1. INTRODUCTION

Type Ia supernovae (SNe Ia) are thought to be thermonuclear disruptions of white dwarf (WD) stars (Hoyle & Fowler 1960), but the details remain uncertain. One possibility for the progenitors is the single degenerate model in which main-sequence stars or post-main-sequence red giants transfer mass to a WD through Roche lobe overflow or a common envelope and the WD grows close to the Chandrasekhar mass $M_{\text{Ch}}$. Due to compression, the thermonuclear runaway starts near the center leading to the explosion of the WD and a rapidly expanding envelope with a mass close to $M_{\text{Ch}}$. A second possibility is the double degenerate model, in which a pair of WDs merge and lead to an explosion. In most such cases, the resulting mass of the rapidly expanding envelope will be different from $M_{\text{Ch}}$. Residual material from these mergers surrounding the explosions will get swept up by the ejecta forming dense, shell-like structures. Although the explosion of single WDs seems to be favored for the majority of objects, we may expect mergers to contribute to the SNe Ia population (see § 2).

The possibility of different progenitor channels, the population of which may vary with redshift, may pose a challenge for the use of SNe Ia in cosmological studies that rely on a single parameterization, such as a light-curve width to peak luminosity relation, LWR, to reduce the intrinsic scatter in the peak magnitudes and render them standard candles (Phillips 1993; Perlmutter et al. 1997). To first order, the LWR relation can be understood as a relation, $L_{\text{WR}}$, to reduce the intrinsic scatter in the peak magnitudes and render them standard candles. There may be some spread and an offset in LWR introduced by one of the channels if the masses of the envelope differ from $M_{\text{Ch}}$, and/or the density structures differ. This can lead to a systematic shift of LWR with redshift if the evolutionary timescales of the progenitor systems differ. Even if the different progenitor scenarios obey the same LWR, differences in the color could introduce systematic errors in cosmological studies because SNe Ia are known to suffer to some degree from reddening in their respective host galaxies, which has to be taken into account. To correct for this, the maximum light color excess (usually $E_{B-V}$) and an average reddening law are used to determine the amount of absorption. SNe Ia that are intrinsically redder as compared to the average local sample will thus be overcorrected in this fashion to a higher luminosity.

Similarly to the two distinct progenitor channels, qualitative variations in the explosion physics may lead to variables classes of SNe Ia even within the single degenerate scenarios. Standard explosion models include delayed detonations (DD) and deflagrations. In these scenarios, burning during the deflagration phase leads to an unbound WD. In DD models, the deflagration turns into a detonation in an expanding envelope. Because the density structure of the WD declines monotonically with radius, the resulting density structure in the expanding envelope also smoothly declines with mass and radius. A variation of DD models are the pulsating delayed detonation models (PDD; Khokhlov et al. 1993; Höflich et al. 1995a). In these models, the total energy production during the deflagration phase is, by construction, lower and insufficient to unbind the WD. In DD models, the deflagration turns into a detonation in an expanding envelope. Because the density structure of the WD declines monotonically with radius, the resulting density structure in the expanding envelope also smoothly declines with mass and radius. A variation of DD models are the pulsating delayed detonation models (PDD; Khokhlov et al. 1993; Höflich et al. 1995a). In these models, the total energy production during the deflagration phase is, by construction, lower and insufficient to unbind the WD.

1. SN 2005hj: EVIDENCE FOR TWO CLASSES OF NORMAL-BRIGHT SNe Ia AND IMPLICATIONS FOR COSMOLOGY

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ABSTRACT

HET optical spectra covering the evolution from about 6 days before to about 5 weeks after maximum light and the ROTSE-IIIb unfiltered light curve of the “Branch-normal” Type Ia Supernova SN 2005hj are presented. The host galaxy shows II region lines at redshift of $z = 0.0574$, which puts the peak unfiltered absolute magnitude at a somewhat overluminous $-19.6$. The spectra show weak and narrow Si II lines. These profiles do not change in width or depth for 10 days beginning around maximum light, indicating a constant expansion velocity of $\approx 10,600$ km s$^{-1}$. We analyzed the observations based on detailed radiation dynamical models. Delayed detonation and deflagration models that have been used to explain the majority of SNe Ia do not predict a long velocity plateau in the Si II minimum with an unvarying line profile. Pulsating delayed detonations and merger scenarios form shell-like density structures with properties mostly related to the mass of the shell, $M_{\text{shell}}$. We discuss how these models may explain the observed Si II line evolution; however, these models are based on spherical calculations and other possibilities may exist. SN 2005hj is consistent with respect to the onset, duration, and velocity of the plateau, the peak luminosity and, within the uncertainties, with the intrinsic colors for models with $M_{\text{shell}} = 0.2 M_{\odot}$. Our analysis suggests a distinct class of events hidden within the Branch-normal SNe Ia. The predicted relations between observables are confirmed, they may provide a way to separate these two groups. We discuss the implications for cosmological studies.

