SN2005DA: A SPECTROSCOPIC AND PHOTOMETRIC ANALYSIS OF A PECULIAR TYPE IC SUPERNOVA

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by

Jacob Williamson

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"The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff."

-Carl Sagan

OHIO UNIVERSITY

Abstract

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For the Graduation with Honors with a Bachelor of Science

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Core collapse supernovae are an important class of objects in stellar evolution research as they are the final life stage of high mass stars. Supernovae in general are classified into several spectral types; this paper explores SN 2005da, classified as a Type Ic, meaning it lacks hydrogen and helium lines. The supernova was originally classified as a broad-lined Type Ic (Type Ic-BL), with expansion velocities near maximum light of $\gtrsim 15000$ km s^{-1}. However, some of the elements present in the spectrum, namely carbon and oxygen, have narrower lines (FWHM ≈ 2300 km s^{-1}) than other elements, indicating an interaction with a previously ejected envelope. The supernova is also found to have a decay time, with a Δm_{15} of about 1.4 magnitudes, that is significantly faster than typical Type Ic or Ic-BL. This is more akin to a rarer object type known as a Type Ibn, although it lacks the characteristic narrow helium lines of this type. Therefore, SN 2005da appears to be unlike known examples of Type Ic supernovae.

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Contents

Dedicated to my parents, my brother and Dr. Sandra Doty.

Chapter 1

Introduction

Supernovae have been observed for many years; the earliest known example is SN 185, which was observed by Chinese astronomers. They described a so-called "guest star" which appeared in the sky for a short period of time [1]. In order to better study supernovae and understand how they form, we place them into classifications based on their spectra. There are two main spectroscopic types, Type I and Type II, with Type I having no hydrogen lines (H lines) and Type II having H lines [2]. These types are further divided into subtypes such as Type Ib and Ic, which have helium lines (He lines) and no He lines, respectively; Type IIb, which switch from Type II to Type Ib during evolution; and Type Ia, which have prominent singly-ionized silicon lines. Based off current stellar models and observations, including those of SN 185, we believe supernovae occur in one of two ways: either a high mass star ($\geq 8M_{\odot}$) ends its lifespan in a supernova explosion or a white dwarf in a binary system accretes enough mass to pass what is known as the Chandrasekhar limit ($\gtrsim 1.4M_{\odot}$) at which point a sudden outburst of fusion causes the white dwarf to blow itself apart in a Type Ia supernova [3]. For this reason, we typically refer to supernovae of spectral types other than Type Ia as core collapse supernovae. Using this scheme of classification, we currently believe that SN 185 was a Type Ia supernova [1].

Supernovae Type Ia are exceptionally useful for distance measurement because of their well-constrained mass and stellar type, and as such have significant cosmological applications [4] [5]. On the other hand, core collapse supernovae are interesting as they betray information about the end of a massive star's life as well as signify the formation of some of the most exotic objects in the universe: neutron stars and black holes. In this thesis, we will mainly discuss Type Ib/c supernovae as well as the spectral subclasses Type Ic-BL and Type Ibn, which indicate peculiarities in the supernova ejecta or mechanism. In the case of the first subclass, Type Ic-BL supernovae have relatively broad spectral lines, indicating a fast-moving ($\gtrsim 15000$ km s^{-1}) ejecta, as the summation of Doppler shifts from various points around the ejecta broadens the spectral lines.

On the other hand, Type Ibn supernovae display some narrow spectral lines. Not yet fully understood, Type Ibn supernovae are a relatively new class of objects. Originally classified as peculiar Type Ib supernovae, Type Ibn supernovae are characterized by a set of He spectral lines, just as in Type Ib supernovae. However, these do not have the characteristic P-Cygni line profiles, or presence of short absorption features adjacent to prominent emission lines, found in normal Type Ib supernovae and are consistently narrower than the other lines in the spectrum. This indicates an interaction by the supernova ejecta with some surrounding He gas previously ejected by the star. This envelope ejection is a subject of much study, as a normal Type Ib must also have ejected much of its H envelope prior to explosion, so the question is why the Type Ibn supernovae have a circumstellar envelope which was previously ejected, far enough away that the shockwave does not accelerate it, and yet close enough for interaction to take place. Current theories suggest that massive ($\geq 30M_{\odot}$) stars in the luminous blue variable (LBV) stage eject a large portion of their H and He envelopes which cause the luminosity variations characteristic of LBV stars. They then either explode during the LBV phase, or transition to the Wolf-Rayet phase, where they spend the short remainder of their lives before exploding [6].

Another major tool used to study supernovae is the light curve, or loss of luminosity over time. It is useful because the size and shape of the curve is indicative of the mechanism powering the supernova and often signifies the creation of radioactive elements within the supernova's center. When a massive star nears the end of its life, a series of fusion reactions are rapidly occurring in the center of the star. A star can only fuse elements up to iron without losing energy, so an iron core then builds up in the star. Eventually, this core will build up to the point where the star can no longer support itself with fusion; when this happens, the layers above the core will collapse, causing a massive shockwave which then rebounds the layers off the core and creates the initial shockwave. This is believed to release a significant amount of ($\gtrsim 10^{57}$) neutrinos, nearly massless particles which rarely interact with normal matter [7]. When this many neutrinos are released, the rare interactions occur often enough to help power the initial explosion. Without the help of the neutrinos, this shockwave is not potent enough to propagate completely and would die out.

It is believed that the decay of ^{56}Ni then helps power the rest of the light curve. When ^{56}Ni decays, it releases either a gamma ray by gamma decay or a positron by beta decay which then can annihilate with electrons and release more gamma rays. Also when ^{56}Ni beta decays, it then produces ^{56}Co as a daughter nucleus, which can also gamma decay and release gamma rays. These gamma rays undergo Compton scattering which further imparts energy into the ejecta, helping power the SN. Eventually, the ejecta spreads out enough that it is no longer opaque to gamma rays or positrons. At this point, the light curve decays further due to the large amount of energy the photons and positrons carry out. The decay of ^{56}Ni has a half-life of 6.075 ± 0.010 days and ^{56}Co has a half-life of 77.236 ± 0.026 days [8], so by the time the ejecta becomes transparent, the majority of gamma rays are coming from ^{56}Co. The light curve finally lands on the ^{56}Co decay path, which is known as the radioactive tail.

Type Ibn supernovae light curves are powered differently, however. The short decay times in their light curves indicate a secondary process from the normal ^{56}Ni decay is assisting the light curve. The spectra of Ibn supernovae hint at this mechanism from the narrow spectral lines of He. The interaction between the supernova shockwave and the surrounding He gas powers the supernova further, causing decay times that are much shorter than normal Type Ib supernovae.

In this thesis, we consider SN 2005da. This supernova was originally classified by Modjaz et al. [9] as a peculiar Type Ic supernova and then later reclassified by Modjaz et al. [10] as a Type Ic-BL. Here, we present new spectroscopic and photometric data that suggests that the supernova SN 2005da is not a Type Ic-BL, but rather a peculiar Type Ic. The peculiarities we observe and discuss, specifically in the spectrum and light curve, are similar in nature to those observed in Type Ibn supernovae, leading us to suggest a similar phenomenon explains the SN 2005da observations.

