DOCTOR OF PHILOSOPHY

Unravelling the nature of hydrogen-poor thermonuclear supernovae

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Unravelling the nature of hydrogen-poor thermonuclear supernovae

A thesis submitted for the degree of
Doctor of Philosophy

by

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M. R. Magee
March 28, 2018
Abstract

Thermonuclear supernovae take many forms, as demonstrated by the increasing evidence of diversity among type Ia supernovae, particularly at early times, and subclasses of peculiar objects. This thesis presents new observations and modelling tools that explore the diversity of thermonuclear supernovae. We present colour light curves, and optical and near-infrared spectra for SN 2015H, a type Iax supernova, beginning a few days post-explosion. We compare these observations to synthetic light curves and spectra predicted from multi-dimensional explosion models invoking weak deflagrations of Chandrasekhar-mass carbon-oxygen white dwarfs, and find reasonable agreement with a model producing only $\sim 0.07 \, M_\odot$ of $^{56}$Ni. Our results demonstrate that the observational signatures of this explosion scenario are consistent with type Iax supernovae across a range of luminosities. Our analysis of SN 2015H shows that the strength of the deflagration, and hence amount of $^{56}$Ni produced during the explosion, can explain some of the diversity observed among type Iax supernovae. In a subsequent study, we present observations of PS1-12bwh that demonstrate this is not the sole factor affecting the appearance of type Iax supernovae. While the light curve and post-maximum spectra of PS1-12bwh are virtually identical to the prototypical SN 2005hk, the pre-maximum spectrum of the former does not resemble spectra of the latter at a comparable epoch. We perform spectral modelling and find that the unique pre-maximum appearance of PS1-12bwh is consistent with a lower density in the outer ejecta compared to SN 2005hk. Both objects showed similar light curve peaks and shapes, therefore our analysis indicates that there are additional factors responsible for the diversity of type Iax supernovae apart from the amount of $^{56}$Ni produced; hence, type Iax supernovae are not a one-parameter family. The early light curves of type Ia supernovae also display diversity in their colours and shapes. We therefore present a new Monte Carlo radiative transfer code designed for modelling light curves of radioactively driven transients. We perform a parameter study, focusing on the effects of the $^{56}$Ni distribution and density profile within the supernova ejecta. Models with $^{56}$Ni extending throughout the entire ejecta show brighter and bluer light curves at early times. The density profile also plays a significant role in shaping the early light curve; however, this has been neglected in previous studies. Our models show that comparisons with full colour light curves are necessary to constrain the ejecta properties of type Ia supernovae, such as $^{56}$Ni distribution and density profile.
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CO . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . Carbon-oxygen
DDT . . . . . . . . . . . . . . . . . . . Deflagration-to-detonation transition
IGE . . . . . . . . . . . . . . . . . . . . . . . . . . . . . Iron group element
IME . . . . . . . . . . . . . . . . . . . . . . . . . . . Intermediate mass element
PDD . . . . . . . . . . . . . . . . . . . . . . Pulsational delayed detonation
TLA . . . . . . . . . . . . . . . . . . . . . . . . . . . Two-level atom
Publications

A list of publications resulting from the work undertaken during my time as a Ph.D. student.

**Refereed Publications**

   *On the triple peaks of SNHunt248 in NGC 5806*
   2015, Astronomy & Astrophysics, 581, L4

   *The type Iax supernova, SN 2015H. A white dwarf deflagration candidate*
   2016, Astronomy & Astrophysics, 589, A89
   This paper forms Chapter 4.

   *The superluminous transient ASASSN-15lh as a tidal disruption event from a Kerr black hole*
   2016, Nature Astronomy, 1, 0002

Growing evidence that SNe Iax are not a one-parameter family. The case of PS1-12bwh
2017, Astronomy & Astrophysics, 601, A62
This paper forms Chapter 5.

5. Abbott, B. P., et al. incl Magee, M.
   Multi-messenger Observations of a Binary Neutron Star Merger

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   Klose, S., Kostrzewa-Rutkowska, Z., Kowalski, M., Kromer, M., Kuncarayakti, H.,
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   Mattila, S., McBrien, O., Miller, A., Nordin, J., O’Neill, D., Onori, F., Palme-rio, J. T.,
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A kilonova as the electromagnetic counterpart to a gravitational-wave source
2017, Nature, 551, 75

   Modelling the early time behaviour of type Ia supernovae: effects of the $^{56}$Ni
distribution
   2018, Astronomy & Astrophysics, 614, A115
   This paper forms Chapter 6 and §3.5 to §3.9.

   Leibundgut, B.
Type Iax SNe as a few-parameter family
2018, Monthly Notices of the Royal Astronomical Society, accepted

Circulars

29 Astronomers’ Telegrams (ATels).


All things must come to an end, even the stars above us. Many stars end their lives in explosive events known as supernovae (SNe). In the process they feed back energy, light, and matter into the Universe. SNe have been observed for over one thousand years (see e.g. Green & Stephenson 2003); however, it is only since the early 20th Century that we have begun to understand what they are, and how and why they occur. In an effort to further our understanding, similar SNe are grouped into empirical categories based on their observed spectra and light curves. SNe are divided into two classes based on whether they do (type II) or do not (type I) show hydrogen in their spectra (Minkowski 1941). This thesis focuses on those SNe that do not show hydrogen, and specifically those that are believed to result from thermonuclear explosions (as opposed to the core collapse of a massive star) - in other words, type Ia (SNe Ia) and related supernovae.

The aim of this thesis is to establish the explosion mechanism(s) of thermonuclear SNe by exploring the diversity of transients realised in nature. In § 1.1, the main observational signatures of SNe Ia (which can be used to constrain the explosion mechanism) are outlined. Peculiar SNe Ia are introduced in § 1.2, along with discussion of how they differ from so-called normal SNe Ia and the implications for the explosion mechanism. Figure 1.1 shows how peculiar subclasses of thermonuclear SNe differ from normal SNe Ia in terms of their light curve peak and shape. SNe Iax are the focus for much of the work presented in this thesis, and are introduced in § 1.3. This section discusses observations of these objects and places them into context among normal SNe Ia and the peculiar objects also highlighted. The main proposed explosion models are presented in § 1.4 and discussed in relation to the observed properties of thermonuclear SNe. Finally, a summary is given in § 1.5.

The cover image for this chapter shows the supernova remnant SNR 0509-68.7 and the outskirts of NGC 1850. Image credit: NASA, ESA, and Y.-H. Chu (Academia Sinica, Taipei).

1.1 Type Ia supernovae

SNe Ia are believed to result from the thermonuclear disruption of a white dwarf (WD; for reviews, see e.g. Wheeler 1981; Woosley & Weaver 1986) – the remnant of a star with an initial mass up to \( \sim 8 \, M_\odot \). As WDs no longer undergo nuclear fusion, they are supported against gravitational collapse entirely by electron degeneracy pressure. The maximum mass this pressure can support, however, is approximately 1.4 \( M_\odot \) – known as the Chandrasekhar limit. Lone WDs with masses below the Chandrasekhar limit are expected to simply cool over the lifetime of the Universe. It has therefore been suggested that SNe Ia must occur in binary systems that contain at least one WD.
Figure 1.1: Peak absolute $B$-band magnitude is plotted against decline rate (the difference in magnitude measured at peak and 15 days later; see § 1.1.1) for a sample of SNe that are believed to be thermonuclear. Peculiar sub-classes are generally distinct from SNe Ia photometrically and highlighted in different colours. The Phillips relation (see § 1.1.1) is marked by a solid, black line. Figure from Taubenberger (2017).
Whelan & Iben 1973; Iben & Tutukov 1984). If the WD were to accrete material from its companion, such that its mass approached the Chandrasekhar limit, it would explode as a SN Ia. Later work has demonstrated that it may be possible for a WD to explode as a SN Ia above or below this limit (so-called super- and sub-Chandrasekhar mass explosions; e.g. Nomoto 1980, 1982). Both single degenerate (binaries containing a single WD) and double degenerate (binaries or triple systems containing two WDs) progenitor systems have been proposed to explain SNe Ia. Single star systems have also been proposed as progenitors of SNe Ia; however, the evolutionary pathways leading to such a scenario appear unlikely (e.g. Tout 2005, 2007). It is not yet clear whether a single progenitor system can explain all of the observed properties of SNe Ia. Explosion mechanisms resulting from both of these progenitor systems are discussed in §1.4.

The exceptional intrinsic brightness of SNe Ia means that they account for most of the SNe we are able to observe. Li et al. (2011) find that SNe Ia constitute \( \sim 80\% \) of all SNe in a magnitude limited survey – in other words, not accounting for the fact that some SNe are fainter or more distant than others and are therefore harder to detect. Large samples of objects have demonstrated the relative uniformity in both the light curves and spectra of SNe Ia, and the wealth of data that has accumulated has allowed for significant progress in our understanding of these explosions. There are still many unanswered questions remaining, however, such as the nature of the progenitor system and the explosion mechanism. The observed properties of SNe Ia are outlined in §1.1.1 and 1.1.2.

### 1.1.1 Light curves

It is the amount of radioactive $^{56}$Ni synthesized during the explosion that drives the luminosity of SNe Ia (Colgate & McKee 1969). At early times, this luminosity is provided by the decay of $^{56}$Ni to $^{56}$Co, which proceeds through electron capture, with a half life of $t_{1/2} \approx 6$ days. As $^{56}$Ni decays, $\gamma$-rays are emitted that interact with the expanding ejecta and are converted to lower frequency photons. The rate at which these photons diffuse through the ejecta is dependent on many factors, including the density and composition of the ejecta, but they eventually escape and form the light curve that is observed. At later times, the decay of $^{56}$Co to $^{56}$Fe dominates the luminosity ($t_{1/2} \approx 77$ days). While the majority of this decay is also due to electron capture, \( \sim 20\% \) results from positron emission and provides a significant amount of the luminosity (Arnett 1979). Figure 1.2 shows the light curve shapes for a sample of normal and peculiar SNe Ia (see §1.2 and 1.3).

During times shortly after explosion, the luminosity of SNe Ia is often approximated
Figure 1.2: *BVRI* light curves for a normal SNe Ia (SN 1994D), SN 1991T, SN 1991bg, and a SN Iax (SN 2002cx). It is clear that thermonuclear SNe can show quite different light curve shapes. SN 1991T declines in brightness more slowly than a normal SN Ia, while SN 1991bg declines more quickly. SN 1991bg also does not show a secondary bump in the *I*–band. The light curve of SN 2002cx is similar to that of SN 1994D in the *B*–band. The *R*– and *I*–band light curves of SN 2002cx are noticeably different, showing much broader peaks and no secondary maximum. Figure from Li et al. (2003).

as an ‘expanding fireball’ (Riess et al. 1999b). In this approximation, the optical filters are assumed to lie in the Rayleigh-Jeans tail of the hot SN SED. Flux is proportional to the effective temperature of the fireball, \( f_\lambda \propto T \), and the luminosity is therefore given by:

\[
L = 4\pi R^2 f \propto v^2 t^2 T. \tag{1.1}
\]

The photospheric radius is given by \( R \) and, following from homologous expansion (meaning the ejecta is freely expanding, see § 3.2), \( R = vt \). Here, \( v \) is the photospheric velocity and \( t \) is the time since explosion. As a crude approximation, the photospheric velocity and temperature are both assumed to be effectively constant during the early light curve phase, hence the luminosity is given by:

\[
L = \alpha t^2, \tag{1.2}
\]
where $\alpha$ is a normalising constant. Recent studies have demonstrated, however, that the light curves of SNe Ia deviate from this simplistic model and show a range of rise indices ($L \propto t^n$) – that is, all SNe Ia do not necessarily follow the same shape at early times (e.g. Ganeshalingam et al. 2011; Firth et al. 2015). Chapter 6 focuses on modelling the early light curves of SNe Ia and also looks at variations in the shape of the rising light curve.

After the rising phase, approximately two to three weeks post explosion, the SN ejecta have sufficiently expanded that the light curve has reached peak brightness. At this point the energy output is equal to the instantaneous energy deposited by the decay of $^{56}\text{Ni}$ (Arnett 1979). The majority of the thermal radiation is in the form of ultraviolet (UV) radiation, which excites the ejecta to high energy levels. These atoms typically de-excite by fluorescence – multiple lower energy photons are emitted, resulting from multiple lower energy transitions. The reduced opacity of longer wavelength photons results in the brightness peaking first in the near-infrared (NIR) bands, followed by the optical bands a few days later (Contardo et al. 2000). SNe Ia generally show a peak absolute magnitude in the $B$–band of approximately $-19.3$ (Hamuy et al. 1996). The luminosity following maximum light is typically characterised by the decline rate, $\Delta m_{15}$ – the difference between the magnitude at peak and 15 days later. A strong correlation between peak magnitude and decline rate is observed among SNe Ia, with brighter objects declining more slowly – this is known as the Phillips relation, and is shown in Fig. 1.1 (Pskovskii 1977; Phillips 1993; Phillips et al. 1999).

The Phillips relation is empirical and not fully understood, but it has been suggested to result from a variety of causes, as discussed in Kasen & Woosley (2007). Höflich et al. (1996, 2002) and Pinto & Eastman (2001) argue that explosions that produce more $^{56}\text{Ni}$ (i.e. brighter SNe) experience higher temperatures (due to increased heating from the decay of $^{56}\text{Ni}$). The resulting higher temperatures lead to increased ionisation within the ejecta, and therefore increased opacities. This results in a longer diffusion time and more slowly declining light curve. Mazzali et al. (2001) argue that the longer diffusion time and increased opacities is due to the amount of iron group elements (IGEs; elements from Sc to Ni, inclusive) produced. Conversely, Kasen & Woosley (2007) argue that an increased diffusion time must be secondary to some other effect. Kasen & Woosley (2007) present a series of models with different $^{56}\text{Ni}$ masses that produce approximately the same light curve shape. They favour an interpretation of different $B$–band decline rates as being due to slight differences in the colour evolution, driven by the $^{56}\text{Ni}$ mass. Whatever the physical origin of the Phillips relation, it is clear that the light curves of SNe Ia hold many potential clues to the underlying explosion physics.
Following the declining phase, most SNe Ia show a secondary maximum in the NIR bands (see Fig. 1.2). This feature was investigated thoroughly by Kasen (2006), who found that it is directly related to the ionisation state of IGEs within the ejecta. The appearance of this secondary maximum is dependent on some amount of stratification within the SN ejecta – that is, different elements must occupy different regions of the ejecta and specifically the IGEs must be concentrated towards low ejecta velocities (see § 1.1.2). As the initially hot ejecta expands and cools, the IGE-rich inner regions recombine and transition from a predominantly doubly-ionised state to singly-ionised, leading to increased emission at NIR wavelengths. Again, this demonstrates how light curves may be used to probe the explosion physics, as explosion models for SNe Ia must be able to reproduce this effect.

SNe Ia generally display a relatively uniform colour evolution at later times, beginning approximately 30 days post $B$-band maximum, known as the Lira relation (Lira 1996; Phillips et al. 1999). As with the Phillips relation, this is a purely empirical observation. Deviations from this uniform evolution are commonly used to estimate the level of host galaxy reddening in individual SNe Ia. That SNe Ia seem to show an intrinsic colour evolution is further evidence that the explosion physics must be similar for the majority of objects, while the different evolution of peculiar objects indicates that they could result from a different explosion mechanism. Figure 1.3 shows the similar colour evolution for a sample of normal SNe Ia, and how peculiar objects deviate from this.

### 1.1.2 Spectra

SNe spectra are the fingerprints of the underlying explosions. After explosion, the SN photosphere provides a pseudo-continuum of radiation, the shape of which gives some clues as to the temperature of the ejecta. The products of nuclear burning are on full display as light escapes from the photosphere and interacts with the ejecta, superimposing its signatures on the pseudo-continuum. As the ejecta expands and cools, the photosphere recedes and deeper and deeper ejecta layers are exposed. Therefore each spectrum taken probes different regions and provides a unique picture of the ejecta and explosion. In addition, comparing spectra from different SNe highlights how the physical conditions of each explosion differ and how they evolve over time. This type of analysis forms much of the work presented in Chapter 5.

The large ejecta velocities typical of SNe Ia ($\gtrsim 12,000$ km s$^{-1}$ around maximum light) result in numerous blended spectral features. The strong blending that is observed presents a challenge for identifying spectral features, which requires comparisons to spectral models. Nevertheless, identifications have been made for many of the observed
Figure 1.3: Unreddened colour evolution for a normal SNe Ia (1994D), SN 1991T, SN 1991bg, and a SN Iax (SN 2002cx). SN 1991bg is clearly significantly redder in all colours. SN 1991T is broadly similar to normal SNe Ia. The colour evolution of SN 2002cx is somewhat redder in $B - V$ post-maximum, but significantly redder in $V - R$ and $V - I$ at all epochs. Figure from Li et al. (2003).

optical features (Mazzali et al. 1993). In addition, blending of features is particularly important at short wavelengths, where a forest of blended lines due to IGEs results in a suppression of flux, in what is commonly referred to as ‘line blanketing’. Observed spectra are therefore highly sensitive to the exact composition of the ejecta, and may be used to infer the products of explosive nucleosynthesis.

Indeed, detailed modelling of the spectral evolution of SNe Ia has demonstrated that these burning products occupy different regions of the ejecta and appear to exhibit a layered structure (although layers are not necessarily separated by a sharp boundary), with the heaviest elements typically interior to lighter elements (e.g. Stehle et al.
2005; Mazzali et al. 2008). Up to shortly after maximum light, SNe Ia show a strong absorption feature due to Si\textsc{ii} $\lambda$6355. This is a defining characteristic of SNe Ia and is used to classify SNe spectra as such. Additional features due to other neutral and singly-ionised intermediate mass elements (IMEs; elements from Na to Ca, inclusive) are also present, including the Ca\textsc{ii} H&K lines and NIR triplet. As the SN evolves beyond maximum light, features due to IMEs decrease in strength, while those due to IGEs become more prominent. In particular, post-maximum spectra of SNe Ia show numerous features due to Fe\textsc{ii} and Co\textsc{ii}. Figure 1.4 presents the spectral evolution for one of the best observed SNe Ia, SN 2011fe.

At later times still, the ejecta has expanded and cooled sufficiently that the assumption of a photosphere separating optically thick and thin regions is no longer valid. Once the entire ejecta has become optically thin, the SN has entered the so-called ‘nebular phase’. Nebular phase spectra may be used to probe the very deepest layers of the SN, where the explosion first originated. The photosphere has disappeared at these epochs and the observed spectra are driven primarily by $\gamma$-rays and positrons from the decay of $^{56}$Co (the daughter nucleus of $^{56}$Ni), which deposit their energy in the form of fast electrons. These electrons may then excite atoms within the ejecta to metastable levels – in other words, levels for which the chance of spontaneous re-emission is very small. Given the low density of the ejecta at these epochs, a second collision resulting in de-excitation is highly unlikely. Therefore atoms may exist in these metastable levels for a long period of time and radiative de-excitation becomes increasingly important, despite the low probability. Once emitted, photons may propagate unperturbed, again due to the low densities. Spectra therefore do not show a pseudo-continuum with superimposed spectral features as before, but instead are defined by a series of emission profiles from these ‘forbidden transitions’. Hence, these features remove energy from the ejecta, radiating it away, and are the dominant method by which SNe Ia cool at late times. Figure 1.5 shows a nebular spectrum for a SN Ia, SN 1998bu.

1.2 Peculiar type Ia supernovae

In 1991, two peculiar SNe Ia were discovered that have since become prototypes for their own respective sub-classes: the over-luminous SN 1991T (Filippenko et al. 1992b) and the under-luminous SN 1991bg (Filippenko et al. 1992a). The discovery of these objects highlighted that there is clearly a diverse set of explosions that are realised in nature. Explosion scenarios are discussed further in § 1.4.

Due to uncertainties in distance and host reddening estimates, the peak absolute magnitude of SN 199T has been revised numerous times in the literature (e.g. Phillips
Figure 1.4: Spectroscopic sequence of one of the most well observed SNe Ia, SN 2011fe. Phases are given relative to an estimated explosion data and B-band maximum. Tellurics and notable spectroscopic features are marked. Figure from Parrent et al. (2012).

et al. 1992; Ruiz-Lapuente et al. 1992; Saha et al. 2001). It is generally agreed, however, that 91T-like SNe are at least slightly more luminous than SNe Ia, and are therefore indicative of explosions producing more $^{56}$Ni (Blondin et al. 2012). Disregarding differences in peak luminosity, the overall light curve shape (Fig. 1.2) and colour evolution (Fig. 1.3) of SN 1991T was similar to SNe Ia (Phillips et al. 1992). Figure 1.1 shows how the peak magnitudes and decline rates of 91T-like SNe compare to those of normal SNe Ia. Despite disagreement over the luminosity of SN 1991T, the spectroscopic peculiarities were unmistakable. The pre-maximum optical spectra did not resemble that of other SNe Ia (Filippenko et al. 1992b). They instead showed a blue continuum with the only notably strong features resulting from Fe $\text{m}$. Around maximum light, features due to IMEs began to appear but never reached the strengths seen in SNe Ia – the strong absorption features in SNe Ia due to Si line and other IMEs were substantially weaker. After maximum light, the spectroscopic evolution of SN 1991T was similar to that of SNe Ia, until a few weeks later when it was virtually indistinguishable. Detailed spectral modelling of SN 1991T was performed by Sasdelli et al. (2014), who found that the ejecta region dominated by IMEs is much smaller than in SNe Ia, which could explain the weak features due to IMEs. The presence of IGEs in
the outer regions of the ejecta (i.e. IGEs are visible at early times) and the lower amount of IMEs produced is further evidence for diversity in thermonuclear explosions.

SN 1991bg lies on the under-luminous side of SNe Ia, being approximately three magnitudes fainter at peak in the $B$-band (Filippenko et al. 1992a). SN 1991bg showed a markedly different light curve to SNe Ia (Fig. 1.2). Following peak, SN 1991bg declined almost twice as fast as SNe Ia, indicating it may have ejected less material during the explosion. Together with the overall fainter peak luminosity, this would imply a less energetic explosion than is typical for SNe Ia. In addition, SN 1991bg showed intrinsically redder colours (Fig. 1.3) and no signs of a NIR secondary maximum (Fig. 1.2), potentially pointing to differences in ejecta composition or structure as well. In contrast to SN 1991T, the spectra of SN 1991bg appeared broadly similar to that of SNe Ia, although with slightly lower velocities and some differences in relative line strengths. In addition, modelling of a 91bg-like SN by Hachinger et al. (2009) indicated that the ejecta experienced incomplete Si-burning and less material was ejected to high velocities overall. Again, these differences compared to SNe Ia further highlight the diversity of explosion mechanisms that may be necessary to understand SNe Ia and these peculiar objects.

During the intervening years many other peculiar SNe Ia were discovered. Perhaps the most numerous of which are those that resemble SN 2002cx (Li et al. 2003). Much of the work presented in this thesis is aimed at establishing a more complete theoretical understanding of their nature.

1.3 Type Iax supernovae

SN 2002cx was discovered in May 2002, slightly offset from its host galaxy (Wood-Vasey et al. 2002). Based on subsequent photometric and spectroscopic follow-up observations, it was called ‘the most peculiar known type Ia supernova’ (Li et al. 2003). The overall behaviour of SN 2002cx was unlike any other SN previously observed; a pre-maximum spectrum showed similarities to SN 1991T, but the low luminosity light curve appeared more similar to that of SN 1991bg. A few dozen SNe with properties similar to SN 2002cx have been discovered. The class of objects that resemble SN 2002cx (‘02cx-likes’) have also been given the name type Iax SNe (SNe Iax) to distinguish them from SNe Ia (Foley et al. 2013). Foley et al. (2013) presented new and previously published literature data to investigate some of the properties of the class. A recent review is given by Jha (2017).

Thus far, no SNe Iax have been observed to occur in elliptical galaxies. The host galaxy distribution of SNe Iax is instead skewed towards late type galaxies (Foley et al.
2009), similar to core collapse SNe and unlike SNe Ia, which occur in all types of
galaxies (Maza & van den Bergh 1976). In addition, the locations of SNe Iax within
their host galaxies tend to show a preference for star-forming regions (Lyman et al.
2013, 2018). That SNe Iax tend to occur in late-type, star-forming hosts indicates that
the progenitor systems may be younger than those of SNe Ia.

1.3.1 Light curves

At peak, the $B$–band absolute magnitude of SN 2002cx was approximately one magni-
tude brighter than SN 1991bg in the $B$–band, and two magnitudes fainter than SNe Ia
(Li et al. 2003). With the discovery of more SNe Iax, their peak absolute magnitudes
have been shown to span a broad range, from $M_R \simeq -14.5$ (SN 2008ha; Valenti et al.
2009) to $M_r \simeq -18.6$ (SN 2012Z; Stritzinger et al. 2015). Despite the fact that SNe
Iax are at most as bright as SNe Ia, they generally show similar decline rates (Phillips
et al. 2007; Foley et al. 2013), although some objects have been observed to exhibit
extremely fast (Valenti et al. 2009; Stritzinger et al. 2014) or extremely slow (Narayan
et al. 2011) decline rates. Given the low luminosity for their light curve shape, SNe Iax
do not fall on the Phillips relation (see Fig. 1.1). The lower luminosities observed in
SNe Iax would indicate that these objects produce less $^{56}$Ni than SNe Ia. Estimates for
the amount of $^{56}$Ni produced by SNe Iax range from approximately 0.003 $M_\odot$ (Valenti
et al. 2009) to 0.3 $M_\odot$ (Narayan et al. 2011), much lower than in SNe Ia (Mazzali et al.
2007). Estimates for the ejecta mass range from approximately 0.1 $M_\odot$ (Valenti et al.
2009) to the $\sim 1.4$ $M_\odot$ (Narayan et al. 2011) that is typical of SNe Ia (Mazzali et al.
2007). That SNe Iax generally produce less $^{56}$Ni and ejecta (and lower ejecta veloci-
ties, see § 1.3.2) is a clear indication that these explosions must be less energetic than
SNe Ia. Furthermore, as SNe Iax have been shown to produce a range of $^{56}$Ni and ejecta
masses, there must also be a range of explosion strengths for these objects. The light
curves of SN 2002cx are shown in Fig. 1.2.

Unlike SNe Ia, there is also large diversity in the colours of SNe Iax and they do
not appear to follow the standard colour evolution of SNe Ia (see Fig. 1.3) or even
a standard colour evolution among the class. The colour evolution of SNe Iax was
investigated by Foley et al. (2013). Foley et al. (2013) show how, even when assuming
arbitrary reddening corrections, it is not possible to construct a tight colour evolution
across all photometric bands (akin to the Lira relation in SNe Ia, § 1.1.1) for SNe Iax.
Differences in colour evolution may be related to different nucleosynthetic yields or
physical conditions in the ejecta, and serve as further evidence for the diversity in the
explosion mechanism of SNe Iax. SNe Iax also do not show signs of the secondary
maximum observed in SNe Ia, and it has been suggested that this results from strong
mixing of the ejecta (see § 1.3.2; Jha et al. 2006; Phillips et al. 2007).

Due to the range in luminosities and light curve shapes of SNe Iax, the rate at which they occur is unclear. Li et al. (2011) find that SNe Iax occur at a rate of $\sim 5\%$ that of SNe Ia\(^1\). This sample lacked extremely faint objects and may therefore underestimate the true rate of SNe Iax. Foley et al. (2013) include a correction factor in their rate estimate, to account for the extremely faint objects that are less likely to be detected. They find that the rate of SNe Iax may be as high as $\sim 30\%$ that of SNe Ia. White et al. (2013) do include extremely faint objects ($M_R \approx -14$) in their volume limited sample and therefore neglect a correction factor, giving a rate comparable to that of Li et al. (2011). The rate at which these objects occur has obvious implications for proposed progenitor scenarios; however, it is clear that the range in luminosities produced by SNe Iax must be fully explored and understood before their true rate can be known.

1.3.2 Spectra

Spectra of SNe Iax are defined by low ejecta velocities, ranging from $2000 \lesssim |v| \lesssim 8000$ km s\(^{-1}\) at maximum light (Li et al. 2003; Valenti et al. 2009; Foley et al. 2013). SNe Iax generally show a weak correlation between ejecta velocities and peak brightness, with brighter objects having higher ejecta velocities. There exist notable outliers to this trend, however, indicating that SNe Iax may not necessarily be described as a single parameter family (Narayan et al. 2011; Tomasella et al. 2016). Together with the lower inferred $^{56}$Ni and ejecta masses, the low ejecta velocities of SNe Iax are further evidence that they result from explosions that release less energy than SNe Ia.

Pre-maximum spectra of SNe Iax appear similar to SN 1991T – a blue continuum, with weak features due to IMEs and strong features due to highly ionised IGEs (Li et al. 2003). Identification of spectral features in SNe Iax is aided by their low ejecta velocities, and therefore less line blending. Features due to IGEs are observed to be dominant throughout the spectral evolution (Branch et al. 2004). Figure 1.5 demonstrates the spectral evolution of a few SNe Iax. The identification of features due to IGEs at all epochs has led to the suggestion that the ejecta of SNe Iax is highly mixed, in direct contrast to that of SNe Ia (see § 1.1.2; Phillips et al. 2007). It has also been suggested, however, that some SNe Iax do show a layered structure similar to that of SNe Ia (Stritzinger et al. 2015; Barna et al. 2017). For one of the brightest SNe Iax, SN 2012Z, Stritzinger et al. (2015) argue in favour of a layered ejecta structure based on similarities in the velocities and their evolution compared to explosion models that

\(^1\)Note that here ‘SNe Ia’ also includes 91T- and 91bg-likes
produce a layered structure. Whether these models can reproduce the observed spectra and light curves of SN 2012Z remains to be seen. Barna et al. (2017) also argue that SN 2011ay is consistent with a layered ejecta structure, based on the agreement with empirical models that show a layered composition and disagreement with those that show a mixed composition. These objects demonstrate that perhaps multiple explosion scenarios may be necessary to explain the class and a more thorough investigation into the effects of mixing is warranted.

As discussed in § 1.1.2, SNe Ia transition to the nebular phase a few months post-maximum, where the spectrum is dominated by a number of emission features due to forbidden transitions. In contrast, it has been suggested that SNe Iax never transition to a fully nebular phase. Instead, SNe Iax show features due to permitted transitions at times far later than when SNe Ia have transitioned to the nebular phase (see Fig. 1.5; Jha et al. 2006; Sahu et al. 2008). Jha et al. (2006) present spectra of SN 2002cx over 200 days after maximum light that show a forest of narrow lines due to permitted transitions of IMEs and IGEs. Later still, Sahu et al. (2008) present the spectroscopic evolution of SN 2005hk up to almost 400 days post-maximum. Even at these extremely late times, SN 2005hk had not transitioned to a nebular phase and still showed the narrow permitted features observed at earlier epochs and in SN 2002cx. Foley et al. (2016) present an investigation into the late time spectra (> 100 days post maximum light) of a larger sample of objects (ten). They argue that the late time spectra of SNe Iax can be explained by a two component model. Here, the forbidden line emission is due to the low density SN ejecta (as in the case of SNe Ia), while the narrow permitted features result from a wind driven by a remnant of the explosion (see § 1.3.3). The diversity in late time spectra could therefore be due to differences in the relative strengths of these two components.

Carbon signatures in SNe Ia spectra are indications of incomplete thermonuclear burning and therefore provide constraints on the explosion scenario. Foley et al. (2013) investigate a sample of 11 SNe Iax with pre-maximum or maximum light spectra. They claim between 82 to 100% of their sample show either clear or suggestive signs of C II absorption features. The number of SNe Ia showing C features has been shown to be much lower ($\lesssim$ 30%; Parrent et al. 2011; Thomas et al. 2011; Folatelli et al. 2012; Silverman & Filippenko 2012). That C appears much more prevalent in SNe Iax could be an indication that more of the material is left unburned in SNe Iax relative to SNe Ia.

One of the most intriguing open questions related to SNe Iax spectra is the presence of helium features. He features have never before been observed in the spectra of SNe Ia and have clear implications for the progenitor system, as lone WDs are not expected
Figure 1.5: Spectra of SNe Iax (SNe 2002cx, 2005hk, and 2008A) and a SN Ia (SN 1998bu) at late times. Phases are given relative to the date of maximum light. All three SNe Iax show similarities to each other and are clearly distinct from the SN Ia. Figure from McCully et al. (2014b).

to contain He. Two SNe Iax have been claimed to show He\textsc{i} features, SN 2004cs and SN 2007J; however, whether these objects are indeed SNe Iax is currently debated (Foley et al. 2013; White et al. 2015; Foley et al. 2016). The presence of the reported He\textsc{i} features in SN 2007J increased in strength over time until the final spectrum obtained, approximately two or three months after maximum light. In order to determine whether SNe Iax do indeed show He\textsc{i}, it is therefore necessary to obtain a spectral sequence out to these relatively late epochs, as these features may not be visible at earlier times. In addition, He\textsc{i} produces a relatively strong transition around 10830 Å, while optical transitions are less easily excited. Therefore, spectra covering this wavelength region may provide a better opportunity for identifying He\textsc{i} in SNe Iax.

1.3.3 Progenitors & Remnants

SNe Iax are unique among thermonuclear SNe in that there have been claimed detections of a progenitor and a bound remnant for certain members of the class. To date there has been no direct detection of the progenitor to a SN Ia and SNe Ia are not ex-
pected to leave behind bound remnant objects. Therefore, the study of SNe Iax has allowed for an investigation into new areas of thermonuclear explosions that were previously not accessible.

McCully et al. (2014a) present the detection of a source (which they designate S1) in pre-explosion Hubble Space Telescope (HST) imaging that is coincident with the location of one of the brightest SNe Iax, SN 2012Z. These images were obtained up to seven years before the SN explosion. S1 was a luminous, blue source that showed some evidence of variability, leading McCully et al. (2014a) to argue that it was the helium star companion to an accreting WD. No other SN Iax has a claimed progenitor detection, yet pre-explosion imaging is available for a few other SNe Iax, allowing for useful constraints and massive stellar progenitors to be ruled out (Foley et al. 2010b, 2015). Subsequent follow-up will be able to determine whether S1 has disappeared following the explosion, and if it was indeed the companion star to a WD.