Subject heading: supernovae: individual (SN 2005hj)

Online material: color figures

1 Based on observations obtained with the Hobby-Eberly Telescope, which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen.

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(Höflich et al. 1996; Umeda et al. 1999). There may be some spread and an offset in LWR introduced by one of the channels if the masses of the envelope differ from $M_{\text{Ch}}$, and/or the density structures differ. This can lead to a systematic shift of LWR with redshift if the evolutionary timescales of the progenitor systems differ. Even if the different progenitor scenarios obey the same LWR, differences in the color could introduce systematic errors in cosmological studies because SNe Ia are known to suffer to some degree from reddening in their respective host galaxies, which has to be taken into account. To correct for this, the maximum light color excess (usually $E_{B-V}$) and an average reddening law are used to determine the amount of absorption. SNe Ia that are intrinsically redder as compared to the average local sample will thus be overcorrected in this fashion to a higher luminosity.

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very similar light curve and spectroscopic properties, but with a total mass close to \( M_{\text{Ch}} \) (Höflich & Khokhlov 1996).

These two groups, consisting of DD and deflagration models such as W7 (Nomoto et al. 1984), which lack shells, and the models with shells (mergers and PDDs), can be differentiated by their predictions for the photospheric evolution and maximum light colors (Khokhlov et al. 1993; Höflich & Khokhlov 1996).

For the former group, the photospheric velocities, \( v_{\text{ph}} \), smoothly decline with time and the models show a blue color at maximum light, \( B - V \approx 0 \) mag; in the latter group, \( v_{\text{ph}} \) shows a plateau in the evolution as the photosphere recedes through the shell. These models are intrinsically redder and slightly overluminous because of the lower expansion rate in the inner region. As shown in Khokhlov et al. (1993) the color, length, and velocity of the plateau are correlated with the mass of the shell, and this potentially allows the two groups to be distinguished even for similar brightnesses.

Indeed, there is a growing sample of SNe Ia showing photospheric velocity plateaus (e.g., 1990N [Leibundgut et al. 1991; Mueller & Höflich 1994]; 1991T, 1999aa [Garavini et al. 2004]; 1999ee [Hamuy et al. 2002]; and 2000cx [Li et al. 2001a]; see also Benetti et al. 2005). Many of these SNe Ia have been reported as having a red color \( B - V \) at maximum, but this is typically attributed to reddening along the line of sight. Alternatively, this sample may suggest the contribution of events with shell-like density structures in the observed population. These events may be understood in terms of mergers or PDDs; however, the inhomogeneities and incompleteness of individual data sets in the literature preclude definite conclusions.

To address this problem and others, we started the Texas Supernovae Search (TSS; R. Quimby et al. 2006) with the goal of providing a homogeneous set of quality data for several supernovae beginning well before maximum light. In this paper we present our observations of SN 2005hj and analysis of the data. In § 2 we describe the discovery and give the details for both the photometric and spectroscopic follow-up. In § 3 we discuss generic properties of explosion models and suggest a secondary parameter to separate models with and without shells, and analyze the peculiarities of SN 2005hj. Conclusions and discussion are presented in § 4.

2. OBSERVATIONS

SN 2005hj was discovered on October 26.13 UT in the field of Abell 194 as part of the TSS. The TSS uses the wide field (1.85° × 1.85°) 0.45 m ROTSE-IIIb telescope (Akerlof et al. 2003) at the McDonald Observatory in Texas to scan nearby galaxy clusters nightly for transients with a modified version of the PSF-matched image subtraction code from the Supernova Cosmology Project. SN 2005hj was found at an unfiltered magnitude (calibrated against the USNO-B1.0 R2) of \( C_{R} = 17.4 \) and is located at \( \alpha = 01^\text{h}26^\text{m}48.27^\text{s}, \beta = -01^\circ 14'16.8'' \). The foreground reddening at this location is \( E_{B-V} = 0.039 \) mag (Schlegel et al. 1998). Examination of ROTSE-IIIb images from October 20 and 22 shows the SN was detected prior to discovery, but not significantly enough to pass the search pipeline’s automatic cuts. Figure 1 shows the ROTSE-IIIb light curve for SN 2005hj through 40 days after maximum light. To construct the light curve, we co-added images taken on a given night (usually six) excluding any frames of significantly lower quality due to passing clouds or wind shear, and then subtracted the reference image convolved to the same PSF. Magnitudes were determined by fitting the local PSF (derived from the co-added nightly images) to the location of the SN on the subtracted frame using custom software and the