Chapter 2

Observations

2.1 Discovery

SN 2005da was discovered on 2005 July 18 UT based on unfiltered Katzman Automatic Imaging Telescope (KAIT) images from the Lick Observatory Supernova Search (LOSS); the SN took place at R.A. = $18^h37^m46^s.89$ and Decl. = $+17^o32'35".3$, which is 108".4 west and 34".8 north of UGC 11301, the host galaxy [11]. We adopt the same redshift, 0.015010 ± 0.000011, and distance, 68 Mpc, to SN 2005da as to UGC 11301, where the distance is an average of all calculated distances currently found in the literature [12] [13] [14] [15] [16] [17]. It was classified as a peculiar Type Ic SN, spectrally similar to SNe such as 1998bw and 2002ap with broad absorption lines and no detected H or He lines [9]. This SN classification was retested by Modjaz et al. [10] using the automated Supernova Identification (SNID), and they found that SN2005da is a Type Ic-BL.

Date(MJD)	Unfiltered(mag)	I(mag)	R(mag)	V(mag)
53569.35	15.856 ± 0.089	-	-	-
53570.34	16.013 ± 0.091	-	-	-
53571.31	16.019 ± 0.088	-	-	-
53574.29	16.307 ± 0.088	-	-	-
53581.28	16.813 ± 0.088	-	-	-
53583.28	16.877 ± 0.089	-	-	-
53589.28	17.661 ± 0.089	-	-	-
53594.28	-	17.691 ± 0.065	18.551 ± 0.047	-
53597.24	-	17.719 ± 0.029	18.712 ± 0.059	18.738 ± 0.056
53601.30	-	18.35 ± 0.16	19.79 ± 0.35	19.50 ± 0.11
53604.25	-	18.49 ± 0.16	19.58 ± 0.20	19.64 ± 0.20
53605.24	18.688 ± 0.098	-	-	-
53607.27	-	18.94 ± 0.24	19.65 ± 0.59	19.66 ± 0.20
53610.22	-	19.19 ± 0.32	-	-
53614.19	-	19.45 ± 0.14	20.90 ± 0.32	20.89 ± 0.17
53615.19	-	19.51 ± 0.19	-	-
53617.18	-	19.82 ± 0.25	-	21.89 ± 0.50

Table 2.1: The photometry of SN 2005da used in Figures 3.1 and 3.5. The dates are given in Modified Julian Days. The photometry was taken either using the KAIT unfiltered band or the Johnson-Cousins UBVRI filter set, specifically the VRI bandpasses.

2.2 Photometry

The light curve data was taken by KAIT. This is a robotic telescope designed and programmed to image a set of objects over a predetermined path each night. It has a Ritchey-Chrétien mirror set with a f/8.2 focal ratio. The CCD used is an Apogee back-illuminated, 512×512 pixel chip with a scale of 0.8 arcsec/pixel. The images are mostly taken in standard Johnson-Cousins UBVRI filters with some images in an unfiltered bandpass. In order to ensure proper calibration is done, on specific nights the predetermined path is overwritten to take images of standard star fields at different airmasses. This procedure as well as the specifics of the telescope are discussed in greater detail in Ganeshalingam et al. [18]. The photometry data of SN 2005da is summarized in Table 2.1.

Photometry was also taken of UGC 11301 on 2015 November 13 UT to determine if there is a host dwarf galaxy in the vicinity of the SN. Images were taken with the Hiltner 2.4m telescope at MDM Observatory using the OSMOS instrument [19] with the R4K detector in 6 300 sec exposures in the Sloan Digital Sky Survey (SDSS) r band. The R4K detector has a read noise of $\approx$ 3 electrons and a gain of 2. The chip reads out with alternating amplifiers and in 4 quadrants, so proper reduction is essential to minimize systematic errors. If this is not done, a "checkerboard with pinstripes" pattern will be evident in the final image due to inconsistencies in the way each amplifier reads out.

2.3 Spectroscopy

The spectrum we are presenting was taken using the Kast spectrograph on the Shane 3 m telescope at the Lick Observatory. This spectrograph consists of two arms, each of which measures either the blue end or the red end of the spectrum. Both ends use a 1200x400 Reticon CCD with pixel sizes of 27 μm, which corresponds to 0.78 arcsec/pixel. We used a 600/4310 grism for the blue side and a 300/7500 grating for the red side, which leads to a wavelength range of 3300-10400 Å with overlap between 5200-5500 Å to check for consistency as well as for calibration. Using our slit length of 2 arcsec, we have a blue side resolution of 6 Å and a red side resolution of 11 Å[20].

Modjaz et al. [9] previously presented 3 spectra for SN 2005da; the spectrum we have now has longer wavelength coverage, revealing previously unseen spectral features. These features suggest a reexamination of the previous classification is in order. We include the spectra from Modjaz et al. [9] for the purpose of comparison.

2.4 Image Reduction

For the KAIT light curve photometry images, a standard pipeline for reduction developed by Ganeshalingam et al. [18] was applied. First, bias and dark current were removed and the flat-field images were applied; this reduced the raw data images to a background-minimized set of images, allowing us to more easily extract useful data. The supernova images were then calibrated using the standard stars. Standard stars have a well-determined magnitude and so, assuming day-to-day variations in the detector are minimal, we used these to convert the counts read out by the detector to a magnitude (mag) scale. Then, using a reference image in each filter of the field without the supernova, we subtracted as much background as possible from the data images to isolate the supernova itself and remove contribution from the nearby stars and galaxies. Finally, we determined an aperture size which collects as much of the light from the supernova as possible while minimizing background and, using the aperture photometry routines in IRAF, this was converted to a magnitude [18]. This was done to all images on each of the days we have images. Galactic reddening was corrected according to the dust map by Schlafly and Finkbeiner [21] which assumes a reddening law according to Fitzpatrick [22] with $R_V = 3.1$ and $A_B = 1.690$.

The MDM image of the host galaxy was reduced by bias overscan subtraction and flat-field image application, as with the other photometric images. The IRAF routine CCDCLIP was applied as cosmic ray rejection in order to ensure minimal cosmic ray contamination. Due to the nature of the CCD, the image has "icicles" resulting from saturation, so in order to increase image quality, we remove a section of the image from the top and bottom. The icicles are far enough above and below center to not affect the integrity of the galaxy and supernova location data.

Spectroscopic reduction was done according to standard techniques. We first corrected bias and night sky effects on the raw data image using overscan correction techniques and flat fields, respectively. Then, after correcting individual pixel variations across the image, we extracted the spectrum from the object; this can introduce background data into the spectrum if we are not careful, so we ensured that any background emission was removed before extraction. Subsequently, using arc-lamp spectra, we wavelength calibrated the spectrum using a polynomial fit. Finally, we removed cosmic rays, corrected for atmospheric absorption, and combined any spectra taken of the same object on the same day.

The spectrum we are introducing, in addition to the spectra from Modjaz et al. [9] of SN 2005da, Foley et al. [23] of SN 2006jc and SN 2002ao, and Foley et al. [24] of SN 2002ap, was corrected for galactic reddening according to the dust map by Schlafly and Finkbeiner [21] which assumes a reddening law according to Fitzpatrick [22] with $R_V = 3.1$ and $A_B = 1.690$. A redshift correction was also applied according to the accepted redshift values from the NASA Extragalactic Database (NED) for each supernova's host galaxy [12] [25] [26] [27].

