# Analyzing Type IIn Supernovae spectra to determine if some arise from runaway stars

**A THESIS**
**SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL**
**OF THE UNIVERSITY OF MINNESOTA**
**BY**

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**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS**
**FOR THE DEGREE OF**
**MASTER OF SCIENCE**

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**May, 2020**

# Acknowledgements

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The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

The author wishes to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to use observations from this mountain.

This research has made use of the Keck Observatory Archive (KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExScI), under contract with the National Aeronautics and Space Administration.

# Dedication

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## Abstract

We have analyzed observations of Type IIn supernovae taken by the DEIMOS spectrograph on Keck II in order to determine if there is a significant offset in the peak of the SN H$\alpha$ emission with respect to the predicted H$\alpha$ peak wavelength of the host galaxy. An offset of 30 km s$^{-1}$or greater would imply a runaway progenitor star, ejected via dynamical interaction or as the mass-gaining companion of a binary star system. Significant amounts of runaway progenitors would have an impact on how the progenitors of SNe IIn are viewed, and seeing as luminous blue variable stars are commonly seen as a progenitor star it could also have impacts on the evolutionary path for LBV stars. LBVs are not seen in evolution models as an end-of-life stage but rather a transition stage, and they are also not expected to be the result of a binary supernova kick.

Spectra and resulting offset velocities were analyzed and computed for six SNe IIn, of which two returned as possible runaway candidates. Of these two, SN 2010jl had direct observations by the Hubble Space Telescope approximately 10 years prior to explosion. These observations show a luminous blue source, which was theorized to either be an extremely bright and young star cluster or a massive luminous blue variable star. The other runaway candidate, SN 2013dz, does not appear in the literature but shows signatures of an asymmetrical circumstellar medium. The remaining four SNe IIn show no significant evidence of runaway behavior, and are assumed (excepting for projection effects) to be relatively stationary. It is unknown what caused these explosions, but their lack of offset velocity lends credence to massive, quickly-evolving stars exploding either during or after the LBV phase as a progenitor for SNe IIn.

With a sample size of six observations, it is difficult to make any statistically significant conclusions, however due to the external nature of SNe IIn it may be fair to claim that both scenarios may make up a part of the progenitor population. More observations of progenitors, SNe, and post-SNe regions are needed to reach a more robust conclusion.

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# Chapter 1

# Introduction

## 1.1 Supernovae

When stars reach the end of their lives, they will either go with a bang or a whimper depending on their initial masses. Stars that start with less than 8 solar masses ($M_\odot$) at birth tend to fall into the latter category, releasing their outer layers into a planetary nebula and leaving their collapsed cored as a white dwarf star. Stars more massive than $8M_\odot$, on the other hand, fall in the former category. These stars will undergo a sudden core collapse, with the resulting explosion ejecting several solar masses of outer layers at extreme speeds while the core collapses into a neutron star or, if massive enough, a black hole. These events are called supernovae (SNe, singular: supernova/SN), and can some of the most luminous transient events in astronomy.[1]

### 1.1.1 Types of SNe

There are two main types of SN, distinguished by the presence or lack of hydrogen in their spectra - Type I SNe lack hydrogen emission while Type II have it present. Each type is further divided into subtypes. Type I SNe are divided between Type Ia which has a silicon absorption feature, while Types Ib/c lack the Si II feature.[2] Type II SNe are divided in four main ways:

[1] The core collapse supernova (CCSN, plural: CCSNe) describes this event, but white dwarfs can also undergo supernova. If a white dwarf accretes enough mass to pass the Chandrasekhar limit ($1.4M_\odot$), it will undergo runaway nuclear fusion and explode as a Type Ia SN (spectrum described in Sec. 1.1.1).

[2] These are further split based on the presence of a He I line at 5876 Å.

- Type IIb SNe lose their hydrogen emission over time and become similar to SNe Ib.
- Type IIn SNe show narrow lines of hydrogen emission.
- Type II-L SNe show a linear decrease in their light curve, and have no narrow lines.
- Type II-P SNe show an extended period of luminosity (a "plateau" in their light curve, hence the "P") before decreasing in brightness.

In this thesis we take a specific eye towards Type IIn SNe.

### 1.1.2 Type IIn Supernovae

Type IIn supernovae (SNe IIn) are a subclass of CCSNe which show strong, narrow Balmer lines of hydrogen in their spectra (Schlegel, 1990), and make up approximately 10% of all CCSNe. It is expected that these narrow lines arise from the supernova shock interacting with a dense, pre-existing circumstellar medium (CSM) surrounding the progenitor star (Smith, 2017), though the exact origins of the CSM is still up for debate. No matter the progenitor, some sort of extreme mass-loss is required in the decades prior to the explosion in order to generate such a CSM.

Because of the dense, surrounding CSM, the basic structure of a SNe IIn differs significantly from other SNe. As seen in Fig. 1.1, Smith (2017) splits the SN IIn into four physical zones: the unshocked CSM (1), the shocked CSM (2), the shocked SN ejecta (3), and the freely expanding SN ejecta (4). At the boundaries of each zone are the forward and reverse shocks, as well as the cold dense shell (CDS) between zones 2 and 3. In a non-SNe IIn, an observer would see radiation emerging almost entirely from zone 4, but since the CSM is so dense for these explosions, each zone can provide significant contributions towards emitted radiation (Smith, 2017). In early times when the photosphere is still in zone 1, radiation from the shock is electron scattered by the photosphere and unshocked CSM, creating narrow H$\alpha$ emission lines with broad Lorentzian wings (Smith, 2017). As the explosion progresses and the photosphere recedes into zones 2 and 3, the gas piled into the CDS is constantly reheated by the shock and emits strong H$\alpha$ intermediate-width lines.

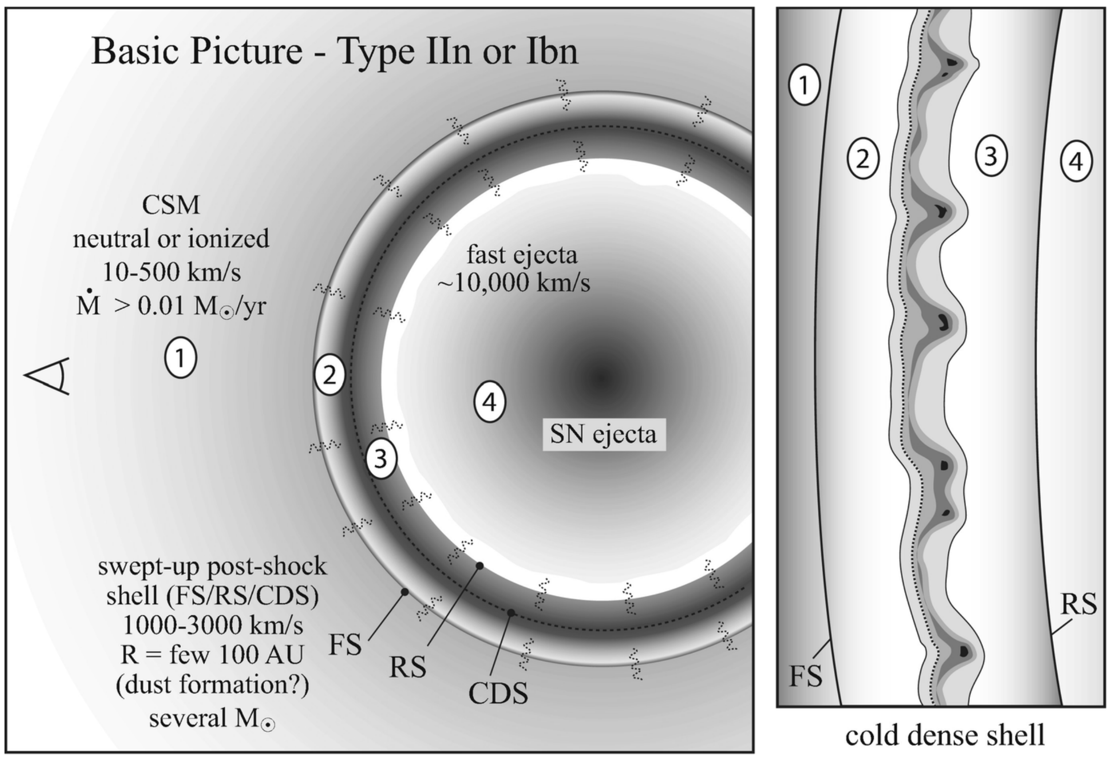


Figure 1.1: Cartoon of the basic structure of a SNe IIn. SNe IIn can be split into four separate zones: (1) the unshocked CSM, (2) the shocked CSM, (3) the shocked SN ejecta, and (4) freely expanding SN ejecta. At each boundary is a different event: between (1) and (2) exists the forward shock, between (2) and (3) is the cold dense shell (CDS), and between (3) and (4) is the reverse shock. X-rays and UV radiation can also be generated by the shock and propagate forwards into the CSM or back into the SN ejecta, and this is represented by the squiggly lines. This figure has been adapted from Smith et al. (2008).

It is important to remember that SNe IIn are an *external* phenomenon - they may actually mask other types of supernovae. Any type of core collapse supernova or even thermonuclear supernova can create the narrow Balmer lines seen in SNe IIn, so long as there is a dense enough hydrogen-rich medium surrounding the explosion (Smith, 2017). Because of this, it is impossible to trace all SNe IIn to a single type of progenitor star or explosion type. A SN IIn could be covering up a SN II-b, II-L, or II-P, and because of the dense CSM it is impossible to know what the explosion type truly is. There are also Type Ibn SNe (referenced in Fig. 1.1) which display prominent narrow helium lines, as well as Type Ia-CSM SNe which show signs of a dense CSM surrounding the thermonuclear SNe.

The luminosity of an SN IIn can be used to obtain information about the mass-loss rate of the progenitor star (Smith, 2017), allowing observers to determine other properties of the progenitor. SNe IIn can end up being much more luminous than other SNe, as the radiative shock from CSM interaction is extremely efficient at transforming the kinetic energy of the SN shockwave into visible-wavelength light (Smith, 2017). Because the luminosity is directly tied to the CSM, it can be expressed as

$$L = \frac{1}{2} w V_{\mathrm{CDS}}^3 \tag{1.1}$$

where $w$ represents the wind density parameter, $w = \dot{M}/V_{\mathrm{CSM}}$ (where $\dot{M}$ is the mass-loss rate and $V_{\mathrm{CSM}}$ is the speed of the circumstellar medium), and $V_{\mathrm{CDS}}$ is the speed of the cold dense shell, the contact discontinuity where the SN shock and CSM meet (Smith, 2017). $V_{\mathrm{CDS}}$ can be estimated from the full width half maximum (FWHM) of intermediate-width lines in the optical spectrum, while $V_{\mathrm{CSM}}$, the velocity of the CSM untouched by the SN shock, can be measured from narrower components. Combining this together, the mass-loss rate of the progenitor can be estimated by

$$\dot{M}_{\mathrm{CSM}} = 2L \frac{V_{\mathrm{CSM}}}{V_{\mathrm{CDS}}^3}. \tag{1.2}$$

One major caveat to this equation is that it requires a constant mass-loss rate and $V_{\mathrm{CSM}}$ over time in order to have the CSM density decrease as $r^{-2}$. If Eq. 1.2 is used when the CSM density profile is shallower, it will return a much larger mass-loss rate than is true (Dwarkadas, 2011). A review by Dwarkadas (2011) of several SNe IIn show that their mass-loss rates were overestimated, adding further confusion as to what the progenitors to these explosions are. Additionally, many SNe IIn show signs of significant asymmetries in their CSM, which will further alter the discrepancies between the results from the equation and the actual star.

