m</td>
<td>9987</td>
<td>∼100</td>
<td></td>
</tr>
<tr>
<td>SNIFS 101</td>
<td>3373</td>
<td>UH 88inch</td>
<td>11500</td>
<td>∼2000</td>
<td></td>
</tr>
<tr>
<td>FLOYDS 91</td>
<td>3258</td>
<td>Faulkes Telescope North</td>
<td>11933</td>
<td>400-700</td>
<td></td>
</tr>
<tr>
<td>ALFOSC 76</td>
<td>3346</td>
<td>Nordic Optical Telescope</td>
<td>9069</td>
<td>95-5000</td>
<td>190-10000</td>
</tr>
<tr>
<td>GMOS 80</td>
<td>3625</td>
<td>Gemini North</td>
<td>9294</td>
<td>500-4400 (0.5 arcsec) or 8800 (0.25 arcsec)</td>
<td></td>
</tr>
<tr>
<td>DIS 57</td>
<td>3350</td>
<td>Apache Point 3.5m</td>
<td>9586</td>
<td>1000-5000</td>
<td></td>
</tr>
<tr>
<td>ACAM 29</td>
<td>4433</td>
<td>WHT 4.2m</td>
<td>9243</td>
<td>450 or 900</td>
<td></td>
</tr>
<tr>
<td>DOLORES 23</td>
<td>3683</td>
<td>Telescopio Nazionale Galileo</td>
<td>8328</td>
<td>585-5953</td>
<td></td>
</tr>
<tr>
<td>FIRE 12</td>
<td>12517</td>
<td>Magellan Baade</td>
<td>24836</td>
<td>6000 or 12000</td>
<td></td>
</tr>
<tr>
<td>GMOS 12</td>
<td>3625</td>
<td>Gemini South</td>
<td>9294</td>
<td>500-4400 (0.5 arcsec) or 8800 (0.25 arcsec)</td>
<td></td>
</tr>
<tr>
<td>LRS 6</td>
<td>4181</td>
<td>Hobby-Eberly Telescope</td>
<td>10242</td>
<td>1100-1900</td>
<td></td>
</tr>
<tr>
<td>X-Shooter</td>
<td>3198</td>
<td>VLT</td>
<td>13118</td>
<td>8400 (UVB), 13200 (VIS), 8300 (NIR)</td>
<td>8400 or 12000</td>
</tr>
<tr>
<td>FOSC 2</td>
<td>4027</td>
<td>Wise 1m</td>
<td>8278</td>
<td>∼1000</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.3: A flowchart showing how the Spextractor code works from the initial data input to the output line velocities and pseudo equivalent widths (pEW). Graph from Paper III.
account for narrow spikes in the spectra. Then we return and do another GP model on the “clean” spectrum. The smoothed spectrum is now ready to fit for integration points to measure line velocities and pseudo equivalent widths (pEW) for each of the features listed in Table 6.2, these are taken from [91] with small modification for the Mg II lower boundaries. This modification was made to ensure that the same integration limit was used for the end of feature 2 and beginning of feature 3.

### 6.4.1 Expansion velocities

The velocities are found by identifying the local and global minima, \( \lambda_m \) of the GP smoothed spectrum with using signal processing and then using equation 6.1 and the rest-wavelengths, \( \lambda_0 \) from Table 6.2.

\[
v = \frac{c}{\sqrt{\left(\frac{\lambda_m}{\lambda_0}\right)^2 - 1}} \frac{\left(\frac{\lambda_m}{\lambda_0}\right)^2 + 1}{\left(\frac{\lambda_m}{\lambda_0}\right)^2}
\]  

(6.1)

### 6.4.2 Pseudo Equivalent widths

Another way to get information from the spectra is to measure the pseudo equivalent width (pEW)

\[
pEW = \sum_{i=1}^{N} \left(1 - \frac{f(\lambda_i)}{f_c(\lambda_i)}\right) \Delta\lambda_i
\]  

(6.2)

of the absorption features. Here \( f(\lambda) \) is the observed flux at a given wavelength, \( \lambda \) and \( f(\lambda)_c \) is the flux at the pseudo continuum at the same wavelength (since
the real continuum is absent and replaced with a straight line this is referred to as pseudo). The error in pEW is given by

\[ \sigma_{pEW}^2 = \sum_{i=1}^{N} \left( \frac{\sigma_{f_i}^2(\lambda_i)}{f_i^2(\lambda_i)} + \frac{f_i^2(\lambda_i)\sigma_{c_i}^2(\lambda_i)}{f_i^2(\lambda_i)} \right) \times \Delta \lambda_i \]  

(6.3)

is a lower estimate of the uncertainty in the measurement since the error in the integration points is not taken into account. The error in the continuum is estimated using a parallelogram about the integration points and estimating the area within it given the error of the data points. This measure, although not directly attributed with a physical interpretation, has been shown (in the literature) to correlate with quantities such as light-curve width and in addition used to sub-classify different types of supernovae Ia, as we saw in section 6.2.