Chapter 3

Analysis

3.1 Photometry

Figure 3.1 gives the light curves of SN 2005da in the V, R, I, and unfiltered bands. For KAIT, the unfiltered band is approximately equivalent to V and R bands. In our case, we approximated this to R band in order to better make comparisons with the other supernovae. Li et al. [28] demonstrated that the unfiltered KAIT photometry can be shifted to the R band in the Johnson-Cousins system with an uncertainty of $\approx 5\%$ after application of a color term. Unfortunately, the supernova was affected heavily by dust extinction, so we had to perform a qualitative fit to best approximate the color term due to reddening. We shifted the unfiltered photometry by 0.5 magnitudes in order to match it up with the R band and we see that, in the time where the unfiltered and R bands overlap, our shift of 0.5 magnitudes lines up sufficiently for comparison. Note the I band has more detections; however, the I band is not often used in the literature due to high susceptibility to atmospheric absorption, so we used R band for comparisons.

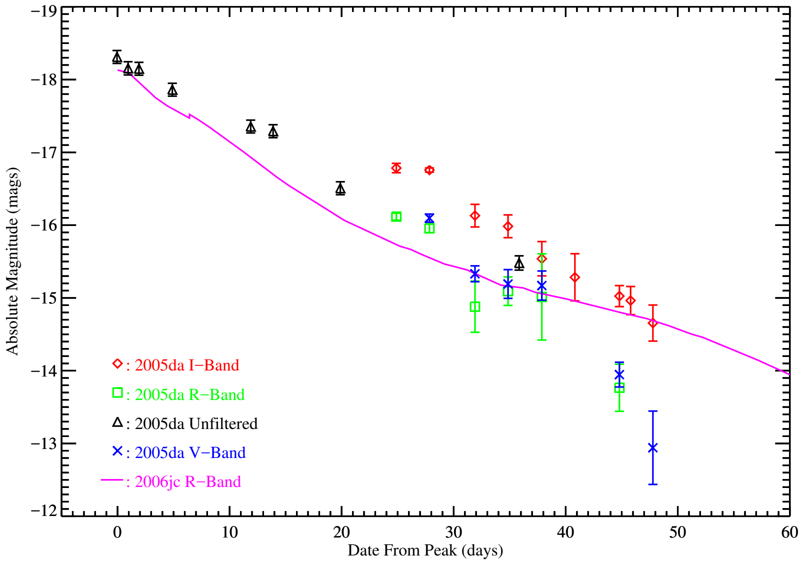

FIGURE 3.1: The photometry of SN 2005da as taken by KAIT in V, R, I, and unfiltered bands. For comparison, the R-band data of SN 2006jc is overplotted. Notice the similar evolution patterns and times between SN 2006jc and SN 2005da. The earliest points we have are unfiltered, which is not commonly used in the literature, making comparison difficult. According to Li et al. [28], the unfiltered band can be shifted to the R band with an uncertainty of $\approx 5\%$ after application of a color term. Here, the unfiltered band is shifted by 0.5 magnitudes to match up with the R-Band; this shift was done qualitatively to best approximate the color term due to reddening, which heavily affects this supernova. Because we only have unfiltered points before 20 days from peak, the Δm_{15} and $t_{1/2}$ values we found are insensitive to the shift.

SN 2005da was discovered late in its initial evolution: the light curve was already declining when photometry was taken. In addition, the last non-detection of the supernova location was in the previous season, which does not allow for a useful constraint on the date of peak. As such, we make the assumption that the first photometric data point is the peak magnitude for purposes of comparison. Therefore we found a peak absolute magnitude of $\lessapprox -18.4$ mag. As this is a difficult value to compare to the literature, since distances have large error values and supernovae of different types and from different progenitors have widely varying peak magnitudes, we instead used two parameters, often used for comparison in the literature, which characterize light curve decay.

The first of these parameters is Δm_{15}, the total magnitude drop over a period of 15 days from peak. For SN 2005da, we measured $\Delta m_{15} = 1.408 \pm 0.070$ mag. Comparing these values, we found that SN 2005da has an unusually rapid light curve decay; however, we also see that the average value found for Type Ibn supernovae seems to fall near our measured value for SN 2005da. Figure 3.2 shows the Δm_{15} values from literature samples of Type Ib/c, Ic-BL, and Ibn supernovae [29] [30] [31] [32] [33] [34] [35] [36] [37] [23] [38] [39]. The red square shows the location of the SN 2005da value. Note that SN 2005da falls in the lower end of Type Ib/c and Type Ic-BL supernovae values, yet falls near the median of the Type Ibn values. This suggests that the underlying light curve powering mechanism between SN 2005da and Type Ibn supernovae are similar. Figure 3.3 shows a probability distribution of the same Δm_{15} data. We can see SN 2005da falls in 90-99th percentile range for Type Ic-BL, 80-85th percentile range for all Type Ib/c, and 40th percentile for Type Ibn.

The second such measurement is $t_{1/2}$, the time it takes for the luminosity to drop by a factor of 2. We measured $t_{1/2} = 8.02 \pm 0.40$ d for SN 2005da; Figure 3.4 shows this value compared to a literature sample of Type Ib/c and Type Ic-BL supernovae [40]. We can clearly see that the value for SN 2005da is on the lower end of Type Ib/c supernovae and is $\approx 5 - 6$ days less than the Type Ic-BL supernovae. This is, again, indicative of the unusually rapid decline of the SN 2005da light curve. The peak magnitude, Δm_{15}, and $t_{1/2}$ values of SN 2005da are compared to the mean values of Type Ib/c, Type Ic-BL, and Type Ibn supernovae in Table 3.1

We found the Δm_{15} and $t_{1/2}$ values by performing a linear least-squares fit to the R-band light curve, removing some of the points on the later end in order to better fit the early-time regime of Δm_{15} and $t_{1/2}$. Note that we did not take measurements of the actual maximum of SN 2005da, so our Δm_{15} and $t_{1/2}$ values may be off. As a counterpoint, we examine the top plot of Figure 3.5, where the light curve of SN

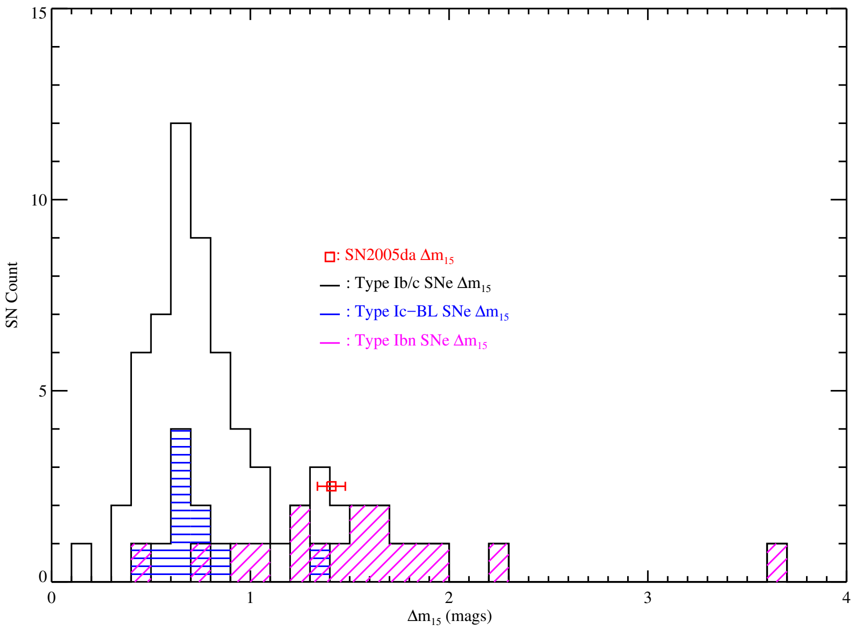

FIGURE 3.2: A histogram distribution of Δm_{15} values found in the literature [29] [30] [31] [32] [33] [34] [35] [36] [37] [23] [38] [39]. We found our calculated value is large compared to most of the values found in the literature; near the upper limit of Type Ic-BL and Type Ib/c values while near the median of Type Ibn values. See also Table 3.1 and 3.3.