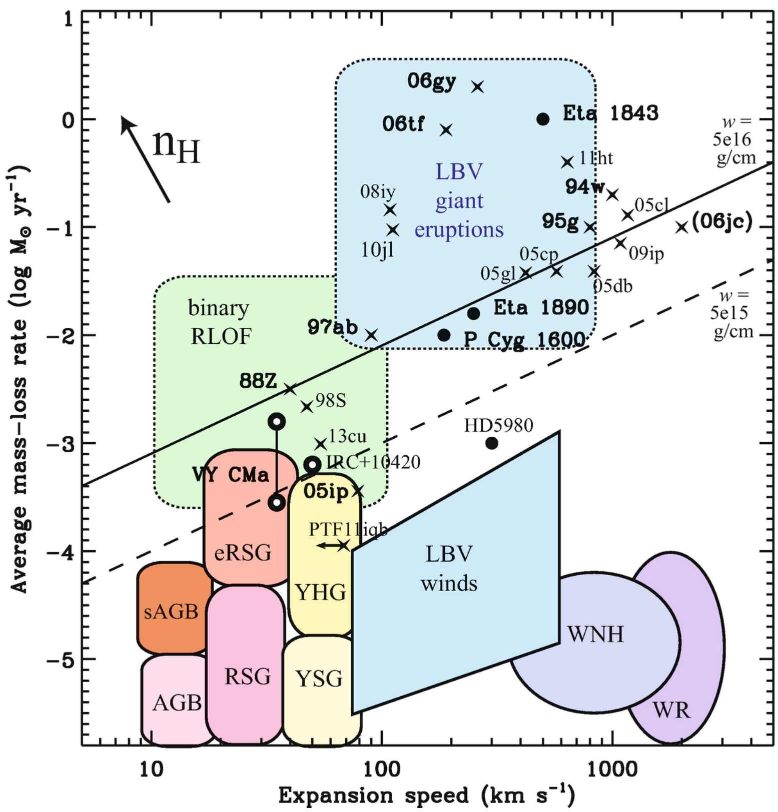


Figure 1.2: Plot of mass-loss rate as a function of wind velocity, with comparisons to known SNe IIn explosions and possible progenitor stars. Observational estimates of different SNe IIn are represented by X's, and some stars with high mass-loss (e.g. $\eta$ Car) are represented by circles. The patches represent the approximate parameter spaces for different types of stars. Represented in this plot are asymptotic giant brach (AGB) and super-AGB (sAGB) stars, red supergiant (RSG) and extreme-RSGs, yellow super- and hypergiants (YSG, YHG), winds and eruptions from luminous blue variables (LBVs), Wolf Rayet stars (WR, WNH), as well as progenitors arising from basic binary Roche lobe overflow (RLOF). This figure was adapted from Smith (2017).

Even with this setback, conclusions can be made about what kind of stars are able to produce fast enough winds and high enough mass-loss rates seen in SNe IIn. A plot from Smith (2017) comparing mass-loss rate and wind velocities of several SNe IIn and comparing them to progenitor properties can be seen in Fig. 1.2. It is worth noting that most SNe IIn require some sort of giant luminous blue variable (LBV) eruption in the decades preceding explosion to create enough CSM to form the narrow lines present in SNe IIn.

## 1.2 Luminous Blue Variables

Luminous blue variables (sometimes referred to as S Doradus variables) are extremely luminous, evolved, and unstable massive stars near the Eddington limit[3] which undergo irregular eruption events (Humphreys and Davidson, 1994). LBVs have a higher luminosity to mass ratio ($L/M$) than a typical star, as well as a larger Eddington factor ($\Gamma = L/L_{\text{Edd}} > 0.5$).

When in their eruptive phase, LBVs can create a large amount of dense ($N \sim 10^{11}$ cm$^{-3}$), cool ($7000-9000$ K) CSM surrounding the star (Humphreys and Davidson, 1994). The most explosive of these eruptions (such as $\eta$ Car and SN 2009ip[4] ) can be luminous enough to be misinterpreted as SNe (known as supernova imposters). LBVs can also have a quiescent phase with decreased mass-loss and temperatures of 12,000 to 30,000 K (Humphreys and Davidson, 1994). In this visual minimum, LBVs can resemble hot supergiants or Of/WN stars.

Two main classes of LBVs exist with completely separate evolutionary histories. "Classical" LBVs originate from stars with initial masses ($M_{\text{ZAMS}}$) greater than $50M_{\odot}$ and have bolometric magnitudes between -9.7 and -11.5 mag. Their high mass-loss rates means that they lose mass too quickly to cool and become a red supergiant (RSG). Making up the second class are less luminous LBVs, originating from stars in the range of 25 to 40 $M_{\odot}$ and have bolometric magnitudes of -8 to -9.5 mag. These stars are expected to have completed their RSG stage and moved back towards the blue end of the H-R diagram, passing through an LBV phase where they lose up to half of their initial mass (Humphreys et al., 2016). This mass-loss allows such stars to achieve an $L/M$ similar to the more luminous LBVs.

Traditionally the more massive LBVs serve as a transition stage between an O-type

[3] The *Eddington limit* is the maximum luminosity an object can have while still maintaining hydrostatic equilibrium, the balance between gravitational pull inwards and radiation pressure outwards.

[4] SN 2009ip actually exploded as an SN IIn in 2012, though this is debated (Mauerhan et al., 2012).

star to a hydrogen-poor Wolf-Rayet (WR) star (Smith and Owocki, 2006). For massive, classical LBVs, the evolutionary path is

$$\text{O} \rightarrow \text{WNL (H-rich)} \rightarrow \text{LBV} \rightarrow \text{WN (H-poor)} \rightarrow \text{WC}$$

where the LBV plays the role of ejecting the WNL star's H-rich envelope (Langer et al., 1994; Gräfener and Hamann, 2008). In order to reconcile that the direct progenitor of a SNe IIn is not an LBV, (Dwarkadas, 2011) suggest a very short WR phase or a clumpy CSM to create the necessary CSM properties, but the general consensus in the literature is that LBVs mysteriously serve as the main progenitor.

Referring back to Fig. 1.2, we see that while some SNe IIn could arise from binary Roche lobe overflow (RLOF) or extreme red supergiants (eRSGs), it is clear that mass-loss estimates and wind speeds favor an LBV progenitor for most SNe IIn. Indeed, direct observations of progenitors for SNe IIn explosions such as SN 2009ip (Mauerhan et al., 2012, still debated) and SN 2010jl (Smith et al., 2011) appear to show a progenitor LBV in the location of the future explosion, though follow up observations to see if they are just SN imposters are not only uncommon but difficult since some SNe IIn transients can last for many decades before fading away.

## 1.3 Runaway Stars

Runaway stars are defined as stars that have space velocities of 30 to 40 km s$^{-1}$(Blaauw, 1961; Eldridge et al., 2011), though some can reach velocities over 200 km s$^{-1}$. As described in Eldridge et al. (2011), the two main scenarios to create runaway stars are through a dynamical ejection scenario (DES) and through a binary supernova scenario (BSS), though the fastest runaway stars could have been created by a combination of both. In the DES, stars would be ejected via encounters with other massive stars in a dense cluster - this can be single stars or even entire binary systems of stars. The BSS, on the other hand, occurs when one of the stars in a binary explodes, unbinding the system and kicking the secondary star. The two methods are expected to contribute roughly equal amounts of runaway stars, but it is possible to differentiate between the two by looking at their compositions as BSS runaways should show evidence of binary interaction (Eldridge et al., 2011). Again, since entire binary systems can be ejected in DES, it is reasonable to assume that some of those binary systems undergo BSS as well.

The most common type of runaway star are O- and B-type stars (Blaauw, 1961), massive stars that can lead to core collapse explosions. Since these stars are launched in excess of 30 km $s^{-1}$, it is not unreasonable that secondary stars kicked in a BSS could travel many parsecs before exploding in their own SN. The simulations run by Eldridge et al. (2011) (seen in Fig. 1.3) do in fact find that for Type II SNe as well as Type Ib and Ic SNe that these progenitors can be launched in excess of 100 pc before explosion from the star-forming region they were born in.

### 1.3.1 LBV Runaways as Possible SNe IIn Progenitors

While the simulations by Eldridge et al. (2011) do not look at SNe IIn specifically, Habergham et al. (2014) analyzed 39 SNe IIn and SN imposters and looking to see how they trace H$\alpha$ emission (a tracer of star formation) in their host galaxies. Based on these observations, Habergham et al. (2014) concluded that not only do SNe IIn not correlate to star formation regions, they correlate even less to star formation than other explosions such as SNe II-P. The authors attribute this as an indication that SNe IIn are unlikely to have high mass progenitors, as they expect them to follow star forming regions as well as SN Ic, which have massive progenitors as well. This implies that whatever progenitor is creating many Type IIn explosions must either be low enough mass to survive longer than higher mass stars, or they have been isolated by some other means.

Although this appears to be contradictory, observations by Smith and Tombleson (2015) of LBVs in the Milky Way (MW), Large Magellanic Cloud (LMC), and Small Magallanic Cloud (SMC) imply that LBV stars almost always find themselves isolated from other O-type stars and star-forming regions (Smith and Tombleson, 2015). This matches up nicely with the view of LBVs serving as the progenitors for SNe IIn.

Smith and Tombleson (2015) analyzed 29 LBVs and LBV candidates in the MW, LMC, and SMC, and determined the distance between the object and the nearest O-type star. A plot of the cumulative fraction versus distance to nearest O-type star of several different classes of stars (Fig. 1.4) appears to show that the LBV population have a distinct distribution independent of O-type stars (which they would follow if they were all young massive stars) and RSGs (which they would follow if they are much older than expected).