![Figure 1](image-url)

**Fig. 1.**—ROTSE-IIIb unfiltered light curve of SN 2005hj (filled circles). The best-fit \( R \)-band template from Knop et al. (2003) is plotted as a solid line over the fitting range, and as a dotted line continuing on to later phases when the rapid decline of the flux below \( \sim 5500 \) Å causes our unfiltered light curve to fade faster than the \( R \)-band decline rate. Arrows mark \( 5 \sigma \) upper limits of the subtractions determined from the noise level in annuli centered on the location of the SN. Epochs with HET spectra are marked with “S.”

**DAOPHOT PSF-fitting routines** (Stetson 1987 ported to IDL by Landsman 1989).

The unfiltered CCD response of ROTSE-IIIb has an approximate full width of \( \sim 4000 \) Å centered in the \( R \)-band around 6000 Å. Because we do have some sensitivity in the blue and since the \( B - V \) colors of SNe Ia typically grow \( \sim 1.0 \) mag redder in the 30 days after maximum (Phillips et al. 1999; Krisciunas et al. 2003), there is a blue deficit at later times that causes our unfiltered magnitudes to decline more rapidly than the true \( B \)-band fading. Note that \( V - R \) colors of SNe Ia are close to zero at maximum light. We therefore limit the light-curve fitting to data taken before 10 days after maximum (determined through several iterations of the fit), during which the color evolution is minimal. The best-fit \( R \)-band template from Knop et al. (2003) is also shown in Figure 1. The date of maximum light determined from the fit is November 1.6 with a formal error of 0.7 days (note the template phases are relative to the \( B \)-band maximum). The best-fit stretch factor (Perlmutter et al. 1997) for the light curve-width \( a \) is \( 1.2 \pm 0.1 \). The preliminary measurement of the observed \( B - V \) color at \( V \) maximum from the Carnegie Supernova Project is \( 0.07 \pm 0.05 \) mag after removal of the host light but before any extinction or \( k \)-corrections are applied (M. M. Phillips 2007, private communication).

Near real-time photometric analysis combined with target of opportunity (ToO) time on the neighboring 9.2 m Hobby-Eberly Telescope (HET) allowed us to obtain optical spectra just 4 hr after the discovery images were taken and every few days over the next 6 weeks. These observations are detailed in Table 1. The instrumental response is such that very little second-order light is expected blue of 8900 Å even with the GG385 blocking filter. The data were reduced in the optimal manner using IRAF and custom IDL scripts. The wavelength scale was calibrated against Cd and Ne lamps and its accuracy was verified by comparing night sky lines to the spectral atlas of Hanuschik (2003).

Because the HET pupil size varies for different tracks, absolute flux

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4 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
1999aa and SN 2005hj, we assume that we can model our observations around 7000 Å by the line centers. The line redshifts are best fit by $z = 0.0574 \pm 0.0002$, and we adopt this value for the SN. This gives SN 2005hj an absolute peak magnitude of $-19.6$ in our unfiltered band pass (assuming $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$), and places the host well behind Abell 194 ($z = 0.0180$; Struble & Rood 1999). The brightness and broad light-curve shape suggest that SN 2005hj is a slightly overluminous SN Ia.