SN/Type	M_{max}(mag)	Δm_{15}(mag)	$t_{1/2}$(days)
SN 2005da	-18.4	1.408 ± 0.070	8.02 ± 0.40
Ib/c	-16.04 ± 1.28Ic or -17.01 ± 0.41Ib	0.92 ± 0.54	18.0 ± 7.1
Ic-BL	N/A	0.73 ± 0.25	16.4 ± 2.4
Ibn	$-19.47^{-0.32}_{+0.54}$	1.54 ± 0.70	N/A

TABLE 3.1: The peak absolute magnitude [41] [42] [43] [38], Δm_{15}[29] [30] [31] [32] [33] [34] [35] [36] [37] [23] [38] [39], and $t_{1/2}$ [40] values of SN 2005da compared with the averages of various supernova spectral types. The errors for the average values are the standard deviation from the quoted means. See also Figures 3.2, 3.4, and 3.3.

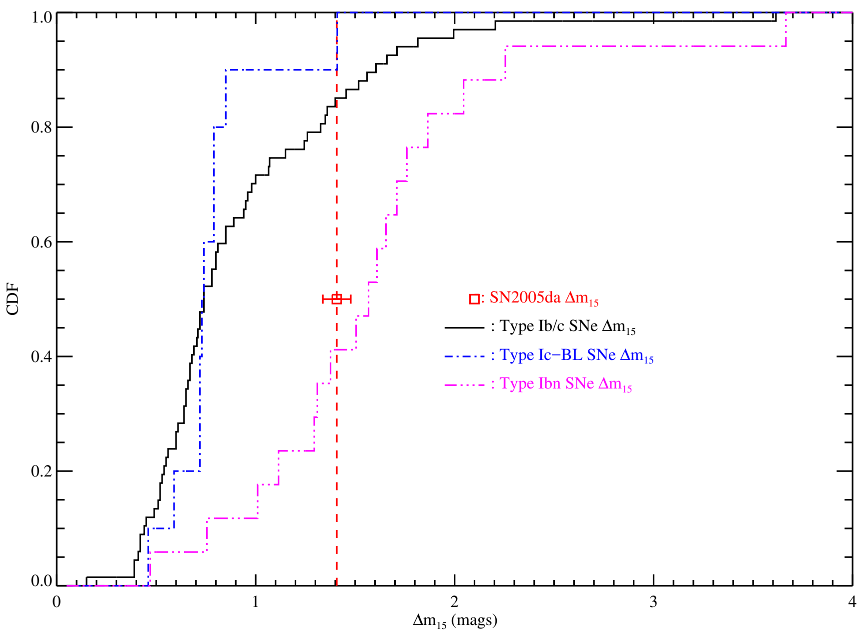

FIGURE 3.3: A probability distribution graph of the Δm_{15}values found in the literature compared to SN 2005da. SN 2005da falls within the 90-99th percentile range for Type Ic-BL, 80-85th percentile range for all Type Ib/c, and 40th percentile for Type Ibn. See also Table 3.1 and Figure 3.2.

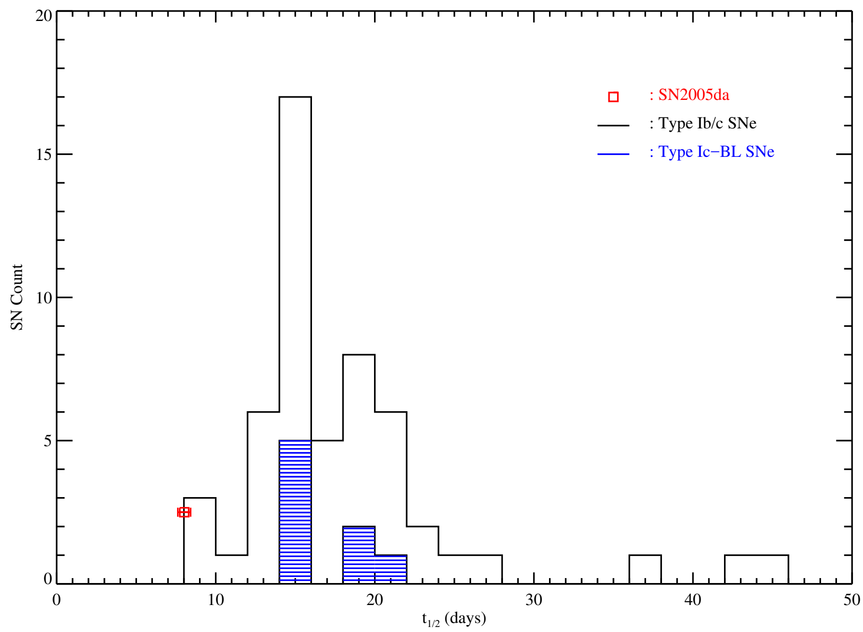

FIGURE 3.4: A histogram distribution of $t_{1/2}$ values found in the literature [40]. We found our value is near the lower limit of the distribution and is much lower than any Type Ic-BL supernovae we have found in the literature. See also Table 3.1

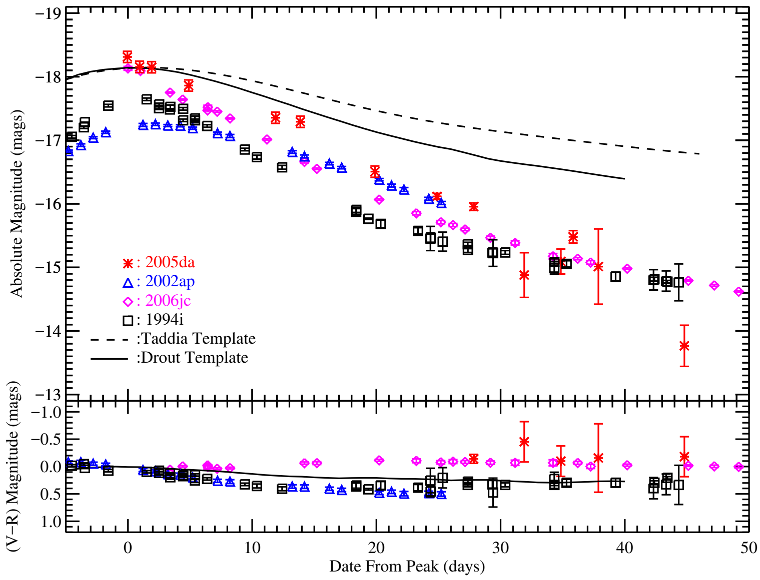

FIGURE 3.5: (Top) An R-Band light curve comparison between SN 2005da, Type Ibn SN 2006jc, Type Ic-BL SN 2002ap, and Type Ic SN 1994I in addition to two template models [35] [23] [24] [37] [44]. SN 2005da has a light curve combining unfiltered points with a 0.5 magnitude shift and R-Band points, see also Figure 3.1. Note the rapid decline of the light curve of SN 2005da when compared to the templates and other supernovae. (Bottom) A (V-R) color curve comparing the supernovae and one of the templates [23] [24] [37] [44]. Notice the bluer color evolution shown by SN 2005da, similar to that of SN 2006jc and contradicting that of the template.