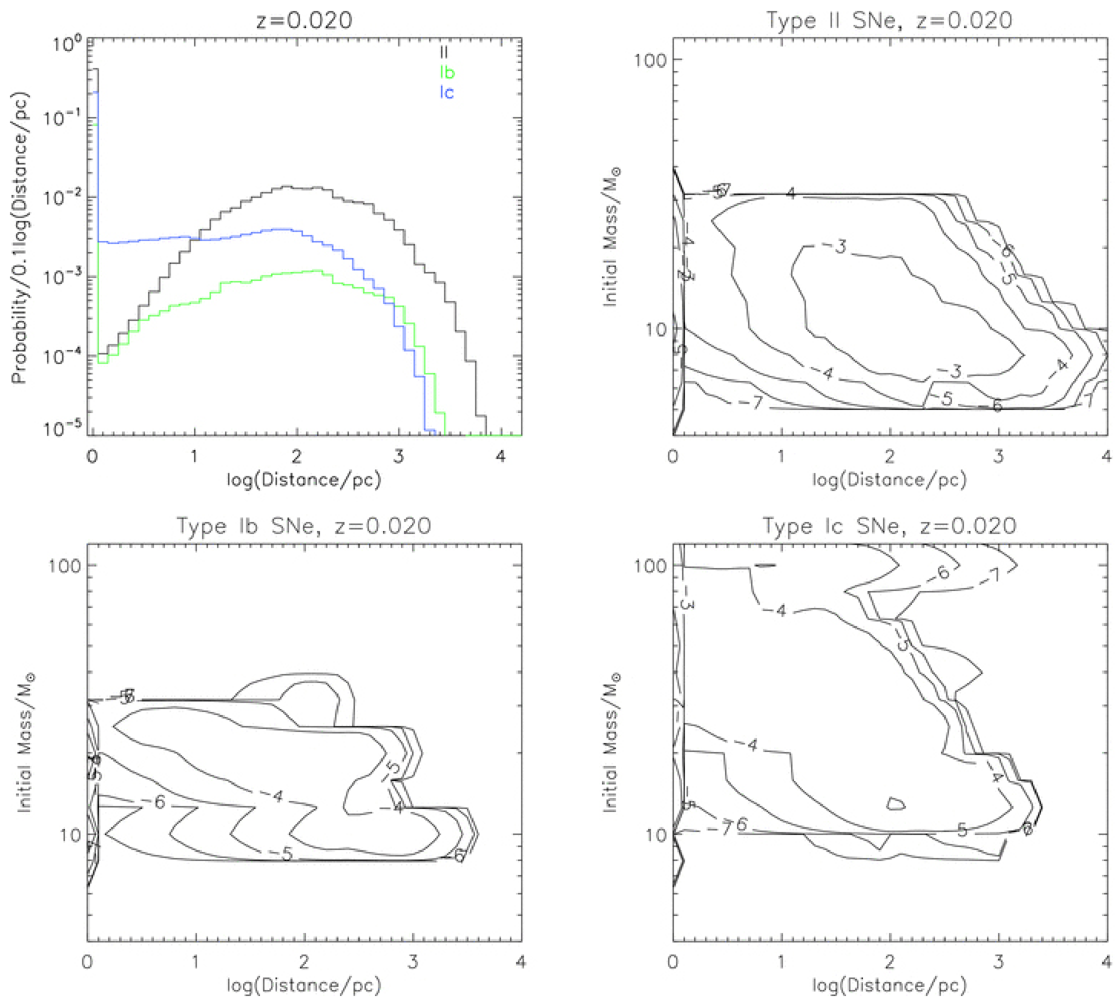


Figure 1.3: Plot showing the distribution of distance traveled by SN progenitors versus the progenitor's original mass, in solar metallicity. The data comes from the simulations of Eldridge et al. (2011). The contours represent the probability in $\log_{10}$ of a SN progenitor of that initial mass traveling that distance. This figure has been adapted from Eldridge et al. (2011).

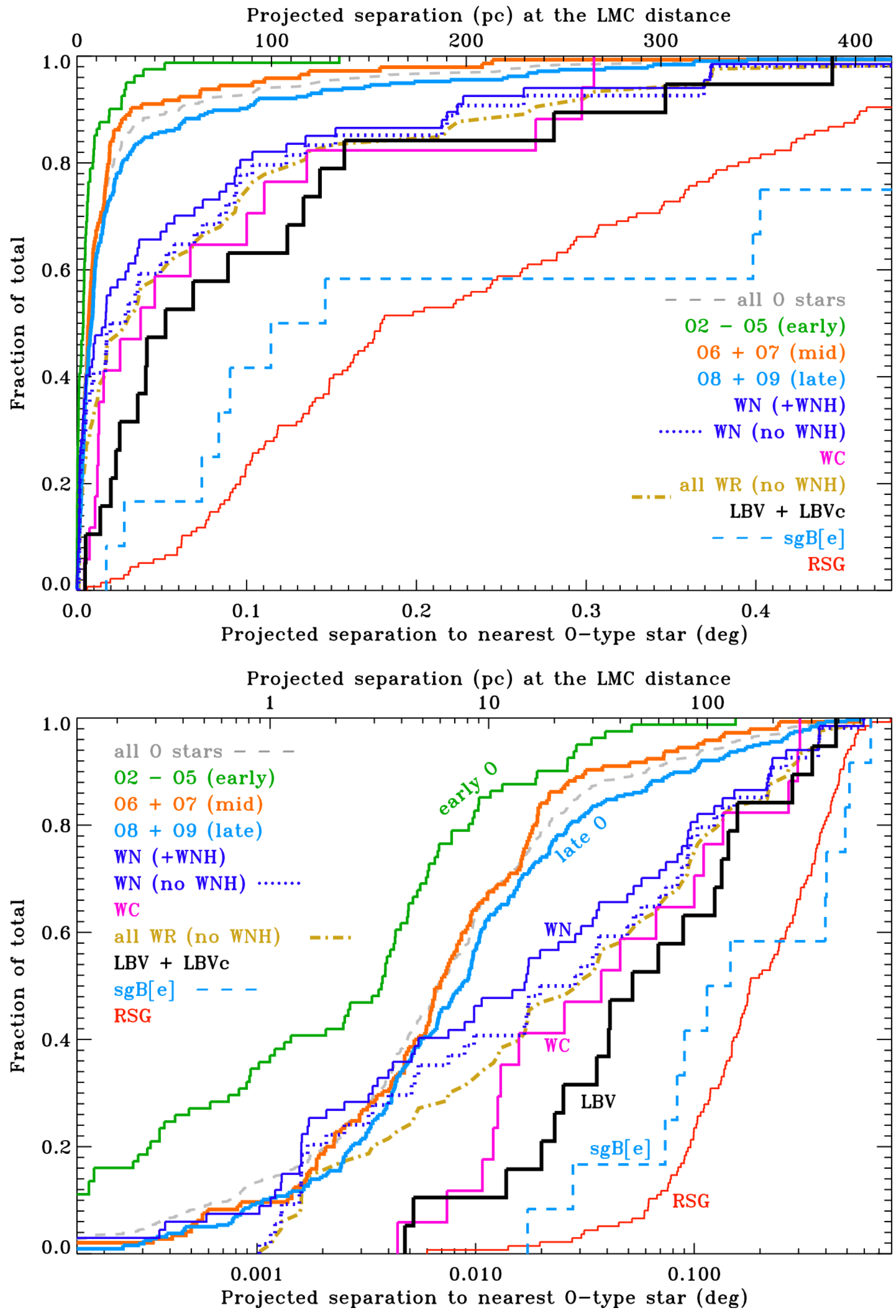


Figure 1.4: Plot comparing the cumulative fractions of different classes of stars and their distances to the nearest O-type star. The full list of classes can be seen in Fig. 4 of Smith and Tombleson (2015). All LBVs and LBV candidates from the MW, LMC, and SMC are combined into one group and appear to show that they are a distinct population from O-type stars and RSGs. This figure has been adapted from Smith and Tombleson (2015).

In order to reconcile the fact that according to traditional stellar evolution models LBVs should not be found isolated, Smith and Tombleson (2015) suggest that most LBV stars are actually the end stage for the kicked mass gaining companion in the BSS. With the LBV progenitor being kicked from its binary, Smith and Tombleson (2015) claim it can then travel the adequate distance to be found later in a region of relative isolation from other O-type stars and star forming regions. The important aspect of this scenario is that the LBV progenitor, serving as the secondary star, accretes mass through RLOF from the primary star prior to the primary star's explosion. This allows the star to substantially increase its own mass and luminosity, and therefore appear younger than the stars around it (known as "blue stragglers") (Smith and Tombleson, 2015). These stars will still have an extended lifetime compared to stars of their new mass and luminosity, and as such can travel great distances before evolving and exploding (Smith and Tombleson, 2015). Additionally, the process of RLOF will allow them to gain significant angular momentum and velocity, which may be important to LBV instabilities and eruptions (Smith and Tombleson, 2015).

A closer look at this from Humphreys et al. (2016) appears to directly rebutt this claim, however, and even claim that the data from Smith and Tombleson (2015) support the traditional view of LBV evolution. They achieve this by emphasizing the class split of LBVs into the "classical" more luminous LBVs and the less luminous LBVs, and the important evolutionary differences between them.

Because the less luminous LBVs originate from stars that have already been through a RSG phase, they should be expected to be much older than their classical counterparts and therefore have similar isolation rates to RSGs. The classical LBVs are much younger when they reach their LBV phase, and therefore should have similar isolation statistics to O-type stars. Although they have a very small sample size due to only using LMC and SMC confirmed LBVs, Humphreys et al. (2016) find this trend to be supported by the data (see Fig. 1.5).

Humphreys et al. (2016) also claim that many of the objects used by Smith and Tombleson (2015) are not truly LBVs, finding that eight objects (six in the LMC and two in the SMC) used in the original analysis are not confirmed LBVs in the literature. They are also careful to distinguish between confirmed LBVs and "candidate" LBVs, and even find that the candidates follow the same trend as RSGs as well.