The unfiltered ROTSE-Illb reference image shows that the host for SN 2005hj is relatively bright ($C_R = 17.8$) and compact, and is therefore likely a significant contaminant to our spectra. Thus, we have to subtract the galaxy contribution (see Fig. 2). Lacking an observed spectrum for the host galaxy excluding the SN light, we constrained the galaxy SED using archival Sloan Digital Sky Survey (SDSS) $ugriz$ observations and obtained a template galaxy spectrum (N. Drory 2005, private communication). The relative amounts of SN and galaxy light in the spectral apertures will vary not only with the changing SN brightness, but also with the seeing, slit width, and positioning. Also plotted in Figure 2 is a spectrum of SN 1999aa (blue curve) constructed via a linear interpolation of the −7 day and −3 day spectra presented by Garavini et al. (2004). Noting the similarity of the spectral features of SN 1999aa and SN 2005hj, we assume that we can model our observed spectra as a linear combination of our galaxy template and the SN 1999aa spectra interpolated to the same phase as the SN 2005hj observations. We perform a least-squares fit to determine the relative contributions of each component. The red line in figure 2 shows the derived contribution of galaxy light in the −6 day spectrum. Aside from a few small differences (most noticeably in the Mg II 4481 triplet), some of which may be explained by calibration errors, the combined SN 1999aa + host spectrum (purple curve) is a good fit. The over all fit is improved if we interpolate the SN 1999aa spectra to −5 days instead of −6, especially in the 5400–6500 Å range, which could imply a −1 day error in the date of maximum light or different timescales for the spectral evolutions of the two SNe. We repeated this process for all the SN 2005hj spectra, each time using the same galaxy template and the SN1999aa spectra (interpolated to the appropriate phase) as reference to determine the relative amount of galaxy light. In general, the galaxy template added to the SN 1999aa spectrum does an excellent job of reproducing the observed SN 2005hj spectra. The galaxy light typically dominates the flux red of 7000 Å. Figure 3 shows the spectral evolution of SN 2005hj recorded by the HET between days −6 and +34 with the derived galaxy contribution subtracted.

### 2.1. Spectral Characteristics of SN 2005hj

Overall, SN 2005hj shows spectra with lines dominated by intermediate-mass and iron-group elements, as is typical for...
SNe Ia. While the lines show normal expansion velocities, the absorption components are more narrow and, for the early phases, weaker than typically observed, as exemplified by the Si\textsubscript{ii} \textit{k}6355 line (see Fig. 4). SN 2005hj also shows an atypical velocity evolution of these features over time.

Line minima are useful diagnostic indicators of the ejecta structure as they give the abundances and velocities of the material. The actual measurement of the velocity at the minimum of the line profile is complicated by the presence of the continuum, other blended lines, and some uncertainty in the true line-profile shape. Detailed modeling is required to accurately sort out all the components and how they relate to the photospheric layer to reveal the velocity distribution of the ejecta.\footnote{In general, Si\textsubscript{ii} lines form above the photosphere and velocities measured from such absorption minima can be 1000–2000 km s\textsuperscript{-1} larger than those measured from weak lines. However, for shell models the steep density gradients cause even strong lines to form very close (in radius) to the actual photosphere.}

Figure 3.—Spectral evolution of SN 2005hj recorded by the HET from −6 to +34 days after maximum light (2005 November 1.6). The estimated galaxy contamination has been subtracted and the spectra have been shifted for clarity. For display purposes, portions of the spectra with low signal-to-noise ratios have been smoothed (\textit{thin line segments}). The typical telluric absorption spectrum is shown by the gray shading along the top of the figure. (See the electronic edition of the Journal for a color version of this figure.)

Figure 4.—Comparison of the spectra of SN 2005hj (\textit{colored lines}) and SN 1994D (\textit{black lines}; Patat et al. 1996) at 5 days before and 2 days after maximum light. The spectra have been shifted for clarity. At both phases shown, the absorption component of the Si\textsubscript{ii} \textit{k}6355 line is more narrow for SN 2005hj. The relative line depths for this feature are similar at +2 days, however, the Si\textsubscript{ii} \textit{k}6355 absorption is much weaker for SN 2005hj in the −5 day spectrum. Despite these differences, the velocities inferred from the minima of the Si\textsubscript{ii} \textit{k}6355 lines are consistent between SN 2005hj and SN 1994D to within 5\%, the former being 560 km s\textsuperscript{-1} slower at −5 days and 150 km s\textsuperscript{-1} slower at +2 days. (See the electronic edition of the Journal for a color version of this figure.)
The filter cutoff frequency, $\nu_c$, and attenuation scale, $\sigma$, were determined as follows: (1) the spectra were converted into a power spectrum, $P(\nu)$, via FT; (2) the slope of log ($P$) is fit over the noise-dominated high frequencies and interpolated through the low frequencies to determine the noise spectrum; (3) $\nu_c$ is taken as the frequency at which log ($P$) drops to within 3 times the dispersion about the noise spectrum; (4) $\sigma$ is chosen such that the slope of log $[P(\nu_c+2\sigma)]$ is twice the noise spectrum slope (i.e., $\nu = \nu_c + 2\sigma$ is the frequency above which noise is clearly the dominant component). For this analysis, only the spectral bins with signal to noise above 25 were considered (note the peak throughput for HET/LRS is near the Si $\textsc{ii}$ $\lambda$6355 line). For consistency, we adopt a single filter for all our analysis, choosing the results from our noisiest data, $\nu_c = 0.0066$ $\text{Å}^{-1}$ and $\sigma = 0.0053$ $\text{Å}^{-1}$, which removes noise in the data but also some real information related to “sharp” features in the spectra, such as the narrow core to the Si $\textsc{ii}$ $\lambda$6355 absorption in the day +10 spectrum.