2005da is compared to those of Type Ibn SN 2006jc, Type Ic-BL SN 2002ap, and Type Ic SN 1994I in addition to two templates [23] [44] [35] [37]. We note that SN 2006jc was also measured after peak had passed, so the date and magnitude of maximum are also unknown. Also, the template curves decrease in slope with increasing date, as is expected by light curves powered by radioactive decay. This implies that, if we measured SN 2005da far after peak, we would expect our Δm_{15} to be too low and our $t_{1/2}$ to be too high. In addition, Hosseinzadeh et al. [38] mention that many of the supernovae in Figures 3.2, 3.3, and 3.4 were discovered after maximum and so their Δm_{15} and $t_{1/2}$ values are measured after peak.

The bottom plot of Figure 3.5 shows the V-R color index of the supernovae from the top plot as well as the Drout et al. [37] template [23] [44]. Despite the large error bars on SN 2005da, we can see that it is clearly trending more blue, with an average (V-R) after 30 days of -0.22 and a standard deviation of 0.16, than the template (average (V-R) after 30 days: 0.280, standard deviation: 0.010), Type Ic-BL SN 2002ap (average (V-R) after 30 days: 1.13, standard deviation: 0.25), or Type Ic SN 1994i (average (V-R) after 30 days: 0.300, standard deviation: 0.047). Note that SN 2006jc also displays this trend, with an average (V-R) after 30 days of 0.15 and standard deviation of 0.26. This in conjunction with the similarities between SN 2005da and Type Ibn parameters lends credence to the suggestion of further similarities between SN 2005da and Type Ibn supernovae.

Another development which further increases the intrigue of SN 2005da is its proximity to its host. Figure 3.6 shows that SN 2005da is at a distance of about 37.6 kpc from the center of UGC 11301. As this is a significant multiple of the galactic radius, ≈ 2 galactic radii, we explored the possibility of an undiscovered dwarf galaxy. Taking the same distance to this possible galaxy as to UGC 11301, we found that there is no host dwarf galaxy for SN 2005da brighter than $\lessapprox -12.5$ mag. Our light curve measurements suggest that, upon correcting for extinction, SN 2005da has a peak absolute magnitude value near that of other supernovae, so it is unlikely that the supernova went off farther away. It is also unlikely that a dwarf galaxy can have sufficient star formation to create a star massive enough to explode in a Type Ic supernova while remaining too dim to detect with our telescope. We do note, however, there is evidence that UGC 11301 possibly extends out to the location of SN 2005da, suggesting the supernova progenitor may have been part of the outer reaches of the disk. Even if this is the case, according to Kelly and Kirshner [45], Type Ic supernovae tend to go off at small offsets from the host galaxy center, with $\approx 75\%$ occurring within 1 galactic radius and $\approx 95\%$ occurring within 1.5 galactic radii. Type Ic-BL supernovae have a similar, but slightly broader, distribution, with

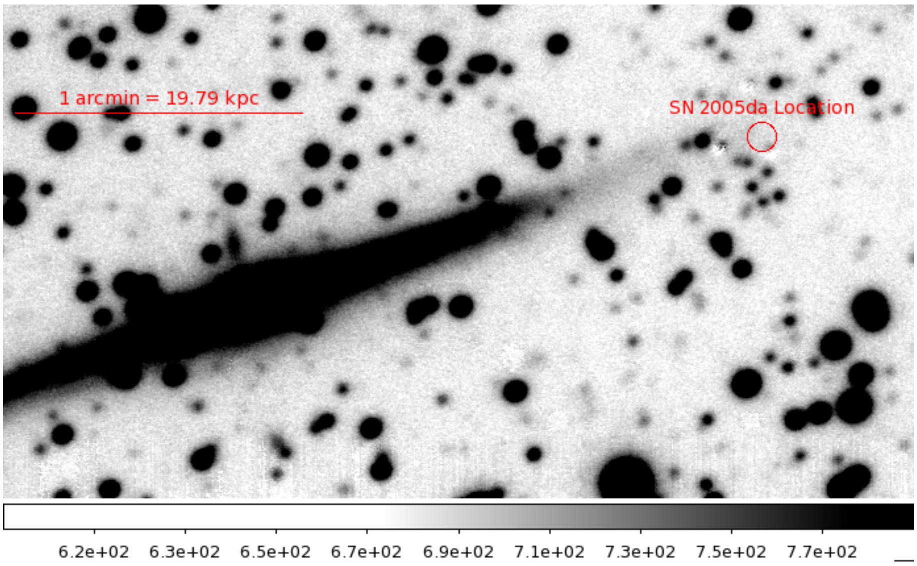

FIGURE 3.6: The location of SN 2005da taken on 2013 November 13 UT. Nearby stars were subtracted using a model PSF and measurements were taken near the circled region for the determination of a possible host outside of the main galaxy. There is a convincing lack of a dwarf galaxy to within an absolute magnitude of ≈ -12.5 in the locale of the supernova, however it is clear that the emission of UGC 11301 extends out to the supernova region.

$\approx 60\%$ occurring within 1 galactic radius and $\approx 80\%$ occurring within 1.5 galactic radii.

3.2 Spectroscopy

SN 2005da was classified by Modjaz et al. [9] as a peculiar Type Ic and reclassified by Modjaz et al. [10] as a Type Ic-BL. In order to test this classification, we used the SNID system [46]. We compared the previous three spectra from Modjaz et al. [9] to the default SNID template package, the template package by Modjaz et al. [10], and the template package by Silverman et al. [20] called BSNIP. We found that, as to be expected, the classification matched up with that in Modjaz et al. [10] of a Type Ic-BL supernova. However, here we introduce a new, late-time spectrum, as seen in Figure 3.7, which includes longer wavelength data not previously visible. After comparing this new spectrum with the SNID template packages mentioned above, we found that the Type Ic-BL classification is called into question. Using the default templates, the automated comparisons suggested a Type Ic classification. However, these templates do not include the Type Ic-BL or Type Ibn subclasses, so this result is expected. The BSNIP templates suggested a Type Ic-BL classification, however there were some normal Type Ic matches. Again, these do not include the Type Ibn subclass. Finally, the Modjaz templates, the only template package to include the classification of Type Ibn, split the classification evenly between Types Ic and Ib, especially Type Ibn. This is significantly different from the previous classification of Type Ic-BL, especially considering the absence of He lines, so we reconsidered the classification of this supernova. Since the SNID classification included Type Ibn supernovae, this suggests there is a significant similarity between the Type Ibn supernovae and SN 2005da. Because of this, we suggest the reclassification of SN 2005da from a Type Ic-BL to a peculiar Type Ic.