An example on the fit applied to different spectra, noise and resolution values is shown in 6.4.

### 6.5 Spectral properties of PTF and iPTF SNe

In Paper III we use this code to look at the largest sample of type Ia SNe spectra discovered with the same telescope and investigate correlations with both photometric and host galaxy parameters (see Chapter 7). It allows us to look at global trends in spectral features, unbiased by host galaxy environment and to quantify the strength of correlations.

Due to the inhomogeneity of the spectroscopic sample and despite the automatic feature of the Spextractor code, each SN spectrum fit has to be checked by hand since artefacts in the spectra can affect the results. In addition the redshift has to be verified and a good light-curve has to be available to get an accurate phase estimate. The phase, i.e. the time with respect to maximum, is important when you want to compare several SNe spectra together since the Ia spectrum changes significantly with time as described in Section 6.1. Since this vetting takes significant time we present here only a small portion of the SNe from the entire PTF and iPTF sample. The analysis presented in this version of Paper III reflects that, but can be scaled up as soon as the proper vetting of each SN redshift and spectrum fit has been performed.

### 6.6 Calculating expansion velocities for individual supernovae

As mentioned in Section 2.5, one approach to learn more about the systematics of type Ia SNe cosmology is to study nearby individual supernovae in more
Figure 6.4: An example on how the SpeXtractor code selects integration limits for the pEW and velocity calculation for different spectra. The dashed lines show the global minima of each feature.

detail. In Paper IV, V, [92] we use previous versions of the SpeXtractor code to calculate velocities and pEW of individual SNe.

[92] presents the supernova 2014J, one of the closest type Ia supernovae in recent years, and examines its photometric and spectroscopic properties. For this latter point the expansion velocity of Si λ6355 for the spectra available for this source was calculated using Gaussian fitting of the absorption line and a semi-manual pick of integration points. A point near the optically ideal integration limit was picked and the maximum of the smoothed spectra within 50 Å was selected, following the method by [93].

For Paper IV and V we used the global minimum in the same way SpeXtractor uses it, described in section 6.4.
Paper IV studies a small sample of nearby supernovae in the wavelength range $0.2 - 2 \mu m$ to study the extinction from dust (see section 2.3) in type Ia SN.

Figure 6.5: This plot from Paper IV shows the expansion velocities of Si $\lambda 6355$ for the SN sample in the paper. The grey band shows the average SN velocity range from [93].

In Figure 6.5 we show the results of the Si II velocity evolution from both papers where the evolution of Si II $\lambda 6355$ velocity against phase is plotted. In [94] the pseudo equivalent widths and velocities are used to compare supernovae with each other to see if the template for one can be used in another. Figure 6.5 also shows a band of normal type Ia SN for reference.

Paper V tests for redshift evolution (see section 2.5) with the strongly lensed SN PS1-10afx at $z = 1.4$ by comparing the spectra with intermediate and low-redshift spectra. No spectral evolution was found.
Chapter 7

Host galaxy properties

7.1 The hosts of PTF and iPTF SNe

In this Chapter we discuss the host galaxy properties of the type Ia SNe from PTF and iPTF, how they we are obtained and the correlation between these and the Hubble-Lemaître residuals and present work from Paper I and III. The entire sample of host galaxies for all SNe (not just type Ia SNe) from PTF and iPTF will be presented in a paper led by L. Hangard (in prep.) not included in this thesis.

![Figure 7.1: The data coverage of each of the catalogue data used for the host galaxy properties of the type Ia SNe from PTF and iPTF. Courtesy of L. Hangard.](image-url)
To get the host galaxy properties we first need to determine which galaxy hosts each SN. We use catalogue data from the Sloan Digital Sky Survey (SDSS) (95) Data Release 12 (96) photometric catalogue (97, 98) and the SDSS spectroscopic catalogue (99) for photometric data in different wavelength bands and for spectroscopic redshifts. We show the coverage in Figure 7.1 for the SNe in PTF and iPTF.

7.1.1 Host identification

The first step in identifying the most likely host galaxy is to select every galaxy within a 100 kpc radius around the SN position which has a redshift within 3σ of the SN redshift. Wherever spectroscopic redshift was available that was used, otherwise photometric redshift was used for the comparison.