Using the relativistic Doppler formula and the $gf$-weighted Si $\textsc{ii}$ $\lambda$6355 rest velocity in the host galaxy frame, we convert the wavelengths of the line-profile minima into expansion velocities. For each spectrum we conducted 250,000 Monte Carlo simulations in which normally distributed noise based on the statistical flux errors was added to the data and the FT-smoothed minimum was found. The peak of the distribution and the interval containing 68% of the simulation results were used to calculate the velocity of the minimum and its error, respectively. We also measured the relative shift in the H $\beta$ region lines over all epochs and found the scatter to be 80 km s$^{-1}$, which we add in quadrature to the individual errors. The results are given in Table 2 and plotted in Figure 6. We find that the data points are at 10,600 ± 150 km s$^{-1}$ between maximum light and +18 days, somewhat faster prior to maximum, and significantly slower on day +25. By day +34, the Si $\textsc{ii}$ $\lambda$6355 absorption has all but completely disappeared.

From maximum light through day +10, the Si $\textsc{ii}$ $\lambda$6355 line profile shows little change in both depth and width in addition to maintaining a constant absorption minimum velocity. Of specific relevance is the blue wing of the absorption profile; this section of the line is formed by the material at the greatest distance from the photosphere and at the highest velocities, and as such it should be the first to vanish as the photosphere recedes. The consistency of this blue wing from maximum light through day +10 suggests the photosphere falls within the Si enriched layers for at least this period. By day +18 the blue wing has shifted significantly to the

### Table 2

| Phase (days) | Velocity (km s$^{-1}$) | $\sigma_{\text{vel}}$ (km s$^{-1}$) | Depth$^*$ (Å) | FWHM |
|-------------|------------------------|-----------------------------------|--------------|------|
| -6 .. | 10820 | 140 | 0.38 | 140 | |
| -5 .. | 10800 | 110 | 0.32 | 120 | |
| 0 .. | 10640 | 90 | 0.52 | 110 | |
| 2 .. | 10440 | 100 | 0.60 | 110 | |
| 3 .. | 10640 | 90 | 0.57 | 110 | |
| 5 .. | 10680 | 80 | 0.57 | 110 | |
| 10 .. | 10530 | 100 | 0.60 | 100 | |
| 18 .. | 10550 | 120 | 0.48 | 90 | |
| 25 .. | 9850 | 90 | 0.25 | 60 | |
| 34 .. | ... | ... | ... | ... | |

**Notes.**—Quantities measured from the FT-smoothed data. The Si $\textsc{ii}$ $\lambda$6355 line is not clearly detected in the +34 day spectrum and thus no measurements are reported.

$^*$ As in Leonard et al. (2002), depth is defined as $(f_c - f_{\text{min}})/f_c$, where $f_{\text{min}}$ is the flux at the minimum of the smoothed line and $f_c$ is the estimated continuum level at the corresponding wavelength.

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**Fig. 6.**—Velocity of the Si $\textsc{ii}$ $\lambda$6355 line minimum as determined from the FT-smoothed minima. The error bars are the quadrature sum of the 1 $\sigma$ confidence intervals found via Monte Carlo simulations and the 80 km s$^{-1}$ scatter found in the H $\beta$ region line centers among the different epochs. [See the electronic edition of the Journal for a color version of this figure.]
red, while the red wing remains constant except for the effects of an Fe II blend around 6250 Å. Other Fe II features begin to appear or strengthen at this phase as well. This behavior could be a signal that the Si layers are becoming detached from the photosphere by day +18.