The detection of a remnant object has also been claimed for one of the faintest SNe Iax, SN 2008ha. Foley et al. (2014) present HST imaging, taken four years after the SN, showing a luminous, red source coincident with the location of SN 2008ha. They argue that this source is unlikely to be flux from the SN and instead suggest it is either the companion star to the progenitor WD or the remnant of the explosion. Determining whether this object is indeed a remnant of the explosion has profound implications for the explosion mechanism of SNe Iax. Models for exploding WDs, including those that are believed to produce bound remnants, are discussed further in § 1.4.

### 1.4 Explosion models

Understanding the explosion mechanism for thermonuclear SNe is the goal driving the work in this thesis. By modelling explosion scenarios, their observational signatures may be predicted and compared to observations of real SNe. Differences between models and observations may be used to further refine our theoretical understanding and future modelling efforts. This section discusses the proposed explosion scenarios for SNe Ia and SNe Iax, and how they relate to the observed properties discussed in § 1.1 and 1.3.

#### 1.4.1 Chandrasekhar mass explosions

In Chandrasekhar mass ($M_{\text{Ch}}$) explosions, the progenitor WD accretes material from a companion star. As the mass of the WD approaches $M_{\text{Ch}}$, the density within the core increases until eventually spontaneous carbon-oxygen (CO) burning begins. Burning is confined to a thin region, separating the burned and unburned material. Exactly how
this burning front propagates throughout the WD is not clear (see e.g. Hillebrandt & Niemeyer 2000, for a review).

In the prompt detonation scenario, the burning front moves throughout the WD as a supersonic shock wave (a detonation), igniting the CO fuel in front of it through compressional heating. As the detonation moves at supersonic speeds, the CO fuel has no time to expand and is burned completely to iron-peak nuclei (Arnett 1969). The prompt detonation of a M\text{Ch} WD therefore produces too much $^{56}$Ni and lacks the significant amount of IMEs expected from spectral observations, as discussed in § 1.1.2. Hence, the prompt detonation scenario is not regarded as a viable model for SNe Ia.

In order to produce a significant amount of IMEs, the WD must be pre-expanded to lower densities. This can be achieved if the burning front propagates as a subsonic flame, known as a deflagration. This subsonic propagation allows material ahead of the burning front to be heated and expand before it is consumed, therefore the amount of material fully burned to IGEs depends on the speed at which the deflagration front propagates (Nomoto et al. 1976). Initial one dimensional models used a parameterised description for this deflagration speed. The most well known of these is the W7 model (Nomoto et al. 1984), which provides excellent agreement with the light curves and spectra of SNe Ia and is still commonly used today. Subsequent multi-dimensional models suggested that pure deflagrations do not reach the velocities required to fully disrupt the WD (Livne 1993; Arnett & Livne 1994; Khokhlov 1995). More recent simulations have shown that the deflagration front is enhanced by Rayleigh-Taylor instabilities (e.g. Reinecke et al. 2002a,b). As the burning front propagates, it leaves hot, low density ash in its wake. The buoyancy of this ash accelerates the deflagration further to a point where it may be sufficient to unbind the WD.

Röpke et al. (2007) demonstrated that even the strongest of their explosion models (which do completely unbind the WD) do not produce enough $^{56}$Ni ($\lesssim 0.3$ M\odot) to explain the bulk of SNe Ia (approximately 0.3 M\odot to 1 M\odot of $^{56}$Ni; Mazzali et al. 2007). This was further demonstrated by Fink et al. (2014), who show that the light curve of their strongest deflagration models (producing 0.34 M\odot of $^{56}$Ni) is too faint to be consistent with SNe Ia. In addition, the strong mixing induced in the ejecta is contrary to what is observed for SNe Ia (see § 1.1.2), and spectra lack the strong features due to IMEs (such as Si ii) that are defining characteristics of SNe Ia. Figure 1.6 shows the evolution of the turbulent flame for a pair of pure deflagration models.

It has since been demonstrated, however, that the properties which make pure deflagrations unsuitable for SNe Ia make this scenario a promising potential candidate for producing SNe Iax. In particular, the light curves and spectra of SNe Iax appear to
Figure 1.6: Evolution of the explosion for N1def (left) and N20def (right) models, where the numbers correspond to the number of sparks used to ignite the model and typically correlate with $^{56}\text{Ni}$ production. Times are given relative to explosion. The ejecta has been colour coded to the products of nucleosynthesis. Black outlines in the centre of the bottom panels indicate the regions that do not become gravitationally unbound at the end of the simulation. Figure from Fink et al. (2014).

be in good agreement with pure deflagrations that are sufficiently weak as to not fully disrupt the WD (Kromer et al. 2013, 2015). The low luminosities of this scenario can
match the faintness of SNe Iax, while spectra show low velocities and weak features due to IMEs, similar to what is observed in SNe Iax. Models invoking these so-called ‘failed deflagrations’ have been shown to leave behind a remnant object that remains gravitationally bound immediately after the explosion. The possible bound remnant discovered for SN 2008ha (see § 1.3.3) is qualitatively consistent with predictions for these models (Foley et al. 2014), potentially indicating a failed deflagration origin. Detections of further bound remnants for SNe Iax could provide a clear signature of a pure deflagration. The pure deflagration scenario as a viable model for SNe Iax is discussed further in Chapter 4.

Neither prompt detonations nor pure deflagrations are suitable for SNe Ia. A combination of the two scenarios, however, has proven to be extremely promising. The deflagration-to-detonation transition (DDT) scenario begins initially as a subsonic deflagration before transitioning to a supersonic detonation (Khokhlov 1991a). As in the pure deflagration scenario, the initially subsonic burning provides time for the WD to expand. This allows the subsequent detonation to burn material at lower densities, producing the IMEs that were absent from prompt detonations. In addition, the detonation wave burns more of the WD to 56Ni than in the pure deflagration scenario and overwrites the inhomogeneities produced by the turbulent motion of the deflagration, producing a layered ejecta structure similar to what is inferred for SNe Ia.

The exact circumstances of the transition are not known, but are often treated as a free parameter in simulations. In the one-dimensional models presented by Hoeflich & Khokhlov (1996), a detonation is enforced during the explosion by artificially accelerating the deflagration front once the density ahead of the front reaches a critical value. Hoeflich & Khokhlov (1996) find that their models can reproduce the light curves and velocity evolution of SNe Ia. In addition, they find that the strength of the explosion generally scales with the transition density, which could explain some of the diversity observed in SNe Ia. Kasen et al. (2009) present two-dimensional simulations of DDT models, in which a detonation was triggered depending on certain mixing and density criteria. They showed that this scenario is able to broadly reproduce the Phillips relation (see § 1.1.1). Furthermore, Seitenzahl et al. (2013) present a series of multi-dimensional DDT models in which the strength of the initial deflagration is treated as a free parameter and the detonation is artificially triggered in regions with sufficiently high turbulent velocities. Unlike the case of pure deflagrations, Seitenzahl et al. (2013) find that the strength of the explosion (and hence 56Ni mass produced) is inversely proportional to the strength of the initial deflagration – in other words, those models with strong deflagrations sufficiently perturb the WD such that the detonation occurs at lower densities, and hence less 56Ni is produced. While some of these models produce the appropriate luminosity and match spectra of SNe Ia around maximum light (Sim
et al. 2013), noticeable differences remain, particularly in the velocities and colour. These models are also not able to reproduce the Phillips relation (see § 1.1.1), therefore Sim et al. (2013) suggest that either this scenario does not dominate the production of SNe Ia or the strength of the deflagration is not the primary parameter driving variation among SNe Ia resulting from this scenario. Figure 1.7 demonstrates the evolution of the turbulent burning front and transition to detonation.

Related to DDT models are the so called pulsational delayed detonation (PDD) models (Khokhlov 1991b). Similar to DDT models, burning initially begins as a sub-sonic deflagration and expands the WD. In the case of PDD models, however, the deflagration does not spontaneously transition to a detonation. Instead, the burning front eventually stops due to the expansion and decreased density (similar to the case of failed deflagrations), and the WD then begins to contract again. Mixing of the hot burned ash and cool unburned fuel allows for burning to continue again; the WD experiences a ‘pulsation’ and it is at this point that the detonation triggers, due to the compression of the mixed material (Nomoto et al. 1976; Hoeflich et al. 1995). The pulsation and resulting detonation can have profound implications for the ejecta morphology, discriminating this scenario from the more standard DDT. Following the pulsation, material falling back towards the centre of the WD interacts with the outgoing detonation shock wave, forming a shell of increased density (Hoeflich et al. 1995). Owing to their different ejecta structures, predictions for observations at early times from PDD models differ significantly from DDT models (Dessart et al. 2014a). The range of $^{56}$Ni masses produced by PDD models means that this scenario could account for the bulk of SNe Ia; however, as with DDT models, this scenario is not able to reproduce the full Phillips relation (Blondin et al. 2017). In addition, whether the PDD scenario is realised in multi-dimensional models remains to be seen. The ability of PDD models to produce a range of $^{56}$Ni masses and a layered ejecta structure led Stritzinger et al. (2015) to argue that this may be a viable scenario for SNe Ia and SNe Iax.

1.4.2 Sub-Chandrasekhar mass explosions

As mentioned in § 1.1, it may be possible for WD explosions to occur below $M_{\text{Ch}}$. In this case, the initial burning is triggered not from the core of the WD approaching $M_{\text{Ch}}$, but instead from some external source. Stritzinger et al. (2006) have shown that a range of ejecta masses may be necessary to explain SNe Ia, rather than the canonical $\sim 1.4\, M_{\odot}$ of $M_{\text{Ch}}$ models. Such a scenario (as well as a range of $^{56}$Ni masses) could naturally be explained by sub-$M_{\text{Ch}}$ models, and could directly relate variations in the explosions to the stellar masses.
Figure 1.7: Evolution of the explosion for N3 (left) and N100 (right) models, where the numbers correspond to the number of sparks used to ignite the model and typically inversely correlate with $^{56}$Ni production. Times are given relative to explosion. The evolution of the turbulent deflagration wave is shown in white, while the detonation is shown in blue. The entire explosion is shown inside a volume rendering of the density. Figure from Seitenzahl et al. (2013).

Sim et al. (2010) study the prompt detonation scenario (as discussed in § 1.4.1) applied to sub-$M_{\text{Ch}}$ WDs. Although they do not consider the cause of this detonation,
detonations of sub-M_{Ch} WDs naturally explain the presence of a relatively large mass of IMEs, due to the lower mass of the WD and hence burning at lower densities. They show how detonations of approximately 1 M_{\odot} to 1.2 M_{\odot} WDs can produce light curves of approximately similar luminosity and shape to SNe Ia. These models also produce an ejecta structure that is qualitatively consistent with SNe Ia, and spectroscopic features around maximum light broadly match the strengths and velocities of those in SNe Ia.

One possibility for triggering the explosion of a sub-M_{Ch} WD is the double detonation scenario, in which He is accreted onto the WD from the companion star and triggers a detonation in the outer He layer. Such detonations may then drive a shock through the WD that is powerful enough to ignite CO burning in the core, leading to the explosion of the WD (Livne 1990). Early double detonation models invoked relatively large He shell masses (approximately 0.1 M_{\odot} to 0.3 M_{\odot}) to detonate WDs with masses ranging from approximately 0.6 M_{\odot} to 1.0 M_{\odot} (Livne & Glasner 1991; Woosley & Weaver 1994). These models are able to produce $^{56}$Ni masses and light curves in broad agreement with observations of SNe Ia; however, the presence of $^{56}$Ni and He at high velocities and the lack of strong features due to IMEs puts these models in disagreement with observations (Hoeflich & Khokhlov 1996; Nugent et al. 1997). Recent simulations have shown that lower mass He shells (approximately 0.003 M_{\odot} to 0.13 M_{\odot}) may be sufficient to detonate the He layer (Bildsten et al. 2007; Shen & Bildsten 2009; Fink et al. 2010), and that once a detonation is triggered here, a second detonation within the core is all but inevitable (Fink et al. 2007). Kromer et al. (2010) present predictions for the light curves and spectra from the double detonation models of Fink et al. (2010). They show how these models are also able to broadly reproduce observations of SNe Ia; however, the production of various IGEs within the He shell generally leads to strong line blanketing (see § 1.1.2) and reduced flux at ultraviolet and near-ultraviolet wavelengths. Kromer et al. (2010) also demonstrate how the nucleosynthetic yield of the explosion is highly sensitive to the initial composition of the He shell, and improved agreement with observations may be achieved if the He shell was polluted with other elements (specifically carbon).

The merger of two WDs may also trigger a sub-M_{Ch} explosion (Iben & Tutukov 1984; Webbink 1984). Although each WD may have a mass below M_{Ch}, the total mass of the system will typically exceed M_{Ch}. Initial simulations of merging WDs did not produce explosions, but instead resulted in the more massive WD accreting material from the less massive companion and eventually collapsing to form a neutron star (Saio & Nomoto 1985; Benz et al. 1990; Nomoto & Kondo 1991). Recent simulations have demonstrated the possibility of other merger scenarios (Pakmor et al. 2010). In ‘violent mergers’, as the period of the binary system shortens, the two WDs will eventually reach a point where one of them is disrupted due to tidal forces. The disrupted
WD begins to merge with the remaining WD, causing compressional heating. If this compressional heating is large enough, CO burning may be ignited, and a detonation formed. One of the main advantages of the violent merger scenario is that it naturally explains the lack of H and He in the spectra of SNe Ia. While Pakmor et al. (2010) were able to achieve an explosion in their violent merger models, the low density of the merged object results in the production of predominantly IMEs and only a small \( ^{56}\text{Ni} \) mass (\( \sim 0.1 \text{ M}_\odot \)). Therefore, this particular realisation of WD mergers is not suitable for normal SNe Ia, but provides relatively good agreement to SN 1991bg-like SNe (Pakmor et al. 2010). Pakmor et al. (2012) investigate a binary system containing a primary \( 1.1 \text{ M}_\odot \) WD and a secondary \( 0.9 \text{ M}_\odot \) WD (as opposed to the two \( 1.1 \text{ M}_\odot \) WDs of Pakmor et al. 2010). They find this configuration is able to produce the large \( ^{56}\text{Ni} \) mass typical of SNe Ia (\( \sim 0.6 \text{ M}_\odot \)) and better matches their light curve shape. In addition, spectra from this scenario are able to reproduce many (but not all) of the features observed in SNe Ia. During the merger, the secondary WD is completely destroyed and the primary remains largely unaffected. Therefore, the density of the primary WD strongly affects the amount of \( ^{56}\text{Ni} \) and IGEs produced during the explosion, and the total amount of \( ^{56}\text{Ni} \) synthesised is directly correlated with the mass of the primary WD (Pakmor et al. 2012).

It is clear that each explosion scenario presents unique strengths and weaknesses. Currently, no single explosion mechanism is capable of fully matching all SNe Ia, therefore multiple scenarios may be necessary. Only by comparing models and their predictions to observations will the true nature of thermonuclear SNe become clear.

1.4.3 Core collapse

Although the thermonuclear nature of SNe Ia has been well established at this point (as described in the previous sections), whether this also held true for SNe Iax was initially somewhat unclear. For completeness, this section outlines the alternative scenarios, which were primarily argued for on the basis of a single object, SN 2008ha.

It has been argued that SNe Iax are not in fact thermonuclear in nature, but instead result from the core collapse of a massive star (Valenti et al. 2009; Moriya et al. 2010). Core collapse refers to the process by which the core of a star with an initial mass \( \gtrsim 8 \text{ M}_\odot \) is no longer able to produce enough energy to support the star against gravitational collapse. Valenti et al. (2009) present observations of SN 2008ha beginning approximately three days before \( R \)-band maximum. Valenti et al. (2009) argue that the faint peak absolute magnitude (\( M_R \approx -14.5 \)), low ejecta velocities (\( \sim 2300 \text{ km s}^{-1} \)), and rapid photometric and spectroscopic evolution of SN 2008ha are more consistent with a class of faint SNe II, and have never been observed in thermonuclear SNe. Figure 1.8
shows a late time spectrum of SN 2008ha compared to SNe of other types. Valenti et al. (2009) propose two alternative explosion scenarios for SN 2008ha: the direct collapse of a massive star (\(\gtrsim 40 \text{ M}_\odot\)) to a black hole or the collapse of an oxygen-neon core of a massive star (approximately 7 \(\text{ M}_\odot\) to 9 \(\text{ M}_\odot\)) due to electron captures. Recognising the similarities of SN 2008ha to SN 2002cx and other members of the class, they argue that, by extension, all SNe Iax may be core collapse SNe.

For stars with initial masses \(\gtrsim 40 \text{ M}_\odot\), the core will continually fuse heavier elements over the lifetime of the star until it forms iron. At this point, there is no longer sufficient energy production to halt the collapse and the massive iron core may collapse to form a black hole either directly or later through the accretion of fallback material on the proto-neutron star (MacFadyen et al. 2001; Heger et al. 2003). Such an explosion is expected to produce only a faint SN (if any), and Moriya et al. (2010) show that models of core collapse, followed by fallback, can reproduce the light curve of SN 2008ha. Alternatively, core collapse may be induced via electron capture. Stars with initial masses between approximately 7 \(\text{ M}_\odot\) and 9 \(\text{ M}_\odot\) will develop degenerate oxygen-neon-magnesium cores. Electron capture onto \(^{20}\text{Ne}\) and \(^{24}\text{Mg}\) can then trigger core collapse by reducing the electron degeneracy pressure (Miyaji et al. 1980). These explosions are also expected to release only a small amount of energy, consistent with SN 2008ha (Kitaura et al. 2006).

Foley et al. (2010a) presented a previously unpublished spectrum of SN 2008ha, taken approximately one week before the earliest spectrum of Valenti et al. (2009), that shows clear sulphur features. They argue that the strong S features observed in SN 2008ha indicate a WD progenitor, and that observations of SN 2008ha are instead consistent with a failed deflagration scenario. Studies of failed deflagrations in CO WDs have shown that this scenario produces too much \(^{56}\text{Ni}\) to match the low luminosities of SN 2008ha (Jordan et al. 2012; Fink et al. 2014). Recent simulations, invoking hybrid WDs (a carbon-oxygen core, surrounded by an oxygen-neon mantle) have shown some promise in reproducing the low \(^{56}\text{Ni}\) mass required of SN 2008ha (Kromer et al. 2015). In this case, the initial carbon burning deflagration begins as described in § 1.4.1. Once the deflagration front reaches the O-Ne mantle, however, \(^{56}\text{Ni}\) production is halted, as C burning can no longer continue. The result is that only a small amount of \(^{56}\text{Ni}\) is produced or mass ejected, and the remaining material continues to be bound. The model presented by Kromer et al. (2015) is able to reproduce many of the features observed in SN 2008ha and produces a remnant object qualitatively similar to that discussed in § 1.3.3; however, it shows an overall evolution much faster than what is observed. In addition, Brooks et al. (2017) argue that mixing between the CO core and O-Ne mantle will occur before the hybrid WD is able to reach \(M_{\text{Ch}}\), and therefore
Figure 1.8: Spectroscopic comparison of SN 2008ha (black) at 62 days post $B$–band maximum compared to SNe of other types (red): SN 2007J (a possible SNe Iax or SNe IIb; see § 1.3.2), SN 1989B (SNe Ia); SN 2004aw (a peculiar SN Ic originally classified as SN Ia); SN 2005cs (a peculiar and low-luminosity SN II); SN 2005E (a so-called ‘Ca-rich’, under-luminous SN Ib). Spectra of SNe 1989B and 2004aw have been artificially redshifted by 3 000 km s$^{-1}$. Figure adapted from Foley et al. (2009).

it is unclear if the models of Kromer et al. (2015) may be realised in nature.

Stritzinger et al. (2014) present extensive observations (ranging from ~2 days before maximum light to over 250 days later) for SN 2010ae, another extremely low-luminosity SNe Iax (peak absolute magnitude of $-13.8 > M_V > -15.3$), which appeared
similar to SN 2008ha. They argue that the observations of SN 2010ae are fully consistent with a thermonuclear origin. As demonstrated by SN 2008ha, observations at early and late times can play a critical role in correctly identifying and understanding SNe Iax. Chapter 5 demonstrates how spectra at early times may provide additional constraints on the explosion mechanism. While mounting evidence would seem to suggest that SNe Iax are indeed thermonuclear and not due to core collapse, the exact explosion mechanism remains an open question. Much of the work presented in this thesis aims at addressing the current lack of understanding regarding the explosion mechanism and related physics of SNe Iax.

1.5 Summary

The purpose of this chapter has been to highlight the observational diversity of thermonuclear SNe and the equally diverse set of explosion scenarios proposed. We have seen how SNe Ia have broadly similar peak magnitudes and colour evolutions, and their spectra indicate a layered structure to the ejecta. SNe Iax, on the other hand, are much more heterogeneous. They display vastly different light curve luminosities and shapes, and their spectra do not show the same strong features due to IMEs observed in SNe Ia.

The similarities of SNe Ia to each other could be indicative of a common explosion mechanism, while the diversity of SNe Iax could indicate either multiple explosion mechanisms are necessary or the same explosion mechanism can produce vastly different results. Regardless, extensive modelling efforts have shown that many different thermonuclear explosion scenarios are possible, and that each scenario has its own strengths and weaknesses. In addition, multiple scenarios are capable of producing models for which the level of agreement compared to observations is similar. We must therefore look to specific signatures that may be used to discriminate between these cases.

In this thesis, we will aim to add further constraints to the explosion mechanisms for thermonuclear SNe. We will investigate the diversity of SNe Iax and the implications for specific scenarios. We will also show how the early light curves of SNe Ia may provide a necessary differentiator between explosion mechanisms.
The purpose of this chapter is to describe the process of data reduction for astronomical images and spectra. When an astronomer images the sky, he or she is generally only concerned with a particular source or sources. The purpose of data reduction is therefore to extract as much information as possible from the source of interest and remove any contamination. For example, this may be removing noise introduced by the CCD or electrical equipment, or removing the sky background during spectral extraction. For the data reduction performed throughout this thesis (Chapter 4), the PESSTO pipeline, as described in Smartt et al. (2015), was used. The PESSTO pipeline is a Python wrapper around standard IRAF tasks. This section details the complete steps and IRAF tasks used during the reduction process that are applicable to the reduction of data in general. The process of reducing imaging data and photometry is described in § 2.1, while § 2.2 describes reducing spectroscopic data.

The cover image for this chapter shows the supernova SN 1993J in M81. Image credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA); Acknowledgment: A. Zezas (Harvard-Smithsonian Center for Astrophysics).

2.1 Imaging

2.1.1 Optical reduction

Although no light may be falling on a CCD, a signal will still be registered when it is read out. This signal is known as the bias and represents the background level for all exposures taken on that CCD, regardless of the exposure length. The bias is typically removed from all CCD images through the use of bias frames, a series of zero second exposures taken usually either before a night of observing begins or once it has ended. Around 10 to 20 bias frames are taken per observing night and are stacked to produce a master bias. Stacking is performed using the IRAF task ZEROCOMBINE, which takes the median value of each pixel in the frame from the stack. By median combining a stack of bias frames, the uncertainty in the bias level is reduced and any signal resulting from errant cosmic rays is removed. The master bias may then be subtracted from each subsequent image taken, through the CCDPROC task.

Another form of noise generally present in CCD imaging is the dark current. Similar to the bias, the dark current is also present when no light falls on the CCD. During any exposure time, random thermal motions of the electrons within the CCD will produce a signal. The rate at which this signal increases is known as the dark current, and is typically given as a number of electrons per pixel per hour. Correcting science exposures for this effect requires scaling the dark current to the appropriate exposure time and subtracting. Alternatively, the dark current may be sufficiently reduced by cooling
the CCD. This is the case for the observations presented in Chapters 4 & 5, where the respective CCDs are cooled to between approximately 100 K and 150 K and the dark current is therefore sufficiently small as to be ignored.

Even after correcting for the bias and dark current, if a telescope were to be pointed at a uniformly illuminated source, the same signal would not necessarily be registered in every pixel of the CCD. Dust and other optical defects may affect the amount of light that actually reaches the CCD, while each pixel will also generally vary slightly in its sensitivity or quantum efficiency (QE). Correcting for such pixel-to-pixel variation is known as flat-fielding and produces an image of the target as if each pixel responded in exactly the same way.

For images, flat-fielding is generally performed with twilight flats and/or dome flats. As their names suggest, twilight flats are images taken of the night sky during twilight before and/or after an observing night, while dome flats are taken of a uniformly illuminated source (usually a screen) inside the observatory dome. Flats may also be stacked in the same manner as bias frames, using the FLATCOMBINE task. Indeed, this may be particularly important for twilight flats if stars are visible. By offsetting the telescope slightly between exposures, stars can be removed in the combined image, leaving just the twilight sky. As the sources of noise mentioned above (e.g. dust, QE variations) are multiplicative in nature (e.g. dust will block some fraction of the incident light), the procedure for flat-fielding is to first normalise the flat to the mean pixel value across the CCD and then divide each science image by the normalised flat. As with the bias correction, this is also performed using the CCDPROC task.

Figure 2.1 shows an image before and after bias and flat-field correction. The data reduction pipelines mentioned in § 4.3 & 5.2 for LSQ (Baltay et al. 2013), LCOGT (Brown et al. 2013), PS1 (Magnier 2007; Schlafly et al. 2012), FTN (Brown et al. 2013), and LT (Steele et al. 2004) images perform these calibrations automatically.

2.1.2 Near-infrared reduction

Unlike optical images, separate bias corrections are not applied to the IR data presented in § 4.3. This is due to the fact that IR arrays operate differently compared to CCDs. Zero second exposures are not possible for IR arrays, as there is no shutter. Instead, integrations are defined electronically by sampling the voltage between two (or more) different times. The bias level is therefore subtracted automatically from each pixel. In addition, the dark current will usually vary with exposure time and incident flux. The dark current is therefore subtracted along with the sky background and separate
Flat-fielding IR images is also slightly different compared to optical images. Flats for IR images are taken by alternatively exposing the dome screen, with (on-lamp) and without (off-lamp) illumination. The off-lamp flats may then be subtracted from the on-lamp flats, to remove the thermal background of the system which does not depend on the intensity of the incident light, using the `imarith` task. The procedure is then similar to that described above for optical images.

An important aspect of IR imaging is the sky background, which is typically much higher than for optical images. To combat this, IR images are taken in a dither pattern. This involves imaging the desired target at multiple positions that are offset from each other. The telescope is then moved a few arcseconds away, where an uncrowded field is imaged, again at multiple offset positions. Images of the uncrowded field are combined to obtain the sky background, which is then subtracted from each image of the target. Finally, the target images are aligned and stacked, using `imcombine`, to produce the final science image. This is known as off-source or on-off sky subtraction, and was used for the IR observations of SN 2015H presented in § 4.3.1.

### 2.1.3 Photometry with SNOoPY

The vast distances associated with observing stars and SNe allows these objects to act as point sources. When imaging with telescopes, however, they are generally not confined to a single point on the CCD, but are instead dispersed across perhaps a few pixels.
This results from both atmospheric disturbances and diffraction due to the telescope optics, and is known as a point spread function (PSF). In order to accurately determine the brightness of an object, all of the light from this PSF must be collected. Throughout this thesis, this was performed through PSF-fitting photometry with the SuperNOva PhotometrY (SNOoPY)\(^1\) package. As the name suggests, PSF-fitting is an attempt to model the shape of the PSF for a specific image and use it for photometry, thereby collecting light that may otherwise be lost (in the wings of the PSF, for example) to aperture photometry.

SNOoPY is an IRAF package designed for easily performing PSF-fitting photometry. The target image is displayed and the user is requested to select a number of reference stars. In order to obtain an accurate model of the PSF, these stars should be bright relative to the background and not lie in crowded areas. The PSF of each reference star is measured and used to create an average PSF for the entire image. Figure 2.2 shows an example PSF measured for one of the reference stars listed in Table 4.2. Once the PSF of the image has been calculated, it is scaled to match each of the reference stars and then subtracted, giving their instrumental magnitudes.

With the PSF of the image obtained, photometry can now be performed on the SN. The target image is displayed again and the user is now requested to select the SN. A fit to the background surrounding the SN is obtained and subtracted from the image. The PSF is then scaled to match the SN and subtracted from the image, giving an initial

\(^1\)http://sngroup.oapd.inaf.it/snoopy.html
Figure 2.3: Residual of the SN subtraction from SNOoPY. Left: The original SN image. Middle: The fit obtained for the PSF to the SN. Right: The location of the SN, with the fitted PSF subtracted

estimate of the instrumental magnitude of the SN. A new estimate for the background is obtained from the residual image and the procedure iterated upon, in order to obtain the final SN magnitude. Figure 2.3 shows an original image of the SN, the PSF scaled to match the SN, and the residual image obtained after subtracting the PSF fit. An estimate of the uncertainty in the instrumental magnitudes is obtained through so-called ‘artificial stars’. Here, fake sources with the same PSF shape and magnitude are placed in various positions slightly offset to that of the SN. Their magnitudes are then measured with the same technique used for the real source, with the dispersion in the recovered magnitudes giving the uncertainty for the instrumental magnitude. This uncertainty is then added in quadrature to the uncertainty from the PSF fit.

If the SN lies in a crowded field or is contaminated by host galaxy light, template subtraction may be necessary before photometry can be performed. Template subtraction refers to the process of subtracting an image of the SN field (a template) from the target image. The template should be from long before or after the SN became visible – in other words, it should not contain any light from the SN. Template subtraction will produce a difference image that only contains light from the SN. A reference PSF can be built up on the target image in the same manner as before. This PSF can then be used on the difference image for photometry of the SN, as described above.

Finally, the instrumental magnitudes must be calibrated and placed on a standard photometric scale. This can be done through comparisons with known catalogue magnitudes of the PSF reference stars. The calibrated magnitude of the target is given by:

\[ m_x = m_{\text{inst}} + ZP_x + C_{xy} \times (m_x - m_y), \]  

(2.1)

where \( m_{\text{inst}} \) is the instrumental magnitude, \( ZP \) is the zero-point, \( C \) is a colour coefficient, and \( x \) and \( y \) are filters. An average zero-point may be calculated from the difference
between the instrumental and catalogue magnitudes of the PSF reference stars. When comparing observations across different telescopes and catalogues, there may be small differences in the filter functions that could result in slightly different calibrated magnitudes. Therefore, it is sometimes necessary to include a colour correction to place the observations on exactly the same filter system. The colour coefficient, $C_{xy}$, may be calculated iteratively from the offset between $m_{\text{inst}} + ZP$ and the catalogue magnitude for each of the reference stars, as a function of colour, $m_x - m_y$. Generally, this correction is small, and may even be less than the photometric uncertainty on the instrumental magnitudes.

2.2 Spectroscopy

Reducing spectroscopic data requires the same bias and dark current correction that is applied to imaging data, as described in § 2.1.1. The process for spectral flat-fields is somewhat different compared to imaging flat-fields. As the incident light is dispersed across the CCD, the measured pixel-to-pixel variation is now also a function of wavelength. An example of this is shown in Fig. 2.4. In addition, twilight flats cannot be used for spectroscopic reduction, as a uniform source is required and the sky spectrum is home to numerous spectral features. Therefore, dome flats are used with the screen mentioned above illuminated by a continuum spectrum. Using the task `apflatten`, the wavelength response of the CCD is fit and used to divide the master flat along the dispersion axis. The result is a master flat that no longer depends on wavelength, but only the pixel-to-pixel variation of the CCD, as shown in Fig. 2.5. As before, each science image may then be divided by this flat, again using `ccdproc`.

For IR spectroscopy separate bias and dark current corrections are not applied (as discussed in § 2.1.2), and flat-fielding uses on- and off-lamp exposures – similar to IR imaging. As with IR imaging, the high sky background necessitates observing in a dithering pattern – ABBA, in the case of PESSTO. An exposure is first taken with the target at position A in the slit. The target is then moved along the slit to B, at which point two exposures are taken. The target is moved back to position A and a final exposure taken. Pairs of AB images are subtracted from each other (A $-$ B, B $-$ A) producing bias and sky subtracted frames, each containing a positive and negative spectrum. The images are then shifted, such that the positive spectra lie at the same pixel coordinates, and combined – similar to combining IR imaging frames.

Having removed unwanted sources of noise and produced a uniform response image, the data can now be calibrated. Generally, we do not wish to present spectra as
**Figure 2.4:** *Left:* Spectroscopic flat-field image before removing the wavelength variation. The red line shows the column for which the pixel-to-pixel variation was measured. The variation in counts is represented by the grey scale. *Right:* Pixel-to-pixel variation along the dispersion axis for a single column. The wavelength response is clearly demonstrated, as low pixel values tend to have much lower signal than high pixel values.

**Figure 2.5:** *Left:* Spectroscopic flat-field image after removing the wavelength variation and normalising. The red line shows the column for which the pixel-to-pixel variation was measured. Grey-scale shows variation in counts. The image shows a more uniform grey colour than Fig. 2.4, indicating the count values measured no longer depend on wavelength. Fringe patterns are also clearly visible after removing wavelength variations. *Right:* Pixel-to-pixel variation along the dispersion axis for a single column. The wavelength response of the CCD has been removed. Due to the low signal-to-noise ratio at short wavelengths, standard PESSTO practice is to set the first 300 pixels equal to unity for this grism. After removing wavelength variation and normalising, fringing effects become more apparent for larger pixel values.
functions of pixel positions. The purpose of wavelength calibration is therefore to assign a wavelength value to each pixel along the dispersion axis. This is usually done through the use of a comparison spectrum with known emission features, commonly referred to as an ‘arc’. Comparison spectra are observed with the same instrumental set-up as the science target. Once observed, the location of each emission feature on the CCD can be paired to the known wavelength value at which this feature occurs, using the IDENTIFY task. A fit to the relation between these quantities is known as the dispersion solution, $\lambda(x)$, and can be used to give the wavelength value of any pixel on the CCD. The dispersion solution can then be applied later to science images to convert their CCD coordinates into wavelengths. Figure 2.6 shows an example of a comparison spectrum used for wavelength calibration, and the identification of emission features transformed into wavelength coordinates.