Figure 7.2: This flow chart shows the procedure which was followed to train a ML model when identifying the host galaxy for every SN in our sample.

We then select a sample consisting of 300 random SNe from our sample and determine the host galaxies by hand. This will serve as a training (200 SNe) and test set (100 SNe) for the Machine learning (ML) algorithms to predict the most likely host galaxy for any given SN in our sample. This follows the general procedure for classification ML, summarised in Figure 7.2, where the data is first split into 2 samples, then a model is trained on the training set (training the ML algorithm) and subsequently tested on the test set (which checks the efficiency of the ML algorithm). We use the following parameters for each SN to determine the host: redshift, brightness of the host galaxy, the distance from the centre to the supernova, projected galaxy radius and
Table 7.1: Parameter importances in the identification of the host galaxies of the PTF/iPTF SN sample.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance of SN to the galaxy centre</td>
<td>40%</td>
</tr>
<tr>
<td>Redshift difference (SN-galaxy)</td>
<td>29%</td>
</tr>
<tr>
<td>Galaxy radius (kpc)</td>
<td>23%</td>
</tr>
<tr>
<td>Confusion parameter</td>
<td>5%</td>
</tr>
<tr>
<td>Galaxy brightness</td>
<td>3%</td>
</tr>
</tbody>
</table>

a confusion parameter similar to the one described in [100]. The confusion parameter measures how hard it is to select the host galaxy based on how crowded the field is, i.e. how many other galaxies there are around the SN. Our modified confusion parameter used the Petrosian radius ([101]) instead of the directional light radius (DLR) since we were not able to calculate the DLR using our catalogue data.

We tested a number of ML algorithms or classifiers on our training and test sample as described in Figure 7.2 and found that the Random Forest (RF) classifier performed best with an 8% average error on the host identification, determined by the test sample performance. We thus get a probability for each SN that a particular galaxy is its host and use the host properties for further analysis. In order to check if higher redshift galaxies were more often misidentified we checked for correlations between misidentified hosts and the SN redshift but found no correlation.

The most important parameters for host identification are shown in Table 7.1 in order of their importance for the RF model.

We note that 15% of the chosen host galaxies are not the closest galaxy despite the redshifts being compatible within 3σ. They have in common a higher confusion parameter than average and typically the chosen galaxy is the brightest of the candidates.

7.1.2 Extracting the host galaxy properties

Once we have identified the most probable host galaxy associated with the SN we do a SED fitting to the photometry from SDSS and the Two Micron All-Sky Survey (2MASS) catalogue [102] using the Fitting and Assessment of Synthetic Templates (FAST) code [103]. The portion of SNe with good SED fits is shown in Figure 7.1 under “FAST”.
From this we get estimates of the age, stellar mass, star formation rate (SFR) and extinction ($A_V$) of each host galaxy. We use these estimates in Paper III to see how they correlate with spectral properties.

### 7.2 Mass step for type Ia hosts

In Paper I we investigated to see if there is a correlation between the host mass and Hubble-Lemaître residuals. This correlation has been observed to varying degrees of significance in B-band for colour corrected SNe e.g. [20, 104–111].

![Plot from Paper I showing the Hubble-Lemaître residuals (HLR) in R-band, $\Delta M_R$ vs. the log of the host stellar mass, $\log_{10} M_*/M_\odot$, for 131 of the SNe in our sample that have reliable host masses and with $z < 0.13$. The dashed line shows the definition of high and low mass host galaxy e.g. [4, 105], and the horizontal lines with the shaded areas show the mean and standard error for each of the two host mass bins.

**Figure 7.3:**

Our results, shown in Figure 7.3, are consistent with those of [20] and also consistent with no correlation. As is done in the literature we divide our sample into high and low mass galaxies, at $10^{10} M_*/M_\odot$ and investigate the possible
difference between these. We restrict the SNe for this analysis to $z < 0.13$ to avoid biased results by including Malmquist biased SNe and measure the Hubble-Lemaître residual step to be $0.037 \pm 0.068$ magnitudes. The error-bar includes K-correction, calibration, photometric and peculiar velocity errors.
Chapter 8
Summary and Outlook

8.1 Summarising the thesis

In this thesis we present the entire sample of both light-curves and spectra from the 2059 type Ia SNe observed by PTF and iPTF. This un-targeted, low-redshift survey allows us to study statistical properties of type Ia SNe in order to better understand the physics behind these explosions, their dependence on host galaxy environment and to quantify the many systematic uncertainties that are present when using type Ia SNe as distance indicators for cosmology (some of which are described in Section 2.5). By being an un-target survey the sampling bias is minimised which together with the uncertainty in cross-calibration between different telescopes allows the distributions obtained to be more representative of the true values. This was brought forward as one of the key pieces to improve the precision of cosmological parameters and ultimately to understand the origin of dark energy.