Figure 3.8 compares SN 2005da with 2 Type Ibn supernovae, SN 2006jc and SN 2002ao, as well as with a Type Ic-BL supernova, SN 2002ap [23] [24]. Figure 3.9 also compares SN 2005da with Type Ibn SN 2006jc and Type Ibn 2002ao [23]. We can see that the Type Ibn supernovae clearly have an upturn near the blue end, which is expected considering the color curve of SN 2006jc shown in Figure 3.5. We can see that SN 2005da has this upturn as well and SN 2002ap does not have this upturn, instead turning down. A possible explanation of this phenomenon was suggested by Foley et al. [23] who proposed that Fe fluorescence could be responsible for the exceptionally blue color of Type Ibn supernovae.

We also found narrow emission and absorption features in the SN 2005da spectrum similar to those found in Type Ibn supernova, which suggests shockwave interaction with an envelope of slowly-moving material. Yet, we found them not as He I lines, but as neutral oxygen (O I) and carbon (C I) lines; these are highlighted in Figure

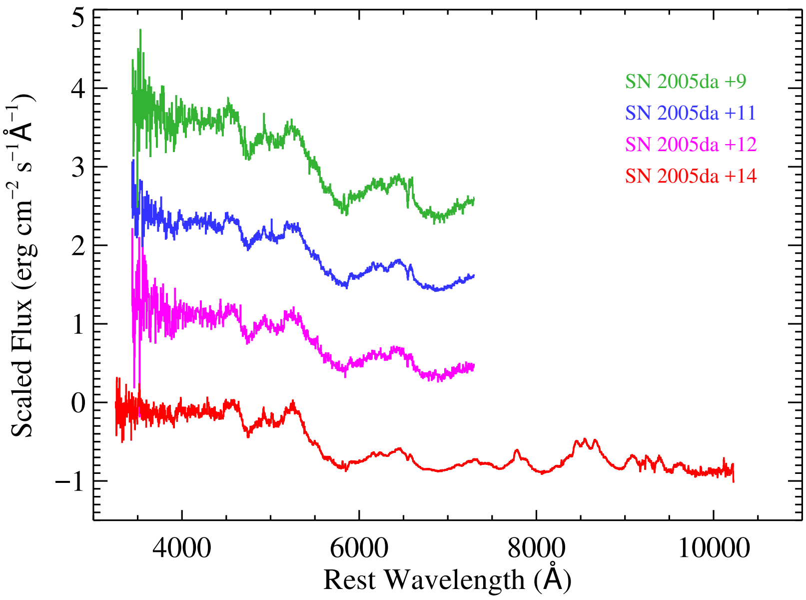

FIGURE 3.7: A side-by-side comparison of all of the spectra we have for SN 2005da using normalized flux units with arbitrary shifts applied. The spectrum taken 14 days after peak is our new spectrum. Note the longer wavelength coverage compared to the spectra taken 9, 11, and 12 days after peak from Modjaz et al. [9].

3.9. There is a clear lack of visible prominent He I and Hα lines while the singly-ionized calcium (Ca II) triplet, O I triplet, and C I quadruplet are clearly visible in the SN 2005da spectrum. The rest of the spectrum is heavily blended with few distinct lines, suggesting a high ejecta velocity. The visible C I and O I lines, however suggest a slowly moving envelope comprised of carbon and oxygen is interacting with SN2005da, as these lines are much narrower than the other, blended lines.

In order to quantify the velocity suggested by these narrower lines, we measure the width of the carbon lines and oxygen line around 9000 Å, as this is indicative of the possible surrounding envelope and its velocity due to the Doppler effect. Table 3.2 shows the FWHM velocities of the carbon lines plotted in Figure 3.10. From the table, we can see that the broadest line has a velocity of 4027 ± 97 km s^{-1}; however, this is a blend of various lines and therefore is not indicative of the velocity of the envelope. The narrowest FWHM is 2279 ± 88 km s^{-1}. Nevertheless, these lines

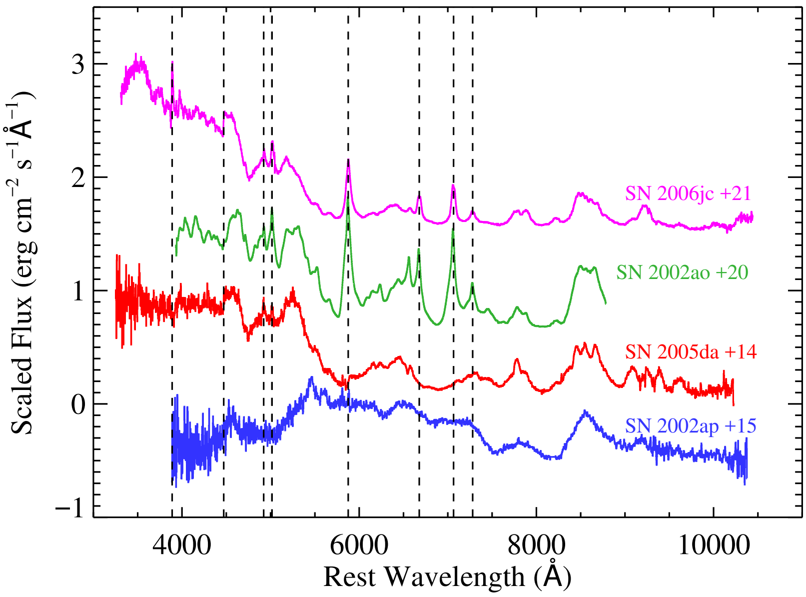

FIGURE 3.8: A side-by-side comparison of SN 2005da, Type Ibn SN 2006jc, Type Ibn SN 2002ao, and Type Ic-BL SN 2002ap using normalized flux units with arbitrary shifts applied [23] [24]. All of these spectra were taken at approximately the same time after maximum light. The dotted lines denote the He I lines, showing the lack of He I lines in SN 2005da. All Type Ibn supernovae as well as SN 2005da have an upturn in the spectrum at low wavelengths, while SN 2002ap does not. This has been suggested to be Fe fluorescence due to the presence of Fe II lines in the blue end of the spectrum of Type Ibn supernovae [23].

suggest a slow-moving envelope of circumstellar material, made up of neutral carbon and oxygen, was surrounding the supernova progenitor pre-explosion and interacted with the shockwave a time after explosion.