Spectral extraction is performed using the APALL task, and refers to the process of identifying the rows and columns of the CCD that correspond to the spectrum of the target, known as the trace. If the dispersion axis ran perfectly parallel to one of the CCD axes, then extraction would require simply defining the minimum and maximum boundaries for the extraction aperture. Due to optical distortions, however, this is generally not the case and the trace usually also curves slightly along the spatial axis of the CCD. This is demonstrated in Fig. 2.7. The extraction aperture must then also vary along the spatial axis. The procedure is to define the extraction aperture at a single point and fit for the location of the trace along the dispersion axis. Flux within the aperture may then be counted, giving the intensity of the spectrum as a function of CCD position, $A(x)$. This intensity will also include some background due to the sky, therefore addi-
Figure 2.7: Left: Defining the aperture for extracting trace of standard star, LTT3864. The horizontal axis shows the \( x \)-coordinate on the CCD, while counts are shown along the vertical axis. The positions of the extraction and background apertures are marked in black. Right: Location of the trace (aperture centre) along the CCD. The CCD \( y \)-coordinate is given by the horizontal axis, and the CCD \( x \)-coordinate is given by the vertical axis. The fit shows a slight curvature of a few pixels across the CCD.

Estimation apertures surrounding the trace are defined to include only the background, \( B(x) \). The science spectrum is then given by subtracting the background, \( I(x) = A(x) - B(x) \). Combining the spectrum with the dispersion solution previously calculated, \( \lambda(x) \), gives the science spectrum intensity as a function of wavelength, \( I(\lambda) \). Figure 2.7 shows how the extraction and sky background apertures are initially defined, and how the location of the trace varies along the CCD.

The extracted and wavelength calibrated spectrum includes not just the spectrum of the target, but also the effects of the CCD response and atmospheric transmission, both of which vary with wavelength. In addition, this spectrum is given in counts and not flux. Transformation to physical flux units, as well as response corrections, are performed by comparison with spectroscopic standard stars. As with arcs, standard stars must be observed with the same instrumental set-up as the target, and ideally at as close to the same airmass as possible.

Using the standard task, the observed spectrum of the calibration star is integrated over small bandpasses at various wavelengths. The sensfunc task then compares the observed magnitudes to the standard magnitudes and computes a correction factor for each wavelength, known as the sensitivity function. An example sensitivity function is shown in Fig. 2.8. The observed science spectrum is then divided by the sensitivity function, using the calibrate task, which removes the wavelength response of the CCD and converts the observed counts into physical flux units.

The final step involves correcting for the presence of tellurics – strong absorption
features due to water vapour and O$_2$ in the Earth’s atmosphere. Correcting for these telluric features is particularly important for IR spectra, where they may entirely dominate certain regions of the spectrum. Optical spectra are also affected by tellurics but to a much lesser extent. The standard star spectrum is first divided by a template spectrum with the same spectral type. This removes the spectral features due to the star and produces a spectrum containing only the telluric features, which can then be divided into the science spectrum to remove the tellurics.

Figure 2.9 shows a comparison between a raw image taken by a telescope and the fully reduced and calibrated spectrum. With a reduced and calibrated spectrum, analysis can now be performed.
Figure 2.9: Top: Raw spectral image of SN 2015H taken with EFOSC on the New Technology Telescope (NTT). Bottom: Spectrum after the full reduction process.
Chapter 3

Monte Carlo radiative transfer
Monte Carlo techniques generally refer to any method by which random numbers are used to perform an experiment or simulation of some kind. This section details the Monte Carlo methods used in radiative transfer modelling of SNe. Specifically, this section describes in detail a new Monte Carlo radiative transfer code used to model the light curves of radioactively driven transients, TURTLS\(^1\), that was developed during the course of this thesis. The physical assumptions fundamental to our code are introduced in § 3.1, 3.2, 3.3, & 3.4. The operation of the code itself is described from § 3.5 to § 3.9. These sections have been accepted for publication as part of “Modelling the early time behaviour of type Ia supernovae: effects of the \(^{56}\text{Ni}\) distribution”, Magee et al., Astronomy & Astrophysics, in press, 2018, reproduced with permission © ESO. Tests of the sensitivity to various model parameters and assumptions in our code are discussed in § 6.2. In addition, TARDIS (Kerzendorf & Sim 2014) was used throughout this thesis to model SNe spectra (specifically in § 4.4.3 & 5.4.3). TARDIS is a publicly available radiative transfer code for modelling single spectra of SNe. Many of the same principles discussed here also apply to TARDIS. The main differences that are relevant to TARDIS are discussed in § 3.10.

The cover image for this chapter shows the supernova SN 1987A within the Large Magellanic Cloud. Image credit: NASA, ESA, R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation), and M. Mutchler and R. Avila (STScI).

3.1 Random sampling

Fundamental to the Monte Carlo method is the use of random numbers to describe events based on probability. Typically, random number generators will produce a uniform distribution of numbers \(z \in [0,1]\). A Monte Carlo simulation is performed by mapping this random number onto a distribution describing the outcomes of a specific event. Suppose the outcomes for this event are all equally likely – in other words, the distribution \(i \in [i_{\text{min}},i_{\text{max}}]\) is uniform. The random number \(z\) can be mapped onto \(i\) through:

\[
i = z(i_{\text{max}} - i_{\text{min}}) + i_{\text{min}}. \tag{3.1}\]

In general, however, the outcomes may not be uniform. To map \(z \in [0,1]\) onto a general, non-uniform \(x \in [a,b]\), two methods were used in this thesis.

The first method is known as inverse transform sampling. Consider that \(P(x)\) gives the probability density for selecting a variable \(x \in [a,b]\). Suppose that the distribution

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\(^1\)TURTLS: The Use of Radiative Transfer for Light curves of Supernovae
of $x$ values can be described by a cumulative distribution function $C(x)$, where:

$$
C(x) = \int_a^x P(x)dx = z.
$$

(3.2)

$C(a) = 0$ and $C(b) = 1$, thus we have a direct map between any random number $z \in [0, 1]$ and a non-uniform distribution $x \in [a, b]$. We must simply generate a random number $z$, and choose $x$ such that $C(x) = z$. This method is used in § 3.7 to, for example, randomly select an initial position for photons emitted by $^{56}\text{Ni}$ within the model region, as determined from the pre-defined distribution of $^{56}\text{Ni}$ (see § 3.7, Fig. 3.1).

The second method is known as rejection sampling and, as the name implies, simply involves selecting random numbers and rejecting those that do not meet the desired criteria. For example, suppose we have a segment of a circle with radius $r = 1$ and a square with sides of length $a = 1$. If we choose a selection of random numbers $x, y \in [0, 1]$ we will create a selection of points lying inside the area of the square. Next, if we select only those points for which $x^2 + y^2 \leq 1$, and reject all others, we will be left with only those points that lie inside the circle. This is a common method used to numerically estimate the value of $\pi$, and is demonstrated in Fig. 3.2. In § 3.7, rejection
Figure 3.2: Using rejection sampling to estimate the value of $\pi$. 10000 pairs of random numbers are generated, $x, y \in [0, 1]$. Those for which $x^2 + y^2 \leq 1$ are selected and shown in red. Those for which $x^2 + y^2 > 1$ are rejected and shown in blue. Comparing the number of points selected to the total number of points generated allows for an estimate of $\pi$ to be obtained.

sampling is used to randomly select injection times for our packets that are less than a pre-defined end time for the simulation.

### 3.2 Photon redshifting

Most of the energy released in thermonuclear SNe is used to unbind the star and accelerate the ejecta. Simulations have shown that beginning very shortly after explosion (approximately one minute), the kinetic energy of the ejecta is dominant over the gravitational and thermal energies, and therefore the ejecta of SNe Ia is expanding freely (Röpke 2005). This forms the basis of the assumption of homologous expansion – an approximation that is fundamental to many codes designed for radiative transfer in SNe. Here, the radius of a specific matter element within the ejecta at any time is simply given by:

$$r = vt,$$

where $v$ is the velocity of the matter element and $t$ is the time since explosion.

Resulting from this is the fact that as a photon propagates through the ejecta, its
frequency in a fluid frame co-moving with the ejecta, $\nu_{ff}$, is continuously redshifting. Consider a photon of frequency $\nu$. Following from the Doppler formula, the frequency in the fluid frame is given by:

$$\nu_{ff} = \nu \left(1 - \mu \frac{v}{c}\right), \quad (3.4)$$

where $\mu = \cos \theta$, and $\theta$ is the angle between the radial and photon propagation directions. By differentiating Eqn. 3.4 along the path of the photon, $s$, we see how the fluid frame frequency evolves:

$$\frac{d\nu_{ff}}{ds} = -\frac{\nu}{c} \left[ \frac{v}{r} \left(1 - \mu^2\right) + \mu^2 \frac{dv}{dr} \right]. \quad (3.5)$$

From Eqn. 3.5, it can be seen that $\frac{d\nu_{ff}}{ds}$ is always negative (arising from the fact that $\mu^2 \leq 1$, and $v$ and $\frac{dv}{dr}$ are both positive). Hence the fluid frame frequency of photons is continuously redshifting. This phenomenon greatly simplifies the process of photon transport and serves as the basis for another approximation commonly used in radiative transfer calculations for SNe, the Sobolev approximation.

### 3.3 The Sobolev approximation

The foundation of the Sobolev approximation is that photon absorption by a specific line can only occur for a small range of frequencies – those centred around the rest frequency of the transition. When combined with the fact that photons are continuously redshifting (see § 3.2) it becomes clear that as a photon propagates, it will redshift into and out of resonance with particular lines. The distance over which the photon is in resonance is known as the Sobolev region and is the distance over which a line interaction may occur.

The validity of the Sobolev approximation can be demonstrated from Eqn. 3.5. Consider the case where $\mu^2 = 1$, the spatial region over which a photon is in resonance with a particular line is given by:

$$ds = -\frac{c}{\nu} \frac{dv_{ff}}{dr}. \quad (3.6)$$

If we assume the line width is dominated by Doppler broadening, then $dv_{ff} = \frac{v}{c} v_{th}$, where $v_{th}$ is the thermal velocity of the material. Finally, if we estimate $\frac{dv}{dr} \sim \frac{v_0}{s_0}$ where $v_0$ and $s_0$ are typical velocity and length scales, respectively, over which properties in the ejecta vary, it follows that:

$$\frac{\Delta s}{s_0} = \frac{v_{th}}{v_0}. \quad (3.7)$$

In SNe, $v_{th}$ is on the order of 1 km s$^{-1}$ while $v_0$ is on the order of 1000 km s$^{-1}$. 43
Therefore, the large velocities in the ejecta of SNe ensures that photons are only in resonance with spectral lines over an extremely small region, much smaller than the length scales over which ejecta properties vary, $\Delta s \ll s_0$.

Once a photon has redshifted into resonance, it experiences the entire optical depth of that line. The optical depth for a photon with frequency $\nu$ along a path $s$ is given by:

$$\tau_\nu = \int_s \kappa_\nu ds,$$

where $\kappa$ is the opacity for a bound-bound transition:

$$\kappa_\nu = \frac{\pi e^2}{mc^2 f n_l} \left[ 1 - \frac{n_u g_l}{n_l g_u} \right] \phi(\Delta \nu),$$

where $u$ and $l$ are the upper and lower levels, respectively, $n$ and $g$ are the corresponding level population number densities and statistical weights, respectively, and $f$ is the oscillator strength of the transition. $\phi(\Delta \nu)$ is a function describing the profile of the line in terms of the difference in frequency with respect to the line centre ($\Delta \nu = \nu_{\text{ff}} - \nu_0$) that is strongly peaked around $\Delta \nu = 0$ and normalised to $\int_{-\infty}^{\infty} \phi(\Delta \nu) d\nu = 1$. In the Sobolev approximation, $\phi(\Delta \nu)$ is a Dirac delta function. Combining Eqns. 3.8 and 3.9 with those of homologous expansion (Eqn. 3.3) and photon redshifting (Eqn. 3.5), it can be shown that the Sobolev optical depth is given by:

$$\tau_S = \frac{\pi e^2}{mc} \lambda_{\text{Atm}} n_l \left[ 1 - \frac{n_u g_l}{n_l g_u} \right].$$

3.4 Expansion opacities

As previously mentioned, the Sobolev approximation greatly simplifies photon-matter interactions, and allows for lines to be treated sequentially. If there are many lines,
however, this can quickly become computationally prohibitive. The expansion opacity formalism further simplifies photon-matter interactions by combining lines into opacity bins over discrete frequency intervals.

As a photon redshifts through the frequency bin $\nu, \nu + \Delta \nu$, it travels a distance $\Delta z_c$ (see § 3.2). The expansion opacity approximation assumes there are $N_{\text{lin}}$ lines in this frequency interval with which a photon may interact, and the probability of interaction with line $j$ is given by $1 - \exp(-\tau_{S,j})$. Summing over all lines in the frequency interval gives the total number of interactions and can be used to calculate the mean free path of a photon within the frequency bin. Using Eqn. 3.6, the mean free path can be related to the frequency bin, and the expansion opacity within $\nu, \nu + \Delta \nu$ is then given as:

$$\kappa_{\text{exp}}(\nu) = \frac{\nu}{\Delta \nu c t_{\text{exp}}} \sum_j (1 - \exp(-\tau_{S,j})),$$

(3.11)

where $t_{\text{exp}}$ is the time since explosion, $\tau_{S,j}$ is the Sobolev optical depth (see § 3.3, Eqn. 3.10), and the summation is performed over the $N_{\text{lin}}$ lines in the frequency interval. The expansion opacity approximation sums each line individually, and therefore is valid provided the spacing between lines is larger than the Doppler width of the line (Eastman & Pinto 1993).

### 3.5 General overview of the code

Having described the physical approximations made in our code, we now discuss the algorithms and numerical implementation. Our Monte Carlo code calculates the emergent luminosity of the SN during discrete time intervals (i.e. the light curve), and was written as part of this thesis. It follows the indivisible energy-packet scheme outlined by Lucy (2005) and previous studies (Abbott & Lucy 1985; Lucy & Abbott 1993; Mazzali & Lucy 1993; Lucy 2002, 2003), applied in one dimension. Throughout the following, we adopt the naming convention of Lucy (2005); $\gamma$-packets represent bundles of $\gamma$-ray photons; radiation-packets (r-packets) represent bundles of $UVOIR$ photons; $z_1, z_2$, etc. are independent, random numbers.

Packets represent discrete monochromatic bundles of photons. They are injected into the model region and their propagation followed, during which they may undergo electron scattering or absorption and re-emission by the ions and atoms in the ejecta. The number of photons and frequencies represented by a packet may change during the simulation; however, energy is always conserved in the fluid frame, and packets are neither created nor destroyed during interactions with the ejecta. Radiative equilibrium and conservation of the total energy are therefore enforced throughout the simulation.
Observed light curves are created by binning emerging packets in frequency and time.

Throughout our simulations, packet properties such as propagation direction, energy, etc. are followed in the observer frame, and transformed to and from the local fluid frame when appropriate, through a first-order Doppler correction. The Doppler correction is given by

$$D_\mu = (1 - \mu \beta)$$

where \( \beta = v/c = r/ct \) (following from homologous expansion of the ejecta; see § 3.2), and, as before, \( \mu = \cos \theta \), where \( \theta \) is the angle between the radial and photon propagation directions.

### 3.6 Model set-up

In our implementation, the density and composition of the SN ejecta are free parameters, defined by the user. The ejecta is assumed to be spherically symmetric and defined by a series of zones, each having the following properties upon input: inner and outer velocity boundaries; density at some reference time, \( t_0 \); \(^{56}\)Ni mass fraction and composition at \( t_0 \).

The temperature of each zone at the start of the simulation, \( t_s \), is determined by the local heating that has occurred since the explosion due to the decay of \(^{56}\)Ni. Following Lucy (2005), we determine the initial radiation energy density in each zone as:

$$U_R = \left( \frac{t_{Ni}}{t_s} - \left[ \left( 1 + \frac{t_{Ni}}{t_s} \right) \exp \left( \frac{-t_s}{t_{Ni}} \right) \right] \frac{\chi \rho E_{Ni}}{m_{Ni}} \right)$$

where \( t_{Ni} \) is the decay time of \(^{56}\)Ni (8.8 days), \( \chi \) is the initial mass fraction of \(^{56}\)Ni in that zone, \( \rho \) is the density of that zone at \( t_s \), \( E_{Ni} \) is the energy emitted by the decay of a \(^{56}\)Ni atom (1.728 MeV), and \( m_{Ni} \) is the mass of a \(^{56}\)Ni atom (9.3 \times 10^{-26} kg). The mean intensity of the radiation field in each zone is given by:

$$J = \frac{U_R c}{4\pi}$$

and the radiation temperature of each zone by:

$$T_R^4 = \frac{\pi J}{\sigma_{SB}}.$$

For zones without \(^{56}\)Ni at the start of the simulation, we set an initial temperature of 1 000 K. We treated 1 000 K as a minimum temperature in each zone throughout the entire simulation. We tested other values for a minimum temperature (up to 5 000 K), but found that this did not have a noticeable effect on the resultant light curves. For the epochs considered in this work, we do not expect the outer temperature to be significantly lower.
3.7 Packet initialisation

With the model region constructed, packets must be initialised with the following properties: time of injection, position, direction of propagation, and energy.

Following the $^{56}$Ni decay chain, $^{56}$Ni $\rightarrow$ $^{56}$Co $\rightarrow$ $^{56}$Fe, $\gamma$-packets are injected and randomly assigned an emitting species (proportional to their probabilities) of either a $^{56}$Ni or $^{56}$Co nucleus. The $^{56}$Ni decay chain is assumed to be the dominant form of energy production. Other decay chains are therefore not implemented currently, but could be included in future work. The injection time for $^{56}$Ni decays is given by $t_{\gamma} = -\ln z \times t_{\text{Ni}}$. For $^{56}$Co decays, the time of injection is given by $t_{\gamma} = -\ln z_1 \times t_{\text{Ni}} - \ln z_2 \times t_{\text{Co}}$, where $t_{\text{Co}}$ is the decay time of $^{56}$Co. Following Lucy (2005), $\gamma$-packets injected before the start time of the simulation are converted to $r$-packets, and given an injection time equal to this start time. Work done by packets on the ejecta during this time is also accounted for. As mentioned in §3.1, injection times greater than the end time of the simulation ($t_{\gamma} > t_e$) are rejected. New injection times are chosen until $t_{\gamma} < t_e$. The total number of packets rejected is tracked and accounted for in the energy output of the SN (see Eqn. 3.17).

As discussed in §3.1, the radial position of the packet at the injection time is determined by sampling the $^{56}$Ni distribution within the SN ejecta. The initial zone in which a packet is injected is drawn by sampling the cumulative distribution function of $^{56}$Ni within the SN ejecta. Following from Eqn. 3.1, the position of the packet inside the zone ($r \in [r_{\text{in}}, r_{\text{out}}]$) at the time of injection is given by:

$$r^3 = z_{\gamma}^3 (v_{\text{out}}^3 - v_{\text{in}}^3) + (t_{\gamma} v_{\text{in}})^3,$$  \hspace{1cm} (3.15)

where $v_{\text{in}}$ and $v_{\text{out}}$ are the inner and outer velocity boundaries of the injection zone, respectively. The distribution of propagation directions within the fluid frame is assumed to be isotropic. Each packet is assigned a random propagation direction, $\mu_f = 2z - 1$, which is then transformed into the observer frame following Castor (1972):

$$\mu_o = \frac{\mu_f + \beta}{1 + \mu_f \beta}.$$  \hspace{1cm} (3.16)

In our indivisible energy packet scheme, the total energy emitted by the SN in the fluid frame, $E_{\text{tot}}$, is discretised evenly among all packets. The observer frame energy of each packet is therefore given by:

$$E_{\text{packet}} = \frac{E_{\text{tot}}}{N + N_{\text{rej}}} \frac{1}{D_{\mu_o}},$$  \hspace{1cm} (3.17)
where $N$ is the number of packets injected within the time domain of the simulation, $N_{\text{rej}}$ is the number of packets rejected, and the factor $D_{\mu_0}$ is due to the transformation from fluid frame to observer frame energy.

Packets that have converted from $\gamma$- to $r$-packets by the start of the simulation also require an initial frequency. The fluid frame frequency is selected by sampling the Planck function at the temperature appropriate for that packet’s zone, following from Carter & Cashwell (1975) and Bjorkman & Wood (2001).

3.8 Packet propagation

With all packets initialised, the simulation can begin. As we wish to calculate how the luminosity varies with time, the simulation operates by propagating packets in logarithmically spaced time steps between chosen start, $t_s$, and end, $t_e$, times.

Once a packet has been injected we simulate its random walk by calculating four time intervals: time for the packet to redshift into the next frequency bin ($t_f$), time for the packet to reach a zone boundary ($t_b$), time for the packet to reach an interaction point ($t_i$), and time until the end of the current time step ($t_{\text{nts}}$). We propagate each packet until it reaches the first of these four events to occur and perform the event. New time intervals are then calculated and the procedure repeated, if necessary. This is performed for all packets in all time steps until the chosen end of the simulation is reached.

In the following, we describe each interval in more detail. We begin by describing numerical events in § 3.8.1, followed by physical events in § 3.8.2.

3.8.1 Numerical events

As packets propagate, their fluid frame frequency is continuously redshifting (see § 3.2). If the time to the next frequency bin is shortest, the packet is propagated to this point, the fluid frame frequency updated, and new time intervals calculated.

The trajectory of the packet is followed from its current position until it intersects either the inner or outer boundary of the zone – depending on the direction of travel. The time to a boundary can be calculated from simple geometry. Following from the law of cosines (see Fig. 3.3), the time to a boundary is related to the velocity of the boundary and the initial trajectory as follows:

$$v^2(t_0 + t_b)^2 = r_0^2 + (ct_b)^2 + 2r_0c\mu_b,$$  \hspace{1cm} (3.18)
Figure 3.3: Trajectory of packet inside a zone. The initial position of the packet is shown as a red circle, at a radius $r_0$. The trajectory of the packet is shown as a red arrow, at an angle $\theta$ relative to the radial direction. The packet propagates a distance $ct_b$ along the current trajectory until it intersects the zone boundary at a radius of $v(t_0 + t_b)$.

where $v$ is the velocity of either the inner or outer boundary ($v_{\text{in}}, v_{\text{out}}$), $t_0$ is the time at the beginning of the trajectory, $t_b$ is the time to the boundary, $r_0$ is the initial radial position of the packet, and $\mu = \cos \theta$ is the propagation direction. Solving Eqn. 3.18 for $t_b$ provides the time to the boundary. If the time to a boundary is shortest, the packet is propagated to the appropriate boundary and new time intervals are calculated. If a packet is propagated to the outer boundary of the final zone, it has escaped the simulation. As packets escape the outer grid zone with an escape time $t_n$, they are perceived by a distant observer to have been emitted at an observed time $\tau_n = t_n - \mu R_{\text{max}}/c$ (see Fig. 3.4; Lucy 2005). R-packets that have escaped the model domain are binned in observed time and frequency. Frequency bins are then convolved with the desired set of filter functions to construct the model light curves.

If the beginning of the next time step is the next event to occur, the packet is propagated along its current trajectory until the end of the current time step. Once the next time step has begun, the process of calculating new time intervals begins again.
Figure 3.4: Light travel time of packets emitted from the model region. Consider the SN ejecta as a spherical expanding shell. Packets 1 and 2 are emitted at the same time, \( t_1 = t_2 \), but at different positions on the surface of the shell. Packet 1 is emitted at a pole, while packet 2 is emitted closer to the equator. To a distant observer, packet 2 has travelled an extra distance, \( \Delta l = \mu R_{\text{max}} \) relative to packet 1 before escaping, and will therefore arrive first. Here, \( R_{\text{max}} \) is the radius of the outer boundary of the last zone. Note that this figure does not appear in Magee et al. (2018).

3.8.2 Physical events

The final interval calculated is the time until a packet reaches a randomly selected optical depth, given by:

\[
t_i = \frac{-\ln z}{c \kappa},
\]

(3.19)

where \( \kappa \) is the opacity.

For \( \gamma \)-packets, we used a fixed grey mass opacity of \( \kappa/\rho = 0.03 \text{ cm}^2\text{g}^{-1} \) (Ambwani & Sutherland 1988). Despite this approximation, our code is able to reproduce the \( \gamma \)-ray deposition obtained using the more sophisticated treatment of Lucy (2005) (see § 6.3.1, Fig. 3.5). For a \( \gamma \)-packet experiencing its first interaction, it is immediately destroyed and re-emitted as an \( r \)-packet.

For \( r \)-packets, the opacity is based on an atomic data set that includes \( 4.5 \times 10^5 \) lines and is sourced from Kurucz & Bell (1995). Treating each line individually would be computationally prohibitive; therefore we used TARDIS (see § 3.10; Kerzendorf & Sim 2014) to calculate Thomson scattering opacities and expansion opacities (see
Figure 3.5: Bolometric light curve and γ-ray deposition curve for the model presented by Lucy (2005) compared to a calculation performed in this work. Our code reproduces the results of Lucy (2005). Figure from Magee et al. (2018).

§ 3.4; Eastman & Pinto 1993). We assumed LTE when determining the ionisation and excitation levels. At the end of each time step, the zone densities and temperatures, and time since explosion are input into TARDIS to calculate the opacities. We also take into account the change in composition that results from the decay of $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$.

If an interaction is the next event, the packet is propagated to the interaction point and a new direction randomly selected in the local fluid frame. Energy is always conserved in the fluid frame during interactions. Therefore the new packet energy is given by:

$$E(\text{after}) = E(\text{before}) [1 - \mu_o(\text{before})\beta] \frac{1}{1 - \mu_o(\text{after})\beta}$$

(3.20)

The form of interaction (electron-scattering or absorption) is chosen randomly at the point of interaction, in proportion to their probabilities - in other words, if $z \leq \frac{k_{\text{Th}}}{k_{\text{Th}} + k_{\text{exp}}}$ the packet scatters, where $k_{\text{exp}}$ and $k_{\text{Th}}$ are the expansion and Thomson scattering opacities, respectively. If a packet is electron-scattered, we also conserve frequency in the fluid frame, following a similar equation as Eqn. 3.20 for frequency.

For packets that experience absorption, we use the two-level atom (TLA) approach.
outlined by Kasen et al. (2006), which greatly reduces the computational demands of the simulation. In real systems, when an atom absorbs a photon through a line transition, there may be multiple transitions through which that photon could be re-emitted. In the TLA approach, once packets are absorbed, they are immediately re-emitted with either the same frequency or a new frequency chosen by randomly sampling (see § 3.1) the local thermal emissivity, \( S(v_i) \), given by:

\[
S(v_i) = B(v_i) \kappa(v_i),
\]

(3.21)

where \( B(v_i) \) is the Planck function and \( \kappa(v_i) \) is the expansion opacity. The probability of redistribution, as opposed to coherent line scattering, is given by the redistribution parameter, \( \epsilon \). In principle, \( \epsilon \) is unique for each line; however, Kasen et al. (2006) show that a single value close to unity for all lines is sufficient to reproduce a more detailed treatment of fluorescence. The effects of varying \( \epsilon \) are discussed in § 6.2.5. For our production simulations, we fix \( \epsilon = 0.9 \). Once a packet has finished the interaction process, new time intervals are calculated.

### 3.9 Updates to the plasma state

Once all packets have propagated through the current time step, the density, temperature, and source function for each zone are updated. Following from Mazzali & Lucy (1993) and Long & Knigge (2002), we use a Monte Carlo estimator to determine the mean intensity in each zone, given by:

\[
J_{\text{est}} = \frac{1}{4\pi\Delta t V} \sum E l D \mu,
\]

(3.22)

where \( \Delta t \) is the time step duration, \( V \) is the volume of the zone, \( E \) is the energy of the packet, and \( l \) is the distance travelled by the packet during the current time step. The summation is performed over all packets that have travelled inside the zone during the current time step. We then calculate new temperatures using Eqn. 3.14, new opacities using TARDIS, and update the source function (Eqn. 3.21) in each zone.

### 3.10 TARDIS

TARDIS is a one dimensional Monte Carlo radiative transfer code designed for rapidly producing synthetic spectra of SNe, and was used throughout this thesis. A detailed description of the code is provided by Kerzendorf & Sim (2014). Briefly, TARDIS approximates the SN as a black-body emitting into a line forming atmosphere (the SN ejecta). Packets are injected from the black-body into the pre-defined model region.
and propagate through. While propagating, packets may interact with the ions and atoms in the ejecta. Packets that reach the outer boundary of the model region have escaped and are binned in frequency to form a spectrum. The spectrum can then be compared with observations and physical parameters of the model tweaked to improve agreement. Many of the procedures and techniques described in previous sections also apply to TARDIS. The purpose of this section is to highlight key differences between TARDIS and our own code.

Each TARDIS simulation is defined by a number of input parameters: desired luminosity of the spectrum ($L_o$), time since explosion ($t_{\text{exp}}$), inner and outer velocity boundaries ($v_i, v_o$), and density and composition profiles. One of the main differences between our code and TARDIS is that the former provides the time evolution of the SN luminosity (i.e. the light curve), while the latter provides a single spectrum - a snapshot in time. As such, in TARDIS, all packets may be considered to be injected as r-packets and propagated through the model region during a single time step – there is no time evolution. Therefore, the luminosity and time since explosion for each TARDIS model are treated as free parameters during the fitting process, but may be estimated from the light curve of the observed SN. In contrast, our code injects $\gamma$-packets at random times from the decay of $^{56}\text{Ni}$ or $^{56}\text{Co}$ and follows their propagation during discrete time intervals (see § 3.7).

A schematic representation of a TARDIS model is shown in Fig. 3.6. In each simulation, the inner and outer velocity boundaries are used to construct the model region. The inner boundary defines the photosphere of the emitting black-body and all packets are injected here. This is in contrast to our code where the initial location of packets is determined by the distribution of $^{56}\text{Ni}$. Injecting packets at the inner boundary means that they are not propagated through regions of the highest optical depths. TARDIS is therefore well suited for its goal of rapid spectral synthesis and can be used to quickly explore a large parameter space to infer properties of the ejecta in real SNe, as demonstrated in § 5.4.3. Packets emerging from the photosphere are assumed to have thermalised and hence packets are injected with their frequencies drawn from sampling a black-body distribution.

Above the photosphere, the model region is discretised into a series of zones, similar to our code. Within each zone, the density and composition are constant. Another key difference between our code and TARDIS is in the treatment of the opacities and photon-matter interactions as packets propagate through zones. Whereas in our code, line transitions are combined into discrete frequency bins (see § 3.4), TARDIS treats each line individually, and calculates the distance a packet must travel before it redshifts.
Figure 3.6: Schematic representation of TARDIS model region. The model region is defined by an inner and outer boundary, and discretised into zones. Within each zone, the density and composition are held constant. The inner boundary represents the surface of an emitting black-body and all packets are initially injected at this point with frequencies drawn from sampling a black-body distribution at the appropriate temperature. Once packets have reached the outer boundary, they have escaped the simulation and are binned in frequency to construct synthetic spectra. Packet 1 has propagated through the entire model region and experienced no interactions. Packet 2 propagates until it is absorbed by an atom (represented as a blue circle). It is then re-emitted and propagates in a new, random direction.

into resonance with the next line in the sequence (see § 3.2). This is much more feasible in TARDIS than in our code due to the photosphere approximation and the lack of time evolution.

If an interaction is the next event to occur, there are multiple methods by which TARDIS can represent the absorption process. In the simplest approach, all interactions are treated as resonance scattering events, meaning packets are emitted with the same fluid frame frequency at which they were absorbed. This is the “pure scattering” mode and atoms may be thought of as containing only two levels. In the most sophisticated approach, atoms can contain many different levels and are known as macro-atoms. During an interaction, a macro-atom is activated by absorbing an r-packet. Once absorbed, the packet may undergo numerous internal transitions within the macro-atom, deter-
Figure 3.7: Schematic representation of a macro-atom interaction. A photon with energy $\epsilon_0$ and frequency $\nu$ in the local fluid frame encounters a macro-atom and is absorbed. In this example, the macro-atom has five levels and is activated to level four. The packet randomly undergoes two internal transitions; a downward transition to level two and an upward transition to level three. The packet is then emitted from level three with the same energy and a new frequency determined by the emitting transition, $\nu'$. Figure from Lucy (2002)

Simulations performed by TARDIS are iterative. TARDIS requires the temperature of the emitting black-body to determine the flux distribution and luminosity entering the model, and the temperature of the ejecta within the model region to calculate the level populations of excited and ionised atoms, and hence opacities. As a first guess, the temperature of the black-body is estimated from the Stefan-Boltzmann relation as:

$$T_i = \left( \frac{L_0}{4\pi r_i^2 \sigma} \right)^{1/4}. \quad (3.23)$$

The black-body radius, $r_i$, follows from homologous expansion (see § 3.2) and is given by $r_i = v_it_{\text{exp}}$. Having determined an initial temperature of the emitting black-body, the
first iteration begins assuming a constant temperature for the model region. Packets are propagated through the model and Monte Carlo estimators are used in a similar manner as our code (see § 3.9) to determine the temperature profile, and hence level populations, for the next iteration. In addition, the luminosity emerging from the outer boundary is compared against the desired luminosity, $L_0$, and $T_i$ is either increased or decreased for the next iteration to obtain better agreement between the two luminosities. This procedure (altering $T_i$, determining the temperature profile of the model region) is repeated for a desired number of iterations, and simulations typically converge after ~5 to 10 iterations. We see now how the physical parameters of the model ($L_0, v_i, t_{\exp}$) can be altered to change the shape of the SED and emergent spectrum, to improve agreement with observations. Of course, the density and composition of the model can also be altered to change the shape of the SED and/or spectral features.

TARDIS is an incredibly useful tool for inferring properties of the ejecta within SNe and can be used to very efficiently explore a large parameter space. The results of TARDIS simulations are presented in § 4.4.3 and 5.4.3.
Chapter 4

SN 2015H: Type Iax supernovae as pure deflagrations
We present results based on observations of SN 2015H which belongs to the small group of objects similar to SN 2002cx, otherwise known as type Iax supernovae. The availability of deep pre-explosion imaging allowed us to place tight constraints on the explosion epoch. Our observational campaign began approximately one day post-explosion, and extended over a period of about 150 days post maximum light, making it one of the best observed objects of this class to date. We find a peak magnitude of $M_r = -17.27 \pm 0.07$, and a $(\Delta m_{15})_r = 0.69 \pm 0.04$. Comparing our observations to synthetic spectra generated from simulations of deflagrations of Chandrasekhar mass carbon-oxygen white dwarfs, we find reasonable agreement with models of weak deflagrations that result in the ejection of $\sim 0.2 M_\odot$ of material containing $\sim 0.07 M_\odot$ of $^{56}$Ni. The model light curve, however, evolves more rapidly than observations, suggesting that a higher ejecta mass is to be favoured. Nevertheless, empirical modelling of the pseudo-bolometric light curve suggests that $\lesssim 0.6 M_\odot$ of material was ejected, implying that the white dwarf is not completely disrupted, and that a bound remnant is a likely outcome.