8.2 ZTF and other surveys

The successor of iPTF, ZTF, [112] is coming online 2017 and will be 15 times more efficient than iPTF. With a substantially larger camera, 47 deg², faster reading\(^1\) and slewing\(^2\) speed it is expected to be able to find 15 times the amount of transient events, including many SNe Ia. See Figure 8.1 for a comparison of the field of view between different future and current telescopes. An important improvement to the PTF and iPTF surveys is that the survey is perfomed in r, g and i-band allowing for measurements of the individual SN

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\(^1\)Time it takes to read out the data from the camera.
\(^2\)Time it takes the telescope to move from one target to another.
colours to be measured. Other future surveys of importance for SN Ia discovery and follow-up include the Large Synoptic Survey Telescope (LSST) [113] which is scheduled to be operational in 2022.

Figure 8.1: Fields of view of current and planned survey missions. These surveys, including those currently in operation are: the Dark Energy survey (DES) [114], PTF/iPTF, Hyper supreme-Cam (HSC) [115], the Panoramic Survey Telescope & Rapid Response System (PS1) [116], ZTF [112] and future surveys such as the Large synoptic survey telescope (LSST) [113]. Credit: Joel Pearson Johansson

8.3 Outlook

These next generation facilities will undoubtedly give us much greater number statistics and there is hope that we can find answers to some of the questions that currently dominate the systematic uncertainties. It is important to also note that in this new era of larger supernova samples we will not have a spectrum for each of the supernovae and if one is obtained its resolution will be low. From our spectroscopy results we now know that if we want to be able to use them for more than a certain classification (that these transients are indeed type Ia supernovae) flux calibration is important and a consistent reduction of data.

We have also pointed out the importance of a secondary filter to be able to perform colour corrections, this lesson has influenced how the ZTF will divide
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its time between its filters. Higher, and more consistent cadence will also be important in order to explore the early light-curve where PTF/iPTF lacked the sufficient data to put limits on progenitor channels.
Svensk sammanfattning


I artikel I studerar vi de allmänna egenskaperna hos ljuskurvor i R-bandet, såsom stigningstid, ljusstyrvkurvor och inneboende ljusstyrka över tid, för att undersöka om det finns multipla populationer i någon av parametrarna som skulle tyda på olika ursprungskanaler. Vi fann inte några indikationer som pekade på detta.

I artikel II indentifierade vi den andra maxima i R-bandet och fann en korrelation med dess tidpunkt, $t_{r_2}$, och "color-stretch"-parametern $s_{BV}$ som är en proxy för $^{56}$Ni massa. Vi fann också att det integrerade flödet under detta andra maxima, $\tilde{F}_{r_2}$ korrelerar med tidsgränsen för transparens, $t_{\text{transparency}}$ som är en proxy för den totala utslungade massan. Utifrån dessa två relationer jämförde vi sedan fördelningen från ljuskurvorerna för PTF/iPTF SNe med olika modeller från HESMA arkivet.

I artikel III redogör vi för det spektroskopiska urvalet från PTF/iPTF och genom att använda automatiska verktyg för maskinlärning, kunde vi pröva egenskaperna och korrelationerna hos spektralegenskaperna och hur de förhöll sig till fotometriska och värd-galaktiska egenskaper.

Vidare behandlar artikel IV hur ett litet urval av SNe kan användas för att undersöka en av de viktigaste systematiska osäkerheterna i SNe-kosmologin: extinktionen av stoft i synlinjerna. Slutligen undersöks i artikel V en start linsad SN vid $z=1.4$ för att se om spektral egenskaperna ändras över kosmisk tid. Både i artikel IV och V används koden som utvecklats för artikel II för att analysera spektra.
References


References


[61] R. Pakmor, M. Kromer, F. K. Röpke, S. A. Sim, A. J. Ruiter and W. Hillebrandt, *Sub-luminous type Ia supernovae from the mergers of equal-mass white dwarfs with mass $\sim 0.9\text{M}_{\odot}$*, Nature **463** (Jan., 2010) 61–64, [0911.0926].


[94] R. Amanullah, J. Johansson, A. Goobar, R. Ferretti, S. Papadogiannakis, T. Petrushevska et al., *Diversity in extinction laws of Type Ia supernovae measured between 0.2 and 2 µm*, MNRAS **453** (Nov., 2015) 3300–3328, [1504.02101].