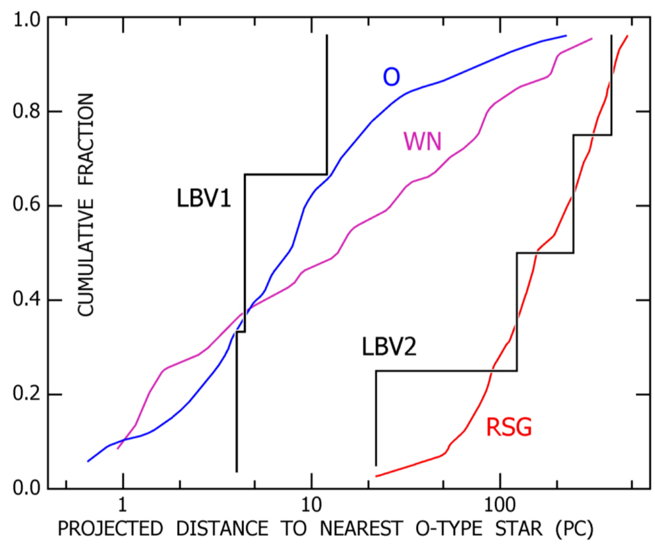


Figure 1.5: Plot comparing the cumulative fractions of different classes of stars and their distances to the nearest O-type star. Displayed are O-type stars, Wolf-Rayet WN stars, RSGs, as well as "classical" LBVs (LBV1) and less-luminous LBVs (LBV2). It is clearly shown that the classical LBVs follow O-type stars and the less luminous LBVs follow RSGs, as expected. This figure has been adapted from Humphreys et al. (2016).

Humphreys et al. (2016) finally claim that they don't find any evidence of runaway-like behavior in any of the LBVs studied. When comparing LBV velocity to the expected galactic rotational velocities at that location, they find that all but one (S119 in the LMC, with an offset velocity of over 100 km $s^{-1}$) have offset velocities $\leq$ 100 km $s^{-1}$, which they set as their minimum cut-off for a runaway star. If we take the 30 km $s^{-1}$prescribed by Blaauw (1961), we find that six of the 26 total LBVs and LBV candidates in the LMC, SMC, M31, and M33 analyzed by Humphreys et al. (2016) may be a runaway.

## 1.4 This thesis

The goal of this thesis is to determine if we see evidence of SNe IIn arising from runaway stars, and if so, place constraints on them in the hope of learning more about their progenitors. In order to do this, I will be analyzing the narrow H$\alpha$ lines of SNe IIn and comparing their line of sight velocities to the expected radial velocity of the galaxy in that location.

Chapter 2 will detail the observed supernovae I use in this thesis, as well as how they were obtained. Chapter 3 will talk about the methods used to analyze the offset velocities of the SNe IIn relative to their host galaxies. Chapter 4 will detail the findings of this thesis as well as any future work that can be done from here. Finally, Chapter 5 will conclude the findings of this thesis.

# Chapter 2

# Observations

## 2.1 Observed SNe IIn

All observations used for this thesis were taken with the DEIMOS (DEep Imaging Multi-Object Spectrograph) multi-object spectrograph on the Keck II (10-m) telescope (Faber et al., 2003). In order to collect as many SNe IIn as possible, a list of SNe IIn was obtained using the Asiago Supernova Catalog (Barbon et al., 1999), a catalog of supernovae dating from 1885 to 2017, as well as the Transient Name Server[1] from the International Astronomical Union. These were then searched in the Keck Observatory Archive to see if any observations were taken of the SNe with DEIMOS. Upon analysis, we also removed any SNe IIn that had already evolved to the point where the SN ejecta was freely expanding (there were no more narrow- or intermediate-width H$\alpha$ lines). All observations used in this thesis are listed in Table 2.1. *Of note: many more SN were downloaded than were analyzed due to errors with the DEIMOS pipeline.*

## 2.2 DEIMOS

DEIMOS is a multi-object spectrograph capable of taking spectra of multiple objects at once. The slitmasks span 16.7' of the sky, and have a wavelength range of 4100 Å to 1.1 $\mu$m (Faber et al., 2003). The observations used in this thesis all utilize the Long Variable Mutlislit (LVM) slitmask. All observations taken prior to 2008 utilized four

[1] `https://wis-tns.weizmann.ac.il/`

| SN | Date (UT) | Galaxy Host | Grating Used | PI |
|---|---|---|---|---|
| SN 2013dz | 2013 Aug 2 | Unknown | 1200G | Filippenko, A. |
| SN 2013W | 2013 Apr 8 | UGC 5448 | 600ZD | Filippenko, A. |
| SN 2012ab | 2012 Nov 15 | Unknown | 600ZD | Filippenko, A. |
| SN 2008en | 2012 Sep 23 | UGC 564 | 1200G | Filippenko, A. |
| SN 2010jl | 2010 Nov 7 | UGC 5189A | 600ZD | Filippenko, A. |
| SN 2005R | 2005 Feb 11 | UGC 6274 | 600ZD | Davis, M. |

Table 2.1: Table of observations

slitlets on the original LVM, while future ones use the LVMslitB or LVMslitC which have 5 slitlets.

DEIMOS has two separate gratings: a lower-resolution aluminized grating with 600 lines mm$^{-1}$ (600ZD) blazed at 7500 Å which offers a width of 5300 Å; and a higher-resolution gold-coated grating with 1200 lines mm$^{-1}$ (1200G) blazed at 7500 Å offering a width of 2630 Å.

Fig. 2.1 shows an image of SN 2015bf prior to being reduced in the DEIMOS pipeline. This image is transposed and rotated such that the $x$ axis represents wavelength (increasing to the right) and the $y$ axis represents the location of the emission. Several night-sky emission lines from the atmosphere can be seen in this image, and are removed in the pipeline.

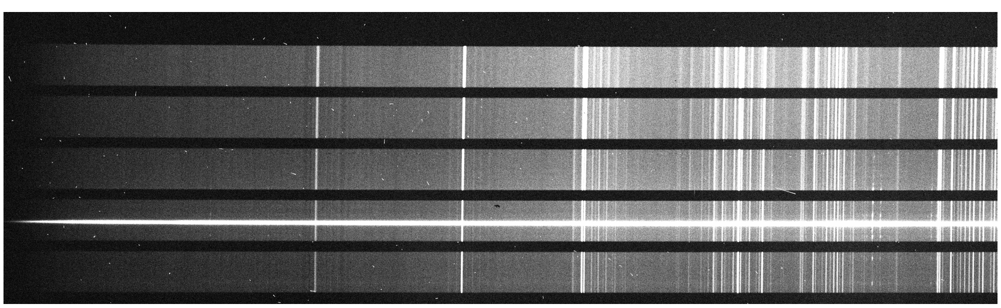

Figure 2.1: An image taken of the blue portion SN 2015bf on DEIMOS, prior to being reduced. This image is transposed and rotated such that the $x$ axis represents wavelength (increasing to the right) and the $y$ axis represents location in the CCD. The SN continuum is clearly visible in the second slit from the left, though there are many skylines still present. This image was taken as part of the Keck-UC Time-domain Exploration.

## 2.3 H$\alpha$ $\lambda$6563

H$\alpha$ is the primary Balmer line of hydrogen, occurring when a hydrogen electron moves from the third energy level to the second energy level. As mentioned in Chapter 1, we expect to see strong emissions of H$\alpha$ in spectra of SNe IIn due to the shock heating of the CDS. We additionally would expect to see nebular H$\alpha$ tracing the SN host galaxy, as it traces high mass stars and star formation rates (as mentioned in Habergham et al. (2014). An example H$\alpha$ spectrum from a SNe IIn can be seen in Fig. 2.2 which displays the narrow (and the beginnings of intermediate) width H$\alpha$ emission in SN 2008en.

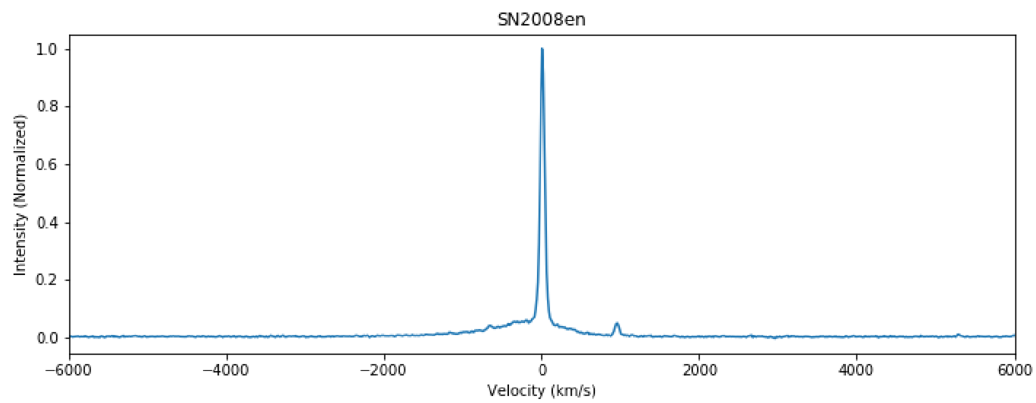


Figure 2.2: Spectrum of the H$\alpha$ emission from SN 2008en. We can see here strong narrow emission lines of H$\alpha$ which is flanked by weak [N II] emission on both sides. This image is centered on the narrow H$\alpha$ emission and shows Doppler velocity on the $x$ axis and normalized flux per unit wavelength on the $y$ axis.

Since DEIMOS has a spatially extended slit, we can expect to see the SN continuum, the SN H$\alpha$, and the host galaxy H$\alpha$ in the same image. An example of this can be seen in Fig. 2.3, which displays the H$\alpha$ of SN 2013dz and its host galaxy. What is typically seen in these observations is a bright continnuum emission from the SN, making it difficult to visiually distinguish the H$\alpha$ emission. We also see H$\alpha$ emission that traces the host galaxy's emission.

One property of this image that is easy to notice is that the galactic H$\alpha$ shifts from left to right in wavelength. This is expected, as this shift represents the Doppler shift of different parts of the galaxy. In Fig. 2.3, the bottom portion of the galaxy is blueshifted, indicating its line of sight velocity is pointed towards the observer, while the top portion is redshifted. This shift can be used to estimate what radial velocity is expected of the SN IIn if it were not a runaway star.

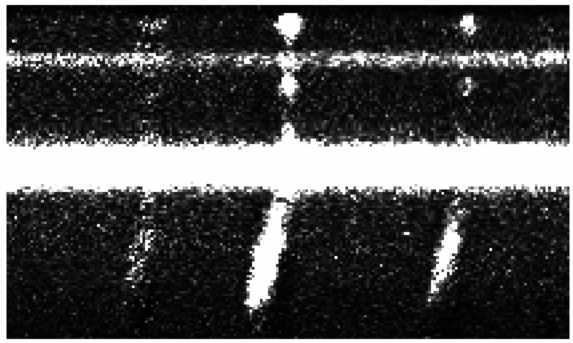

Figure 2.3: An image taken of the red portion of SN 2013dz on DEIMOS, after being reduced. We can clearly see the H$\alpha$ emission from the host galaxy as well as the continuum emission of SN 2013dz. We also can see N II $\lambda$6548 and N II $\lambda$6583 lines of the host galaxy. The H$\alpha$ emission of the SN is difficult to distinguish visually as the SN continuum is already extremely bright.