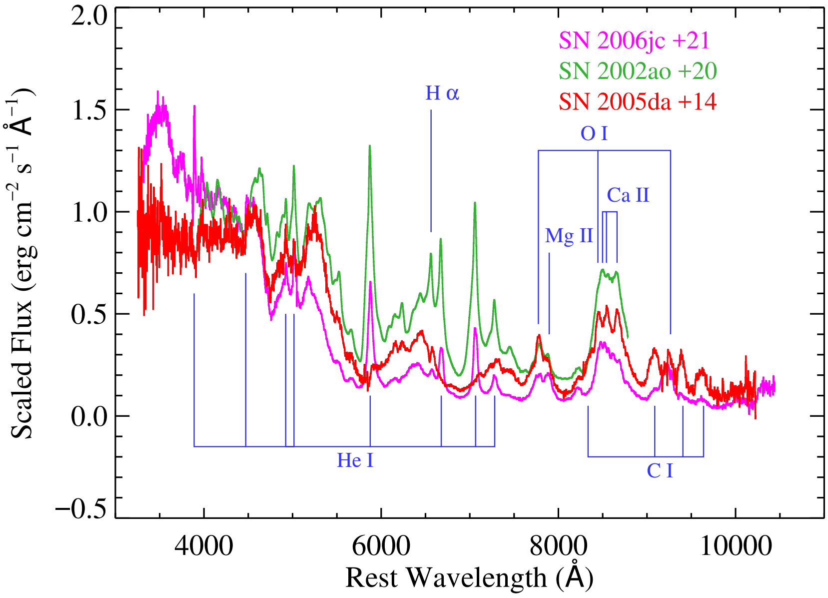

FIGURE 3.9: An overplot of the spectra of SN 2005da, Type Ibn SN 2006jc, and Type Ibn SN 2002ao using normalized flux units for comparison purposes [23]. Various elemental spectral lines are marked to illustrate the differences between the spectra. Of especially high importance are the O I, C I, and He I lines. Note the lack of He I lines as well as the presence of narrow C I and O I lines in the spectrum of SN 2005da. The same C I and O I lines are also somewhat visible in the spectrum of SN 2006jc. See Figure 3.8 for a side-by-side comparison of these spectra and Figure 3.10 for a measurement of the C I and O I lines in the spectrum of SN 2005da.

Line (Å)	Centroid(Å)	FWHM(kms^{-1})
9061/9062/9078/9082/9094/9111 CI	9091.6 ± 1.0	4027 ± 97
9260/9262/9265/9266 OI	9246.7 ± 2.3	3570 ± 220
9405 CI	9387.55 ± 0.95	2279 ± 88
9603/9620 CI	9618.0 ± 1.8	3540 ± 160

TABLE 3.2: The centroid and FWHM of three C I lines and one O I line in the red end of the SN 2005da spectrum. The FWHM especially is indicative of the velocity of the envelope the supernova ejecta appears to be running into. The 9405 Åline gives the most correct value for the envelope velocity as the other lines are made up of blends. See Figure 3.10 for the Gaussian fit to the lines. oxygen and carbon line data from Reader et al. [47].

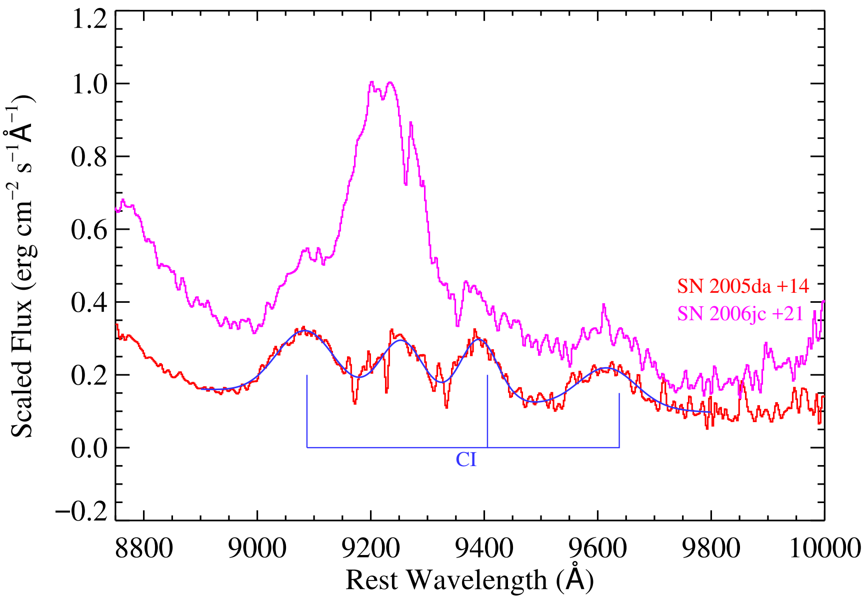

FIGURE 3.10: A quadruple Gaussian fit to the C I and O I lines at the red end of the SN 2005da spectrum. The velocities of these lines are given in Table 3.2

Chapter 4

Discussion

Using SNID analysis, we found that our previously unstudied spectrum is lacking the H or He lines required for a Type II or Type Ib classification, as is expected. We also see broad spectral lines as Modjaz et al. [9] saw in their spectra. However, we see narrow lines at the red end of the spectrum which contrast with the more common broad lines. This indicates two major regions which contribute to the spectrum: a fast-moving source and a slow-moving source. The faster source is the initial supernova ejecta; we hypothesize that the slower source is circumstellar material ejected from the star with which the shockwave is interacting. Cases have been documented of supernovae interacting with an envelope of circumstellar material; yet, all of these examples have an envelope containing H or He, classified as Type IIn and Type Ibn, respectively [23] [48] [38] [49]. Our example shows the broad-line features combined with narrow features of carbon and oxygen indicative of gas velocities around 2300 km s^{-1}, significantly slower than the characteristic 15000 km s^{-1} velocities of Type Ic-BL supernovae. Since the lines show similar properties to the Type Ibn He lines, specifically low velocities relative to the rest of the spectrum, this lends credence to the idea of a similar phenomenon to the Type Ibn supernovae.

Examples of supernovae interacting with a circumstellar envelope are somewhat rare, with only $6.7\%^{+3.0\%}_{-2.9\%}$ of the $69.6\% \pm 6.7\%$ of Type II supernovae in the Lick Observatory Supernova Search being Type IIn; yet, despite the interesting nature and implications of the supernovae, they have only recently been studied in detail [41] [42] [43]. The first instance of the definition of a circumstellar envelope interaction subclass was done by Schlegel [50]. He defined the Type IIn subclass, indicating a normal Type II supernova interacting with a hydrogen-dominated envelope, creating narrow hydrogen lines in the spectrum. The earliest supernova which was proposed to enter this subclass is SN 1978G. The first supernova Type Ibn in the literature is SN 1999cq, presented by Matheson et al. [49]; although, the subclass was not defined until Foley et al. [23] and Pastorello et al. [51] discussed SN 2006jc.

SN 2006jc is perhaps the best studied example in the literature. First described by Foley et al. [23] and Pastorello et al. [51] and later studied in more detail by Tominaga et al. [48], this supernova is often referred to as the "quintessential" Type Ibn supernova, as it was one of the first to be suggested as a member of this subclass. In addition, SN 2006jc is recorded as having experienced an outburst of activity approximately 2 years prior to explosion [51]. This is a strong piece of evidence linking the narrow spectral lines to circumstellar interaction, as the outburst likely came with significant mass loss. In order for the mass loss to lead to a circumstellar interaction, it must occur at a close enough time to the supernova explosion in order for the shockwave to still interact in a visible manner while remaining outside of the initial explosion. Unfortunately, we do not have access to pre-explosion images of SN 2005da to explore for a similar outburst.

In addition, there is one other example of a Type Ic supernova interacting with a circumstellar envelope lacking H and He. SN 2010mb is believed to be interacting with a massive circumstellar envelope lacking H or He, creating strong O I features [52]. Unlike SN 2005da, SN 2010mb has a slowly-declining light curve, with Δm_{15}

< 0.9 mag. Similarly, the light curve cannot be powered by ^{56}Ni and ^{56}Co decay, as the light curve decays too slowly, implying the supernova is likely powered by this interaction mechanism as with SN 2005da [52].