The day +25 spectra show a double minimum at the location of the Si II λ6355 feature (see Fig. 7). Telluric absorption is weak in this wavelength range, and the line profile is clearly seen in each of the three individual exposures, which support the reality of this feature. A possible explanation for this feature is contamination from the host that is not removed by the template subtraction; however, galaxy spectra do not typically exhibit features in this range that could cause such interference, and even if such were the case, we would expect to see similar behavior in the +34 day spectra. A second possibility is contamination from Fe II lines. Using the spectral analysis tool SYNOW (Jeffery & Branch 1990; Fisher et al. 1997, 1999), and the example of SN 1994D as a starting point (Branch et al. 2005), we find that while Fe II likely produces the absorption dips ~100 Å away on either side of the Si II λ6355 line, it is unlikely responsible for the double minimum. The third possibility, which we favor, is that this double minimum simply appears because we are resolving the Si II λ6355 doublet. This result implies that the Si II seen in the +25 day spectra is confined to a very narrow region of velocity space (Δν ≈ 1,500 km s⁻¹).

If accurate, the true minimum of the Si II λ6355 doublet would be about 100–200 km s⁻¹ faster than indicated in Figure 6 and Table 2, but still significantly below the plateau velocity. The emergence of this thin layer may also be responsible for the appearance of the narrow core in the +10 day spectrum as well as the apparent double minimum to the +18 day data. Some remnant of the blue component to the doublet may persist to the +34 day spectrum. Figure 7 also shows the spectra of several other SNe Ia taken around 25 days after maximum light. While the distinctly double minimum appears unique to SN 2005hj, the width and depth of the Si II feature is roughly consistent with the others.

SN 2005hj clearly belongs to the low-velocity gradient (LVG) group in the classification scheme of Benetti et al. (2005) but moreover the velocity derivative from maximum light through day +18, 〈v〉 ≈ 3 ± 7 km s⁻¹ day⁻¹, is consistent with no change.6 From the line-profile evolution (Table 2, Figs. 5 and 6) we can deduce a plateau phase starting at ~2.5 ± 2.5 days that lasts no more than 30 days. Noting the change in the Si II λ6355 line profile in the +18 day spectrum, we conservatively mark the end of the plateau phase as day 17.5 ± 7.5 days, which gives the plateau phase a total duration of 20 ± 10 days.

The Si II λ6355 velocity evolution derived from the minima of FT smoothed spectra of several selected SNe Ia is plotted in Figure 8. The velocity plateau of SN 2005hj is similar to that of

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6 As defined by Benetti et al. (2005), 〈v〉 is the average daily rate of decrease in the expansion velocity from maximum light through the last available spectrum before the Si II λ6355 line disappears; therefore, including the day +25 spectrum, SN 2005hj formally has 〈v〉 = 27 ± 4 km s⁻¹ day⁻¹, but with a χ² per degree of freedom of 3.2.
other overluminous SNe Ia such as SN 1999aa (Garavini et al. 2004) and SN 2000cx (Li et al. 2001a), but it is distinct from normal SNe Ia such as SN 1994D (Patat et al. 1996) and SN 1992A (Kirshner et al. 1993) that do not show a plateau phase.\footnote{We removed the data point at day \textasciitilde 3 from the SN 1999aa curve because all spectral features in these data seem to be frequency shifted including the telluric features.}

3. PHYSICAL CONSTRAINTS FROM EXPLOSION MODELS

There is general agreement that SNe Ia result from some process involving the combustion of a degenerate C/O white dwarf (WD; Hoyle & Fowler 1960). Within this general picture, two classes of models are most likely. The first is an explosion of a C/O WD with a mass close to the Chandrasekhar limit (\(M_{\text{Ch}}\)) that accretes matter through Roche lobe overflow from an evolved companion star (Whelan & Iben 1973). In this case, the explosion is triggered by compressional heating near the WD center. Alternatively, the SN could be an explosion of a rotating configuration formed from the merging of two low-mass WDs, after the loss of angular momentum (Iben & Tutukov 1984; Paczyński 1985). Candidate progenitor systems have been observed for both scenarios: WD binary systems with the correct period to merge in an appropriate timescale with an appropriate total mass (Maxted et al. 2000); and supersoft X-ray sources (Greiner et al. 1991; van den Heuvel et al. 1992; Rappaport et al. 1994; Kahabka & van den Heuvel 1997) showing accretion onto the WD from an evolved companion. There are still open questions about the details of both the merging and accretion processes (e.g., Nomoto 1982; Benz et al. 1990; Piersanti et al. 2003; Nomoto et al. 2003).