# Chapter 3

# Analysis

## 3.1 Reducing DEIMOS Images

We used the Carnegie Python Distribution (CarPy)[1] in order to handle, calibrate, reduce, and analyze the images observed from DEIMOS (Kelson et al., 2000; Kelson, 2003). CarPy includes many routines for processing multi-slit spectroscopic data. The CarPy environment also contains PyRAF[2], a Python based command language to run IRAF[3] (Image Reduction and Analysis Facility) tasks.

Our reduction is based on the standard prescription outlined in Silverman et al. (2012), with slight modifications. Since all of the observations were made on the same instrument (DEIMOS), the only changes that need to be made between different observations is based on the placement of the slitlets, the number of slitlets, and the resolution of the gratings. I will summarize the our pipeline below:

1. Subtract out the overscan region and subtract out the bias. For this, we use `iraf.ccdproc`. Then transpose the image and rotate it 180 degrees such that wavelength is increasing in the $+x$ direction of the image.

2. Combine and normalize the flat-fields using `iraf.flatcombine`.

[1] `https://code.obs.carnegiescience.edu/carnegie-python-distribution`

[2] PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

[3] The Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation (NSF)

3. Rectify the image using the combined flat-fields. The $y$-distortion is calculated using `getrect` and then applied to the flats using `copyrect` such that the wavelength in every vertical strip is the same.

4. Find the locations of the slitlets in the images using `findslits`. Once the slits are found, the locations are written to the image header and copied to the rest of the images.

5. Divide out the flat fields and the blaze from the other images using `flat2d`.

6. Get the rectification for each slit using `getrect`, and then copy them to all the other images using `copyrect`. In this step, we are specifically copying the $x$-distortion.

7. Calibrate the wavelength scale with `waverect`. This uses the assistance of arc-lamp spectra, which typically contained Neon, Argon, Krypton, and Xenon, and sometimes Cadmium, Zinc, and Mercury. This gets applied to all the images.

8. Extract the 1D spectra of the standard star using `iraf.apall`. We interactively remove telluric and absorption features using `iraf.splot` to select the regions and then dividing them out using `iraf.sarith`. This forms a standard continuum spectrum, as well as a sensitivity function.

9. Extract the 1D spectra of the SN, and normalize by the standard continuum. Apply telluric corrections using `iraf.telluric`, and flux calibrate using the sensitivity function.

10. Combine the spectra of the blue and red sides to form one complete spectrum. We can then analyze the location of the peak as well as get a full-width half-maximum (FWHM) measurement of the H$\alpha$ using `splot`.

## 3.2 Analyzing Velocities of SNe IIn

Once we are able to extract the spectra, we want to run steps 9 and 10 from Sec. 3.1 for different points of the galaxy's H$\alpha$ line, as well as on the continuum of the SN to measure the H$\alpha$ emission of the SN. In order to determine the central location and the FWHM of the emission, we utilize a multi-component fit of Lorentzian profiles, determining the narrow-width and intermediate-width emission making up the overall profile. We can then map out the H$\alpha$ emission throughout the galaxy.

With this map, we attempt to fit a cubic polynomial function (reverting to a quadratic for situations where it is not possible, see Fig. B.4 for an example) through the galaxy H$\alpha$ emission. This function provides an estimate for the peak wavelength of the galaxy's H$\alpha$ emission at the location of the supernova, and we can then determine the offset velocity of the SN using a line-of-sight velocity calculation

$$v = \frac{c\left(\lambda_{\text{gal}} - \lambda_{\text{SN}}\right)}{\lambda_{\text{gal}}} \tag{3.1}$$

where $v$ is the offset velocity, $c$ is the speed of light ($3 \times 10^5$ km s$^{-1}$), $\lambda_{\text{gal}}$ is the estimated wavelength of H$\alpha$ emission of the galaxy at the SN location, and $\lambda_{\text{SN}}$ is the observed wavelength of the SN H$\alpha$ emission.

Our results for all observed galaxies can be seen in Table 3.1. The spectra of all the SNe can be seen in Fig. 3.1 and Fig. 3.2. Comparisons of the SNe H$\alpha$ peak to the host galaxy's estimated H$\alpha$ peak can be seen in Sec. B.

As mentioned in Sec. 1.1.2, after their explosion SNe IIn can be seen with a narrow-width H$\alpha$ emission that represents electron-scattering in the unshocked CSM and photosphere as well as an intermediate-width H$\alpha$ emission the results from the reheating of the CDS by the shock. Those with more prominent intermediate-width lines can be assumed to have exploded further in the past from the observation compared to those with less prominent intermediate-width lines. As we can see, it appears that SN 2008en and SN 2013dz were caught relatively close to explosion, while the others (especially SN 2012ab) were caught weeks or months after explosion. The presence of large intermediate-width lines enveloping the narrow-width lines was a frequent issue when analyzing the data, skewing the predicted location of the SN's H$\alpha$ peak by several hundred km s$^{-1}$.

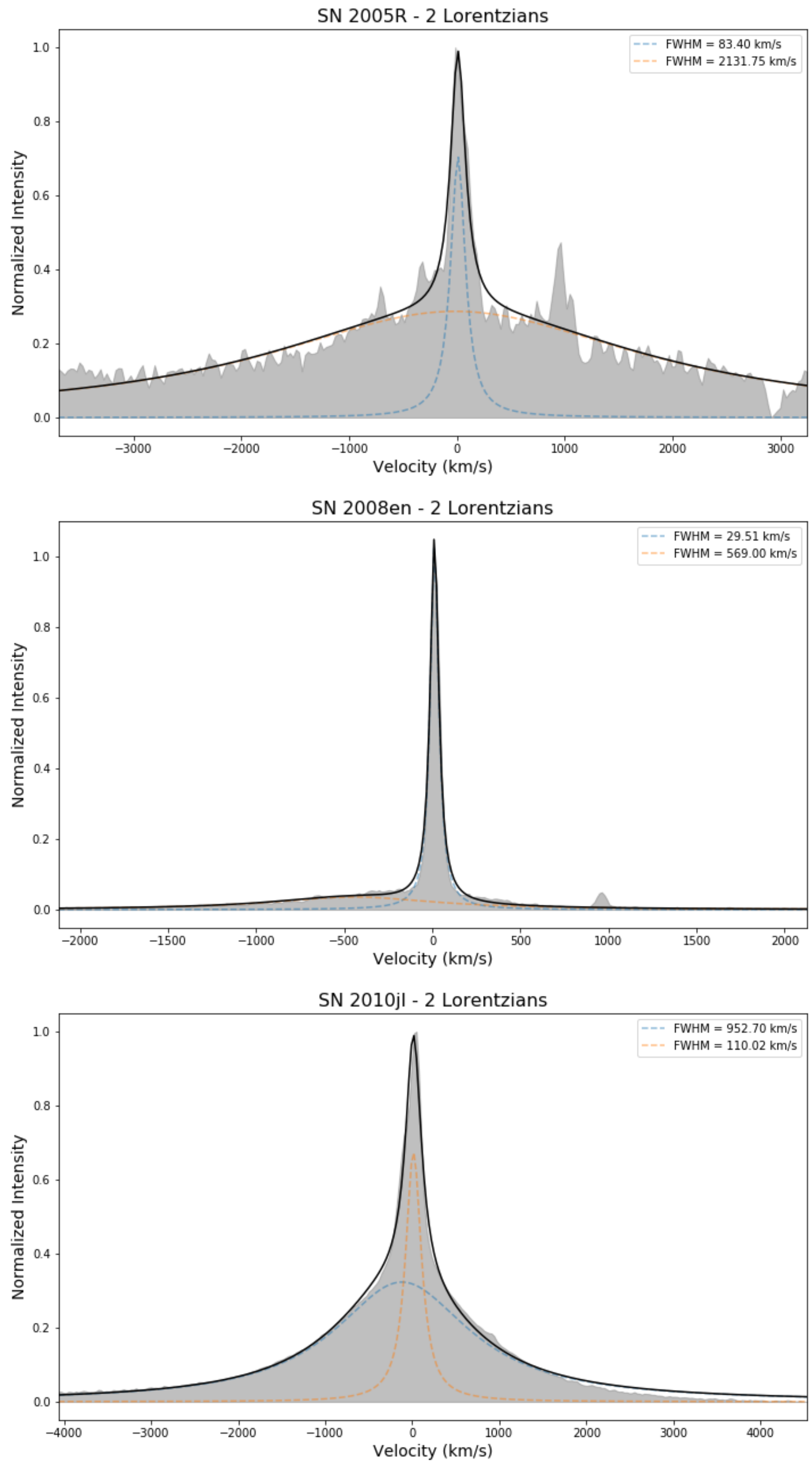


Figure 3.1: Lorentzian fits of three analyzed SNe IIn - SN 2005R, SN 2008en, and SN 2010jl. These are fit with an intermediate-width and narrow-width Lorentzian.