The contents of the following chapter have been published as “The type Iax supernova, SN 2015H. A white dwarf deflagration candidate”, Magee et al., Astronomy & Astrophysics, Volume 589, id.A89, 18 pp., 2016, reproduced with permission © ESO. All of the work is my own. The cover image for this chapter shows the supernova SN 2014J in M82. Image credit: NASA, ESA, A. Goobar (Stockholm University), and the Hubble Heritage Team (STScI/AURA).

### 4.1 Introduction

As discussed in Chapter 1, the explosion mechanism and scenarios leading to explosion remain unclear for thermonuclear supernovae (SNe; e.g. Hillebrandt et al. 2013). Type Iax supernovae (SNe Iax) provide an excellent opportunity to test the extreme boundaries of explosion models. The main observational signatures of SNe Iax are discussed in § 1.3. Briefly, these are slow expansion velocities – roughly half that of normal SNe Ia at similar epochs – spectra that are dominated by intermediate mass and iron group elements (IMEs and IGEs, respectively; Li et al. 2003; Branch et al. 2004), and peak absolute brightnesses that span about five magnitudes: ($-14 \gtrsim M_V \gtrsim -19$; Li et al. 2003; Branch et al. 2004; Foley et al. 2009, 2013).

Given that SNe Iax differ markedly in their properties when compared to SNe Ia, alternative explosion mechanisms, and/or progenitor systems are probably necessary (see § 1.4). As mentioned in § 1.4.1, a possible explosion model for SNe Iax that has been widely considered since the early discoveries is that of pure deflagrations of white dwarfs (Branch et al. 2004; Phillips et al. 2007). Indeed, synthetic observables obtained
from deflagration models presented by Fink et al. (2014), Kromer et al. (2013, 2015),
and Long et al. (2014) have shown broad agreement with SNe Iax observables at early
times. Nevertheless, the models diverge from observations at later times, indicating
that we are missing key pieces in the puzzle that are SNe Iax. In the context of such
models, the range in parameter space spanned by the observations may be attributed to
variations in the details of the ignition. It nevertheless remains to be seen whether a
single class of model is able to account for the full brightness range spanned by SNe
Iax.

4.2 Discovery

SN 2015H (also known as LSQ15mv; Parker 2015) is a relatively recent addition to
the SN Iax class. SN 2015H was discovered in an unfiltered CCD image as part of
the Backyard Observatory Supernova Search\(^1\) (BOSS), on 2015 Feb. 10 with an apparent
magnitude of +16.9. In Fig. 4.1 we show an image of SN 2015H within its host
galaxy, NGC 3464, along with sequence stars used to calibrate LCOGT photometry.
A classification spectrum obtained by the Public ESO Spectroscopic Survey of Transient
Objects (PESSTO, Smartt et al. 2015) on 2015 Feb. 11 showed SN 2015H to be a SN Iax approximately a few days post maximum light, with good matches pro-
vided by SN 2005cc at +5 d and SN 2002cx at +10 d (Zelaya-Garcia et al. 2015). In
what follows, we adopt the distance modulus for NGC 3464 provided by NED\(^2\) of
33.91±0.07, which is based on the Tully-Fisher relation (Tully & Fisher 1977), and
derived by Springob et al. (2009). In Table 4.1 we list the basic characteristics of
SN 2015H and its host galaxy, and our derived parameters for SN 2015H resulting
from our analysis in § 4.4.

In what follows, we begin by presenting our observations of SN 2015H. In § 4.4.2
and § 4.4.3, we present our analysis of the photometric and spectroscopic evolution,
respectively. We compare our data with two well-observed SNe Iax in § 4.5, and to
deflagration models involving Chandrasekhar-mass carbon-oxygen white dwarfs (\(M_{\text{Ch CO WDs}}\)) in § 4.6. We summarize our findings in § 4.7.

4.3 Observations & Data Reduction

Here, we briefly describe the observations and data reduction procedure taken. Data
reduction processes are described more thoroughly in Chapter 2.

\(^1\)http://www.bosssupernova.com/
\(^2\)http://ned.ipac.caltech.edu
Figure 4.1: \(r\)-band image of the site of SN 2015H taken approximately one week post \(r\)-band maximum with the LCOGT (Table 4.5). The position of SN 2015H is indicated by red dashes, and lies approximately 10 kpc from the nucleus of its host galaxy, NGC 3464. The sequence stars marked above were used to calibrate the LCOGT imaging.

### 4.3.1 Optical & near-IR imaging

A follow-up monitoring campaign for SN 2015H was initiated immediately following the discovery by BOSS and subsequent classification by PESSTO. Although first reported by BOSS, SN 2015H had been serendipitously observed by the La Silla-Quest Variability survey (LSQ, Baltay et al. 2013) with images of the field containing SN 2015H extending to approximately three years prior to this date. Incorporating these LSQ images into our analysis of SN 2015H, our full light curve across all filters extends from shortly after explosion (see § 4.4.2 for discussion on the explosion date of SN 2015H) to approximately 160 d later, making it one of the best sampled light curves to date for SNe Iax.
Table 4.1: Summary of details for SN 2015H

<table>
<thead>
<tr>
<th>SN 2015H</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alternative names</strong></td>
<td>PSN J10544216-2104138</td>
</tr>
<tr>
<td><strong>LSQ15mv</strong></td>
<td></td>
</tr>
<tr>
<td>( \alpha ) (J2000.0)</td>
<td>10(^\circ)54'42''.16</td>
</tr>
<tr>
<td>( \delta ) (J2000.0)</td>
<td>−21°04'13''.7</td>
</tr>
<tr>
<td>Host galaxy</td>
<td>NGC 3464</td>
</tr>
<tr>
<td>Redshift</td>
<td>0.012462±0.00001</td>
</tr>
<tr>
<td>Distance (Mpc)</td>
<td>60.57±1.95</td>
</tr>
<tr>
<td>Distance modulus (mag)</td>
<td>33.91±0.07</td>
</tr>
<tr>
<td>Host offset</td>
<td>30''E, 14'' S</td>
</tr>
<tr>
<td>Discoverer</td>
<td>Backyard Observatory Supernova Search</td>
</tr>
<tr>
<td>Discovery date (UT)</td>
<td>2015 February 10.545</td>
</tr>
<tr>
<td>Discovery date (MJD)</td>
<td>57 064.05</td>
</tr>
<tr>
<td>Discovery magnitude (mag)</td>
<td>+16.9 (Unfiltered)</td>
</tr>
<tr>
<td>Galactic extinction</td>
<td>( E(B-V) = 0.048 )</td>
</tr>
<tr>
<td>Host extinction</td>
<td>( E(B-V) = 0 )</td>
</tr>
<tr>
<td>( r )–band maximum date (MJD)</td>
<td>57 061.9±0.4</td>
</tr>
<tr>
<td>( r )–band maximum magnitude (mag)</td>
<td>16.77±0.03</td>
</tr>
<tr>
<td>( r )–band maximum absolute magnitude (mag)</td>
<td>−17.27±0.07</td>
</tr>
<tr>
<td>( \Delta m_{15} ) ( r )–band (mag)</td>
<td>0.69±0.04</td>
</tr>
<tr>
<td>Explosion date (MJD)</td>
<td>57 046±0.5</td>
</tr>
<tr>
<td>( r )–band rise time (days)</td>
<td>15.9±0.6</td>
</tr>
</tbody>
</table>

**Notes.** (1) Parker (2015), (2) NASA/IPAC Extragalactic Database (NED), (3) This paper

Optical imaging in the \( gri \) filters was provided by the Las Cumbres Observatory Global Telescope 1-m network (LCOGT, Brown et al. 2013). We also include the seven \( V \)–band acquisition images obtained with the 3.58-m New Technology Telescope (NTT) + EFOSC2, as part of the PESSTO spectroscopic monitoring campaign for SN 2015H. The LSQ survey makes use of the 40-inch ESO Schmidt telescope and a ‘wide’ filter approximately covering both the SDSS \( g \)– and \( r \)–bands. This filter function is shown in Fig. 4.10(e), along with standard filters. Three epochs of dithered near-IR \( J \)– and \( H \)–band imaging were obtained with NTT+SOFI, ranging from approximately one week post-maximum to over three weeks later, while time constraints limited us to a single \( K_s \)–band observation at one week post-maximum.

Images from LSQ and LCOGT are automatically reduced using their respective pipelines (Baltay et al. 2013; Brown et al. 2013). Images from the NTT were reduced using the custom-built PESSTO pipeline (Smartt et al. 2015). All of these included standard reduction procedures.

Photometry on all images was performed using SNOoPY\(^3\) (see § 2.1.3). Given the availability of pre-explosion imaging from LSQ, we opted to measure the SN brightness from template-subtracted images. For all imaging data, zero points were calculated by

\(^3\)http://sngroup.oapd.inaf.it/snoopy.html
Figure 4.2: Light curve of SN 2015H. We estimate maximum light in the $r$–band to have occurred at MJD = 57 061.9. LCOGT images with seeing $> 2''$ are marked with unfilled circles. Note that a vertical offset (indicated) has been applied to each filter. Also shown is a low-order polynomial fit to the LSQ points from which we derive the peak magnitude and epoch of maximum. A pre-explosion limit (with the appropriate vertical offset) from observations taken approximately 48 hours before our first LSQ detection is shown as a filled circle. Vertical dashed lines indicate epochs of optical spectroscopic observations, while dotted lines indicate epochs of near-IR spectroscopy.

calibrating the instrumental magnitudes of the PSF stars to either SDSS magnitudes for optical images, or 2MASS magnitudes for near-IR images. $V$–band magnitudes of the sequence stars were obtained via transformations from SDSS $gri$ (Jester et al. 2005). We transformed the LSQ photometry directly into the SDSS $r$–band by calculating zero points to SDSS $r$–band as a function of $g – r$ colour. The differing fields-of-view of the instruments necessitated the use of different sets of sequence stars to calibrate the photometry. These are shown in Fig. 4.1 for LCOGT, and listed in Tables 4.2, 4.3, and 4.4 for LCOGT, LSQ, and NTT, respectively. In Tables 4.5 and 4.6 we present the full set of optical and IR photometric observations obtained for SN 2015H, respectively. Figure 4.2 shows our complete light curve.
4.3.2 Optical & near-IR spectroscopy

We present a log of our instrumental configurations and spectroscopic observations in Table 4.7. We obtained seven optical spectra using NTT + EFOSC2 and three NIR spectra using NTT + SOFI. The spectra range from a few days post-maximum to approximately 50 days post maximum light. We were also able to obtain an optical spectrum using the Gran Telescopio Canarias (GTC) + OSIRIS at approximately 113 days post maximum light.

All NTT spectra were reduced in a standard fashion using the PESSTO pipeline (Smartt et al. 2015). For spectroscopic data, this includes standard procedures for flux and wavelength calibration. Our GTC spectrum was taken with Grism R500R and reduced using standard iraf routines, as described in Chapter 2. Additionally, we estimated synthetic magnitudes from our spectra using SMS (Synthetic Magnitudes from Spectra), as part of the S3 package (Inserra et al. 2018). All spectra are then calibrated such that synthetic magnitudes match the photometric observations taken on the same night. We note that all raw data taken via the PESSTO programme on the NTT are publicly available in the ESO archive immediately. The reduced data are released on an annual basis in formal data releases via the Science Archive Facility at ESO. All PESSTO\(^4\) reduced data products are made available both through ESO and WISEREP (Yaron & Gal-Yam 2012).

4.4 Analysis

4.4.1 Reddening

A commonly used method to estimate extinction for normal SNe Ia relies on the expected colour evolution (“Lira relation”; see § 1.1.1; Lira 1996). For SNe Iax, there is currently no evidence of uniform evolution (Foley et al. 2013), so we cannot use this technique. We note, however, that the colours of SN 2015H are relatively blue (Fig. 4.3). The presence of interstellar lines due to Na\(^i\) is another sign of material in the line-of-sight. Numerous caveats notwithstanding, if Na\(^i\) features are observed in absorption, one can nevertheless correlate the equivalent width of these with the extinction (Richmond et al. 1994; Munari & Zwitter 1997; Poznanski et al. 2012). In the case of SN 2015H, the spectra show no sign of the Na\(^i\) D features. Taking both of the above points together, we deem the extinction to be low, and in what follows, we correct the data for Milky Way extinction in the direction of NGC 3464 only. For this, we adopt the value provided by NED, of $E(B - V) = 0.048$ (Schlafly & Finkbeiner 2011) with $R_V$

\(^4\)Details available from www.pessto.org
4.4.2 Photometry

Figure 4.2 shows the full light curve for SN 2015H. Our light curve coverage extends from approximately two weeks before \( r \)-band maximum (a time we estimate to be shortly after explosion) to almost 150 days post-maximum. As described in detail below, we are thus in the fortuitous position to be able to place constraints on a full set of light curve parameters: explosion epoch, peak magnitude, epoch of maximum light, the rise time to maximum, and decline rate, which has thus far been unusual for SNe Iax.

Beginning with our earliest images, we do not detect any source at the site of SN 2015H.
SN 2015H in images taken on or before MJD = 57 045.14 (2015 Jan. 23) - that is, two days before our reported earliest detection, and over two weeks before discovery (2015 Feb. 10). In order to place a limit on the brightness of SN 2015H at this epoch, we recovered the flux from progressively fainter artificial stars placed in the surrounding region. We find that SN 2015H would have had a magnitude of $m_r \gtrsim 20.2$ at this epoch. Studies of SNe Ia have shown that at early times the luminosity can be described by a simple power law, relating to time since explosion ($L \propto t^n$; see §1.1.1; e.g. Riess et al. 1999b; Firth et al. 2015). In order to estimate the date of explosion, we fit the pre-maximum magnitudes of SN 2015H using the simple logarithmic function $m = a \log(t) + b$, and find a likely date of MJD = 57 046±0.5 (Fig. 4.4). This date is consistent with our non-detection approximately one day earlier, despite the relatively shallow limit at that epoch. Excluding later points has no effect on our derived explosion date. Following the same method as Firth et al. (2015), we find a rise index $n$ of $\sim 1.3$. This is comparable to the broad range of values reported by Firth et al. (2015) ($\sim 1.5$ to $\sim 3.5$). Only a handful of SNe Iax have constraints on their explosion epoch (e.g. Phillips et al. 2007; Foley et al. 2009; Narayan et al. 2011; Yamanaka et al. 2015, for SNe 2005hk, 2008ha, 2009ku, and 2012Z, respectively), with SN 2015H being perhaps the most well-constrained to date.

To estimate the date of maximum and peak magnitude of SN 2015H, we fit the LSQ photometry with a low-order polynomial (Fig. 4.2). From this, we estimate that SN 2015H reached a peak absolute magnitude of $M_r = -17.27\pm0.07$ on MJD = 57 061.9±0.4; placing it at an intermediate brightness among the range displayed by SNe Iax, and approximately two magnitudes fainter than normal SNe Ia. Phases of SNe Iax are usually given relative to the date of either $B$– or $V$–band maximum. As we lack observational data in these bands around maximum, throughout this study, all references to the epoch of maximum of SN 2015H refer to the above $r$–band date. Our light curves for SN 2015H show no signs of a secondary maximum in the SDSS $r$– and $i$–bands, consistent with what has been previously reported for other SNe Iax (e.g. Li et al. 2003; Phillips et al. 2007).

The colour evolution of SN 2015H (in $g - r$ and $r - i$) is very similar to both SN 2005hk and SN 2012Z (Fig. 4.3). SN 2015H shows an increase in $g - r$ and $r - i$ colour much sooner than normal SNe Ia, similar to both SN 2005hk and SN 2012Z. In addition, SN 2015H is redder than normal SNe Ia at all observed epochs. Beginning approximately six days post-maximum (the start of our $g$–band coverage), SN 2015H shows a $> 0.5$ magnitude increase in $g - r$ colour over a period of approximately ten days. After this point, the $g - r$ colour shows a steady decrease but remains redder than normal SNe Ia by at least $\sim 0.2$ magnitudes at all epochs. Similarly, the $r - i$ colour
Motivated by our well-constrained explosion epoch and epoch of maximum light, we now investigate the rise time distribution of SNe Iax. For normal SNe Ia, the rise times are determined by the rate at which energy is deposited by radioactive $^{56}$Ni and diffusion through the ejecta (see § 1.1.1). Most SNe Iax are not well observed at these early epochs and therefore rise times exist for only a few events. We determine a rise time to $r$–band maximum for SN 2015H of $15.9\pm0.6$ d. As described below, for other SNe Iax, we either take the value of the rise time quoted in the literature, or estimate a value based on available data. For SN 2005hk, Phillips et al. (2007) estimate that the explosion occurred approximately $15\pm1$ d before $B$–band maximum, which was approximately one week before $r$–band maximum. We therefore estimate that SN 2005hk took approximately three weeks ($21.8\pm1.2$ days) to reach $r$–band maximum. Narayan
et al. (2011) find that SN 2009ku had a rise time of $18.2\pm 3.0\,\text{d}$.\(^5\)

For SNe 2008A and 2012Z, we use the pre-maximum $r$–band photometry presented in Hicken et al. (2012) and Stritzinger et al. (2015), respectively, and find rise times of $16.8\pm 1.8\,\text{d}$ for SN 2008A, and $17.3\pm 1.1\,\text{d}$ for SN 2012Z, respectively. SN 2010ae was undetected up to five days before discovery (Stritzinger et al. 2014). Using this limit, combined with data from Stritzinger et al. (2014), we estimate a rise time to $r$–band maximum of $10\pm 2\,\text{d}$. Based on limited pre-maximum detections of SN 2007qd (McClelland et al. 2010), we estimate a rise time to $r$–band maximum of $11\pm 5\,\text{d}$. In addition to the above objects, we examined the unfiltered light curve of SN 2004cs.

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\(^5\)Based on a $gri$ correction derived by applying a stretch factor to the light curve of SN 2005hk.
Figure 4.6: Decline rate ($\Delta m_{15}$) versus peak absolute $r$–band magnitude for SNe Iax. As in Fig. 4.5, unfilled circles are SNe Iax in the $R$–band, again with the exception of SN 2004cs, which is based on unfiltered imaging. Grey crosses denote the models discussed in § 4.6. Black points are values typical of normal SNe Ia, taken from Carnegie Supernova Project\(^6\) (Hamuy et al. 2006) fits to SNe Ia data. Note objects shown here that are not shown in Fig. 4.5 as they lack good pre-maximum coverage are: SNe 2003gq, 2005cc, 2008ae, 2011ay, PTF 11hyh, and PS15csd. Distances to PS15csd, and PTF 11hyh, 09ego, and 09eoi are derived based on the estimated redshift. The data sources for all objects are listed in Table 4.9.

presented by Foley et al. (2013) and found a rise time of $\sim 9.0 \pm 1.1$ days. In order to estimate the rise time of SN 2008ha, Foley et al. (2009) stretched the light curve of SN 2005hk, and found a rise time of approximately ten days to $B$–band maximum. $R$–band maximum occurred a further four days later, and we therefore assume a rise time for SN 2008ha of $14 \pm 1$ d. Finally, we estimate rise times to $R$–band maximum for PTF 09ego (23$\pm$1 days) and PTF 09eoi (28$\pm$2 days), based on data from White et al. (2015). As shown in Fig. 4.5, those SNe Iax that are brighter, tend to exhibit longer rise times to peak than those that are fainter. The rise times and peak luminosities of SNe Iax in the $r$–band show a range of values up to what is typical for normal SNe Ia, with PTF 09eoi being a clear outlier.
We now turn our attention to the post-maximum evolution of SN 2015H. In Fig. 4.6, we show the relation between peak magnitude and decline rate observed in SNe Iax and normal SNe Ia which has also been considered in previous studies (e.g. Narayan et al. 2011; Foley et al. 2013; Stritzinger et al. 2014). We use the standard definition of decline rate: the change in observed magnitude in a given filter between maximum light and 15 d thereafter. For SN 2015H, we find \( \Delta m_{15} \) = 0.69 ± 0.04 which is similar to that observed in some normal SNe Ia, despite being approximately two magnitudes fainter. It is also consistent with the roughly linear relation observed in SNe Iax (Fig. 4.6), although PTF 09eoi is again a clear outlier, as is SN 2007qd in this instance. Together, Figs. 4.5 and 4.6 show that SNe Iax with longer rise times show slower decline rates, indicating that the width of a SN Iax light curve is indeed linked with its absolute magnitude and tied to \(^{56}\)Ni production.

We test whether the trends observed in Figs. 4.5 and 4.6 represent statistically significant correlations via the use of the Pearson correlation coefficient, \( R_p \), which is a measure of whether a linear correlation exists between two variables. A value of ±1 represents a complete correlation, while zero indicates no correlation. For the decline rate versus peak absolute magnitude, we find \( R_p = 0.39 \) (\( p \)-value \( \sim 0.09 \)) when considering the entire sample. Excluding SN 2007qd and PTF 09eoi\(^7\) we find this value increases to 0.72 (\( p \)-value \( \sim 0.001 \)). For the rise time versus peak absolute magnitude distribution of SNe Iax, we find \( R_p = -0.52 \) (\( p \)-value \( \sim 0.08 \)) when including all objects, and \(-0.71 \) (\( p \)-value \( \sim 0.02 \)) if PTF 09eoi and SN 2007qd are excluded. Thus, our findings are suggestive of the existence of correlations between the absolute (r–band) magnitude of SNe Iax and both rise time and decline rate.

Using the parameters derived from our light curve, we now seek to constrain the amount of \(^{56}\)Ni produced during the explosion, and the total amount of material ejected. Our maximum light coverage of SN 2015H unfortunately only includes one filter, so we are unable to construct a bolometric light curve. We note, however, that the colour and decline rates of SN 2015H and SN 2005hk, are very similar (see Figs. 4.3 and 4.6), and SN 2005hk has extensive pre-maximum coverage in numerous filters. We therefore stretched the light curves of SN 2005hk from Stritzinger et al. (2015) and scaled them to match SN 2015H, allowing us to use these values to construct a pseudo-bolometric light curve for SN 2015H across ugrizJH filters. Applying Arnett’s law (Arnett 1982), and the descriptions provided by Stritzinger & Leibundgut (2005) and Ganeshalingam

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\(^6\)http://csp.obs.carnegiescience.edu

\(^7\)The nature of PTF 09eoi may be uncertain: its limited spectral series shows some similarities to SNe Iax at early epochs, but the matches worsen with time (White et al. 2015). SN 2007qd does not have spectra beyond \( \sim \)15 d post B–band maximum (McClelland et al. 2010). Both PTF 09eoi and SN 2007qd lie in a region of \( M_r \) vs. \( \Delta m_{15} \), separate from the rest of the sample. Given the lack of data for these objects, we are not able to make definitive statements about their nature.
et al. (2012), we estimated the $^{56}$Ni and ejecta masses. By taking a peak bolometric luminosity of $\log(L/L_\odot) = 8.6$, and a rise time to bolometric maximum of $\sim 14.5$ days, we find that SN 2015H produced $\sim 0.06 M_\odot$ of $^{56}$Ni. Using an average ejecta velocity of $\sim 5500$ km s$^{-1}$ ($\S$ 4.4.3, Fig. 4.9) we estimate an ejecta mass of $\sim 0.50 M_\odot$. These values are based on simple scaling laws appropriate for normal SNe Ia. As a test of the validity of our estimates, we used the light curve model described in Inserra et al. (2013) to fit our pseudo-bolometric light curve; we find that it is best matched by $\sim 0.06 M_\odot$ of $^{56}$Ni and $\sim 0.54 M_\odot$ of ejecta. Thus, for SN 2015H, we find our values for the $^{56}$Ni mass and the ejecta mass to be consistent both with other estimates for SNe Iax (see Fig. 15 of McCully et al. 2014b) and the fact that it is of intermediate brightness among this class.

**Figure 4.7:** Spectroscopic sequence of SN 2015H. Spectra have been corrected for redshift and galactic extinction. Epochs are given relative to maximum light at MJD = 57061.9. Regions showing strong telluric features in the NIR have been omitted. Near-IR spectra have also been smoothed, to highlight the features present. We also highlight the features discussed in $\S$ 4.4.3 and those present throughout the spectroscopic evolution which were used for velocity measurements in Fig. 4.9. Arbitrary vertical offsets, and different colours for alternating spectral phases have been used for clarity.
4.4.3 Spectroscopy

In Fig. 4.7 we show the full series of optical and IR spectra for SN 2015H. Our first spectrum is from approximately three days post \( r \)-band maximum, while our last spectrum is 110 days later. The spectra of SN 2015H show features typical of SNe Iax – that is, dominated by IGEs with line velocities lower than those typically measured in normal SNe Ia by a factor of approximately two.

In order to facilitate line identifications, we compare our spectra to calculations made with the one dimensional Monte Carlo radiative transfer code TARDIS\(^8\) (Kerzendorf & Sim 2014). For a given set of input model parameters, TARDIS computes a self-consistent description of the SN ejecta and emergent spectrum. TARDIS is described in § 3.10 and Kerzendorf & Sim (2014), while details of the model adopted here are discussed in Appendix 4.B.

We note that the photospheric approximation employed by TARDIS (i.e. a sharp boundary between optically thick and thin regions) is often used to describe optical wavelengths and leads to synthetic spectra in reasonable agreement to results of other, more sophisticated, radiative transfer codes (Kerzendorf & Sim 2014). This approximation, however, is limited when describing the IR regime where opacities are substantially lower. Accordingly, we limit our TARDIS comparison to optical wavelengths. We carry out our TARDIS modelling on our \(+6\) d spectrum only: between \(+3\) d to \(\sim+30\) d, the spectral features show little evolution in shape and strength, possibly indicating that the ejecta is well mixed; furthermore, our \(+6\) d spectrum has a higher signal-to-noise compared to the earlier \((+3\) d, classification\) spectrum. Beyond epochs of \(\sim30\) d, the assumptions inherent in the TARDIS model (e.g. definition of the photosphere) are no longer robust, so we do not attempt to model spectra taken at these epochs.

In Fig. 4.8 we show a synthetic spectrum that indicates the elements responsible for producing the main spectral features. In order to interpret the spectrum, we show a histogram colour-coded by the atomic number of the element responsible for the last interaction experienced by Monte Carlo packets that escaped from the model region (i.e., those packets that are responsible for contributing to the emergent spectrum). Figure 4.8 shows that the synthetic spectrum is able to reproduce many of the features observed in SN 2015H. From the colour-coded histogram, it is clear that the spectrum is dominated by interactions with IGEs. Below, we discuss a few specific cases of elements that have been reported in other SNe Iax.

\(\text{Si}\ II \lambda 6355\), one of the characteristic features of normal SNe Ia, has been reported

\(^8\)http://tardis.readthedocs.org/en/latest/
Figure 4.8: In the bottom panel of this plot, we show a comparison of our model TARDIS spectrum, in blue, to a spectrum of SN 2015H, in black, at 6 days post $r$–band maximum. Our TARDIS model provides good agreement with many of the features observed in SN 2015H. In the top panel, we colour code a histogram of luminosity per wavelength bin to the atomic number of the element responsible for the last interaction with an escaped Monte Carlo packet. Features below/above the dashed line show the relative contribution of these elements in removing from or adding to the observed flux during the simulation (based on the analysis of interaction histories of escaping MC packets). Packets that do not experience line interactions within the SN ejecta are shown in either black or grey. Black indicates where packets have passed through the entire model region with no interaction, while grey packets have only experienced scattering via free electrons. Dotted vertical lines indicate features for which we measure a velocity, (shown in Fig. 4.9). Dashed vertical lines show features that are discussed further in the main text.

in a number of SNe Iax (e.g. Phillips et al. 2007; McClelland et al. 2010; Stritzinger et al. 2014) at epochs extending from pre-maximum to approximately two weeks post $V$–band maximum. Other features attributed to Si have also been reported in some SNe Iax at early times (e.g. Si $\text{iii}$ $\lambda 4553$ and Si $\text{ii}$ $\lambda 5972$; Branch et al. 2004; Foley et al. 2010a; Yamanaka et al. 2015). About two weeks post-maximum, the Si $\text{ii}$ features blend with features due to Fe $\text{ii}$ and cannot be easily distinguished (Branch et al. 2004). As our spectroscopic campaign only began post $r$–band maximum we cannot identify clear features due to Si $\text{ii}$ in our spectra. This is borne out in Fig. 4.8, where the complex,
broad feature around ∼6 300 Å is likely a blend of Fe II and Si II. Features near 4 550 Å and 5 970 Å can be attributed solely to IGEs for the spectrum under consideration.

Unburned oxygen in the ejecta has been predicted by models of deflagrations of WDs (Gamezo et al. 2004; Jordan et al. 2012; Fink et al. 2014). Features reported as O I λ7 773 have been identified in some SNe Iax (Jha et al. 2006; Sahu et al. 2008; Foley et al. 2009; Narayan et al. 2011). It has also been claimed, however, that similar features in the early spectra of SN 2005hk and late time spectra of SN 2002cx and SN 2008A can be explained by Fe II (Phillips et al. 2007; McCully et al. 2014b). Our spectra show a broad absorption feature around ∼7 600 Å, which our model indicates can be explained by a strong blend of Fe II and O I. Similar to the case of Si II λ6 355 above, we do not identify this feature as being solely due to O I, but instead favour an interpretation where Fe II is the main contributor. We reiterate that features such as Si II and O I may well be easier to identify at earlier epochs.

Having identified the dominant ions shaping our optical spectrum, we now wish to identify the dominant species responsible for the NIR flux. While the TARDIS model discussed above is unsuitable, the more sophisticated simulations discussed further in § 4.6 can be used for this purpose. Based on comparing our spectra to these models, we find that as for the optical spectrum, our 1 μm to 1.6 μm spectrum taken at +16 d is dominated by IGEs, in particular Fe II and weak Co II features (Fig. 4.7).

As with SNe Ia, the detection of H or He in spectra of SNe Iax could be key to shedding light on the progenitor channel(s). Indeed, the recent intriguing detection of the progenitor of the SN Iax 2012Z, has characteristics reminiscent of that of some He novae (McCully et al. 2014a). Possible detections of He I (λ5 876, λ6 678, λ7 065) have in fact been reported for two SNe Iax: SNe 2004cs \(^9\) (Foley et al. 2013) and 2007J \(^10\) (Foley et al. 2009), although whether these two objects are bona fide members of this class is contentious (White et al. 2015).

The atomic energy levels associated with the optical transitions of He I are difficult to excite, so the lack of strong He I features in optical spectra is not surprising, and does not necessarily imply that it is not present in the progenitor system (e.g. Hachinger et al. 2012). Currently, we cannot comment further on optical features (due to the lack of a sufficiently sophisticated treatment of non-thermal excitation/ionisation of He in our models), but we note that at the epoch under consideration, features due to IGEs dominate the spectrum.

\(^9\)SN 2004cs was originally classified as a SN II (Rajala et al. 2005).
\(^10\)SN 2007J was originally classified as being similar to SN 2002cx (Filippenko et al. 2007a). The subsequent development of He I features caused this classification to be revised to a SN Ib (Filippenko et al. 2007b); however, Foley et al. (2009) consider SN 2007J to be a member of the SNe Iax class.
Figure 4.9: Evolution of absorption minima for SN 2015H for a selection of lines that show minimal blending. For comparison, we show velocities measured for Fe II λ6149 for both SN 2002cx and SN 2005hk. Given in black is a typical error bar for measured velocities. Points marked with grey crosses indicate velocities of Fe II λ6247 measured for the N3def model (see § 4.6), at the three epochs shown in Fig. 4.12. Measurements of velocity will be affected, to some degree, by Monte Carlo noise present in the model. We, therefore, estimate a median velocity of these three epochs ±2 d, with the uncertainty given by the standard deviation of these measurements.

Strong He i transitions do exist, however, at NIR wavelengths – for example, the 1s2s 3S – 1s2p 3P transition at 10 830 Å. Many SNe Iax lack observations at these wavelengths; for SN 2015H, not only do we cover this region, but our three NIR spectra were taken at epochs comparable to those of SN 2007J for which the putative He i feature was reported to be growing stronger with time (Filippenko et al. 2007b). In SN 2015H, we find a broad feature around \( \sim 10 700 \) Å, but the inferred velocities are too low when compared with other species to plausibly identify this feature as He i. Based on models described in § 4.6, we find good agreement for this feature with Fe II, and consider this to be a more plausible identification.

We estimated the ejecta velocity by fitting Gaussian profiles to the blueshifted absorption minima of features that show minimal blending. Velocities observed in SNe
Iax at maximum light range from $\sim$2 000 km s$^{-1}$ to $\sim$8 000 km s$^{-1}$ (Foley et al. 2013), and are consistently lower than observed in normal SNe Ia by a factor of approximately two. Figure 4.9 shows the velocity evolution of SN 2015H as measured from a selection of atomic lines that exhibit minimal blending. These velocities show a range from $\sim$5 000 km s$^{-1}$ to $\sim$6 000 km s$^{-1}$ at approximately 3 d post-maximum. Fe II $\lambda$6 149 and $\lambda$6 247 Å in particular show a roughly linear decrease from $\sim$5 000 km s$^{-1}$ to $\sim$1 500 km s$^{-1}$ over the observed time frame. In Fig. 4.9, we also show the velocity evolution as measured from Fe II $\lambda$6 149 for SNe 2002cx and 2005hk; both display higher velocities than SN 2015H, which is consistent with the latter having a slightly fainter peak absolute brightness. For the first 50 d post maximum light, SN 2015H displays a velocity gradient of $\sim$40 km s$^{-1}$ d$^{-1}$. SN 2002cx and SN 2005hk show gradients of $\sim$45 km s$^{-1}$ d$^{-1}$ and $\sim$50 km s$^{-1}$ d$^{-1}$, respectively (Fig. 4.9 and § 4.5). These values are similar to those seen in low-velocity gradient SNe Ia (Benetti et al. 2005).

### 4.5 Comparison with SN 2002cx and SN 2005hk

In Fig. 4.10 we show a selection of SN 2015H spectra ranging from approximately +6 to +113 d and compare these to two other well-observed SNe Iax (SNe 2002cx and 2005hk) at similar epochs, with comparable peak absolute brightnesses and decline rates.