Another peculiarity which makes SN 2005da interesting is its apparent distance from the host galaxy. As shown in Figure 3.6, SN 2005da is approximately 37.6 kpc from the center of its host galaxy. The progenitors of Type Ib/c supernovae must be massive stars ($\gtrsim 22 M_{\odot}$), which typically form around the spiral arms of galaxies and as such are relatively near the center of the galaxy as seen from Earth [43]. We found through photometric analysis that it is unlikely there is a dwarf galaxy at the supernova location to a limiting magnitude of approximately -12.5 mag. However, qualitatively there appears to be some extension of the galaxy luminosity out to the supernova location. Regardless, the distant proximity of the supernova to the galaxy is rare for any Type Ib/c supernova, much less Type Ic-BL supernovae. According to discussion in Kelly and Kirshner [45], Type Ic supernovae typically occur in close proximity to the host galaxy center, with $\approx 75\%$ occurring within 1 galactic radius and $\approx 95\%$ occurring within 1.5 galactic radii. Taking the radius as the distance at which the galaxy surface brightness decays by a factor of 2, same as Kelly and Kirshner [45], we found that SN 2005da went off at about 2 galactic radii, farther than $\gtrsim 99\%$ of the Type Ic supernovae sample from Kelly and Kirshner [45].

Kelly and Kirshner [45] also discuss that Type Ic-BL occur in exceptionally blue regions, indicating intense star formation. High star formation regions typically occur at low host offsets, as a large amount of dust and gas must be present to form a massive enough star. As a result, Type Ic-BL supernovae have a similar distribution to the Type Ic supernovae, albeit distributed slightly farther out. Kelly and Kirshner [45] indicates that $\approx 60\%$ of Type Ic-BL supernovae occur within 1 galactic radius and $\approx 80\%$ occur within 1.5 galactic radii. Again, as SN 2005da is ≈ 2 galactic radii away, it falls at a higher offset than $\approx 90\%$ of Type Ic-BL supernovae.

This large distance could imply an unusual evolutionary history, perhaps a dim cluster, binary system, or ejection from the galaxy by some other mechanism. On the other hand, it could simply be a statistical fluke. It is impossible to know for sure without a systematic large-scale Type Ib/c examination of examples.

One possibility is that the star formed within the galaxy and was ejected. The only observed objects capable of moving at velocities faster than the escape velocity of a galaxy are called hypervelocity stars; these stars can move at velocities around 1000 km s^{-1} [53] [54] [55] [56]. A quick, back-of-the-envelope calculation gives that velocities of this magnitude imply stellar lifetimes of around 36.7 Myrs if the star originated in the center and 18.4 Myrs if the star originated ≈ 1 galactic radius from the center. However, current lifetime constraints based on mass imply lifetimes less than ≈ 11.6 Myrs for stars greater than $\approx 20M_{\odot}$ [57]. In addition, current theories behind hypervelocity stars which can accept masses above $20M_{\odot}$ require a binary of main sequence stars to slingshot around the supermassive black hole at the galactic center, meaning the stars would have had to evolve along the main sequence sufficiently to go through the gravitational interaction, as this interaction takes time to occur [53] [54] [55] [56]. Because of these facts, it is unlikely that the star was ejected from the galaxy.

Another possibility is that this supernova originates from a dwarf galaxy at a farther distance than UGC 11301, far enough that we cannot detect it. This is unlikely since the light and color curves as well as the spectra are de-redshifted according to the values for UGC 11301 and are consistent with the other light and color curves compared in Figure 3.5 and spectra in Figures 3.8 and 3.9. If the supernova did go off farther away than UGC 11301, the galaxy must be dimmer than -12.5 absolute magnitude at the UGC 11301 distance and as such the supernova would have to be much brighter and bluer than any previously measured. Our spectral lines also match up as expected, further detracting from this possibility. Nevertheless, the distance to the supernova from the center of the galaxy is not the only intriguing piece of information on SN 2005da.

The final strange trait of SN 2005da is that, as shown in Section 3.1, we found the supernova light curve has a particularly rapid decline, exceeding the Δm_{15} and $t_{1/2}$ values of most typical Type Ib/c and Type Ic-BL supernovae (see Figures 3.2 and 3.4). One hypothesis suggests that this is due to our photometric data not including the peak, as the supernova was not detected prior to, or during, the peak. This would not affect our measured decline and at worst would imply a more rapid decline from peak, as the SN 1994i curve and templates from Figure 3.5 show a slowing decay rate at later times. In light of this, we are then forced to consider a different light curve powering mechanism from typical Type Ib/c supernovae; SN 2006jc does not have such a slowdown and decays much faster than SN 1994i. Type Ibn supernovae, such as SN 2006jc, are believed to have a light curve powered by circumstellar interaction, further supported by the narrow He I lines in the spectra. Therefore, in combination with the interaction evident in the spectrum, we suggest a light curve powering mechanism similar to that of Type Ibn supernovae is the most likely candidate responsible for the light curve of SN 2005da.

Chapter 5

Conclusion

SN2005da was originally classified by Modjaz et al. [9] as a Type Ic-BL supernova according to the spectra presented in the paper. Here, we present a new spectrum as well as further photometric analysis which suggests that SN2005da is more peculiar than originally thought. According to the newly presented spectrum, which covers a wider range of wavelengths than the ones in Modjaz et al. [9], there are narrow ($\approx$ 2500 kms^{-1}) neutral carbon and oxygen lines present on the red end of the spectrum. In addition, the photometric analysis shows a rapidly-declining light curve with a blue color curve. The only examples of supernovae in the literature which exhibit such rapid declines and blue colors are the rarer Type Ibn supernovae, which exhibit narrow helium lines in their spectra. Such helium lines are absent in all SN2005da spectra, however. Therefore, we believe the powering mechanism behind the light curve is the same for SN2005da as for Type Ibn supernovae, with the difference being the lack of helium.

Type Ibn supernovae exhibit narrow helium lines because the shockwave is interacting with a previously-lost envelope of mainly helium. This interaction overrides the normally-dominant ^{56}Ni and ^{56}Co decay that powers the light curve, accelerating the light curve decay. Since SN2005da shows similar light curve properties and has narrow neutral oxygen and carbon lines, we postulate that the supernova is powered by interaction with a helium-deficient, carbon- and oxygen-rich circumstellar envelope formed from pre-supernova mass loss. Type Ibn supernovae are not unheard of in the literature; however, a helium-deficient supernova with a similar light curve mechanism has never been seen or reported before.

An even more interesting development to the story of SN2005da is its distance from its host galaxy. The supernova went off ≈ 37 kpc, or about 2 galactic radii, from the host with no visible dwarf galaxy nearby. There is some visible emission from the galaxy at that distance, yet it is still expected for Type Ib/c supernovae to go off closer to the center of the host, as the mass required for a star to lose the H and/or He envelopes pre-explosion is exceptionally high for the outer reaches of a galaxy.

SN 2005da is a peculiar example of core collapse supernovae, with narrow spectral lines on top of broad ones, rapidly decaying light curve, and large offset from its host. Comparison with the spectra and light curves of Type Ibn supernovae reveal that SN 2005da likely has a similar interaction mechanism behind its light curve decay. Of further interest is the aforementioned large offset, which is nearly unheard of in stripped envelope core collapse supernovae. Possible explanations have been discussed, but none offer sufficient explanation. Further research can be done to determine if other examples like SN 2005da exist or what could cause the large host offset.

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