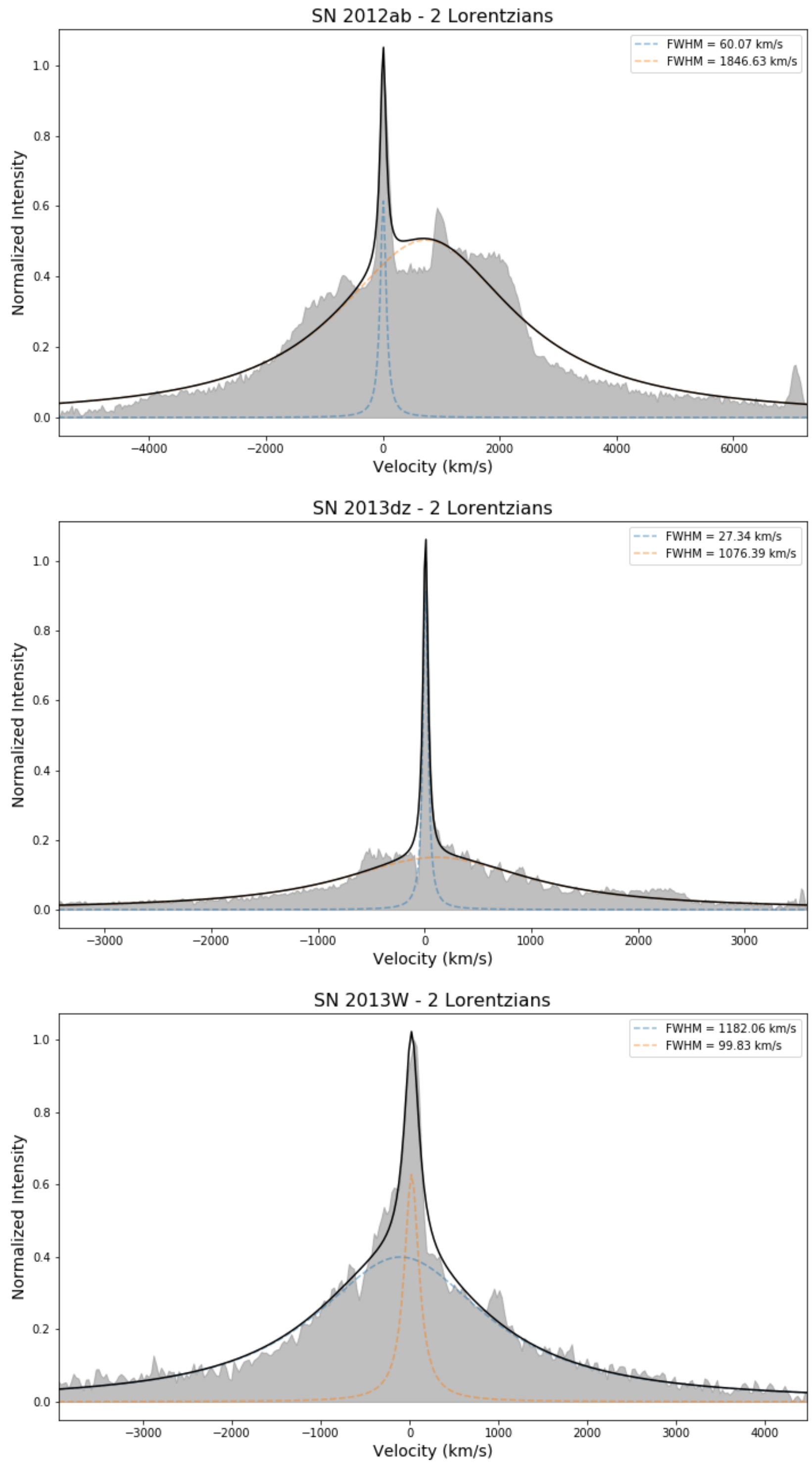


Figure 3.2: Lorentzian fits of three analyzed SNe IIn - SN 2012ab, SN 2013dz, and SN 2013W. These are fit with an intermediate-width and narrow-width Lorentzian.

| SN | Offset Velocity (km $s^{-1}$) | Narrow-width FWHM (km $s^{-1}$) |
|---|---|---|
| SN 2013dz | 39.31 | 27.34 |
| SN 2013W | 18.49 | 99.83 |
| SN 2012ab | 13.27 | 60.07 |
| SN 2010jl | 37.46 | 29.51 |
| SN 2008en | 1.98 | 110.02 |
| SN 2005R | 11.16 | 83.40 |

Table 3.1: List of SNe IIn, the FWHM of their H$\alpha$ emission, and their offset velocities from their host galaxies.

# Chapter 4

# Discussion

Recalling back to Sec. 1.3, Eldridge et al. (2011) and Blaauw (1961) define runaway stars to have space velocities above 30 to 40 km $s^{-1}$. If we look at Table 3.1, we only see two objects that fulfill this definition - SN 2013dz with an offset velocity of 39.31 km $s^{-1}$and SN 2010jl with an offset velocity of 37.46 km $s^{-1}$. All of the other SN have velocities below 20 km $s^{-1}$. It is worth noting that none of these SNe fulfill the definition set by Humphreys et al. (2016) of 100 km $s^{-1}$.

This data, and more significantly the amount of data we have, makes it extremely difficult to come to any significant conclusions. Having only six data points to work with means that it is unreasonable and irresponsible to claim that many SNe IIn arise from runaway LBVs - but the presence of SN 2013dz and SN 2010jl does give it credence.

## 4.1 Runaway Candidates

In this paper, we will define runaway candidates as having a space velocity greater than 30 km $s^{-1}$.

### 4.1.1 SN 2010jl

Smith et al. (2011) goes into detail about the progenitor star of SN 2010jl, as it is one of a few SNe IIn with direct observations of the progenitor prior to explosion. Hubble Space Telescope (HST) observations of the progenitor about 10 years prior to explosion show a luminous and blue point source at the location of the SN, implying that the progenitor could have been in a massive young star cluster or a LBV.

However, it is hard to reconcile the predicted initial mass of 80 $M_\odot$ with a runaway. If it were the runaway companion star, it would fall on the higher end of expected runaway masses in Smith and Tombleson (2015) as a star with $M_{\rm ZAMS} \approx 30 - 40 M_\odot$ accreting enough mass to appear as a $60 - 80 M_\odot$ star. It is certainly not unreasonable to claim that the predicted progenitor mass, the observed offset velocity, and visual observations of the progenitor imply a runaway LBV progenitor, but it is pushing at the lower limits of runaway stars and the higher limits of mass-gaining RLOF stars.

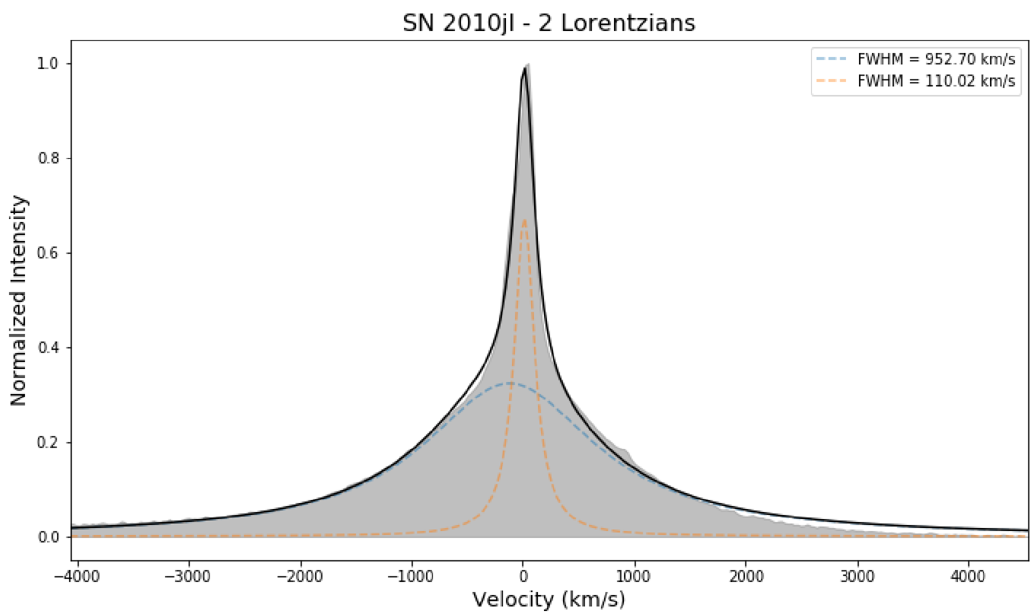


Figure 4.1: This shows the spectrum of H$\alpha$ emission from SN 2010jl (shaded in gray), as well as a fitting of two Lorentzian profiles. This indicates that there is a narrow-width emission with a FWHM of about 110 km s$^{-1}$and an intermediate-width emission of 952.7 km s$^{-1}$.

Smith et al. (2011) also theorizes that the progenitor star could have been a normally fainter and less massive LBV that just happened to be caught mid-eruption. Since such an eruption can last on the order of 10 years, they claim this situation is not improbable. The supernova explosion would then have to happen soon after the LBV eruption or even during it - a situation possibly paralleled by SN 2009ip (Mauerhan et al., 2012).

If we consider the traditional view of LBVs, an $80 M_\odot$ LBV would almost certainly be a classical-type LBV. Because of this, we would expect it to have undergone further evolution into a WN star and then a WC star before explosion, but in order for the CSM to be dense enough to emit narrow lines, this period must have been short as hypothesized by Dwarkadas (2011).

The last possible progenitor presented by Smith et al. (2011) is that the progenitor resided in an extremely massive star cluster, with an age around 5 Myr. This would present a progenitor star with $M_{ZAMS} > 30 M_\odot$. Such a star could have been ejected through DES, providing it with it's higher space velocity, but it does not explain how the progenitor gained the dense CSM necessary to explode as a SN IIn.

### 4.1.2 SN 2013dz

Unlike SN 2010jl, there are no analyses of SN 2013dz in scientific literature. It was discovered by Dhungana et al. (2013) in July 2013 and observed again 20 days later using DEIMOS. The one dimensional spectrum from DEIMOS can be seen in Fig. 4.2. In it, there is blue-shifted hydrogen component and P-Cygni absorption that bears strong similarities to the blue-shifted components of SN 2013L, especially in early times (Andrews et al., 2017, see their Fig. 8, 9). Andrews et al. (2017) claim that this suggests that the SN ejecta began interacting with very dense CSM at this time (approximately 30 d after explosion). If we take the date of first observation by Dhungana et al. (2013) as approximately 10 d after explosion, this timeline matches up exactly with SN 2013L.

Andrews et al. (2017) further analyze the evolution of the spectrum of SN 2013L and come to the conclusion that the progenitor star must have had extremely asymmetric CSM in order to generate the H$\alpha$ profile, suggesting an initial mass of $M > 25 M_\odot$. They also suggest that the asymmetry could be a result of binary RLOF, which aligns well with the hypothesis of the progenitor being a BSS runaway. Andrews et al. (2017) also derive a mass-loss rate for the progenitor of SN 2013L being between $1 \times 10^{-4}$ and $1 \times 10^{-3} M_\odot$ yr$^{-1}$, implying a yellow hypergiant or quiescent LBV.

While we clearly cannot take their results and apply it to SN 2013dz, the similarities in the H$\alpha$ profile do lend their hand to SN 2013dz's progenitor being some sort of massive star with a very asymmetric CSM. It can reasonably be implied that, while not the result of an eruptive LBV, the progenitor could have been ejected through BSS after gaining significant mass and CSM through RLOF.