Figure 4.10 shows that many of the spectral features present in both SN 2002cx and SN 2005hk are also present in SN 2015H. The most noticeable difference between these objects is their expansion velocities, with SN 2015H having a slightly lower velocity (by approximately 1 000 km s$^{-1}$ to 2 000 km s$^{-1}$, see Fig. 4.9). Indeed, the somewhat narrower spectral features of SN 2015H allows for the identification of features that were blended in SN 2002cx and SN 2005hk. Notably, the broad feature around 6300 Å (which we believe to be dominated by Fe II, see § 4.4.3) in our +6 and +16 day spectra shows clear signs of a double (and possibly triple) peak, while both SNe 2002cx and 2005hk show smoother features at these epochs. The spectra also contain permitted lines, for example the Ca II IR triplet, which could easily be identified throughout the SN evolution. It appears as a single, broad absorption feature in this region for SN 2002cx and SN 2005hk, while in SN 2015H clear multiple absorption features belonging to this transition are evident. The lower expansion velocities measured in SN 2015H, together with the fact that it was fainter than both comparison SNe indicates that it was likely a less energetic explosion.

The similarity between the spectra of all three objects, shown in Fig. 4.10(a), (b),

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11http://wiserep.weizmann.ac.il
Figure 4.10: Comparison of SN 2015H to other SNe Iax at similar epochs. Spectra are shown in the rest frame of the host galaxy and corrected for galactic extinction. In panel (e) we show the filter function for the LSQ wide filter, along with standard filters SDSS g and r, and V. Note the we scale each filter such that peak transmission has a value of 1. Spectra of SN 2002cx and SN 2005hk were obtained from WISeREP\cite{11} (Yaron & Gal-Yam 2012) and originally from the following sources: SNe 2002cx: Li et al. (2003); Jha et al. (2006). 2005hk: Blondin et al. (2012); Phillips et al. (2007); Silverman et al. (2012).

and (c), indicates that, despite the different explosion strengths and luminosities, they evolve at a roughly similar rate. Additionally, the similarities between our +115 d spectrum, and the much later spectra of SNe 2002cx and 2005hk (+226 and +371 d post-maximum, respectively) are shown in Fig. 4.10(d)\cite{12}. The similarities between these spectra at such different epochs for objects of a similar decline rate indicates that the spectral features of SNe Iax do not undergo much evolution throughout this period. These late phase spectra show a complex blend of forbidden lines at \(\sim 7300\ \text{Å}\), specifically due to [Fe ii], [Ca ii], and [Ni ii] (Jha et al. 2006).

\cite{12}We have chosen to compare spectra at these epochs, as no spectra of SNe 2002cx and SN 2005hk are available at comparable epochs. The spectrum presented here for SN 2002cx is the earliest spectrum available after \(\sim 50\ d\) post-maximum, while the spectrum for SN 2005hk is the earliest spectrum available after \(\sim 70\ d\) post-maximum.
4.6 Comparison to Deflagration Models

Having shown the similarities of SN 2015H to other SNe Iax, we now further investigate whether deflagration models proposed for this class of object are also consistent with observations of SN 2015H. In particular, we compare our observations to the models published by Fink et al. (2014) and Kromer et al. (2013), which have been shown to provide a reasonable match to SN 2005hk. These models describe the pure deflagration of Chandrasekhar mass CO WDs with hydrodynamics followed from the onset of thermonuclear runaway, which is initiated by inserting multiple spherical ignition spots positioned off-centre within the WD. The subsequent propagating flame is treated as a sharp boundary separating the burned and unburned regions using a levelset approach (Osher & Sethian 1988). The hydrodynamic simulation of the explosion is followed until $t = 100$ s by which point the ejecta are close to following homologous expansion (see § 3.2). Ejecta density and abundances are then used in the radiative transfer calculation with the three dimensional Monte Carlo radiative transfer code ARTIS (Sim 2007; Kromer & Sim 2009). Full details of the hydrodynamics, nucleosynthesis, and radiative transfer calculations are given by Fink et al. (2014).

Fink et al. (2014) found that the energy released during the explosion and the luminosity scale as a function of the number of ignition spots used in the model; more ignition spots lead to the release of more energy. The number of ignition spots in a simulation can therefore be used as a numerical parameter to control the strength of the explosion in the model sequence (but we note that the number of ignition points used should not necessarily be taken literally as a requirement on the ignition configuration). Given that SN 2015H was at least half a magnitude fainter than SN 2005hk, we limit our model comparison to those models with only a few ignition spots, as was done for SN 2005hk by Kromer et al. (2013).

Each model is named corresponding to the number of ignition spots (e.g. N10def uses ten spots) used to initiate the explosion. Fink et al. (2014) used a total of 14 models, from a single ignition spot up to 1600 spots. Models with few ignition spots ($\leq 100$) do not release sufficient energy during the explosion to completely unbind the WD. This results in those models leaving behind a (potentially massive) bound remnant, up to $\sim 1.3 M_{\odot}$. In addition, those models show more complex ejecta structures due to the asymmetric flame propagation. These effects, however, are relatively minor: for those objects with only a few ignition spots, there is only a modest ($\leq 0.2$ magnitude) scatter in the synthetic $V$–band light curves across the entire range of observer orientations (Fink et al. 2014). Furthermore, this scatter is even smaller in the redder bands. Consequently, we focus our comparisons on the angle-averaged observables
Figure 4.11: Synthetic light curves of the N1def, N3def, and N5def models are shown in different filters. Black points are observations of SN 2015H, as in Fig. 4.2. The explosion date of SN 2015H is estimated to be MJD = 57046.

In Fig. 4.11, we compare the light curves of SN 2015H to synthetically generated ones from the N1def, N3def, and N5def explosion models. These are the faintest models produced by the sequence and therefore provide the best chance of matching the lower luminosities exhibited by SNe Iax. We find that of the three models considered here, the best agreement is with the N3def model. In particular, there is excellent agreement between the model and observations in the g– and V–band filters, matching both the observed peak brightness and decline rate. The agreement with the peak brightness observed in the r–band is also reasonable. The ability of the N3def model to reproduce the brightness observed in SN 2015H indicates that the amount of $^{56}$Ni produced during the explosion is similar to that inferred from the observations. In § 4.4.2, we discussed estimates for the amount of $^{56}$Ni and ejecta mass produced by SN 2015H; by fitting the pseudo-bolometric light curve, we found values of 0.06 and 0.54 $M_\odot$, respectively. The N3def model is consistent with our estimate of the $^{56}$Ni mass in that it yielded ~0.07 $M_\odot$ of $^{56}$Ni. The corresponding ejecta mass is 0.2 $M_\odot$. We discuss reasons for this
We compare the spectra of SN 2015H to synthetic spectra generated from the N1def, N3def, and N5def explosion models in Fig. 4.12. As with the light curves (Fig. 4.11), N3def again provides the best overall match to the brightness of SN 2015H. Indeed, this model is able to match many of the broader features observed in the spectra of SN 2015H (e.g. the features around \(\sim 5200 \text{ Å} \) and \(\sim 6300 \text{ Å} \)) as well as many of the narrower features (e.g. Fe \(\text{II} \sim \lambda 6050 \text{ Å}, \sim \lambda 6150 \text{ Å}, \text{ and } \sim \lambda 5500 \text{ Å} \)).

Despite the relatively good agreement around maximum light, there are notable discrepancies between the models and the data that become increasingly apparent at later epochs. This is particularly evident in the light curves around three weeks post-explosion, when the synthetic flux in the redder filters (redward of \(\sim 6700 \text{ Å} \)), drops off too rapidly, as shown in Fig. 4.11; in other words, the N3def model shows a decline rate that is too fast ((\(\Delta m_{15}\)) \(_r \sim 1.1 \) compared to the observations ((\(\Delta m_{15}\)) \(_r = 0.69 \pm 0.04 \))). This mismatch feeds into the ejecta mass estimate for the N3def model, resulting in close to a factor of three difference. This is not surprising as a model with higher
ejected mass would have a longer diffusion timescale and is likely to more effectively trap \( \gamma \)-rays for longer, resulting in a broader light curve with a shallower decline rate. A full exploration of ignition conditions has not been carried out. Indeed, somewhat tweaked initial conditions, such as the WD central density, could potentially yield a better match to the decline rate while yielding roughly the same amount of \( ^{56}\text{Ni} \); this warrants further investigation.

### 4.7 Summary

We presented optical and infrared photometric and spectroscopic observations of a peculiar type Ia SN, SN 2015H. Through our extensive photometric coverage of SN 2015H, we found that it peaked with an absolute magnitude of \( M_r = -17.27 \pm 0.07 \). Pre-explosion imaging allowed us to constrain the epoch of explosion, and consequently, the rise time to maximum to approximately two weeks. The decline rate of SN 2015H is similar to that observed in some normal SNe Ia, in spite of being approximately two magnitudes fainter.

SN 2015H shows many of the spectroscopic features typical of the SN Iax class and similarities to two of the best studied members: SNe 2002cx and 2005hk. Specifically, spectra at all epochs show low-velocity features (velocities approximately half what is observed in normal SNe Ia) and our radiative transfer modelling suggests that many of the features present in the spectra of SN 2015H can be explained by, or at least involve a significant degree of blending with, IGEs.

We compared our observations with the deflagration models of M\textsubscript{Ch} CO WDs published by Fink et al. (2014) and found good agreement, the best match being with one of their fainter models (N3def). For epochs up to approximately 50 d post-explosion, this model accounts for the luminosity observed in the \( g \)– and \( V \)–bands for SN 2015H. We find good agreement between the amount of \( ^{56}\text{Ni} \) produced by this best-matching model (0.07 M\(_{\odot}\)) and our estimate for SN 2015H (\( \sim 0.06 \) M\(_{\odot}\)), based on fitting the pseudo-bolometric light curve. This model is also able to reproduce many of the spectroscopic features observed in SN 2015H.

The agreement between the model and observations, however, begins to deteriorate at approximately three weeks post-explosion, particularly at wavelengths longer than \( \sim 6700 \) Å. While we find that N3def provides good agreement with the peak luminosity in the \( r \)–band, the light curve evolution of the model is too rapid; the rise time of N3def is shorter than SN 2015H while the decline rate is faster (see Figs. 4.5 and 4.6). Kromer et al. (2013) found similar results when comparing the N5def model to SN 2005hk. The most likely cause of faster evolution is that the ejecta mass in the models is too low.
Indeed, N3def produces only 0.20 M⊙ of ejecta, while our fit to the pseudo-bolometric light curve of SN 2015H suggests a value close to ∼0.54 M⊙. Increasing the ejecta mass would increase the diffusion time and slow the evolution, as required by the data. Within the current (Fink et al. 2014) sequence of models, adopting a model with higher ejecta mass would also result in increased 56Ni mass; however, the Fink et al. (2014) simulations were not intended as a systematic exploration of the full parameter space for deflagration models, and there is scope for considerable further study. We note, in particular, that Jordan et al. (2012) presented models adopting a lower WD central density and different ignition conditions from the Fink et al. (2014) simulations, and obtained a lower fraction yield of IGEs to total ejecta mass, suggesting that it might be possible to develop models with higher ejecta mass, without a corresponding increase in the mass of 56Ni. We note that such a model would also be likely to have lower specific kinetic energy and thus lower line velocities, which may further improve the agreement with key spectral features (see e.g. the Ca II near-IR triplet in Fig. 4.12).

A full study testing the parameter space of MCh WDs is needed to explore this further. Similar model exploration should also be considered for alternative scenarios, such as the pulsational delayed detonation (PDD) scenario: as discussed by Stritzinger et al. (2015), this may be a good match for events as bright as SN 2012Z, but it remains to be seen whether events as faint as SN 2008ha and SN 2010ae, or indeed even SN 2015H, can be comfortably fit within such a framework.

An interesting prediction from the deflagration model we have considered is that the SN explosion will leave behind a massive (∼1.2 M⊙ for N3def) bound13 remnant. Our own estimate for the ejecta mass of SN 2015H (∼0.54 M⊙) suggests a smaller, but still substantial, remnant mass of ∼0.85 M⊙ (assuming a MCh progenitor). It may be possible that such a remnant already contributes a non-negligible fraction to the observed flux (Kromer et al. 2013). Indeed, this contribution may be more significant for N3def than brighter models, such as N5def, as the fraction of 56Ni contained within the bound remnant compared to the ejecta is much higher (by ∼40% compared to N5def).

Interestingly, the detection of a point-source at the location of one of the faintest SNe Iax, SN 2008ha has been reported over four years after the SN discovery (see § 1.3.3; Foley et al. 2014), by which time, the SN should have faded away. It is conceivable that an explosion remnant may contribute to this emission, but further investigation is needed.

Models involving the deflagration of CO WDs have previously been shown to be broadly consistent with those SNe Iax that are bright (e.g. SN2005hk, Kromer et al.

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13 As defined by Fink et al. (2014), “bound” is taken to mean gravitationally bound at the end of the corresponding hydrodynamical simulation, t = 100 s.
In this study, we have shown that models of weaker deflagrations in M_{Ch} CO WDs producing \sim 0.07 M_\odot of \^{56}Ni are able to reproduce the features observed in fainter events such as SN2015H. Combined with the hybrid CONe WD deflagration model proposed for the very faintest members of the class (e.g. SN2008ha; Kromer et al. 2015), this suggests that deflagrations of WDs are able to account for SNe Iax across their entire brightness range. Whether such deflagrations are the sole or dominant channel giving rise to SNe Iax requires further investigation, but we conclude that the models discussed here do show promise, and merit continued investigation and refinement. We also stress the need for further observations of this class of supernova, including objects that are discovered post-peak, such as SN 2015H.
## Appendix

### 4.A Tables

**Table 4.2**: Local sequence stars used to calibrate SN 2015H LCOGT photometry.

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<th>r (mag)</th>
<th>i (mag)</th>
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**Notes.** Magnitudes of sequence stars are taken from SDSS9 and shown to two decimal places in the AB system. 1σ uncertainties are given in parentheses.

**Table 4.3**: Local sequence stars used to calibrate SN 2015H LSQ photometry.

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**Notes.** Magnitudes of sequence stars are taken from SDSS9 and shown to two decimal places in the AB system. 1σ uncertainties are given in parentheses.
Table 4.4: Local sequence stars used to calibrate SN 2015H NTT photometry.

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**Notes.** $V$– band magnitudes of sequence stars are derived from SDSS9 $gr$ magnitudes, and shown to two decimal places in the AB system. IR magnitudes are taken from 2MASS Point Source Catalogue in the 2MASS natural system. 1σ uncertainties are given in parentheses.
Table 4.5: Optical photometric journal for SN 2015H

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<td>19.70(0.13)</td>
<td>19.66(0.21)</td>
<td>CPT</td>
</tr>
<tr>
<td>2015 Jul. 04</td>
<td>57 207.72</td>
<td>146</td>
<td>...</td>
<td>...</td>
<td>19.80(0.22)</td>
<td>19.55(0.20)</td>
<td>CPT</td>
</tr>
</tbody>
</table>

Notes. 1σ uncertainties are given in parentheses. CPT, COJ, and LSC refer to telescopes that are part of the LCOGT 1-m network. CPT is located at the South African Astronomical Observatory (SAAO), South Africa; COJ is located at the Siding Spring Observatory (SSO), Australia; LSC is located at the Cerro Tololo Inter-American Observatory (CTIO), Chile.
Table 4.6: IR photometric journal for SN 2015H

<table>
<thead>
<tr>
<th>Date</th>
<th>MJD</th>
<th>Phase</th>
<th>J (mag)</th>
<th>H (mag)</th>
<th>K (mag)</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 Feb. 16</td>
<td>57 069.29</td>
<td>7</td>
<td>16.85(0.03)</td>
<td>16.49(0.04)</td>
<td>16.37(0.06)</td>
<td>NTT</td>
</tr>
<tr>
<td>2015 Mar. 12</td>
<td>57 093.05</td>
<td>31</td>
<td>17.56(0.03)</td>
<td>17.11(0.03)</td>
<td>...</td>
<td>NTT</td>
</tr>
<tr>
<td>2015 Mar. 29</td>
<td>57 110.23</td>
<td>48</td>
<td>18.11(0.04)</td>
<td>17.54(0.05)</td>
<td>...</td>
<td>NTT</td>
</tr>
</tbody>
</table>

Notes. 1\(\sigma\) uncertainties are given in parentheses.

Table 4.7: Spectroscopic journal for SN 2015H

<table>
<thead>
<tr>
<th>Date</th>
<th>MJD</th>
<th>Phase</th>
<th>Instrument</th>
<th>Grism</th>
<th>Wavelength Coverage</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 Feb. 11</td>
<td>57 065.13</td>
<td>3</td>
<td>EFOSC2</td>
<td>Gr #13</td>
<td>3 650 – 9 250</td>
<td>17.5</td>
</tr>
<tr>
<td>2015 Feb. 14</td>
<td>57 068.24</td>
<td>6</td>
<td>EFOSC2</td>
<td>Gr #11 &amp; Gr #16</td>
<td>3 345 – 9 995</td>
<td>14.2 &amp; 13.8</td>
</tr>
<tr>
<td>2015 Feb. 15</td>
<td>57 069.18</td>
<td>7</td>
<td>SOFI</td>
<td>Blue &amp; Red</td>
<td>9 350 – 25 360</td>
<td>23.7 &amp; 28.8</td>
</tr>
<tr>
<td>2015 Feb. 18</td>
<td>57 072.28</td>
<td>10</td>
<td>EFOSC2</td>
<td>Gr #11 &amp; Gr #16</td>
<td>3 345 – 9 995</td>
<td>14.1 &amp; 12.5</td>
</tr>
<tr>
<td>2015 Feb. 24</td>
<td>57 078.12</td>
<td>16</td>
<td>EFOSC2</td>
<td>Gr #11</td>
<td>3 345 – 7 470</td>
<td>21.0</td>
</tr>
<tr>
<td>2015 Feb. 24</td>
<td>57 078.20</td>
<td>16</td>
<td>SOFI</td>
<td>Blue</td>
<td>9 350 – 16 450</td>
<td>22.2</td>
</tr>
<tr>
<td>2015 Feb. 25</td>
<td>57 079.10</td>
<td>17</td>
<td>EFOSC2</td>
<td>Gr #16</td>
<td>6 000 – 9 995</td>
<td>20.7</td>
</tr>
<tr>
<td>2015 Mar. 10</td>
<td>57 092.29</td>
<td>30</td>
<td>SOFI</td>
<td>Blue</td>
<td>9 350 – 16 450</td>
<td>24.1</td>
</tr>
<tr>
<td>2015 Mar. 11</td>
<td>57 093.05</td>
<td>31</td>
<td>EFOSC2</td>
<td>Gr #13</td>
<td>3 650 – 9 250</td>
<td>17.8</td>
</tr>
<tr>
<td>2015 Mar. 27</td>
<td>57 109.15</td>
<td>47</td>
<td>EFOSC2</td>
<td>Gr #13</td>
<td>3 650 – 9 250</td>
<td>17.4</td>
</tr>
<tr>
<td>2015 Jun. 01</td>
<td>57 174.88</td>
<td>113</td>
<td>OSIRIS</td>
<td>R500R</td>
<td>4 800 – 10 000</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Notes. Phases are given relative to an estimated \(r\)-band maximum of MJD = 57 061.9. Resolutions are measured from the FWHM of sky lines. Note that the slit width for EFOSC2 exposures taken on 2015 Feb 24 and 2015 Feb 25 was increased to 1.5”. All other exposures were obtained with 1” slit widths.

Table 4.8: Optical photometric journal for PS15csd

<table>
<thead>
<tr>
<th>Date</th>
<th>MJD</th>
<th>Phase</th>
<th>g (mag)</th>
<th>r (mag)</th>
<th>i (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 Nov. 11</td>
<td>57 338.04</td>
<td>1</td>
<td>19.37(0.03)</td>
<td>18.60(0.02)</td>
<td>18.72(0.02)</td>
</tr>
<tr>
<td>2015 Nov. 16</td>
<td>57 343.00</td>
<td>6</td>
<td>20.22(0.08)</td>
<td>18.93(0.02)</td>
<td>18.80(0.04)</td>
</tr>
<tr>
<td>2015 Nov. 17</td>
<td>57 343.93</td>
<td>7</td>
<td>20.20(0.05)</td>
<td>18.98(0.02)</td>
<td>18.88(0.03)</td>
</tr>
<tr>
<td>2015 Nov. 19</td>
<td>57 345.98</td>
<td>9</td>
<td>20.69(0.05)</td>
<td>19.19(0.04)</td>
<td>18.89(0.03)</td>
</tr>
<tr>
<td>2015 Nov. 21</td>
<td>57 347.86</td>
<td>11</td>
<td>20.81(0.07)</td>
<td>19.42(0.03)</td>
<td>19.03(0.03)</td>
</tr>
<tr>
<td>2015 Nov. 26</td>
<td>57 352.94</td>
<td>16</td>
<td>21.59(0.19)</td>
<td>19.64(0.07)</td>
<td>19.29(0.07)</td>
</tr>
<tr>
<td>2015 Dec. 03</td>
<td>57 359.93</td>
<td>23</td>
<td>21.45(0.16)</td>
<td>19.80(0.06)</td>
<td>19.54(0.06)</td>
</tr>
</tbody>
</table>

Notes. 1\(\sigma\) uncertainties are given in parentheses. All observations were obtained via the Liverpool Telescope. Phases are given relative to an estimated date of \(r\)-band maximum MJD = 57 337.3.
Table 4.9: References for comparison SNe used throughout this paper.

<table>
<thead>
<tr>
<th>SN</th>
<th>SN type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002cx</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2003gq</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2004cs</td>
<td>Ia</td>
<td>1</td>
</tr>
<tr>
<td>2004eo</td>
<td>Ia</td>
<td>2</td>
</tr>
<tr>
<td>2005cc</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2005cf</td>
<td>Ia</td>
<td>3</td>
</tr>
<tr>
<td>2005hk</td>
<td>Iax</td>
<td>4</td>
</tr>
<tr>
<td>2007qd</td>
<td>Iax</td>
<td>5</td>
</tr>
<tr>
<td>2008A</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2008ae</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2008ha</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2009J</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2009ku</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2010ae</td>
<td>Iax</td>
<td>6</td>
</tr>
<tr>
<td>2011ay</td>
<td>Iax</td>
<td>1</td>
</tr>
<tr>
<td>2011fe</td>
<td>Ia</td>
<td>7</td>
</tr>
<tr>
<td>2012Z</td>
<td>Iax</td>
<td>4</td>
</tr>
<tr>
<td>PS15csd</td>
<td>Iax</td>
<td>8</td>
</tr>
<tr>
<td>PTF09ego</td>
<td>Iax</td>
<td>9</td>
</tr>
<tr>
<td>PTF09eoi</td>
<td>Iax</td>
<td>9</td>
</tr>
<tr>
<td>PTF11hyh</td>
<td>Iax</td>
<td>9</td>
</tr>
</tbody>
</table>

Notes. (1) Foley et al. (2013); (2) Pastorello et al. (2007a); (3) Pastorello et al. (2007b); (4) Stritzinger et al. (2015); (5) McClelland et al. (2010); (6) Stritzinger et al. (2014); (7) Nugent et al. (2011); (8) this work; (9) White et al. (2015)

4.B Example TARDIS model for SN 2015H

Here, we describe the TARDIS model used to generate a synthetic spectrum of SN 2015H, as shown in Fig. 4.8. We stress that the model presented here provides a good match to the observed spectrum, but is not a unique solution given the inevitable degeneracy between the input parameters.

As discussed in § 3.10, TARDIS is a one dimensional Monte Carlo radiative transfer code that assumes the SN ejecta are spherically symmetric. In the model adopted here, we use a uniform composition and exponential density profile for the SN ejecta.

\[
\rho(v, t_{\text{exp}}) = \rho_0 \left( \frac{t_0}{t_{\text{exp}}} \right)^3 \exp(-v/v_0),
\]

where \(v\) is the velocity, \(t_{\text{exp}}\) is the time since explosion, and \(v_0\) and \(t_0\) are a reference velocity and time, respectively. The boundaries of the model are set in velocity space at values guided by the velocities measured in SN 2015H as shown in Fig. 4.9. Values for
Table 4.10: Input parameters used in modelling SN 2015H spectrum with TARDIS

<table>
<thead>
<tr>
<th>Supernova properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergent Luminosity</td>
</tr>
<tr>
<td>Time since explosion, $t_{\text{exp}}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Density profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference time, $t_0$</td>
</tr>
<tr>
<td>Reference density, $\rho_0$</td>
</tr>
<tr>
<td>Reference velocity, $v_0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Velocity boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner</td>
</tr>
<tr>
<td>Outer</td>
</tr>
</tbody>
</table>

The emergent luminosity and $t_{\text{exp}}$ are chosen based on our photometric measurements (see § 4.4.2 for discussion on the explosion date of SN 2015H).

In Table 4.11 we compare the composition of the ejecta in our TARDIS model to the deflagration models N3def (Fink et al. 2014) and 2D70 (Jordan et al. 2012). We developed the model ejecta composition by initially including only Ca and fitting the Ca II IR triplet profile. Having obtained good agreement, we progressively added the elements expected in SNe Iax spectra guided by explosive nucleosynthesis models (Fink et al. 2014). Some elements (such as Ne, Al, etc.) were found to have a negligible effect on our model spectrum we therefore do not include them in the TARDIS model, despite them having significant abundances in explosive nucleosynthesis models. In such cases the abundances should be regarded as unconstrained by our TARDIS model.

We find that our preferred ejecta composition is broadly consistent with that of the N3def model published by Fink et al. (2014). There are some notable differences, however: in particular, compared to the N3def (Fink et al. 2014) and 2D70 (Jordan et al. 2012) models, our empirically derived composition favours a lower mass fraction of IMEs. This may be due to the relatively late epochs of our observed spectra, where any strong signatures of IMEs are masked by IGEs. Earlier spectra may have provided more robust constraints on the abundance of IMEs, and/or any potential stratification in the ejecta.
Table 4.11: Comparison of ejecta compositions for SNe Iax deflagration models

<table>
<thead>
<tr>
<th>Abundances</th>
<th>TARDIS</th>
<th>N3def</th>
<th>2D70</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-O:</td>
<td>0.302</td>
<td>0.305(0.369)</td>
<td>0.565</td>
</tr>
<tr>
<td>IMEs:</td>
<td>0.043</td>
<td>0.132(0.087)</td>
<td>0.130</td>
</tr>
<tr>
<td>IGEs:</td>
<td>0.655</td>
<td>0.543(0.526)</td>
<td>0.304</td>
</tr>
<tr>
<td>Helium</td>
<td>1.29 × 10⁻¹</td>
<td>1.22(1.61) × 10⁻¹</td>
<td>4.00(4.05) × 10⁻⁴</td>
</tr>
<tr>
<td>Carbon</td>
<td>6.26(5.10) × 10⁻⁶</td>
<td>9.77(7.03) × 10⁻⁹</td>
<td>1.82(1.66) × 10⁻²</td>
</tr>
<tr>
<td>Oxygen</td>
<td>1.83(2.08) × 10⁻¹</td>
<td>8.01(5.25) × 10⁻²</td>
<td>3.98(2.72) × 10⁻⁴</td>
</tr>
<tr>
<td>Sodium</td>
<td>8.62 × 10⁻³</td>
<td>2.08(1.55) × 10⁻⁴</td>
<td>8.62 × 10⁻³</td>
</tr>
<tr>
<td>Magnesium</td>
<td>1.59(1.09) × 10⁻²</td>
<td>1.05(0.70) × 10⁻³</td>
<td>8.62 × 10⁻³</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1.05(0.70) × 10⁻³</td>
<td>8.01(5.25) × 10⁻²</td>
<td>3.98(2.72) × 10⁻⁴</td>
</tr>
<tr>
<td>Silicon</td>
<td>3.15(2.19) × 10⁻³</td>
<td>1.08(0.89) × 10⁻⁸</td>
<td>8.62 × 10⁻³</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>2.69(1.78) × 10⁻²</td>
<td>5.72(4.25) × 10⁻⁵</td>
<td>2.67(1.67) × 10⁻⁵</td>
</tr>
<tr>
<td>Sulfur</td>
<td>7.67(5.21) × 10⁻⁵</td>
<td>4.28(2.88) × 10⁻³</td>
<td>3.15(2.41) × 10⁻⁵</td>
</tr>
<tr>
<td>Chlorine</td>
<td>2.69(1.78) × 10⁻²</td>
<td>5.72(4.25) × 10⁻⁵</td>
<td>3.15(2.41) × 10⁻⁵</td>
</tr>
<tr>
<td>Argon</td>
<td>4.28(2.88) × 10⁻³</td>
<td>1.08(0.89) × 10⁻⁸</td>
<td>3.15(2.41) × 10⁻⁵</td>
</tr>
<tr>
<td>Potassium</td>
<td>2.67(1.67) × 10⁻⁵</td>
<td>5.72(4.25) × 10⁻⁵</td>
<td>3.15(2.41) × 10⁻⁵</td>
</tr>
<tr>
<td>Calcium</td>
<td>8.62 × 10⁻³</td>
<td>3.15(2.19) × 10⁻³</td>
<td>8.62 × 10⁻³</td>
</tr>
<tr>
<td>Scandium</td>
<td>5.72(4.25) × 10⁻⁵</td>
<td>1.08(0.89) × 10⁻⁸</td>
<td>3.15(2.41) × 10⁻⁵</td>
</tr>
<tr>
<td>Titanium</td>
<td>5.72(4.25) × 10⁻⁵</td>
<td>1.08(0.89) × 10⁻⁸</td>
<td>3.15(2.41) × 10⁻⁵</td>
</tr>
<tr>
<td>Vanadium</td>
<td>3.15(2.41) × 10⁻⁵</td>
<td>5.72(4.25) × 10⁻⁵</td>
<td>3.15(2.41) × 10⁻⁵</td>
</tr>
<tr>
<td>Chromium</td>
<td>3.28(2.97) × 10⁻³</td>
<td>2.03(2.28) × 10⁻⁴</td>
<td>8.62 × 10⁻⁵</td>
</tr>
<tr>
<td>Manganese</td>
<td>2.03(2.28) × 10⁻⁴</td>
<td>8.16(9.05) × 10⁻²</td>
<td>8.62 × 10⁻⁵</td>
</tr>
<tr>
<td>Iron</td>
<td>8.62 × 10⁻²</td>
<td>7.62(7.91) × 10⁻²</td>
<td>8.62 × 10⁻²</td>
</tr>
<tr>
<td>Cobalt</td>
<td>7.62(7.91) × 10⁻²</td>
<td>9.62(8.44) × 10⁻⁵</td>
<td>7.62(7.91) × 10⁻²</td>
</tr>
<tr>
<td>Nickel</td>
<td>9.62(8.44) × 10⁻⁵</td>
<td>6.14(5.85) × 10⁻⁴</td>
<td>9.62(8.44) × 10⁻⁵</td>
</tr>
<tr>
<td>Copper</td>
<td>6.14(5.85) × 10⁻⁴</td>
<td>2.59 × 10⁻¹</td>
<td>6.14(5.85) × 10⁻⁴</td>
</tr>
<tr>
<td>Zinc</td>
<td>2.59 × 10⁻¹</td>
<td>3.02 × 10⁻¹</td>
<td>9.62(8.44) × 10⁻⁵</td>
</tr>
</tbody>
</table>

**Notes.** N3def values are taken from the N3def model published by Fink et al. (2014). 2D70 values are taken from Jordan et al. (2012). Values given here represent mass fractions of each model. Values given in parentheses are mass fractions of the N3def model in the region with velocities between 5 500 km s⁻¹ and 7 500 km s⁻¹, the range of velocities covered in our TARDIS calculations. Here, we define IMEs as elements with atomic number between Z = 11 and Z = 20 (sodium to calcium), while IGEs refers to elements with Z = 21 to 28 (scandium to nickel). Elements not included in the TARDIS model were found to have negligible impact on the spectrum, and are therefore unconstrained by our modelling.
Chapter 5

PS1-12bwh: Additional diversity among type Iax supernovae
In this study, we present observations of a type Iax supernova, PS1-12bwh, discovered during the Pan-STARRS1 3π-survey. Our analysis was driven by previously unseen pre-maximum, spectroscopic heterogeneity. While the light curve and post-maximum spectra of PS1-12bwh are virtually identical to those of the well-studied type Iax supernova, SN 2005hk, the −2 day spectrum of PS1-12bwh does not resemble SN 2005hk at a comparable epoch; instead, we found it to match a spectrum of SN 2005hk taken over a week earlier (−12 day). We are able to rule out the cause as being incorrect phasing, and argue that it is not consistent with orientation effects predicted by existing explosion simulations. To investigate the potential source of this difference, we performed radiative transfer modelling of both supernovae. We found that the pre-maximum spectrum of PS1-12bwh is well matched by a synthetic spectrum generated from a model with a lower density in the high velocity (\( \gtrsim 6000 \text{ km s}^{-1} \)) ejecta than SN 2005hk. The observed differences between SN 2005hk and PS1-12bwh may therefore be attributed primarily to differences in the high velocity ejecta alone, while comparable densities for the lower velocity ejecta would explain the nearly identical post-maximum spectra. These two supernovae further highlight the diversity within the SNe Iax class, as well as the challenges in spectroscopically identifying and phasing these objects, especially at early epochs.

The contents of the following chapter have been published as “Growing evidence that SNe Iax are not a one-parameter family. The case of PS1-12bwh”, Magee et al., Astronomy & Astrophysics, Volume 601, id.A62, 12 pp., 2017, reproduced with permission © ESO. All of the work is my own, with the exception of spectral data reduction and PS1 photometry, which were performed by D. Wright. The cover image for this chapter shows the supernova SN 2012Z in NGC 1309. Image credit: NASA, ESA, The Hubble Heritage Team (STScI/AURA), and A. Riess (JHU/STScI).

5.1 Introduction

Although there is diversity among SNe Ia, they are generally well described as a one parameter family. The amount of $^{56}\text{Ni}$ synthesized in the explosion is the primary driver of observational characteristics, and it is this property that underpins the use of SNe Ia as distance indicators (Branch & Tammann 1992). The same cannot be said for the type Iax SNe; unlike the SNe Ia, they do not exhibit tight correlations in their photometric properties, and are markedly different spectroscopically (see § 1.3). This may suggest that SNe Iax result from a different explosion mechanism (see § 1.4). The fact that many SNe Iax have neither well-constrained peak magnitudes nor decline rates, and even fewer have secure rise time measurements, has further added to the difficulty in interpreting their observed behaviour. The range of observational diversity exhibited by
SNe Iax has not been completely characterized, while the range of expected behaviour remains to be fully explored, particularly in the context of SNe Iax explosion models.