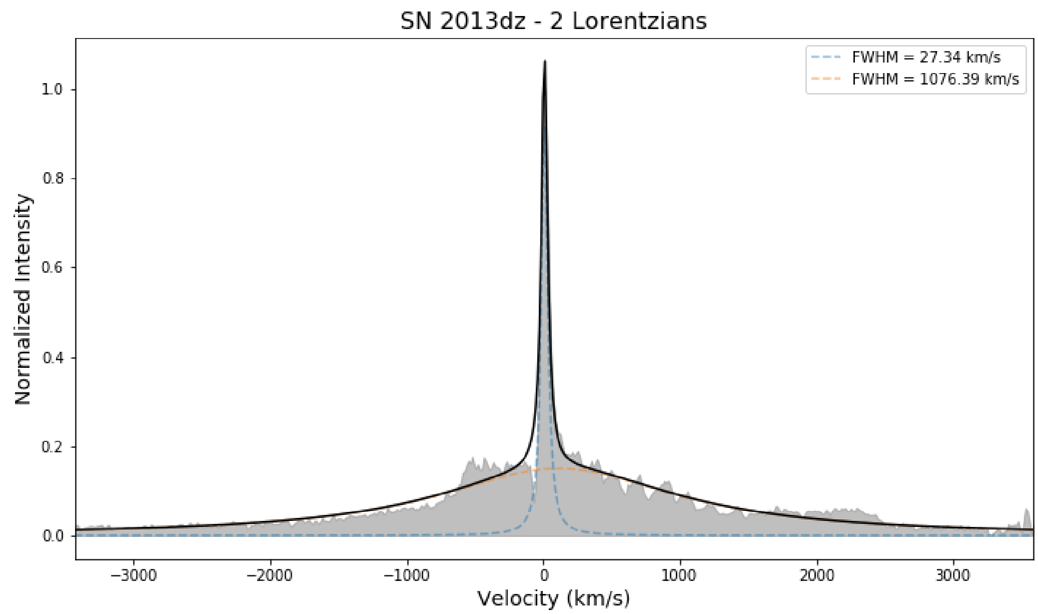


Figure 4.2: 1-D spectrum of SN 2013dz taken by DEIMOS. The absportion on the blueshifted portion of the H$\alpha$ emission has similarities to SN 2013L early in its evolution (Andrews et al., 2017). There does appear to be a strong narrow H$\alpha$ emission line overlaid on an intermediate-width emission.

## 4.2 Implications on progenitors

With such a small sample, having two candidates for runaway progenitors is scientifically interesting. It would also be fair to claim that projection effects may be at play with some other SNe IIn, as their ejection may not be directly towards or away from the observer. A lack of observed Doppler velocity difference may be a result of the progenitor not being ejected through BSS or DES, or it could be the result of the progentior simply being ejected in a direction that we cannot discern a velocity through Doppler shift. The lack of any SN having an offset over 40 km s$^{-1}$, nevertheless up to 100 km s$^{-1}$as Humphreys et al. (2016) demands, does imply that having a runaway progenitor is unlikely.

Even if projection effects are accounted for, the lack of possible runaway progenitors is worth discussion. If, as many claim, LBV stars serve as the typical progenitor for SNe IIn, then we could possibly assume that the progenitors of these SNe without high velocities are more massive classical LBVs who explode before they can be travel far (matching Humphreys et al. (2016)). If most LBVs are truly runaway stars, then the lack of runaway SNe IIn could imply that LBVs are not the typical progenitor star for SNe IIn. This would require more creative solutions to the SNe IIn in the literature with LBV progenitors, or recognition that the observed SNe IIn are atypical for their class.

With that being said, it is important to recall that SNe IIn are *external phenomena* and do not necessarily arise from a single type of progenitor. Any astrophysical event that leads to significant CSM surrounding a progenitor can lead to a SN IIn event, and as such we should not expect every SN IIn to arise from a runaway star, let alone a runaway LBV as Smith and Tombleson (2015) implies.

# Chapter 5

# Conclusion

After spectral analysis of six Type IIn supernovae observed with DEIMOS, we find two SNe (SN 2013dz and SN 2010jl) with offset velocities of 30 km $s^{-1}$or greater relative to their location in their host galaxy. This offset velocity implies that the progenitors of these explosions may have undergone some sort of ejection, either through dynamical interaction with star clusters or through the death of its binary pair. This raises the possibility that, at the very least, some SNe IIn progenitors may be the result of runaway stars. SN 2010jl in particular is the closest thing to a confirmed runaway LBV progenitor for the resulting SNe IIn, having been observed by Hubble approximately 10 years prior to explosion. SN 2013dz, while not present in the literature, shows signs of having an asymmetric CSM which could be caused by bipolar LBV eruptions, binary RLOF, or both.

The remaining four supernovae analyzed, however, show little to no significant offset velocity. Should LBVs truly be a significant portion of the SNe IIn progenitor population, the data would appear to further discount Smith and Tombleson (2015)'s hypothesis that almost all LBVs are the result of runaway stars caused by BSS. Many of these SNe could still be the result of fast-evolving "classical" LBVs, though stellar evolution models still require the progenitor star to progress from the LBV stage to a WN stage before explosion. We would expect these massive stars to not have a high velocity, as they will most likely burn out too quickly to be ejected through DES or BSS.

The presence of both possible runaway progenitors and non-runaway progenitors could imply a "happy medium", where some may be caused by runaway stars and others are caused by extremely massive, fast-burning stars. After all, SNe IIn are external phenomena, and as such the dense CSM seen in them could mask a variety of other SNe types, each with their own set of progenitors.

Only having a sample size of six SNe IIn prohibits us from making any significant conclusions. Work can still be done on tidying up the reduction pipeline, so that many of the SNe IIn observed with DEIMOS can be observed. Additionally, increases in all-sky surveys can help future astrophysicists pinpoint possible progenitors for future explosions, much like was done for SN 2010jl. This pre-explosion direct observation is quite rare, and increasing the number of such observations can help astrophysicists determine the immediate progenitors. Timely notifications of new transients can also help identify SNe IIn prior to intermediate-width lines taking over the spectrum, and will help get actionable data. Additionally, telescope time dedicated to observing the locations of these transients after they have faded will help confirm if the events were truly SNe or not. While this can be made more difficult by the long-lasting brightness of some SNe IIn, being able to prove that the event was not an SN imposter (such as the early SN 2009ip eruptions) can further settle some debates. Utilizing an all-sky survey for this can also be advantageous as telescope time for this area of research has been difficult to acquire.

Ultimately, it is too soon to tell if a large proportion of SNe IIn are caused by runaway stars, and more research (both with observations and with evolutionary models) is needed to determine if there truly is a relationship.

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# Appendix A

# Glossary and Acronyms

Care has been taken in this thesis to minimize the use of jargon, but this cannot always be achieved. This appendix defines jargon terms in a glossary, and contains a table of acronyms and their meaning.

## A.1 Glossary

- **Binary Supernova Scenario** - A method of ejecting stars that involves a binary star system becoming unbound. This typically occurs when one of the stars explodes, kicking the secondary star with significant velocity.
- **Circumstellar medium** - Dense gas surrounding a star, usually caused by winds from the star as it ages and releases its outer envelopes. More dense CSM can be created from LBV eruptions.
- **Dynamical Ejection Scenario** - A method of ejecting stars that involves close encounters with massive stars or star clusters. Such stars could become slingshotted out of their original system at high speeds.
- **Full-width half-maximum** - The measured width of a given Gaussian/Lorentzian distribution. It is taken at the half-maximum of the distribution.
- **Light curve** - The measure of luminosity over a period of time. For supernovae, this will sharply increase at the time of explosion before dropping off gradually.

- **Luminous blue variable** - A massive evolved star that is prone to violent eruptions. These can be split into two classes based on intial mass and evolution (see Sec. 1.2).
- $M_\odot$ - The mass of the Sun, $1.989 \times 10^{33}$ g. Many massive astronomical objects are meassured in units of solar masses.
- **Roche lobe** - The region around a star where matter orbiting is gravitationally bound. It is most relevant when applied to binary star systems, where the Roche lobes of each star meet at a single point.
- **Roche lobe overflow** - A method of mass transfer between stars in a binary system. It occurs when one star in the system expands to become so large that its surface extends past its Roche lobe and flows towards the other star in the system.
- **Zero-age main sequence mass** - The initial mass of a star.

## A.2 Acronyms

Table A.1: Acronyms

| Acronym | Meaning |
|---|---|
| BSS | Binary Supernova Scenario |
| CSM | CircumStellar Material |
| DEIMOS | DEep Imaging Multi-Object Spectrograph |
| DES | Dynamical Ejection Scenario |
| HST | Hubble Space Telescope |
| IRAF | Image Reduction and Analysis Facility |
| LBV | Luminous Blue Variable |
| LVM | Long View Mirror |
| RLOF | Roche Lobe OverFlow |
| SN | SuperNova (plural SNe, SuperNovae) |
| SNe IIn | SuperNova type IIn |