Some of the diversity observed in SNe Iax is illustrated by their maximum light spectra. Absorption features due to intermediate mass elements (IMEs, e.g. silicon, sulphur) are usually apparent, but with strengths that vary substantially from one supernova to another, and are never as strong as in normal SNe Ia. Pre-maximum spectra are unavailable for the vast majority of SNe Iax, but based on the maximum light spectra, one may reasonably expect even greater disparity. Although we showed in Chapter 4 that some of the diversity among SNe Iax can be explained by differences in explosion strength, there is also some evidence that their observed properties are not controlled by a single parameter. For example, SN 2009ku displayed exceptionally low velocities for its peak brightness (Narayan et al. 2011).

Here we present a comparative analysis focussed primarily on the pre-maximum data of the type Iax supernovae PS1-12bwh and SN 2005hk. The study was motivated primarily by the striking differences in pre-maximum spectra accompanied by nearly identical photometric evolution. In what follows, we use the term “ejecta” to refer specifically to unbound material, unless stated otherwise.

5.2 Observations & Data Reduction

PS1-12bwh was discovered during routine operations of the 3π all-sky survey by the Panoramic Survey Telescope and Rapid Response System (hereafter PS1, Kaiser et al. 2010; Magnier et al. 2013) on 2012 Oct. 17. During the early phases of PS1 operations, we ran the Faint Galaxy Supernova survey in which we cross matched sources found in the nightly (undifferenced) images with faint galaxies identified in the Sloan Digital Sky Survey. The first transients were reported by Valenti et al. (2010) and the survey procedures are detailed by Inserra et al. (2013). PS1-12bwh was discovered in this way, and reported by Wright et al. (2012).

Figure 5.1 shows the field around PS1-12bwh. We supplemented the PS1 observations with targeted observations using the 2.0-m Liverpool Telescope (LT, Steele et al. 2004) and the 2.0-m Faulkes Telescope North (FTN, Brown et al. 2013). Our complete set of photometric observations is shown in Table 5.1 and Fig. 5.2.

PS1, FTN, and LT each have custom-built data reduction pipelines that process the images, and apply basic calibrations automatically (Magnier 2007; Schlafly et al. 2012; Brown et al. 2013; Steele et al. 2004, respectively). Given that PS1-12bwh occurred at an offset of only ~3 kpc (projected distance) from the nucleus of its host galaxy,
Figure 5.1: $r$–band image of PS1-12bwh taken with Faulkes Telescope North (FTN) approximately one day post $r$–band maximum. PS1-12bwh (marked by red dashes) is located at $\alpha = 07^{h}09^{m}24^{s}.29$, $\delta = +39^{\circ}06^{\prime}15.8^{\prime\prime}$, and lies approximately 4"N 6"W from the nucleus of CGCG 205-201. Sequence stars used to calibrate photometry are marked and listed in Table 5.4.

CGCG 205-201, we opted to perform the photometry measurements using template-subtracted difference images. For PS1 and FTN images, we used archival pre-explosion SDSS$^1$ images as templates for all bands. When PS1-12bwh had faded well below our detection limits ($\gtrsim 860$ d post-maximum), we acquired templates for the LT images.

Photometry on all images was performed using SNOoPY$^2$ (see § 2.1.3). The stars used to build up a reference PSF are listed in Table 5.4 and shown in Fig. 5.1. Using

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$^1$www.sdss.org
$^2$http://sngroup.oapd.inaf.it/snoopy.html
Figure 5.2: Light curves of PS1-12bwh. Epochs of spectroscopic observations are marked with dot-dashed vertical lines. Light curves of SN 2005hk in the natural system (Stritzinger et al. 2015) have been shifted in time and magnitude to match the light curves of PS1-12bwh, and are shown for comparison as dashed lines. Inset: Absolute $r$–band magnitude light curves of PS1-12bwh and comparison objects used throughout this paper. We limit this comparison to ±20 d relative to $r$–band maximum as an indication of the rise and decline of these objects. With the exception of SN 2008ha, all objects have comparable decline rates in the $r$–band, from 0.60 (PS1-12bwh) to 0.70 (SN 2005hk, Stritzinger et al. 2015) and a spread of absolute peak magnitudes, from $M_{r} = -17.3$ (SN 2015H, Magee et al. 2016) to $M_{r} = -18.6$ (SN 2012Z, Stritzinger et al. 2015). These values can be compared with $M_{r} = -19.24$ for SNe Ia (Hicken et al. 2009). Data sources are listed in Table 5.6.

the procedure described by Tonry et al. (2012), we converted our observed magnitudes in the PS1 filters to the standard SDSS system.

Approximately five days after discovery, a spectrum obtained with the ISIS spectrograph mounted on the William Herschel Telescope (WHT) showed PS1-12bwh to be a SN Iax around maximum light, with notable similarities to SN 2008ae (Wright et al. 2012). We acquired two additional spectra, also from WHT + ISIS, roughly one and
Table 5.1: Photometric journal for PS1-12bwh

<table>
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<th>Date</th>
<th>MJD</th>
<th>Phase (days)</th>
<th>g (mag)</th>
<th>r (mag)</th>
<th>i (mag)</th>
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</table>

Notes. Phases are given relative to the estimated $r$-band maximum of MJD = 56 224.9 - that is, 6.6 d later than $B$-band maximum (Phillips et al. 2007).

two months following the initial classification. All WHT spectra were obtained using the same instrumental set-up: 5 300 Å dichroic with the R300B and R158R gratings. We additionally obtained two spectra; one with the GMOS spectrograph mounted on the Gemini North telescope, and one from the Multiple Mirror Telescope (MMT) with the 300GPM grating. A log of the spectroscopic observations is presented in Table 5.5, and our full spectroscopic sequence is shown in Fig. 5.3.

Spectroscopic data were reduced using standard IRAF routines, as described in Chapter 2. In addition to the flux calibration using spectroscopic flux standards, we adjusted the flux levels of our spectra to the photometry. We did this by calculating synthetic magnitudes of our spectra using SMS (Synthetic Magnitudes from Spectra, Inserra
Figure 5.3: Spectroscopic sequence of PS1-12bwh. All spectra have been corrected for redshift and galactic extinction. Epochs are given in days relative to an $r$-band maximum of MJD = 56 224.9. For clarity, spectra have been offset vertically with the zero point of each offset marked by a dashed line. Features due to telluric absorption, Fe iii $\lambda$4404, Fe ii $\lambda$4555, Si ii $\lambda$6355, and C ii $\lambda$6580 are marked and narrow host emission lines have been removed. Gaps in the $-2$, $+27$, and $+57$ d spectra are due to the instrument configuration (Table 5.5).

et al. 2018) and scaled these such that the synthetic magnitudes match the photometric measurements.

Using narrow emission features due to the host galaxy present in our earliest spectrum, we derive a redshift of $z = 0.0228 \pm 0.0005$ to PS1-12bwh, corresponding to a distance modulus of $\mu = 34.91 \pm 0.15$ ($D_L = 96$ Mpc), assuming $H_0 = 70.0$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$. These values are consistent with the NED values for CGCG 205-201.
5.3 Analysis

5.3.1 Reddening

Unlike normal SNe Ia, SNe Iax as a group do not follow a well defined colour evolution (Foley et al. 2013). This presents a challenge in determining the level of extinction due to the host galaxy, as one must turn to alternative methods. Empirical relations between the strength of Na$^+$ absorption features and extinction are commonly used to estimate the extinction towards SNe. The Na$^+$ doublet is only visible in the $-2$ d spectrum (Fig. 5.4). Prior to measuring the equivalent widths, we normalised the spectrum by fitting and dividing by the pseudo-continuum using a low-order polynomial. This resulted in values of $D1 = 0.42 \pm 0.10$ Å and $D2 = 0.56 \pm 0.07$ Å. Using the equations of Poznanski et al. (2012), this provides an estimate for the host extinction of PS1-12bwh of $E(B - V)_{\text{host}} = 0.20 \pm 0.07$ mag. Combining this with the extinction in the direction of PS1-12bwh provided by NED, this results in a total extinction value of $E(B - V)_{\text{total}} = 0.26 \pm 0.07$ mag, assuming $R_V = 3.1$, which we adopt throughout this study.

5.3.2 Photometry

In Fig. 5.2, we present the full light curve of PS1-12bwh. It includes observations before or around maximum light in each filter, and extends to over 100 d post $r$–band maximum. In keeping with observations of other SNe Iax, PS1-12bwh does not show any sign of a secondary maximum in the $i$ or $z$ bands.

By fitting low-order polynomials, we derived the light curve parameters for PS1-12bwh in each of the $griz$ filters. We find that it attained its peak $r$–band value of $+17.93 \pm 0.04$ on MJD = 56224.9\(\pm1.3\). This corresponds to a peak absolute $r$–band magnitude of $-17.69 \pm 0.24$ using our derived distance modulus and extinction. Decline rates in each filter are calculated from the peak magnitude and the corresponding magnitude 15 d later; the values are listed in Table 5.2. The uncertainty in the absolute magnitude of PS1-12bwh is dominated by the uncertainty in host extinction. From here onwards, all references to the epoch of maximum light refer to the date of $r$–band maximum.

As can be seen from Table 5.2 and Fig. 5.2, PS1-12bwh displays a remarkably similar photometric evolution to SN 2005hk. As a check, we also derived light curve parameters for PS1-12bwh using SN 2005hk as a template (Fig. 5.2), and find them to be consistent with those reported in Table 5.2. Unfortunately, there are no observations of the field of PS1-12bwh in any filter within 100 d prior to discovery, so we are
Figure 5.4: Zoom-in of the −2d spectrum of PS1-12bwh. Na I D absorption features are marked with vertical dashed lines in the frame of the host galaxy.

therefore unable to set a robust limit on its explosion epoch.

5.3.3 Spectroscopy

The full spectroscopic sequence for PS1-12bwh is shown in Fig. 5.3.

5.3.3.1 Pre-maximum spectrum

In spite of the virtually identical light curve evolution of PS1-12bwh and SN 2005hk, it can be seen from Fig. 5.5 that their pre-maximum spectra are markedly different. Indeed, it is clear that the −2 d spectrum of PS1-12bwh is more similar spectroscopically to the −12 d SN 2005hk spectrum, or indeed similar spectra at even earlier epochs, than to the one at −3 d.
Table 5.2: Light curve parameters for PS1-12bwh compared to SN 2005hk

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<th>Filter</th>
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<th>Apparent peak (mag)</th>
<th>Absolute peak (mag)</th>
<th>Decline rate $\Delta m_{15}$ (mag)</th>
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<tr>
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Notes. The light curve parameters of SN 2005hk are taken from Stritzinger et al. (2015).

Figure 5.5: Comparison of the $−2$ d PS1-12bwh spectrum to two pre-maximum epochs of SN 2005hk. The spectrum of PS1-12bwh has been binned to $\Delta \lambda = 5$ Å and the narrow host emission lines have been removed. All spectra were normalised by the average continuum flux. The gap in the PS1-12bwh spectrum around 6 200 Å is due to the dichroic used. The lower panels show the residuals resulting from taking the difference between the spectra in the respective upper panel, confirming that the $−2$ d PS1-12bwh spectrum is a better spectroscopic match for the $−12$ d SN 2005hk spectrum, than the similarly phased $−3$ d spectrum. Features of interest are indicated by full vertical lines. The original data sources for spectra of SN 2005hk are given in Table 5.6.

At pre-maximum epochs, the spectra of SNe Iax generally show blue continua and few notable features, with exceptions being absorptions due to Fe$^{III} \lambda 4404$ and Fe$^{II} \lambda 4555$. Weak Si$^{II} \lambda 6355$ is also seen, but this feature is always far less prominent than in normal SNe Ia. Features due to other IMEs are sometimes also apparent in
SNe Iax (e.g. S II, O I, and Mg II; Phillips et al. 2007; Foley et al. 2010a; Szalai et al. 2015). Features due to Fe II λ 4404, Fe II λ 4555, and Si II λ 6355 are observed in the −2 d spectrum of PS1-12bwh and the −12 d spectrum of SN 2005hk, although the Si II feature is somewhat stronger in SN 2005hk. From the Si II λ 6355 feature, we infer velocities of ≈ 5700 km s⁻¹, ≈ 6100 km s⁻¹, and ≈ 5800 km s⁻¹ for PS1-12bwh at −2 d and SN 2005hk at −12 and −3 d, respectively. Typical uncertainties in these measurements are ±500 km s⁻¹. The values for SN 2005hk reported above are consistent with those reported by Phillips et al. (2007). We also tentatively identify absorption due to C II λ 6580; this feature has been seen in the pre-maximum spectra of other SNe Iax (e.g. Foley et al. 2013), and is indicative of unburned material in the ejecta.

As seen in Fig. 5.5, by −3 d, many of the features observed in SN 2005hk have significantly increased in strength compared to the spectrum taken a week earlier, and bear little resemblance to the −2 d spectrum of PS1-12bwh. This is particularly true of the Fe II λ 4555, and Si II λ 6355 features, which have dramatically increased in strength, although there is little change in the Fe III λ 4404 absorption feature.

5.3.3.2 Post-maximum spectra

In Fig. 5.6 we compare the +2 d spectrum of PS1-12bwh to those of SNe 2005hk (−3 d) and 2012Z (+2 d). As there are no spectra available of SN 2005hk at +2 d, we use SN 2012Z as a proxy, given its similarity to SN 2005hk (Stritzinger et al. 2015). It can be seen that the similarity of PS1-12bwh to spectra of SN 2005hk taken at earlier epochs persists to this post-maximum phase.

Despite the differences in the early spectra, at later epochs the spectra of PS1-12bwh are remarkably similar to the spectra of other SNe Iax at comparable phases, including SN 2005hk, and in particular to those with similar decline rates. Objects shown in Fig. 5.7 have decline rates ranging from ≈ 0.60 (PS1-12bwh) to 0.70 (SN 2005hk; Stritzinger et al. 2015) in the r–band. As is typical of post-maximum SNe Iax spectra, the weak signatures of IMEs visible during the pre-maximum phases of PS1-12bwh have disappeared, and the spectra are now dominated by iron group elements (IGE).

Velocities measured from Fe-group features show a steady decline from around maximum light to two months post-peak: from the Fe II λ 6149 feature in the +2 d spectrum, we find a velocity of ≈ 7500 km s⁻¹. Approximately one month post maximum light, the velocity has decreased to ≈ 4900 km s⁻¹, and further to ≈ 4400 km s⁻¹ by +57 d. SN 2005hk shows a similar evolution in the velocity measured from this
Figure 5.6: Maximum light spectrum of PS1-12bwh compared to SN 2012Z at the same epoch and to SN 2005hk a day earlier. All spectra have been corrected for redshift and extinction, and have been rebinned to the same resolution ($\Delta \lambda = 3$ Å). SNe 2005hk and 2012Z have been offset vertically from PS1-12bwh for clarity, with the zero level of each offset marked by dashed lines. Phases are given relative to the $r$–band maximum. The shaded areas highlight wavelength regions containing features with comparable strengths and shapes in the spectra of PS1-12bwh and SN 2005hk, but not SN 2012Z. PS1-12bwh at $+2$ d appears to be qualitatively more similar to the pre-maximum SN 2005hk spectrum, than to the SN 2012Z spectrum at the same epoch. Data sources are listed in Table 5.6.

feature: $\sim 6300$ km s$^{-1}$ at $+6$ d to $\sim 5000$ km s$^{-1}$ at $+30$ d, to $\sim 4000$ km s$^{-1}$ another month later. We note that at these epochs, features due to IMEs (such as Si ii λ6355) are blended with features due to IGEs, and are therefore not easily identifiable. Figure 5.7 shows a spectroscopic comparison of objects with similar $\Delta m_{15}(r)$ at post-maximum epochs.

5.3.3.3 Host galaxy metallicity

The presence of narrow host galaxy features in our earliest spectrum allows us to estimate the metallicity of CGCG 205-021. We do so by first fitting and subtracting the pseudo-continuum in the $-2$ d spectrum. We then fit Gaussian profiles to the narrow
Figure 5.7: Post-maximum spectra of PS1-12bwh compared with other SNe Iax at comparable epochs. All spectra have been corrected for redshift and reddening. Phases for PS1-12bwh are given relative to the $r$-band maximum (MJD = 56 226.96). The WHT PS1-12bwh spectra have been binned to $\Delta \lambda = 5$ Å and the narrow host emission lines have been removed. Shaded regions are discussed further in the main text. The data sources for all objects are listed in Table 5.6. The spectra have been offset vertically from PS1-12bwh for clarity. All objects appear spectroscopically similar several weeks past maximum brightness, despite differences in velocity and peak brightness, from $M_r \approx -17.3$ (SN 2015H, Magee et al. 2016) to $M_r \approx -18.6$ (SN 2012Z, Stritzinger et al. 2015).

H$\alpha$ and [N II] $\lambda 6583$ features observed. Using the empirical relation derived by Pettini & Pagel (2004) with the N2 index, we find a host metallicity of $12 + \log(O/H) = 8.87 \pm 0.19$ dex. Metallicity measurements for the host galaxies of other SNe Iax derived from the Pettini & Pagel 2004 relation yield comparable values: $12 + \log(O/H) = 8.16 \pm 0.15$, $8.40 \pm 0.18$, and $<8.51 \pm 0.31$ dex for SNe 2008ha, 2010ae, and 2012Z (Foley et al. 2009; Stritzinger et al. 2014; Yamanaka et al. 2015), respectively. SNe Iax therefore appear to show no preference for either sub- or super-solar$^3$ environments. The

$^3$We assume a solar metallicity of $12 + \log(O/H) = 8.69 \pm 0.05$ (Asplund et al. 2009).
Figure 5.8: Comparison of peak absolute magnitude and host galaxy metallicity for a sample of SNe Iax. Metallicity measurements are derived using the relations of Pettini & Pagel (2004) and are shown for SN 2008ha (Foley et al. 2009), SN 2010ae (Stritzinger et al. 2014), and SN 2012Z (Yamanaka et al. 2015). Peak absolute magnitude is shown in the $r$-band, with the exception of SN 2008ha which is shown in the $R$-band. Note that this figure does not appear in Magee et al. (2017).

existence of a link between the host galaxy metallicity and peak supernova magnitude could be used to shed light on the likely progenitor channels. Based on the metallicity estimates currently available in the literature, however, there does not appear to be a clear correlation (see Fig. 5.8).

5.4 Discussion

Here we investigate potential causes for the disparity between the $-3\,d$ spectrum of SN 2005hk and the $-2\,d$ spectrum of PS1-12bwh.

5.4.1 Epoch misidentification

The first and most obvious potential cause is an error in the determination of the phase of either or both supernovae. The light curve of PS1-12bwh is shown in Fig. 5.2, with epochs of spectroscopic observations marked by dashed lines. As described in § 5.3.2, we estimated the $r$–band maximum to have occurred on MJD = 56 224.9±1.3, while our
first spectrum was observed on MJD = 56 223.1 – in other words, only 1.8±1.3 days before $r$–band maximum. While there is inevitably some uncertainty in this phase, the $r$–band light curve of PS1-12bwh is clearly declining only a few days after our first spectrum was taken, and it is therefore not possible that this spectrum was taken close to 12 d before maximum light. The $r$–band maximum of SN 2005hk is well constrained to MJD = 53 691.66±0.23 (Stritzinger et al. 2015). The pre-maximum spectra of SN 2005hk were taken on MJD = 53 679.4 (Chornock et al. 2006) and MJD = 53 688.2 (Phillips et al. 2007), which correspond to phases of −12.26±0.23 and −3.46±0.23, respectively. Therefore, secured by the light curves, we can rule out phasing errors as the source of the difference between the two spectra.

### 5.4.2 Existing explosion models

As discussed previously (§ 1.4), several explosion scenarios have been considered for SNe Iax. Many of these are variants of explosion models first proposed for SNe Ia. These include both deflagration models (Nomoto et al. 1984; Branch et al. 2004), and delayed-detonation models in which an initial deflagration transitions to a detonation (Khokhlov 1991b; Hoeflich et al. 1995; Gamezo et al. 2004). For both of these classes of models, it has been suggested that the fainter peak magnitudes and lower ejecta velocities observed in SNe Iax relative to normal SNe Ia may be explained by relatively low energy explosions. Indeed, the least energetic of these pure deflagration models succeed in only partially disrupting the white dwarf (WD; Jordan et al. 2012; Fink et al. 2014).

It has been demonstrated that both explosion scenarios naturally allow for variations in observational quantities since differences in the explosion parameters such as the ignition configuration in deflagration models (Fink et al. 2014), or variations in the adopted deflagration-to-detonation transition density (e.g. Höflich et al. 2002) can give rise to a range of $^{56}$Ni-masses (approximately 0.03 $M_\odot$ to 0.6 $M_\odot$), which ultimately controls most of the observed properties, especially at early epochs.

Existing models, however, do not explore the parameter space sufficiently to ascertain whether any specific scenario is able to simultaneously account for the spectral differences observed in PS1-12bwh and SN 2005hk, as described in § 5.3.3, without significant differences in their respective light curves. For example, for SNe Ia, Höflich et al. (1995) investigated whether variations in the initial conditions of the progenitor WD could lead to observable differences for pulsational delayed detonation (PDD) models. They find that it is possible to produce similar light curves with different initial conditions and explosions; however, it is unclear whether this could explain the spectroscopic observations of SN 2005hk and PS1-12bwh.
In their study of deflagration models, Fink et al. (2014) carried out a sequence of simulations in which the strength of the explosion was varied by altering the ignition configuration geometry. This resulted in significant variation in $^{56}\text{Ni}$ masses, ranging from approximately $0.03 \, M_\odot$ to $0.3 \, M_\odot$. They also investigated whether a relatively large change in the WD central density could produce noticeably different explosions. Although the models they considered (N100Hdef and N100Ldef) are too bright at peak (by $\gtrsim 1$ mag.) for direct comparisons with PS1-12bwh, they found that the central density does not very significantly affect the observables. Thus, for the pure deflagration models currently available, it appears unlikely that either the $^{56}\text{Ni}$ mass, or variations in the central density could be the discriminating factor between SN 2005hk and PS1-12bwh. Comparable studies for fainter models are not available, but merit investigation.

The multi-dimensionality of the Fink et al. (2014) deflagration models allows us to investigate whether orientation effects could explain the differences between SN 2005hk and PS1-12bwh, at least for this class of model: although the synthetic spectra computed from these models show small variations as a function of angle at all epochs, these are not sufficiently strong to significantly alter any of the spectral features discussed in § 5.3.3. For example, across the full range of viewing angles for the N5def model, the standard deviation from the average equivalent width of the Fe\text{iii} $\lambda 4404$ absorption profile is less than 10%\textsuperscript{5}. We therefore can not ascribe the apparent discrepancies between the pre-maximum spectra of SN 2005hk and PS1-12bwh to orientation effects in the pure deflagration models.

Thus, based on existing explosion models, we cannot easily identify a parameter that drives the observed pre-maximum spectroscopic differences in SN 2005hk and PS1-12bwh. Future simulations that further explore the effects of variations in the WD initial conditions would be needed to investigate this further in relation to specific explosion scenarios. In the remainder of this study, we pursue the alternative strategy of developing empirical models to better characterise the differences in ejecta properties that might be most consistent with the data.
Figure 5.9: Spectroscopic comparison of PS1-12bwh and SN 2005hk to TARDIS model spectra. The spectra of PS1-12bwh have been binned to $\Delta \lambda = 5 \, \text{Å}$, and the narrow host emission lines have been removed. Panel (a) shows the comparison of our favoured models in red (N5-3T and N5-2Tls) to observations in black. Spectra in blue show our favoured models with a carbon abundance reduced by an order of magnitude. The only difference in the resultant spectrum is the decreased strength of the C ii $\lambda 6580$ feature. In panels (b), (c), and (d), the N5-2T model is shown for reference. Green and blue spectra demonstrate the effects of changing certain physical parameters (see Table 5.3) on the resultant synthetic spectrum. As in panel (a), comparisons are to the −2 d PS1-12bwh spectrum. Shaded regions indicate the Fe ii and Fe iii, and Si ii and C ii features that we use to define a satisfactory model (see § 5.4.3). Panel (e) shows a direct comparison of the N5+2Tls model spectrum to the +2 d spectrum of PS1-12bwh.

5.4.3 Empirical modelling

From Fig. 5.5, it can be seen that there is a clear difference in ionisation state between the SN 2005hk −3 d and the PS1-12bwh −2 d spectra. For example, the Fe ii $\lambda 4440$ absorption is stronger than Fe iii $\lambda 4404$ in the SN 2005hk spectrum, while the converse is true for the PS1-12bwh spectrum. Furthermore, SN 2005hk shows strong absorption features due to Si ii and C ii while these are weak in the PS1-12bwh spectrum. Yet Fig. 5.2 and Table 5.2 clearly demonstrate that both objects have remarkably similar

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4The naming scheme adopted by Fink et al. (2014) is as follows: the ‘X’ in NXdef refers to the number of sparks used to ignite the model. The peak brightness of these models typically scales with the number of ignition sparks, from $-16.8 \lesssim M_V \lesssim -19.0$. H/L refer to models with a higher or lower central density, respectively, relative to the standard N100def model.

5As the variations with viewing angle are more significant at shorter wavelengths, we focussed our attention on the prominent Fe iii $\lambda 4404$ absorption feature.
Table 5.3: Input parameters for TARDIS model spectra

<table>
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<tr>
<th>Model</th>
<th>Luminosity log($L/L_\odot$)</th>
<th>Time since explosion $t_{\text{exp}}$ (days)</th>
<th>Inner boundary $v_i$ (km s$^{-1}$)</th>
<th>Outer boundary $v_o$ (km s$^{-1}$)</th>
<th>Density</th>
<th>Composition</th>
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<td>7 800</td>
<td>9 400</td>
<td>N5def</td>
<td>N5def</td>
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<td>7 800</td>
<td>9 400</td>
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<td>N5def</td>
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<tr>
<td>N5+2Tls</td>
<td>8.85</td>
<td>24</td>
<td>5 200</td>
<td>9 400</td>
<td>N5def</td>
<td>N5def</td>
</tr>
</tbody>
</table>

Notes. For the density and composition, we take a spherical average of velocity shells from the N5def model of Fink et al. (2014). The naming scheme of our models is defined as follows: N5-XT refers to TARDIS models (’T’) which are based on the N5def model from Fink et al. (2014), with ‘-X’ referring to the phase of the spectrum. These times correspond to phases of −3 d, −2 d, and +2 d relative to $r$-band maximum, assuming a rise time of ∼22 (Phillips et al. 2007; Magee et al. 2016). The suffixes f/s refer to the photospheric velocity being fast/slow, while h/l refer to the ejecta density being higher/lower relative to the N5def model.

5.4.3.1 Modelling the −3 d SN 2005hk spectrum

As discussed in § 3.10, as input for our spectral synthesis calculations, we require both a luminosity and time since explosion for each spectrum; for SN 2005hk we determine these from the light curves of Stritzinger et al. (2015): we set the luminosity to $L = 10^{9.1} L_\odot$ and the time since explosion, $t_{\text{exp}} = 19$ d, for our SN 2005hk model and treat both as fixed parameters.

The N5def and N3def models described by Fink et al. (2014) have previously been shown to provide reasonable matches to the observables of SNe 2005hk (Kromer et al. 2013) and 2015H (Chapter 4; Magee et al. 2016). Specifically, these models are able to
reproduce important properties of the early spectra of both SNe, including the low line velocities and weak IME features. The corresponding model light curves show good agreement with the peak absolute magnitudes, but decline faster than observed in the redder bands. This may be the result of a lack of $\gamma$-trapping and could indicate that the model ejecta masses are too low, as discussed by Kromer et al. (2013). Indeed, this model results in the production of $\sim 0.4 \, M_\odot$ of unbound ejected material and a $\sim 1 \, M_\odot$ bound remnant, while McCully et al. (2014b) estimate SN 2005hk produced roughly twice as much ejecta. Given the reasonable agreement between the N5def model and SN 2005hk, we opted to determine the density and composition in our model by taking averages of the N5def model in spherical velocity shells.

The only remaining free parameter for the spectral synthesis calculation is the range of velocities included in the line forming region of our model (i.e. the choice of the inner and outer boundaries of the computational domain). This range (7800 – 9400 km s$^{-1}$) was selected to satisfactorily reproduce the observed spectrum. The resulting synthetic spectrum is shown in Fig. 5.9(a), and we denote this model as N5-3T (see Table 5.3).

Although there appears to be a slight difference in velocity, the N5-3T model is able to broadly match many of the features observed in SN 2005hk at $-3 \, d$, including the overall flux level, the strong absorption seen at $\sim 5000 \, \text{Å}$, the numerous features observed at near-UV wavelengths, the ratio of Fe $\text{iii} \lambda 4404$ to Fe $\text{ii} \lambda 4555$, and the relatively strong Si $\text{ii} \lambda 6355$. Indeed, the profiles of Fe $\text{iii} \lambda 4404$, Fe $\text{ii} \lambda 4555$, and Si $\text{ii} \lambda 6355$ clearly demonstrate the differences between the spectra of SN 2005hk and PS1-12bwh. Based on these features, we deem the N5-3T model to provide reasonable agreement with SN 2005hk.

The C $\text{ii} \lambda 6580$ absorption feature (Fig. 5.9a) produced by N5-3T is much more pronounced in the model than in the observed spectrum. This mismatch can also be seen in the comparison of the spectrum resulting from the N5def model for SN 2005hk by Kromer et al. (2013, their Fig. 5). This may be because the amount of carbon entrained in the N5def explosion model is too high to match SN 2005hk. We therefore reduced the carbon abundance in the ejecta of our N5-3T model by an order of magnitude, and find an improved match to the weak C $\text{ii} \lambda 6580$ feature, with little effect on the rest of the spectrum. Models with reduced carbon abundances are shown in blue in Fig. 5.9(a).

5.4.3.2 Modelling the $-2 \, d$ PS1-12bwh spectrum

Having generated an acceptable model for SN 2005hk at $-3 \, d$, we use it as a starting point to identify the possible cause of the differences present in the line-forming re-
gions of the two supernovae. In order to identify a model as satisfactory, we define the following basic criteria that it must meet:

- a lack of lines at wavelengths long-ward of ∼5 000Å, with exceptions being the weak features due to Si II and C II;
- the peak of the SED must occur at relatively blue wavelengths (∼4 000 Å); and
- deeper Fe III λ4 404 relative to Fe II λ4 555.

If a model satisfies these criteria, we expect that it closely approximates the ionisation state of the ejecta. Further discrepancies between the model and observations may of course arise due to differences in the exact density or composition structure, but such an investigation is beyond the scope of the broad, exploratory study here.

We begin by altering the luminosity and phasing of the N5-3T model generated for the −3 d spectrum of SN 2005hk, such that they correspond to the values appropriate for PS1-12bwh at −2 d. The luminosity is set to \( L = 10^{8.95} L_\odot \), somewhat lower than SN 2005hk (0.15 dex). Given the similarity of their light curves at post-maximum epochs, we assume that their pre-maximum light curve evolution is also comparable; this is in fact supported by the limited pre-maximum coverage of PS1-12bwh and the similar post-maximum decline, and hence we set \( t_{\text{exp}} = 20 \) d (i.e., one day later than our N5-3T model or two days before maximum light). These two changes to the N5-3T model form our N5-2T model, which is replicated in red in panels (b), (c), and (d) of Fig. 5.9. It shows strong absorption at near-UV wavelengths that is not observed in PS1-12bwh. It also produces stronger Si II absorption than is observed, and stronger Fe II compared to Fe III, which is the opposite to what is observed. Thus, the N5-3T and N5-2T models demonstrate that the differences between SN 2005hk at −3 d and PS1-12bwh at −2 d cannot be accounted for by simply adjusting for the slight differences in epoch and luminosity.

We tested a variety of models with shorter rise times than the 21.8 d observed for SN 2005hk (Phillips et al. 2007; Magee et al. 2016). We find that the pre-maximum spectrum of PS1-12bwh cannot be accounted for simply by shortening the rise time to peak. In addition, a significantly shorter rise time would appear to contradict the similar post-maximum evolution observed in SN 2005hk and PS1-12bwh. Furthermore we find that we are not able to produce satisfactory matches to the +2 d spectrum of PS1-12bwh when assuming such a rise time. We therefore conclude that the discrepancy between pre-maximum spectra is unlikely to be due to a difference in rise times.

Below we investigate changes in other physical parameters that could shed light on the pre-maximum spectra of SN 2005hk and PS1-12bwh. As we did previously
for the SN 2005hk model above (N5-3T), we treat the original N5def composition as being fixed for the construction of the PS1-12bwh models. We did consider alternative compositions having up to an order of magnitude increase in IGE abundances, but these did not produce the desired results. Consequently, we retain the original N5def composition and focus our analysis on other physical parameters.

We next considered the effect of changing the location of the photosphere in our spectrum calculation – in other words, effectively altering the boundary radiation temperature of the model; this is shown in Fig. 5.9(b). Increasing the photospheric velocity (N5-2Tf), and therefore decreasing the temperature, produces a similar spectrum to our N5-2T model but causes the Si ii to become much weaker. With this increased velocity, the ratio of Fe iii to Fe ii remains practically unchanged. Lowering the photospheric velocity (N5-2Ts), and therefore increasing the temperature increases the strength of the C ii, Si ii, and S ii. Therefore, the placement of the photosphere in the model alone cannot easily account for the observed differences.

At early epochs, it is the outermost layers of the SN ejecta that influence the appearance of the observed spectra. As the differences between SN 2005hk and PS1-12bwh are limited to pre-maximum epochs, it is likely that the main differences also occur in the outermost ejecta layers. We investigate this by altering the density in the outer regions. We constructed density profiles within the region delimited by 5800 – 9400 km s\(^{-1}\) that are a factor of five higher or lower than that of the N5def model. We stress that this is the region of ejecta probed by our models, and we do not comment on ejecta properties outside this region. For the models considered in this study, these regions correspond to \(\sim 25 – 35\%\) of the ejecta mass. We stress that we have taken the relatively simple approach of scaling the total density in the spectrum-forming region by an overall factor. Although simplistic, this approach allows us to easily explore the sensitivity to density; given the limited quality and time-coverage of our spectral series, more detailed attempts to pin down an exact density profile are not warranted here.

At higher densities (N5-2Th) relative to N5def, the model produces many strong absorption features between \(\sim 5000 - 6000\ \text{Å}\), violating our first criterion for an acceptable match above. The lower density model (N5-2Tl), however, matches the redder wavelengths, with only weak Si ii and C ii absorption present. N5-2Tl also matches the Fe iii \(\lambda 4404\) profile, but produces stronger Fe ii \(\lambda 4555\) absorption. We therefore conclude that while a lower density for high velocity ejecta improves upon the N5-2T model, it alone is not sufficient to match the observed spectrum of PS1-12bwh.

Given the rough agreement with the data afforded by a lower density (N5-2Tl), we now test whether changes in photospheric velocity, in conjunction with a lower density, might further improve upon the N5-2Tl model. Doing so yields synthetic spectra that
are shown in Fig. 5.9(d). As mentioned previously, an increased photospheric velocity (N5-2Tf) causes a desirable reduction in the strengths of features at longer wavelengths – this is also observed in the N5-2Tl model. Simultaneously implementing a lower density and increasing the photospheric velocity (N5-2Tlf), however, is not able to overcome the shortcomings of either parameter on its own; the N5-2Tlf model does not reproduce the Fe\textsc{ii} λ4404 to Fe\textsc{ii} λ4555 ratio in the correct sense. Instead, we find that the model that is best able to meet all three criteria described above is one that simultaneously incorporates a lower density for high velocity ejecta and a lower photospheric velocity (N5-2Tls). Indeed, a lower photospheric velocity may be seen as a natural consequence of a reduced density, as the photosphere recedes faster through the less dense ejecta. Therefore these parameters are qualitatively consistent with each other.

We are now in a position to conclude that the divergence between the −3 d spectrum of SN 2005hk and −2 d spectrum of PS1-12bwh can be attributed to differences in their ejecta structures. Specifically, differing densities of the high velocity material (by approximately a factor of a few). Such a scenario naturally explains why this only manifests in the earliest spectra, as it is at these epochs that the highest velocity ejecta are observed. We speculate that the density of the lower velocity material may be comparable for both objects, hence the spectroscopic similarity at later epochs.

In order to test this, we modelled the +2 d spectrum of PS1-12bwh and allowed for material at lower velocities to have a higher density. We adjusted the time since explosion (\(t_{\text{exp}} = 24\) d), and slightly decreased the luminosity (\(L = 10^{8.85} L_\odot\)) and inner velocity boundary (\(v_i = 5200\) km s\(^{-1}\)). For the ejecta above 5 800 km s\(^{-1}\), we maintained the same density profile as our N5-2Tls model, but used an unmodified N5def density profile between 5 800 and 5 200 km s\(^{-1}\); the resulting synthetic spectrum compared to PS1-12bwh is shown in Fig. 5.9(e). Thus, with these adjustments, we were able to reproduce the correct ratio of Fe\textsc{ii} λ4404 to Fe\textsc{ii} λ4555 at +2 d (which has inverted since −2 d) and generate more prominent features at redder wavelengths than are visible at −2 d. Therefore, accepting that the N5+2Tls model results in a spectrum that is broadly consistent with the +2 d spectrum of PS1-12bwh, we can conclude that this spectrum is consistent with the higher velocity ejecta of PS1-12bwh having a lower density compared to SN 2005hk.

It is now clear that there are additional factors that drive the diversity of SNe Iax. Typically, variations in thermonuclear explosions are attributed to differences in total ejecta mass or \(^{56}\)Ni yield. The similarity in light curve properties of PS1-12bwh and SN 2005hk implies that these bulk properties are similar for the two supernovae. Therefore, the difference in pre-maximum spectra is likely due to an additional factor that is
not highly correlated with the amount of $^{56}$Ni produced. We speculate that differences in the initial conditions of the progenitor WD or ignition properties (e.g. location and configuration of thermonuclear runaway) can lead to different ejecta structures while producing comparable amounts of $^{56}$Ni. Further explosion model simulations are required in order to test whether such properties produce variations similar to those observed in SN 2005hk and PS1-12bwh.

5.5 Summary

In this study we presented photometric and spectroscopic observations of PS1-12bwh, a type Iax supernova. We find its light curve to be almost identical to that of SN 2005hk, with only small differences in peak luminosities and decline rates.

At later epochs ($\gtrsim$ 1 month post-maximum light) PS1-12bwh shows spectroscopic similarities to SN 2005hk, as well as other SNe Iax; however, our earliest spectrum of PS1-12bwh appears quite dissimilar to spectra of SN 2005hk at comparable epochs and bears a much closer resemblance to spectra with phases approximately one week earlier. We investigated possible factors that may explain the difference in ionisation state between the two similarly phased spectra of SN 2005hk and PS1-12bwh. We find a likely explanation to be that both objects have different amounts of high velocity ejecta, with PS1-12bwh also having a lower photospheric velocity (by $\sim$2 000 km s$^{-1}$) at $-2$ d than SN 2005hk at $-3$ d. This would naturally explain why the differences are apparent only in the pre-maximum spectra, with the post-maximum spectra being similar both to each other, as well as other SNe Iax with comparable lightcurve properties.

SN 2005hk and PS1-12bwh further underline the heterogeneous nature of SNe Iax. As a corollary, our study highlights the difficulty in assigning spectroscopically estimated epochs to SNe Iax. Without light curve information, the phases inferred from spectroscopic comparisons may be mis-estimated by a week or possibly more, thereby potentially affecting the classification itself, or follow-up of SNe Iax targets. Our study highlights the need for further follow-up of type Iax SNe on the one hand, and investigation into different initial conditions of the progenitor WD on the other.
Appendix

5.A Tables

Table 5.4: Local sequence stars used to calibrate PS1-12bwh photometry.

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<tr>
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<td>15.83(0.01)</td>
<td>15.65(0.01)</td>
<td>15.56(0.01)</td>
</tr>
<tr>
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<td>+39:07:41.3</td>
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<td>16.74(0.01)</td>
<td>16.59(0.01)</td>
<td>16.50(0.01)</td>
</tr>
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<td>17.61(0.01)</td>
<td>17.45(0.01)</td>
<td>17.38(0.02)</td>
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<td>17.02(0.01)</td>
<td>16.90(0.01)</td>
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Notes. Magnitudes of sequence stars are taken from SDSS-DR9 and shown to two decimal places in the AB system. 1σ uncertainties are given in parentheses.

Table 5.5: Spectroscopic journal for PS1-12bwh

<table>
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<tr>
<th>Date</th>
<th>MJD</th>
<th>Phase (days)</th>
<th>Telescope + Instrument</th>
<th>Grating</th>
<th>Wavelength coverage (Å)</th>
</tr>
</thead>
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<tr>
<td>2012 Oct. 22</td>
<td>56.223.14</td>
<td>–2</td>
<td>WHT+ISIS</td>
<td>R300B &amp; R158R</td>
<td>3 500 – 5 200, 5 400 – 9 300</td>
</tr>
<tr>
<td>2012 Oct. 26</td>
<td>56.226.64</td>
<td>+2</td>
<td>Gemini + GMOS-N</td>
<td>B600/450 &amp; R400/750</td>
<td>3 600 – 9 700</td>
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<tr>
<td>2012 Nov. 14</td>
<td>56.245.40</td>
<td>+21</td>
<td>MMT+BlueChannel</td>
<td>300GPM</td>
<td>3 300 – 8 500</td>
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<tr>
<td>2012 Nov. 20</td>
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<td>+27</td>
<td>WHT+ISIS</td>
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<td>3 500 – 5 200, 5 400 – 9 300</td>
</tr>
<tr>
<td>2012 Dec. 20</td>
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<td>+57</td>
<td>WHT+ISIS</td>
<td>R300B &amp; R158R</td>
<td>3 500 – 5 200, 5 400 – 9 300</td>
</tr>
</tbody>
</table>
Table 5.6: References for comparison SNe spectra used throughout this paper.

<table>
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<th>SN</th>
<th>SN type</th>
<th>( M_r )</th>
<th>( \Delta m_{15}(r) )</th>
<th>( E(B-V)_{host} )</th>
<th>Reference</th>
</tr>
</thead>
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<td>2005hk</td>
<td>Iax</td>
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<td>0.70±0.02</td>
<td>0.11</td>
<td>1, 2, 3, 4</td>
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<tr>
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<td>Iax</td>
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<td>5</td>
</tr>
<tr>
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<td>0.11</td>
<td>4</td>
</tr>
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<td>2015H</td>
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<td>0.69±0.04</td>
<td>–</td>
<td>6</td>
</tr>
</tbody>
</table>

Notes. (1) Phillips et al. (2007); (2) Chornock et al. (2006); (3) Blondin et al. (2012); (4) Stritzinger et al. (2015); (5) Stritzinger et al. (2014) (6) Magee et al. (2016). All spectra were obtained from WISeREP (Yaron & Gal-Yam 2012, http://wiserep.weizmann.ac.il).
Chapter 6

The early time behaviour of type Ia supernovae
Recent studies have demonstrated the diversity in SNe Ia at early times and highlighted a need for a better understanding of the explosion physics as manifested by observations soon after explosion. To this end, we present a Monte Carlo code designed to model the light curves of radioactively driven, hydrogen-free transients from explosion to approximately maximum light. In this initial study, we have used a parametrised description of the ejecta in SNe Ia, and performed a parameter study of the effects of the $^{56}$Ni distribution on the observed colours and light curves for a fixed $^{56}$Ni mass of $0.6\, M_\odot$. For a given density profile, we find that models with $^{56}$Ni extending throughout the entirety of the ejecta are typically brighter and bluer shortly after explosion. Additionally, the shape of the density profile itself also plays an important role in determining the shape, rise time, and colours of observed light curves. We find that the multi-band light curves of at least one SNe Ia (SN 2009ig) are inconsistent with less extended $^{56}$Ni distributions, but show good agreement with models that incorporate $^{56}$Ni throughout the entire ejecta. We further demonstrate that comparisons with full UVOIR colour light curves are powerful tools in discriminating various $^{56}$Ni distributions, and hence explosion models.

The contents of the following chapter have been accepted for publication as “Modelling the early time behaviour of type Ia supernovae: effects of the $^{56}$Ni distribution”, Magee et al., Astronomy & Astrophysics, in press, 2018, reproduced with permission © ESO. All of the work is my own. The cover image for this chapter shows the Veil Nebula. Image credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA).

6.1 Introduction

Modern optical transient surveys have led to a wealth of supernova (SN) discoveries at increasingly early times. As the number of SNe Ia discoveries grows, their diversity becomes ever more apparent – despite being once thought of as a relatively homogeneous group (see §1.1). Particular attention has been paid to epochs shortly after explosion, as they probe the outermost layers of the ejecta and provide information on the progenitor not available at later epochs (e.g. Arnett 1982; Riess et al. 1999b; Nugent et al. 2011).

As mentioned in §1.1.1, recent studies have demonstrated differences in the early light curve behaviour of SNe Ia. A sample of 18 low redshift SNe Ia considered by Firth et al. (2015) showed significant variation in the rise time to maximum light, ranging from $\sim 16$ to 25 days, and some SNe rising more sharply than others. Based on the work of Piro & Nakar (2013, 2014), this variation was interpreted as being due to differences in the distribution of $^{56}$Ni within the SN ejecta. Piro & Nakar (2013) show how shallow $^{56}$Ni distributions (i.e. closer to the ejecta surface) lead to shallower rises,
and Piro & Nakar (2014) apply this study to observations of three SNe Ia shortly after explosion. Although SNe Ia generally follow a similar colour evolution (see § 1.1.1), there is also some diversity in the observed colours of SNe Ia before and around maximum light (Maeda et al. 2011; Cartier et al. 2011). Recent multi-dimensional explosion simulations have argued that SNe Ia may be highly asymmetric (e.g. Livne et al. 2005; Kuhlen et al. 2006; Kasen et al. 2009). Based on observations of velocity shifts in late-phase nebular spectra, Maeda et al. (2010a) and Maeda et al. (2010b) also argued that SNe Ia may result from asymmetric explosions. The colour differences of Maeda et al. (2011) were found to be correlated with these velocity shifts, therefore Maeda et al. (2011) and Cartier et al. (2011) interpret the observed diversity as resulting from asymmetric explosions. Although some degree of asymmetry has been argued in SNe Ia explosions, the effect of different $^{56}$Ni distributions on the rise time, and in particular colours, has not been fully quantified for even the spherically symmetric case. The purpose of this work is to develop and exploit light curve models that can address this topic and provide physical links between model parameters and observations of SNe Ia.

Analytical work by Arnett (1982) modelled the early light curves of SNe with a constant, grey opacity. Subsequent numerical work extended this to variable, grey opacities (Cappellaro et al. 1997; Bersten et al. 2011; Morozova et al. 2015). Further advancements came from incorporating realistic treatments of the plasma state and physics (making as few assumptions as possible), multi-dimensionality, and non-grey opacities (Höflich 1995, 2003; Blinnikov et al. 1998, 2006; Kasen et al. 2006; Kromer & Sim 2009; Hillier & Dessart 2012; van Rossum 2012). We aim to bridge the gap between these simple and detailed approaches. We present a Monte Carlo radiative transfer code, TURTLS, that combines these advantages: it is fast and flexible, like the fixed and grey opacity models, but also implements realistic descriptions of the most important physical processes at the epochs of interest. By including realistic time and frequency dependent opacities, our approach allows us to compute band-limited light curves for any $UVOIR$ filter. This substantially increases the utility of our calculations for direct interpretation of data compared to simpler treatments. The flexibility afforded by our approach coupled with the relatively short (roughly dozens of CPU hours) run times facilitates a systematic exploration of the parameter space. It can therefore be used to explore the early light curves and colours of radioactively driven SNe.

Our code was previously described in Chapter 3. The results of convergence studies and tests of our sensitivity to various approximations made are presented in § 6.2, while § 6.3 presents a comparison to existing codes in the literature for the well-studied W7 (Nomoto et al. 1984) explosion model. In § 6.4, we present a set of models for which light curves are simulated, as discussed in § 6.5. We focus on the effects of the $^{56}$Ni
distribution, followed by the density profile. In § 6.6 we demonstrate the importance of a non-grey opacity in determining the light curves. We test the importance of the amount of surface $^{56}\text{Ni}$ in § 6.7 and quantify the rising phase in § 6.8. A comparison between our models and observations of a SNe Ia are presented in § 6.9. Finally, we present our conclusions in § 6.10.

### 6.2 Convergence and sensitivity tests

In this section, we present the tests conducted to assess the robustness of our code, which was described in Chapter 3. All calculations described in this section use the density and composition from the W7 explosion model (Nomoto et al. 1984).

#### 6.2.1 Number of packets

As discussed in § 3.9, we use a Monte Carlo estimator to determine the temperature of each zone. Therefore, the number of packets will affect not only the noise present in the light curve, but also the opacities used in the simulation. We find that, even with a relatively small number of packets ($10^5$), noise in the temperature profile does not have a noticeable effect on the light curves beginning $\sim 3$ days post-explosion.

The effect of a small number of packets is most pronounced at early times ($\lesssim 2.5$ days post explosion) for models that do not have $^{56}\text{Ni}$ extending to the surface of the ejecta. In these models, the diffusion of packets into the outer regions of the ejecta can cause relatively large fluctuations in the temperature across zones, as individual zones may contain only a handful of packets. Nevertheless, sufficiently good statistics can be achieved by selecting an appropriate time span for the simulation.

#### 6.2.2 Number of time steps

After each time step, the plasma state is updated with new temperatures and source functions in each zone, and new opacities are calculated, as discussed in § 3.9. The number of time steps may affect the light curve if they are too few to accurately represent the smooth evolution of the SN ejecta. We test models with 50, 100, 250, and 500 time steps logarithmically spaced between 1.5 and 30 days post-explosion. We find that even with a relatively small number of steps, light curves showed little variation. Typically the largest difference between these light curves is $\lesssim 0.05$ mag for models with more than 100 time steps. We use 250 time steps, as a compromise between accurately capturing the light curve evolution and the computational requirement.
6.2.3 Number of frequency bins

The use of expansion opacities requires that lines are collected into discrete frequency bins. We calculate models for 1 000, 5 000, and 10 000 bins ranging from $10^{14} - 10^{16}$ Hz, and find that increasing the number of frequency bins beyond 1 000 has a negligible effect on the resultant light curves ($\lesssim 0.05$ mag).

6.2.4 Atomic dataset

Our atomic dataset comprises lines drawn from Kurucz & Bell (1995), with a cut in log($gf$) applied to limit the number of weak lines included, and hence the computational time requirement, as in Kromer & Sim (2009). We find that a cut of log($gf$) $\geq -2$ typically produces brighter light curves, particularly in bluer bands. It is unsurprising that a smaller atomic data set would result in brighter early light curves, given that a reduction in the number of lines will result in a reduced opacity. That the effect is most prominent at short wavelengths highlights the importance of the weaker lines due to iron group elements (IGEs). The difference between cuts of $-3$ and $-5$ is far less pronounced, but follows the same trend. Including even weaker lines (log($gf$) $\geq -20$) does not alter the model light curves (Kromer & Sim 2009). We therefore use the log($gf$) $\geq -5$ atomic data set.

Kromer & Sim (2009) also performed tests with atomic data sets that include many more weak lines due to singly- and doubly-ionised Fe, Co, and Ni. These transitions primarily occur at red and NIR wavelengths. Kromer & Sim (2009) showed that including these lines can produce a noticeable deviation in the NIR bands (particularly $J$, $H$, and $K$), but has little effect on the optical light curves.

As shown by Dessart et al. (2014b), forbidden line transitions play an important role in cooling from $\sim 30$ days post-explosion (see also § 1.1.2). We note that the atomic dataset used in our simulations includes only permitted line transitions, and therefore do not extend our simulations beyond approximately maximum light.

6.2.5 Fluorescence parameter

We use the two-level atom (TLA) approach – defined through the use of the redistribution parameter, $\epsilon$ – to approximate fluorescence (see § 3.8.2; Kasen et al. 2006). The probability that packets will be re-emitted with frequencies sampled from the source function is given by $\epsilon$.

As $\epsilon$ values close to unity have been shown to broadly reproduce the effects of
Figure 6.1: Each panel shows the wavelength at which packets are absorbed and re-emitted following their last interaction, and before exiting the simulation. Three values of the redistribution parameter are shown from left to right: scattering dominated ($\epsilon = 0.1$), equal probability for scattering and redistribution ($\epsilon = 0.5$), and redistribution dominated ($\epsilon = 0.9$).

a full fluorescence treatment (Kasen et al. 2006), we adopted $\epsilon = 0.9$ throughout our production simulations. Figure 6.1 shows the redistribution of packet wavelengths for three models ($\epsilon = 0.1, 0.5, \text{ and } 0.9$), following the last interaction experienced by each packet, and demonstrates how models with a low $\epsilon$ value (0.1) do not redistribute as effectively following interactions.

6.3 Code verification

In this section, we test whether our code is consistent with other radiative transfer codes. We first compared our code using models calculated with a grey opacity (§ 6.3.1), followed by models calculated with a non-grey opacity (§ 6.3.2).

6.3.1 Grey opacity

We compare the simple, grey mass opacity ($\kappa/\rho = 0.1 \text{ cm}^2 \text{ g}^{-1}$) model presented by Lucy (2005) to a calculation performed using our code that also incorporates a fixed, grey opacity. This model has a uniform density structure, with an ejecta mass of $1.39 \text{ M}_\odot$, a $^{56}\text{Ni}$ mass of $0.625 \text{ M}_\odot$, and a maximum velocity of 10 000 km s$^{-1}$. The mass fraction of $^{56}\text{Ni}$ at the centre of the ejecta ($M(r) < 0.5 \text{ M}_\odot$) is equal to one, and drops linearly to zero at $M(r) = 0.75 \text{ M}_\odot$.

We used a grey opacity for $\gamma$-ray transport ($\kappa/\rho = 0.03 \text{ cm}^2 \text{ g}^{-1}$; Ambwani & Sutherland 1988), while Lucy (2005) perform a more complete treatment, including non-grey opacities and Compton scattering. Figure 3.5 shows that our code is able to reproduce the results of Lucy (2005), including the $\gamma$-ray deposition. This suggests that our simplified approach to $\gamma$-ray transport does not have a significant effect on our model light curves.
6.3.2 Non-grey opacity

We compare to other non-grey radiative transfer codes using the well studied W7 explosion model (Nomoto et al. 1984). We use $10^7$ packets, 1 000 frequency bins, 250 time steps, and begin the simulation 1.5 days after explosion.

ARTIS (Kromer & Sim 2009) is a three dimensional Monte Carlo radiative transfer code for calculating time-dependent supernova spectra. An important difference between our code and ARTIS is that ARTIS does not use the expansion opacity approximation (see § 3.4), but treats each line individually. This is a significant improvement over our code; however, ARTIS also requires orders of magnitude greater computational time (~100 vs. ~5 000 CPU hours for the models presented here). Figure 6.2 presents ARTIS light curves calculated using an LTE approximation with a standard atomic data set ($4.1 \times 10^5$ lines), and a more detailed ionisation treatment with a larger atomic data set ($8.2 \times 10^6$ lines). This larger atomic data set includes more transitions for singly- and doubly-ionised Fe, Co, and Ni. See Kromer & Sim (2009) for further details.

Figure 6.2 demonstrates that the expansion opacity approximation is able to reproduce the full line treatment implemented in ARTIS. In particular, our model W7 light curves more closely match those of the LTE ARTIS model – this is unsurprising given
Table 6.1: Ejecta model parameters and properties

<table>
<thead>
<tr>
<th>Model</th>
<th>Transition velocity $v_t$ (km s$^{-1}$)</th>
<th>Inner slope $t$</th>
<th>Outer slope $s$</th>
<th>Scale parameter $r$</th>
<th>Bolometric Rise (days)</th>
<th>$B$ Rise (days)</th>
<th>$V$ Rise (days)</th>
<th>$B-V$ (mag) $t=2.5$ d</th>
<th>$B-V$ (mag) $t=25$ d</th>
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Notes. Parameters of the artificial density profiles. We fit each light curve with a sixth order polynomial to determine the rise time to peak and peak absolute magnitude for the bolometric, $B-$, and $V$–band light curves. We also use the fits to determine the $B-V$ colour for $t=5$ days and at $B$–band maximum. We note that our polynomial fit to determine the colour at 25 days is performed for the light curve between two and ten days. For all other cases the fit is performed between 10 and 25 days. Times of maximum that occur later than ~24.5 days are neglected.

the LTE assumptions used in calculating our opacities.

Figure 6.2 also shows early-phase light curves calculated by Noebauer et al. (2017) using STELLA (Blinnikov et al. 1998, 2006), a one dimensional radiation hydrodynamics code. Similar to our code, LTE is assumed in determining the ionisation and excitation levels in STELLA. STELLA also makes use of a slightly smaller atomic data set, ~1.6×10$^5$ lines, and the expansion opacity approximation. Light curves produced by STELLA also show good agreement with those produced by our code and ARTIS.

6.4 Construction of model density and composition profiles

Having described the operation of our code and demonstrated that it produces results similar to other codes in the literature (see § 6.3), we apply it to test the effects of varying the $^{56}$Ni distribution. We describe the set-up of the models presented in this work, while § 6.5 presents the light curves.

Our code requires the density and composition of the SN ejecta as input, both of which are freely defined by the user. Following Botyánszki & Kasen (2017), we

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parametrize the density profile of the ejecta as a broken power law. This produces an ejecta with a shallow inner region, and a more steeply declining outer region. The density at velocity $v$ is given as:

$$
\rho(v) = \begin{cases} 
\rho_0 \left(\frac{v}{v_t}\right)^{-\delta} & v \leq v_t, \\
\rho_0 \left(\frac{v}{v_t}\right)^{-n} & v > v_t,
\end{cases}
$$

(6.1)

where $v_t$ gives the velocity boundary between the two regions, $\delta$ gives the slope of the inner region, $n$ gives the slope of the outer region, and the reference density, $\rho_0$, is given by:

$$
\rho_0 = \frac{M_{\text{ej}}}{4\pi (v_t t_{\text{exp}})^3} \left[ \frac{1}{3-\delta} + \frac{1}{n-3} \right]^{-1},
$$

(6.2)

where $\delta < 3$, $n > 3$, $M_{\text{ej}}$ is the ejecta mass, and $t_{\text{exp}}$ is the time since explosion (Botyánszki & Kasen 2017). In order to test only the effects of the $^{56}\text{Ni}$ distribution, we fix the mass and maximum velocity of the ejecta to be $1.4 M_\odot$ and $30,000 \text{ km s}^{-1}$, respectively, for all density profiles discussed in this section.

Parameters of the models used in this study are given in Table 6.1. These density profiles were constructed such that they broadly span the range predicted by various explosion models, such as pure deflagrations (Nomoto et al. 1984; Fink et al. 2014), deflagration-to-detonation transitions (DDT; Seitenzahl et al. 2013), and the violent merger of two white dwarfs (WDs; Pakmor et al. 2012).

We have constructed $^{56}\text{Ni}$ distributions such that $^{56}\text{Ni}$ is concentrated towards the inner ejecta and extends outwards to varying degrees – approximately following predictions by explosion models for SNe Ia. As a simple functional form, we adopt:

$$
^{56}\text{Ni}(m) = \frac{1}{\exp(s[m - M_{\text{Ni}}]/M_\odot) + 1},
$$

(6.3)

where $m$ is the mass coordinate of the ejecta and $M_{\text{Ni}}$ is the total $^{56}\text{Ni}$ mass in $M_\odot$. The scaling parameter, $s$, is used to alter the shape of the $^{56}\text{Ni}$ distribution; smaller values have a more shallow $^{56}\text{Ni}$ distribution, while larger values produce a distribution that sharply transitions between $^{56}\text{Ni}$-rich and $^{56}\text{Ni}$-poor regions. We present three values of $s$ (3, 9.7, and 100), representing models with an extended, intermediate, and compact $^{56}\text{Ni}$ distribution, respectively (see Fig. 6.3(c)). We have also fixed the total $^{56}\text{Ni}$ mass to be $0.6 M_\odot$ for all models discussed here. Future work will test the effects of varying $^{56}\text{Ni}$ masses, as well as other forms for the $^{56}\text{Ni}$ distributions.

As we wish to test only the effects from different distributions of $^{56}\text{Ni}$, we have taken a simplified approach to the ejecta composition. In each zone, $^{56}\text{Ni}$ constitutes...
Figure 6.3: Ejecta models used in this work. (a) Density profiles for our model sequence. Transition velocity, δ, and n parameters are given for each model. Densities for a sample of explosion models are shown for comparison: W7 (Nomoto et al. 1984), DDT N100 (Seitenzahl et al. 2013), DEF N1600 (Fink et al. 2014), VM (Pakmor et al. 2012). (b) Illustrative composition profile for one model (v12500_d0_n8_s9.7). The three zone structure is clearly demonstrated, with representative species shown. (c) 56Ni distributions for one density profile (v12500_d0_n8). 56Ni distributions for a sample of explosion models are also shown.

100% of the total IGEs immediately after explosion. This is unlikely to be realised in nature but nevertheless allows us to easily test 56Ni distributions in our simple parameter study. The outer ∼0.1 M☉ of the ejecta is dominated by carbon and oxygen, while the remaining material is intermediate mass elements (IMEs). Relative abundance ratios are determined by the W7 model (Nomoto et al. 1984). Future work will test other composition arrangements. Figure 6.3 shows the density and 56Ni profiles discussed and the composition for one model (v12500_d0_n8).

6.5 Model light curves

We perform simulations for the models discussed in § 6.4 and presented in Table 6.1. We first consider the influence of the 56Ni distribution for a fixed density profile (§ 6.5.1) and then the effects of different density profiles (§ 6.5.2).
Figure 6.4: Bolometric, Swift $U$, and Johnson $BVRI$ light curves for our $v7500\_d0\_n8$ density profile, with various scaling parameters ($s = 3, 9.7, \text{and } 100$), and the $UBVRI$ light curves of SN 2009ig. Light curves of SN 2009ig are shown assuming $\mu = 32.6 \pm 0.4$, negligible host extinction, and an explosion epoch of $JD = 2455063.41 \pm 0.08$ (Foley et al. 2012). Filled points represent KAIT light curves, while unfilled points show Swift light curves. Note that for our $s = 3$ model $t_{\text{start}} = 0.5$ days, hence we have omitted the light curve for $t < 1$ day. For $s = 9.7$ and 100, $t_{\text{start}} = 1.5$ days, and we have omitted the light curve for $t < 2$ days in these cases.

6.5.1 Effects of the $^{56}\text{Ni}$ distribution for a fixed density profile

In Fig. 6.4, we show the light curves for $s3$, $s9.7$, and $s100$ models with $v7500\_d0\_n8$. Similar to Piro & Morozova (2016), we show that extended models (e.g. $s3$) exhibit very different light curves to compact models (e.g. $s9.7$ and $s100$). Our $s3$ model is much brighter than either the $s9.7$ or $s100$ models immediately following explosion (by $\gtrsim 2$ mag in the $B$–band at three days post-explosion), and shows a shallower rise to maximum. Between three and ten days after explosion, the $B$–band light curve increases by an average rate of 0.30, 0.49, and 0.54 mag day$^{-1}$ for $s3$, $s9.7$, and $s100$, respectively. In the case of $s3$, there is a relatively large $^{56}\text{Ni}$ mass in the outer ejecta – the outer $\sim 50\%$ of the ejecta mass contains $\sim 20\%$ of the $^{56}\text{Ni}$ mass. As this $^{56}\text{Ni}$ decays to $^{56}\text{Co}$, emitted $\gamma$-rays (and subsequent $UVOIR$ photons) experience fewer interactions and escape more easily, hence the light curve is brighter at earlier times. The $s9.7$ and $s100$
models have $^{56}$Ni distributions more concentrated towards the ejecta centre – the outer ∼50% of the ejecta contains ≲ 5% of the $^{56}$Ni mass in these cases. Therefore, in these models, emitted light has a higher probability of interaction, due to the larger ejecta mass through which it must travel before escaping, hence the light curves are fainter.

The s3, s9.7, and s100 models also show significant variation in their colour evolution, again for a fixed density profile. This is shown in Fig. 6.6 for our v12500_d0_n8 models. At very early times, the s3 model shows a bluer $B - V$ colour (by ≲ 0.3 mag at three days post-explosion) than s9.7 and s100. During the next few days, the s3 model becomes slightly bluer (by ≲ 0.2 mag until approximately one week post-explosion) before gradually becoming redder until the end of our simulation – at 20 days, the $B - V$ colour of s3 has increased to ∼0.75 mag. Overall, the s9.7 and s100 models follow a broadly similar trend, although at different times. At three days, both models show redder colours than s3 ($B - V \approx 0.3$ mag) and continually become bluer until approximately two weeks post-explosion – reaching their most blue colours approximately one week after the s3 model. Following this, both models gradually become redder until the end of our simulations ($B - V \approx 0.3$ mag at 20 days).

That s3 is bluer at early times and redder at later times may be understood by considering the effects of $^{56}$Ni heating within the ejecta. The s3 model has a significant amount of $^{56}$Ni present in the outer ejecta that heats its surroundings as it decays to $^{56}$Co. The outer regions are therefore locally heated at all times. The outer regions of the s9.7 and s100 models lack $^{56}$Ni, hence they rely on diffusion of heat from the hotter inner layers and are relatively cool at early times. This produces an initially redder colour than s3, that gradually becomes bluer as light emitted in the inner regions diffuses outwards. As time increases, the outer ejecta become increasingly optically thin, exposing deeper and deeper layers of the ejecta. The more extended $^{56}$Ni distribution in s3 results in less $^{56}$Ni heating of the ejecta interior. Hence, the temperature in these regions is lower than in s9.7 and s100, and the colour appears redder.

6.5.2 Effects of varying density profiles

The $^{56}$Ni distribution is affected not only by the scaling parameter $s$, but also the shape of the density profile (controlled by $v_t$, $\delta$, and $n$). Having shown how the light curves vary for the same density profiles but different scaling parameters, we now discuss the broad features of all of our models and investigate the effects of each density parameter in turn.

Our models show a complicated behaviour with varying $^{56}$Ni distributions and density profiles. In Table 6.1 we list the light curve parameters for these models. We fit the
light curves from each model with a sixth-order polynomial between 10 and 25 days post-explosion. This was chosen simply to produce the best match to all of the model light curves after the initial rising phase, but before the end of our simulations. From these model fits, we determine rise times and peak magnitudes in each band. These are given for bolometric, $B-$, and $V-$band light in Table 6.1. Table 6.1 also lists $B-V$ colours at an early time ($t=2.5$ days) and at $B-$band maximum. We note that, to determine the colour at 2.5 days, we fit the light curve between two and ten days.

The choice of transition velocity significantly affects the shape of the density profile. A higher transition velocity, $v_t$, results in a larger and less dense inner region, and a smaller and more dense outer region (see Fig. 6.3). Typically this creates a brighter light curve before maximum light and a shorter rise time. Models with $v_t = 7500 \text{ km s}^{-1}$ show a median bolometric rise time of $20.1 \pm 1.2$ days. For models with $v_t = 12500 \text{ km s}^{-1}$, the rise time is typically shorter (median $\sim 16.7 \pm 0.9$ days). Indeed, all $v_t = 7500 \text{ km s}^{-1}$ models have $V-$band rise times $\geq 23.7$ days (most have rise times $\geq 25$ days) – higher than the typical rise time for $v_t = 12500 \text{ km s}^{-1}$ (median $\sim 19.7 \pm 1.2$ days). Higher $v_t$ will spread out more $^{56}\text{Ni}$ to higher velocities, therefore light will be allowed to escape more easily in these cases. Similarly, $v_t$ has a significant effect on the colour evolution. For $\lesssim 3$ to 7 days after explosion, higher $v_t$ models generally appear bluer as they produce more high frequency photons – resulting from the increased density in the outer regions, and hence higher temperature. These regions quickly become optically thin, however, exposing the inner regions. Models with higher $v_t$ will produce cooler inner regions, appearing redder at later times in both $U-B$ and $B-V$. Despite differences in rise times and colour evolutions, models with different $v_t$ generally produce similar peak absolute magnitudes (within $\sim 0.2 \pm 0.2$ mag).