# Appendix B

# Images and Spectra

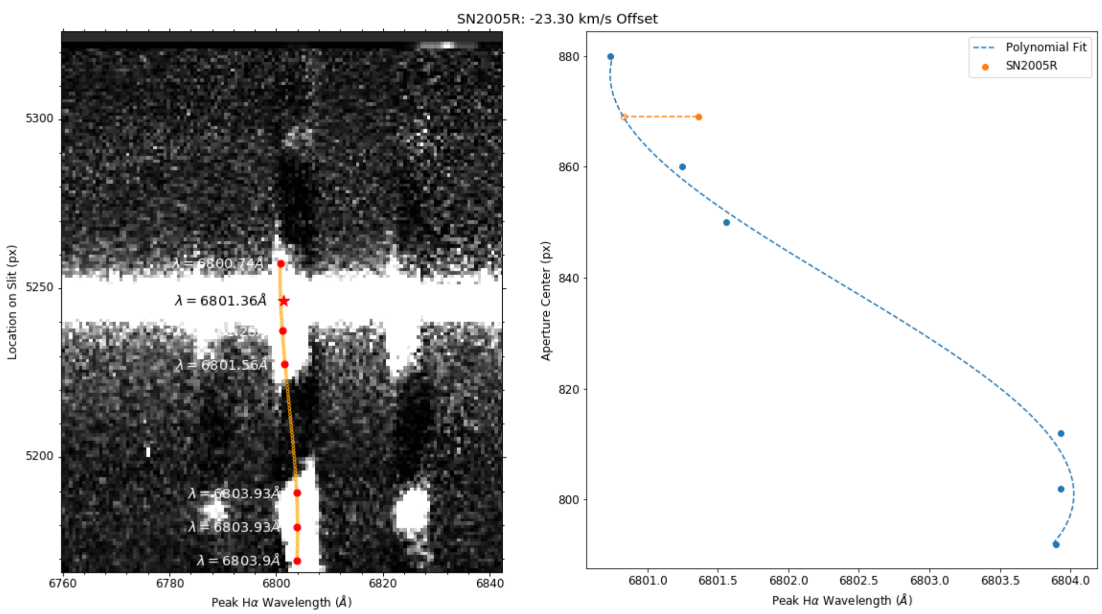


Figure B.1: SN 2005R Hα relative to host galaxy

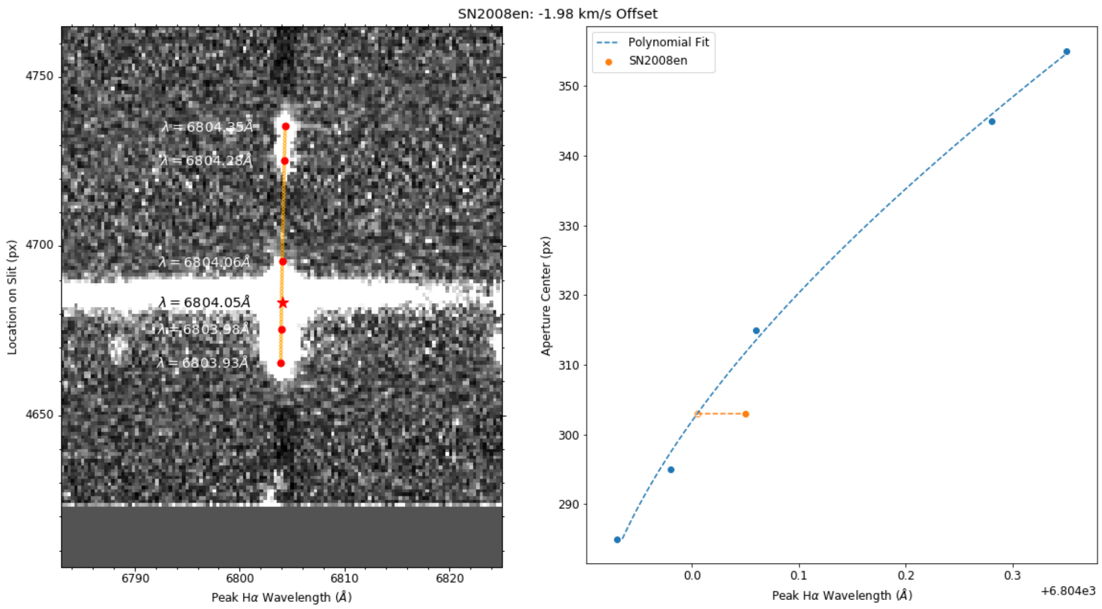


Figure B.2: SN 2008en H$\alpha$ relative to host galaxy

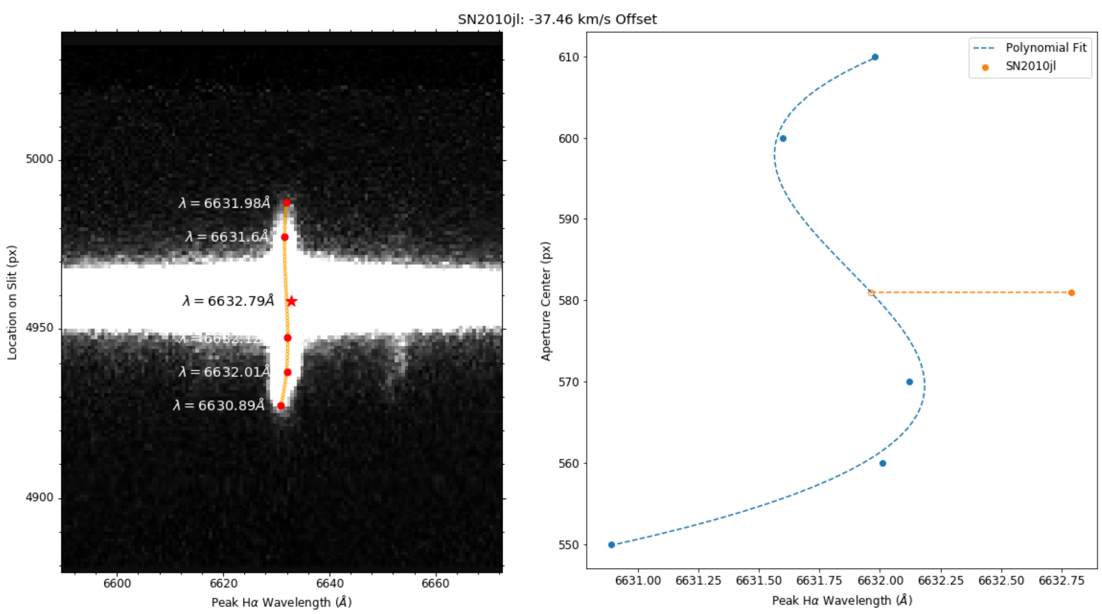


Figure B.3: SN 2010jl H$\alpha$ relative to host galaxy

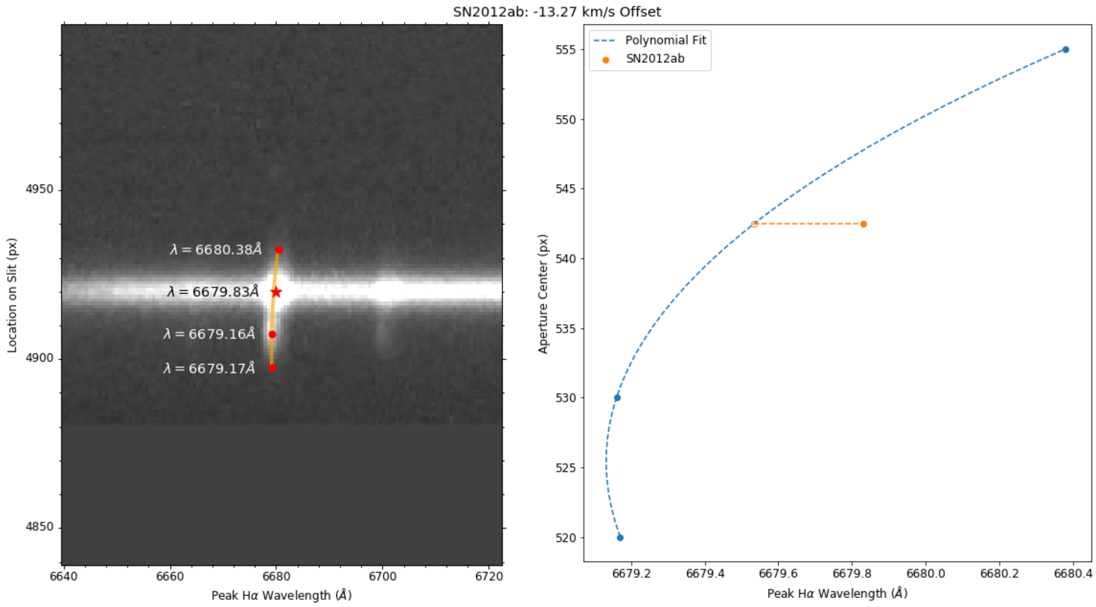


Figure B.4: SN 2012ab H$\alpha$ relative to host galaxy

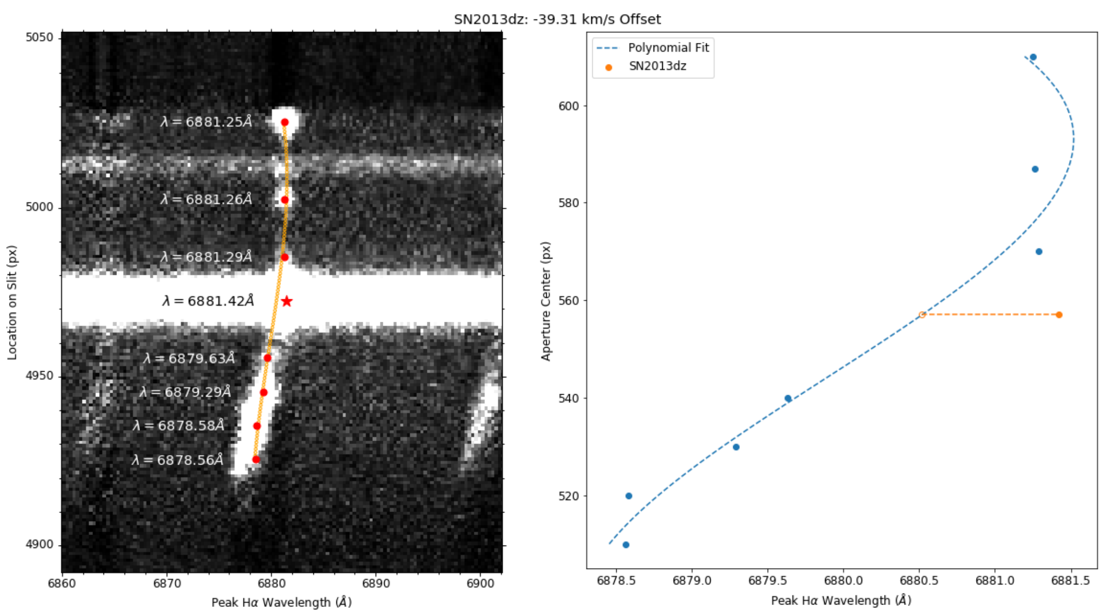


Figure B.5: SN 2013dz H$\alpha$ relative to host galaxy

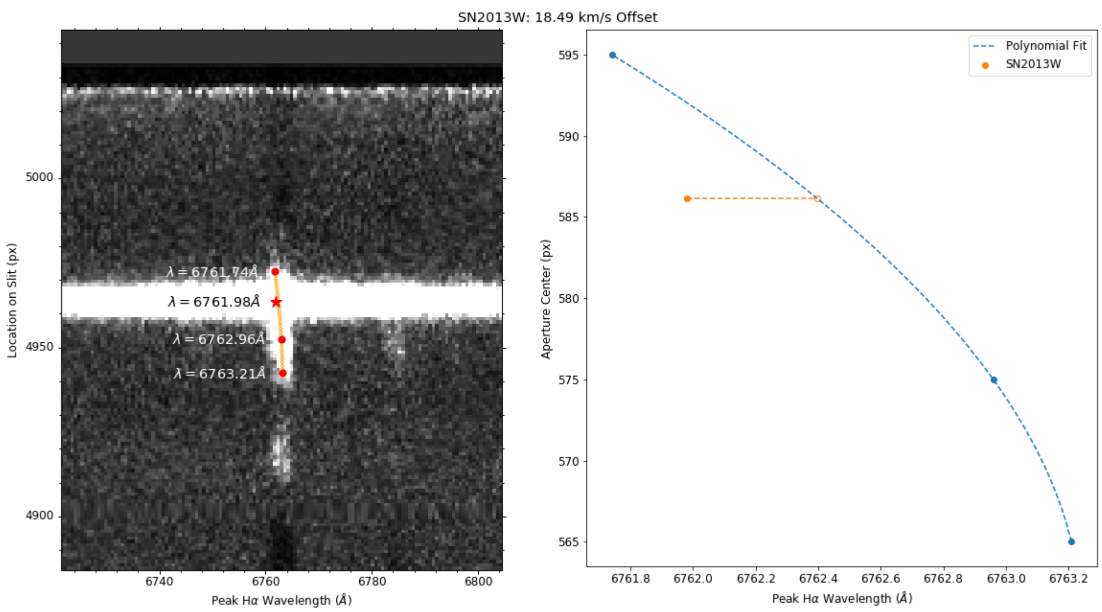


Figure B.6: SN 2013W H$\alpha$ relative to host galaxy