The effect of a steeper inner density profile (larger $\delta$) is less pronounced at times up to maximum light. A larger $\delta$ shifts mass to lower velocities, causing a decrease in density at higher velocities. This change in density is relatively small everywhere except the very centre of the ejecta (Fig. 6.3). This generally produces a delay in the rise of the light curve, a slightly longer rise time (by $\lesssim 1.5$ days in all but one case), and a small decrease in peak magnitude (within typical photometric uncertainties of $\sim 0.02$ for the $B-$ and $V-$band). Higher $\delta$ values may become more significant at later times, as the deepest layers of the ejecta are exposed, but this is beyond the scope of this work.

For steeper outer density profiles (larger $n$), again, more of the ejecta mass is shifted to lower velocities. The result is similar to that of a larger $\delta$: the light curve is generally fainter in the optical bands during the pre-maximum phase and shows a slightly longer rise time. The $U-$band, however, is brighter for larger $n$. This is likely due to the fact that the inner regions are hotter for higher values of $n$, and the lower density outer
region allows photons to escape more easily. Hence, more of the light escapes as higher frequency photons and the other optical band light curves, although fainter, also appear bluer. The effect is less significant in models with higher s values, as most of the $^{56}$Ni is already concentrated in the inner regions for these models.

We have shown how the model light curves respond to different density and $^{56}$Ni distributions. Our models broadly reproduce the peak magnitudes and rise times observed in SNe Ia; however, the exact shape of the light curves and colours may not agree exactly. With an understanding of each parameter, tweaks may be made to produce light curves that better match observations. Model light curves will also be affected by changes in composition, but this will be investigated in future work.

### 6.6 Importance of a non-grey opacity

Given the complicated behaviour displayed by our models, here we demonstrate the importance of a frequency-dependent opacity in effectively capturing the evolution of the light curves and colours. We take one density profile (v12500_d0_n8) and perform new simulations using a grey, mean opacity for each of the $^{56}$Ni distributions discussed in § 6.4 (i.e. extended, intermediate, and compact).

During each simulation, we calculated expansion and Thomson scattering opacities using TARDIS, as described in § 3.8.2. We added the additional step of calculating
either the Planck or Rosseland mean opacity, which is then used during the next time step. We calculate the Planck mean opacity as:

\[
\kappa_P = \frac{\int_0^\infty \kappa_{\text{Tot}}(\nu) B_\nu(T) d\nu}{\int_0^\infty B_\nu(T) d\nu} = \frac{\pi}{\sigma T^4} \int_0^\infty \kappa_{\text{Tot}}(\nu) B_\nu(T) d\nu, \tag{6.4}
\]

while the Rosseland mean opacity is given as:

\[
\frac{1}{\kappa_R} = \frac{\int_0^\infty \kappa_{\text{Tot}}(\nu)^{-1} \partial B_\nu(T) / \partial T d\nu}{\int_0^\infty \partial B_\nu(T) / \partial T d\nu}, \tag{6.5}
\]

where \(B_\nu(T)\) is the Planck function. The total opacity, \(\kappa_{\text{Tot}}(\nu)\), is given by \(\kappa_{\text{Tot}}(\nu) = \kappa_{\text{exp}}(\nu) + \kappa_{\text{Th}}\), where \(\kappa_{\text{exp}}(\nu)\) is the Eastman & Pinto (1993) expansion opacity (given in Eqn. 3.11) and \(\kappa_{\text{Th}}\) is the Thomson scattering opacity. The Planck mean opacity is more appropriate for optically thin plasmas (such as the diffuse outer regions of the SN ejecta) and is dominated by frequency intervals with high opacity, while the Rosseland mean opacity is more applicable for optically thick plasmas (such as the inner regions of the ejecta) and is dominated by frequency intervals with low opacity.

For these simulations, as we use a grey opacity, escaping packets are no longer binned by frequency and only contribute to the observed bolometric luminosity. To convert our bolometric luminosity to observed colours, we find the position of the photosphere (\(\tau = 2/3\)), and calculate an effective black-body temperature, following the Stefan-Boltzmann law. We then calculate bolometric corrections for the desired filters using this effective temperature. This is repeated for each point in the light curve.

Figure 6.5 shows the effect of both approximations on the model opacity for three ejecta velocities at different times. As the Rosseland mean opacity is dominated by low opacity frequency intervals, it typically under-estimates the opacity for UV and near-UV photons (\(\nu \gtrsim 10^{15} \text{ Hz}\)). Conversely, the opacity is over-estimated for optical photons (\(\nu \lesssim 10^{15} \text{ Hz}\)). Figure 6.6 demonstrates how the light curves are affected by this approximation, and presents light curves calculated using our full non-grey opacity, and the Planck and Rosseland means. It is clear from Fig. 6.6 that the Rosseland mean opacity produces light curves that are overall fainter in optical light, while being brighter in UV and near-UV light. Most photons are injected with UV or near-UV frequencies and therefore experience fewer interactions than in the non-grey opacity case. These photons then escape the ejecta more easily and produce a brighter U–band light curve. The optical light curves are directly affected by this also, as fewer photons are reprocessed to lower frequencies. In combination with this is the fact that the optical opacities themselves are also higher, which will further contribute to fainter optical
Figure 6.6: Light curves obtained for various opacity treatments. *Top*: Light curves of v12500_d0_n8 models using grey opacities and using our full, non-grey opacity treatment. Light curves have been offset vertically from each other for clarity. *Bottom*: B − V colours for v12500_d0_n8 models using grey opacities and using our full, non-grey opacity treatment.

The Planck mean opacity produces an overall similar effect to that of the Rosseland mean opacity. From Fig. 6.5, the Planck mean opacity is significantly higher than both the Rosseland mean and non-grey opacities for all frequencies (with the exceptions of a narrow frequency window centred around $\nu \approx 2 \times 10^{15}$ Hz and $\nu > 5 \times 10^{15}$ Hz). As a consequence, packets experience more interactions, hence fewer photons escape and the light curves are fainter (Fig. 6.6).

From Fig. 6.6 it is clear that grey opacities and a colour correction are insufficient to capture the full evolution of the model light curves, and they become increasingly poor at later times and for models with extended $^{56}$Ni distributions. This is unsurprising, given that in models with more extended $^{56}$Ni distributions, there may be a relatively large $^{56}$Ni mass above the photosphere. Assuming these models operate as a blackbody with a well defined photosphere is therefore a rather poor approximation. Even in models with $^{56}$Ni concentrated more towards the ejecta centre, the photosphere approximation becomes increasingly poor at later times, as the photosphere recedes into deeper layers of the ejecta where $^{56}$Ni is more prominent.

Having investigated each opacity approximation, we have shown that the Rosseland
mean opacity can serve as a moderately good approximation for the early light curves in some regards. This grey opacity approximation, however, is not suitable for cases where there is a large source of energy external to the photosphere – in other words, it has significant limitations when applied to models with extended $^{56}$Ni distributions (at all times) or if applied later than the first few days (all models). Therefore, complete quantification of the effects of the $^{56}$Ni distribution does need a full non-grey radiative transfer treatment.
6.7 Relevance of surface $^{56}\text{Ni}$ to light curve properties

Although the total ejecta mass is fixed for each model, the shape of the density profile is controlled by three parameters ($v_t$, $\delta$, $n$), with an additional parameter, $s$, controlling the distribution of $^{56}\text{Ni}$ within the density profile. We have shown how each parameter affects the light curve separately, but they may also be may be combined into a single parameter – column density. This gives an overall estimation of the amount of $^{56}\text{Ni}$ present in the outer ejecta or the proximity of the majority of $^{56}\text{Ni}$ to the ejecta surface (i.e. higher column densities indicate the majority of the $^{56}\text{Ni}$ mass is more deeply embedded within the ejecta). Following Noebauer et al. (2017), we investigate correlations between column density (measured at 10 000 s after explosion) and the light curve properties given in Table 6.1. The column density is given by:

$$\eta = \int_{r_{\text{Ni}}}^{\infty} \rho(r) dr.$$  \hspace{1cm} (6.6)

Noebauer et al. (2017) define $r_{\text{Ni}}$ to be the outermost point at which $^{56}\text{Ni}$ constitutes 1% of the ejecta composition. As the mass fraction of $^{56}\text{Ni}$ does not drop to 1% in some of our models (see Fig. 6.3), we instead define $r_{\text{Ni}}$ as the point at which the majority of the $^{56}\text{Ni}$ is enclosed – that is, the radius at which 90% (or 99%; see Table 6.1 for further details) of the total $^{56}\text{Ni}$ mass is contained. Table 6.2 gives the column densities measured for our models. In determining the significance of trends, we use the Spearman rank correlation coefficient, $R_S$ – a measure of whether any possible monotonic correlation (but not necessarily linear) exists between two variables. Note that $R_S = \pm 1$ indicates the variables are completely correlated, while zero indicates no monotonic correlation.

Figure 6.7(a) shows the rise times for our bolometric, $B-$, and $V-$band light curves as a function of column density. We find evidence for a strong correlation between bolometric rise time and column density, with $R_S = 0.90$ ($p$-value $\approx 4 \times 10^{-9}$). The column density defined here is simply a measure of the amount of surface $^{56}\text{Ni}$, therefore it is unsurprising that models with $^{56}\text{Ni}$ close to the ejecta surface (i.e. the column density is low) have significantly shorter rise times. Correlations in the $B-$ and $V-$bands are less significant, with $R_S = 0.57$ ($p$-value $\approx 4 \times 10^{-3}$) and $R_S = 0.73$ ($p$-value $\approx 2 \times 10^{-3}$), respectively. The strength of the correlation in the $V-$band is likely affected by the fact that a large number of our models peak after or close to the end of the simulations, and hence are not included. While the correlation between column density and rise time is fairly strong in bolometric light, it is less so in the $B-$ and $V-$bands. This would indicate that there are more subtle effects determining the colour light curves than purely the $^{56}\text{Ni}$ distribution. The v7500_d0.1_n8_s100 models, for example, are
noticeable outliers in the $B$–band – their rise times are significantly shorter than models with similar column densities. Hence, we caution against attempts to determine the levels of surface $^{56}\text{Ni}$ simply by measuring rise times in individual observed bands.

Similarly, we test for correlations between the column density and peak absolute magnitude. For the bolometric, $B$–, and $V$–band light curves we find $R_S = 0.82$ ($p$-value $\approx 9 \times 10^{-7}$), $0.88$ ($p$-value $\approx 4 \times 10^{-8}$), and $0.88$ ($p$-value $\approx 1 \times 10^{-5}$), respectively. The primary factor in determining the peak brightness of SNe Ia is the total amount of $^{56}\text{Ni}$ produced during the explosion. Our results indicate that the distribution of $^{56}\text{Ni}$ itself adds a further complication. Future models with varying $^{56}\text{Ni}$ masses will allow for an investigation into the degeneracy between the total amount of $^{56}\text{Ni}$ and its distribution.

Finally, we investigate column density and colour. We find that models with higher levels of surface $^{56}\text{Ni}$ (low column densities) tend to show redder colours at $B$–band maximum ($R_S = -0.84$; $p$-value $\approx 3 \times 10^{-7}$). Conversely, these models produce bluer colours very shortly after explosion ($R_S = 0.82$; $p$-value $\approx 9 \times 10^{-7}$). As in the case for fixed density profiles, these trends demonstrate that models with extended $^{56}\text{Ni}$ distributions (lower column densities) are typically hotter at early times and cooler at later times. Again, this is a result of the amount of $^{56}\text{Ni}$ heating being probed at different points within the ejecta.

Our analysis shows the complicated sensitivity of the light curves to the parameters describing the ejecta, and general trends among the models. Although we find relatively strong correlations with colour and column density, these do not capture the shape of the light curves. For example, our $v7500\text{d0}_n12\text{s3}$ and $v12500\text{d1}_n12\text{s3}$ models show similar colours shortly after explosion, but their colours and light curve shapes quickly diverge. Therefore, while colours and peak magnitudes, for example, may give a general sense of the level of surface $^{56}\text{Ni}$, caution is to be advised if one attempts to quantitatively infer the $^{56}\text{Ni}$ distribution. Fully characterising the $^{56}\text{Ni}$ distribution requires comprehensive comparisons with complete model light curves and colours.

### 6.8 Rise index

Having investigated the light curve parameters, we now quantify the overall shape of the rising phase for our models. We perform fits for the rise index ($z$) in the same manner as Firth et al. (2015). For each model, we normalise the light curves using the peak absolute magnitudes from our polynomial fits (Table 6.1). We then fit the rising phase using:

$$f(t) = \alpha t^z,$$

(6.7)
Table 6.2: Ejecta model rise indices and column densities

<table>
<thead>
<tr>
<th>Model</th>
<th>Bolometric</th>
<th>( U )</th>
<th>( B )</th>
<th>( V )</th>
<th>( R )</th>
<th>( I )</th>
<th>( \eta )</th>
<th>( \eta ) (g cm(^{-2}))</th>
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<td>v7500_d0_n8_s3</td>
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<td>1.76</td>
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<td>2.69</td>
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<td>2.37</td>
<td>1.46</td>
<td>…</td>
<td>2.21 ( \times 10^6 )</td>
</tr>
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<td>…</td>
<td>…</td>
<td>…</td>
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</tr>
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<td>…</td>
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<td>…</td>
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Median | 2.20(0.44) | 2.93(0.64) | 2.06(0.56) | 1.76(0.18) | 2.08(0.33) | 1.58(0.22) |

Notes. Rise indices as measured from Eqn. 6.7. Median values for each filter are also given, along with standard deviations in brackets. Note that the models explored here are not exhaustive and future work will be able to further explore an extended range of parameters. We show the median and standard deviations simply to demonstrate the spread achievable from this specific set of models.

where \( f \) is flux, \( t \) is the time since explosion, \( \alpha \) is a normalising factor, and \( z \) is the rise index. As in Firth et al. (2015), we define the rising phase as times where \( f < 0.5f_{\text{Peak}} \).

Table 6.2 shows our fitted rise indices in each band, along with the median rise index.

Firth et al. (2015) show how the rise index of SNe Ia covers a broad range, from \(~1.5\) to \(~3.7\) for the PTF \( R \)–band and the broadband LSQ filter (which covers approximately the range of the SDSS \( gr \) filters). Our model rise indices are consistent with those of Firth et al. (2015), with fits to bolometric light curves producing rise indices ranging from 1.54 to 3.02. Based on the work of Piro & Nakar (2014), Firth et al. (2015) argue that the observed distribution of rise indices can be explained by differences in the \(^{56}\text{Ni} \) distribution. Our models support this conclusion and show that various \(^{56}\text{Ni} \) distributions can produce a wide range of rise indices. For a fixed density profile, our models show that an increasingly extended \(^{56}\text{Ni} \) distribution generally produces a more shallow rising light curve (lower rise index), but the rising behaviour shows
additional complexities. For a given value of $s$, the $^{56}$Ni distribution is fixed in terms of mass coordinate, yet changing the density parameters also affects the rise index. Therefore, although useful, the rise index is not a perfect indicator of the $^{56}$Ni mass depth probed by the light curves: the effects of the density and its overall shape must also be considered.

6.9 Comparison with the SN Ia SN 2009ig

In Fig. 6.4, we show the light curve of a SNe Ia, SN 2009ig (Foley et al. 2012), and demonstrate how our models may be used to constrain the $^{56}$Ni distribution in SNe Ia. The light curve of SN 2009ig shows remarkably good agreement with our v7500_d0_n8_s3 model light curve, despite the relatively simple, parametrised approach to our model set-up (e.g. broken power law density profile, simple composition). It is clear from Fig. 6.4 that the early rise of SN 2009ig is too shallow to result from a compact $^{56}$Ni distribution.

Despite very good agreement in the $BVR$ light curves, there are notable differences between the model and observed $U$– and $I$–band light curves. Our model $U$–band light curve shows a shallower rise to maximum than SN 2009ig, and is generally brighter (by between ~0.2 to 0.8 magnitudes). The $U$–band is strongly affected by line blanketing from IGEs, and even trace amounts of IGEs may have a dramatic effect. We have assumed that $^{56}$Ni is 100% of the total IGE mass (as a means of testing purely the effects from the $^{56}$Ni distribution), while explosion models typically predict that this is not the case. For example, for the set of deflagration-to-detonation transition models presented by Seitenzahl et al. (2013), $^{56}$Ni constitutes between ~60 to 90% of the total IGE mass. Therefore, our models likely underestimate the total IGE mass in SNe Ia, hence the $U$–band light curve in particular appears brighter than what is observed. In addition, trace amounts of IGEs may also be present in the progenitor WD, and therefore affect the $U$–band light curves (Höflich et al. 1998; Lentz et al. 2000). Future work will test different compositions for our models.

SN 2009ig shows a relatively flat $I$–band light curve from approximately seven days after explosion. The model light curve instead shows a smooth rise over the same period. This is likely a consequence of our LTE assumption. The recombination of IGE results in a strong secondary maximum in the NIR light curves of SNe Ia, and a slight ‘shoulder’ in some of the optical bands (e.g. $R$ and, to a much lesser extent, $V$; see § 1.1.1; Kasen 2006). As discussed by Kromer & Sim (2009), the assumption of LTE has important implications for this effect. Kromer & Sim (2009) show that when using a detailed ionisation treatment, as opposed to LTE, the IGEs in the ejecta remain more highly ionised for longer. This generally results in the recombination of Fe III to
Fe II happening at earlier times in LTE. Hence, the first and secondary maxima blend together, forming a single peak that is broader than is observed in SNe Ia. This could explain why the model $I$–band in particular is most discrepant with SN 2009ig.

Figure 6.4 shows a comparison of our model light curves to SN 2009ig assuming an explosion epoch of JD = 2 455 063.41. Foley et al. (2012) infer this explosion epoch for SN 2009ig following the method of Riess et al. (1999a), where $L \propto t^2$. Piro & Nakar (2014) infer an explosion epoch 1.6 days earlier (JD = 2 455 061.8) by fitting the velocity evolution of absorption features (where $v \propto t^{-0.22}$). We compared all of our models to SN 2009ig using both explosion epochs and found best agreement with our v7500_d0_n8_s3 model and the explosion epoch of Foley et al. (2012). As an additional test, we fit this model to SN 2009ig by varying the explosion epoch. We find a best match explosion time to be consistent with that of Foley et al. (2012), JD = 2 455 063.34; however, we stress that the model agreement with SN 2009ig is not perfect and therefore could affect our explosion time estimate.

### 6.10 Conclusions

We presented a new Monte Carlo code, purpose built for modelling the early light curves of radioactively driven transients. Light curves computed by our code for the well-studied W7 explosion model (Nomoto et al. 1984) are consistent with those from other radiative transfer codes.

We performed an extensive parameter study of the $^{56}$Ni distribution and density profile, and explored their effects on model light curves. Similar to Piro & Morozova (2016) and Noebauer et al. (2017), we find that the light curve is strongly affected by the $^{56}$Ni distribution. For a given density profile, models with $^{56}$Ni extending throughout the ejecta are typically brighter and bluer at earlier times than models in which $^{56}$Ni is embedded deep within the ejecta. The density profile also has significant effects on the model light curves.

We demonstrated the importance of a full radiative transfer treatment through comparisons with models that use grey opacities. We show how a grey (Rosseland) opacity is typically only applicable for times less than approximately one week after explosion and for models that do not have extended $^{56}$Ni distributions, and hence may produce inaccurate estimations of the $^{56}$Ni distribution.

Relations between the amount of surface $^{56}$Ni (or column density) and rise time, peak magnitude, and colour were investigated. We found that while correlations do exist, the scatter is sufficiently large that significant caution must be applied if individual light curve parameters (e.g. rise time to $B$–band maximum) are used to infer $^{56}$Ni
distributions. A comprehensive comparison of full colour light curves is necessary to quantify the $^{56}$Ni distribution in individual objects.

Finally, we compared our series of models to observations of the SN Ia SN 2009ig (Foley et al. 2012). We find remarkably good agreement with a model that has $^{56}$Ni extending to the outer ejecta, despite the relatively simple approach we have taken with, for example, the composition. It is clear that SN 2009ig is inconsistent with a $^{56}$Ni distribution that is concentrated towards the ejecta centre, and likely had a significant amount of $^{56}$Ni present in the outer ejecta. Piro & Nakar (2014) conclude that SN 2009ig must have had a $^{56}$Ni mass fraction, $X_{56}$ of $\sim 0.1$ at $\sim 0.1$ M$_{\odot}$ from the ejecta surface. All of our models with $s = 3$ have similar compositions to this (i.e. $X_{56} = 0.1$ at $\sim 0.1$ M$_{\odot}$ from the ejecta surface), but only our v7500_d0_n8_s3 model matches the light curve shape of SN 2009ig. This demonstrates the considerable power of early-phase light curve analysis to constrain a range of ejecta properties (such as the density profile) in addition to the $^{56}$Ni mass depth. Future work will focus on models with varying $^{56}$Ni and ejecta masses, as well as different compositions and more complex $^{56}$Ni distributions.

Our models clearly demonstrate that colour information is necessary to characterise the $^{56}$Ni distribution. In the case of SN 2009ig, our models show a preference for an extended $^{56}$Ni distribution, similar to detonation-to-deflagration and pure deflagration models. Whether other explosion models can induce similar degrees of mixing remains to be seen. Upcoming surveys will discover tens of thousands of SNe Ia. The high cadence and large field of view of the Large Synoptic Survey Telescope (Ivezic et al. 2008; LSST Science Collaboration et al. 2009) for example, means that many of these discoveries will occur shortly after explosion. Comparison to a larger observed sample will demonstrate whether the majority of SNe Ia typically show similar $^{56}$Ni distributions and place greater constraints on the explosion mechanism(s) of this class of supernovae.
Chapter 7

Conclusions
The purpose of this thesis has been to investigate the explosion mechanism(s) and physics for thermonuclear SNe. To that end, we presented comprehensive observations for two new extreme thermonuclear SNe, SN 2015H and PS1-12bwh. Both objects are members of the type Iax class and we demonstrated that currently proposed thermonuclear explosion models are able to broadly reproduce many of the properties of the class; however, additional modelling is needed to characterise the full diversity of SNe Iax. Having investigated extreme objects, we turned our attention towards the more common type Ia supernovae. We presented a new Monte Carlo radiative transfer code that is capable of exploring the early light curves of radioactively driven transients. We applied this code to testing the effects of the density profile and \(^{56}\text{Ni}\) distribution within the ejecta of SNe Ia – diagnostics of the explosion mechanism. We found good agreement with (at least) one object. Future comparisons with other SNe will allow for a more thorough investigation into the ejecta properties of SNe Ia.

The cover image for this chapter shows the Crab Nebula. Image credit: NASA and ESA; Acknowledgment: J. Hester (ASU) and M. Weisskopf (NASA/MSFC).

7.1 Discussion

The first SN Iax was discovered in 2002 (Li et al. 2003) and since then their numbers have grown to a few dozen objects (Foley et al. 2013; Jha 2017). Many of the observed properties of the class are now well defined: low luminosity, low ejecta velocities, weak features due to intermediate mass elements (IMEs), and spectral signatures suggestive of mixing in the ejecta. Based on these properties, scenarios producing only weak explosions (relative to SNe Ia) have been proposed. Particular attention has been paid to the pure deflagration scenario – in which carbon-oxygen burning proceeds subsonically through the WD and may fail to unbind it (Branch et al. 2004; Jha et al. 2006). The work presented in this thesis has used new observations and modelling tools to explore the dependence of the observable light curves and spectra on model parameters.

We showed, for the first time, that synthetic observables of the pure deflagration scenario are consistent with observations of SNe Iax across a range of peak luminosities. Similar to Kromer et al. (2013), we compared our observations of SN 2015H to the models of Fink et al. (2014). We found that a model producing only \(\sim 0.07 \, M_\odot\) of \(^{56}\text{Ni}\), \(N3\text{def}\), was able to broadly reproduce the light curve peak and shape of SN 2015H, and many of the spectral features observed a few weeks post-explosion. Our result provides a clear indication that at least some, or perhaps all, SNe Iax may be produced by the pure deflagration scenario, and at least some of the differences observed among members of the class is likely due to differences in explosion strength, and hence \(^{56}\text{Ni}\) mass.
There is some disagreement, however, between the Fink et al. (2014) models and observations of SNe Iax. This specific set of models appears to systematically evolve quicker than the observations. This could indicate that the ejecta mass is too low for this particular realisation of pure deflagrations. Indeed, our analysis of the light curve of SN 2015H suggests an ejecta mass of $\lesssim 0.6 M_\odot$, while N3def produced only $\sim 0.2 M_\odot$. To resolve this discrepancy, the next step should be to investigate the conditions necessary to produce a larger ejecta mass for a given $^{56}$Ni mass. The sequence of models presented by Fink et al. (2014) is not an exhaustive exploration of the full parameter space for deflagration models (nor was it intended to be). Simulations with changes in the initial conditions of the WD (such as central density, metallicity) should allow us to determine whether it is possible to obtain better agreement with observations, thereby providing constraints on not just the explosion mechanism, but also the progenitor.

Although we have shown that some of the diversity among SNe Iax can be explained by differences in explosion strength, this is not the complete picture. We presented observations of PS1-12bwh that demonstrate previously unseen behaviour. We found both the peak luminosity and overall light curve shape of PS1-12bwh to be almost identical to that of SN 2005hk, indicating that both objects share similar $^{56}$Ni and ejecta masses. In addition, the post-maximum spectra (beginning approximately a few weeks after maximum light) were almost identical for both objects. Pre-maximum spectra, however, were noticeably different. Therefore, while both objects must have had similar explosion strengths, our results clearly demonstrate that this property alone can not explain the full diversity of SNe Iax, and therefore SNe Iax are not a one-parameter family.

We performed detailed spectral modelling of SN 2005hk and PS1-12bwh, and found that the unique pre-maximum spectrum of the latter can be reproduced if the outer layers of the ejecta had a lower density than in the former. As with SN 2015H, our work demonstrates the need for a larger set of explosion models. Typically, model sequences will vary the explosion strength, but we have clearly demonstrated different models of similar explosion strengths are necessary. Again, simulations of pure deflagrations should test various initial conditions to explore their effect on the observed light curves and spectra. This will allow us to constrain the physical properties necessary to reproduce the differences observed between SN 2005hk and PS1-12bwh, or rule out scenarios that are unlikely. In addition, the pulsational delayed detonation (PDD) scenario should be extended to multi-dimensional simulations to test whether this scenario is a viable candidate for SNe Iax. Dessart et al. (2014a) demonstrate how the PDD and more standard deflagration-to-detonation transition (DDT) models can produce different spectra at early times, but similar spectra at late times. This is qualitatively similar to the behaviour of SN 2005hk and PS1-12bwh, but these models
are too bright and have ejecta velocities too high to be consistent with these objects. Further investigation is needed to explore whether similar models with lower explosion strengths can produce lower luminosities at peak and/or the unique behaviour we have shown.

In the era of modern surveys, a growing number of SNe Ia are being discovered within hours or days of explosion. These objects have shown that SNe Ia display a broad range of behaviours in their early light curves. We presented a new Monte Carlo radiative transfer code designed for modelling these early light curves. Our work significantly improves over previous modelling attempts by using non-grey opacities without any loss to the speed or flexibility of the code. The use of non-grey opacities allows for the direct comparison between our model light curves and the observed SNe Ia light curves, while the flexibility of our code allows for the systematic exploration of a large parameter space – hence, we investigated the effects of various ejecta properties on the model light curve.

We found that models with extended $^{56}$Ni distributions produce light curves that are bluer and rise faster at early times. The shape of the density profile itself also plays a significant role in determining the resultant light curve. This point had been neglected in previous work, but our study clearly shows the shape of the density profile must be taken into account. Finally, we compared our set of models to SN 2009ig and found good agreement with a model containing $^{56}$Ni throughout the entire ejecta. The favourable agreement between one of our simple models and SN 2009ig demonstrates how our code may be used to constrain the properties of the ejecta in SNe Ia.

Having demonstrated the utility of our code, future work should expand to include a larger sample of models and objects. Future models should test how sensitive the light curves are to different compositions, potentially constraining the nucleosynthetic yields within SN 2009ig. In addition, future models should test multiple $^{56}$Ni and ejecta masses. This will facilitate a broader comparison to multiple SNe Ia and demonstrate whether or not brighter/fainter SNe Ia show a preference for certain ejecta configurations. Are the ejecta configurations intimately tied to the explosion strength, and will this demonstrate different explosion mechanisms are necessary for SNe Ia? More complicated $^{56}$Ni distributions should be explored, in addition to the parameterised approach we have adopted here. This will be essential for testing certain explosion scenarios, such as double detonations, which may show a thin outer shell containing $^{56}$Ni. Finally, improvements to our code could be made to explore other scenarios that can influence the early light curves of SNe Ia, such as the ejecta interacting with a companion star. This would allow us to clearly show signatures of a single degenerate explosion for SNe Ia and determine what observations are necessary to provide evidence of such
a scenario.

### 7.2 Future outlook

Future improvements in our understanding of SNe Iax will require a larger sample of objects, enabling us to better determine the full breadth of properties among the class and the range of explosion scenarios that may be necessary. Identifying and classifying SNe Iax quickly enough to obtain the necessary observations, however, may prove to be one of the big challenges going forward. Recent work has shown that it may be possible to identify SNe Iax based on their unique colour evolution (Miller et al. 2017); however, at least one outlier to this evolution exists (SN 2009ku). Whether all SNe Iax can be identified in such a manner should be investigated further. With PS1-12bwh, we showed that the early phases are crucial to gaining a full understanding of the class. Therefore, considerable effort should be made to not just identify SNe Iax as quickly as possible, but also to respond equally quickly with follow-up observations. This would require having the necessary facilities and time in place to co-ordinate observations efficiently.

Although we have focused mostly on the pure deflagration explosion scenario (based on the good agreement between model and observed light curves and spectra), at least one SN Iax has been argued to be consistent with a different explosion scenario – PDD models (Stritzinger et al. 2015). As previously mentioned, PDD models should be extended to full multi-dimensional simulations, and their light curves and spectra compared against observations of SNe Iax, including SN 2012Z. Arguments in favour of PDD models for SN 2012Z are partly based on the layered ejecta structure these models produce. Claims of layering in the ejecta of SN 2012Z have been made based on the velocities and evolution of certain spectral features; however, there is some uncertainty in these velocity measurements and it is unclear if layering has been robustly detected in the case of SN 2012Z. In addition, Barna et al. (2017) argue that the spectra of SN 2011ay are consistent with an ejecta structure that differs significantly from the pure deflagration models; they argue that the distribution of iron group elements (IGEs) within their best fit model is at odds with the distribution in the Fink et al. (2014) models. SNe 2011ay and 2012Z are among the brightest SNe Iax known, therefore perhaps the brightest objects require different explosion mechanisms to the faintest.

It is clear that the evidence for layering within the ejecta and the observable signatures, particularly as related to the spectral features, warrant further investigation. Future work should investigate the signatures of stratification by producing spectra from a model sequence with progressively mixed ejecta. Such models will allow us to determine whether SNe Iax require mixing, layering, or if current observations are unable to
effectively distinguish between the two cases to any significance. This will further con-
strain the explosion mechanism and comparisons with SNe Iax will highlight whether
ejecta structures differ across the class.

An outstanding question related to SNe Iax is whether they show the presence of
helium in their optical spectra. Two objects have been claimed to show \( \text{He}\,\text{I} \) features
(SNe 2004cs and 2007J) on the basis of optical spectra, but whether these objects are
in fact SNe Iax is currently debated (Foley et al. 2013; White et al. 2015; Foley et al.
2016). \( \text{He}\,\text{I} \) features have not been claimed in other SNe Iax; however, the lack of
strong optical features does not necessarily indicate that \( \text{He} \) is not present, as these
optical features are difficult to excite. In addition, the optical spectra of SNe Iax are
dominated by strong blending of features due to IGEs, further adding to the difficulty in
making robust detections of \( \text{He} \). Therefore, particular consideration should be given to
obtaining NIR spectra of SNe Iax. \( \text{He}\,\text{I} \) can produce a strong transition at 10 830 Å and
this particular region of the spectrum is home to fewer features, allowing for easier
identification. If \( \text{He}\,\text{I} \) can be clearly identified in a large number of objects, it would
have clear implications for the progenitor system and strengthen the claims of McCully
et al. (2014a) that the progenitor system of SNe Iax may include a \( \text{He} \) star donor.

In addition to the claimed detection of a possible progenitor system to SN 2012Z
by McCully et al. (2014a), a potential remnant was discovered for SN 2008ha by Fo-
ley et al. (2014). These two objects make SNe Iax unique among thermonuclear SNe,
as there have never before been plausible claims for the detections of progenitors or
gravitationally bound remnants for SNe Ia. Continued follow up observations of these
sites and other SNe Iax will determine whether these exciting claims can be confirmed.
Although a possible progenitor has been detected for one object, observations of the
sites of other SNe Iax have provided only upper limits (Foley et al. 2010b, 2015). Such
remnants are expected to be red and faint, therefore IR observations utilising more sen-
sitive instrumentation might provide more clues to SNe Iax, through targeted surveys
aimed at detecting remnants. If multiple objects are observed to produce remnants this
could provide a ‘smoking gun’, indicating that potentially many SNe Iax are the result
of failed deflagrations.

With the advent of ZTF (Bellm 2014) and LSST (Ivezic et al. 2008; LSST Science
Collaboration et al. 2009), we are currently on the verge of a new age of transient re-
search. Thanks to these and other surveys, potentially hundreds of thousands of SNe
will be discovered in the coming years. At least some fraction of these will be discov-
ered very shortly after explosion, yielding orders of magnitude more objects than are
currently available. Our new radiative transfer code will be ideally placed to provide
constraints for these objects, through comparisons with the larger model suite previ-
ously mentioned.

In summary, future observations for SNe Iax should focus on acquiring spectra as early as possible. These phases are essential for providing constraints on the outermost ejecta that are not visible at later times and will help to demonstrate whether PS1-12bwh was unique or if similar objects may have been missed in the past. Observing large numbers of SNe Iax at these times may prove challenging, however, and methods of identifying SNe Iax quickly should be investigated further. In addition, programmes should be in place to quickly capitalise on these discoveries and schedule follow-up observations efficiently. A larger sample of NIR spectra should also be obtained to determine whether He i is indeed present among SNe Iax. Sites of SNe Iax should be surveyed using more sensitive NIR instruments, in the hope of detecting faint possible remnants. Comparisons between a large sample of early SNe Ia light curves and future models will allow us to determine whether SNe Ia show a preference for any particular ejecta configuration, and hence explosion mechanism.
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