From the observed spectral and light-curve properties, the first scenario appears to be the most likely candidate for the majority of normal SNe Ia. In particular, delayed detonation (DD) models (Khokhlov 1991; Yamaoka et al. 1992; Woosley & Weaver 1994) have been found to reproduce the majority of the observed optical/ infrared light curves (LC) and spectra of SNe Ia reasonably well (Höflich 1995; Fisher et al. 1995; Höflich & Khokhlov 1996; Lentz et al. 2001; Höflich et al. 2002; Marion et al. 2003, 2006). In the DD scenario, a slow deflagration front turns into a detonation. The WD preexpands during the deflagration and undergoes complete burning during the detonation phase. Similarly, the classical deflagration models W7 (Nomoto et al. 1984) show behavior similar to that of DDs, but only by neglecting instabilities due to the deflagration fronts (Gamezo et al. 2003). For recent reviews, see Branch (1998), Hillebrandt & Niemeyer (2000), and Höflich (2006).

Despite the success of classical DD and W7 models, both lack the basic features seen in SN 2005hj. Neither predicts a long plateau in velocity; they instead show a smooth decline of the photospheric velocity\footnote{Although the Si \(\lambda 6355\) line is an imperfect tracer of the photospheric velocity as mentioned in \$2.1\), the observed SNe Ia population typically exhibits a 1000\textendash 3000 km s\(^{-1}\) decrease in the measured line velocities between 1 week before maximum light to 2 weeks after (Branch et al. 1988; Benetti et al. 2005), and the deflagration and classical delayed detonation models employed to explain these events have shown a correspondingly large decrease in photospheric velocities over the same period (Khokhlov et al. 1993). These models are inconsistent with the corresponding \(\approx 300\) km s\(^{-1}\) shift measured for SN 2005hj.} as a function of time (Fig. 9). This happens because in expanding envelopes the photosphere recedes in mass and, because of the homologous expansion, in velocity as well. This behavior results from the smoothly declining density structure of the WD and the fact that variations in the specific energy production are small.

In contrast, shell-like density structures will produce velocity plateaus in a natural way because the photosphere remains in the shell for some time as shown by Khokhlov et al. (1993) and Höflich & Khokhlov (1996). To form a shell-like structure requires interaction of rapidly expanding material with a surrounding envelope. Various mechanisms have been suggested to supply this surrounding matter: the pulsating delayed detonation scenario (Höflich et al. 1996), mergers, or tamped detonation models. Shells may also form by the interaction of an exploding single WD within the progenitor system (Gerardy et al. 2004; Quimby et al. 2006).

We analyzed the observations of SN 2005hj based on detailed, spherical models for supernovae published in the literature. The models are based on detailed calculations for the explosion, light curve, and spectra. The models considered include delayed detonations, deflagrations, pulsating delayed detonations, and tamped detonation/merger scenarios. In Figure 9 we show the photospheric velocities as a function of time for these models along with the Branch-normal SNe Ia to illustrate the formation of a plateau in the models that naturally form a shell. Note for lower shell masses, this “plateau” is more accurately described as a period of slowly declining velocities.

In classical delayed detonation models and for normal-bright SNe Ia, Si is present over a wide range in mass, spanning about 0.4\textendash 0.5 M\(_{\odot}\), which corresponds to velocities from about 8000 to 9000 km s\(^{-1}\) to more than 20,000 km s\(^{-1}\). The Si layer is thick (in the mass frame) because explosive oxygen burning occurs over a wide range of temperatures. The density gradient is smooth and Si is mostly in Si \(\Pi\), so initially the velocity derived from the minimum of the Si \(\lambda 6355\) line smoothly declines with the receding photosphere governed by the geometrical dilution of the expanding envelope. Eventually, the photosphere begins to recede below the Si layer, at which point the evolution of the Si \(\lambda 6355\) line profile will show the following behavior: (1) the optical depth of the...
highest velocity material at the largest radii will begin to decline below 1 and as such the blue wing of the line profile will start to drift toward the red; (2) as the optical depth decreases, the strength of the line as measured from the line depth will decrease; (3) the line minimum may continue to slow, but it will grow increasingly discrepant with the photospheric velocity. This phase typically begins 1–2 weeks after maximum light for normal SNe Ia and is heralded by the appearance of Fe ii lines. While this behavior is commensurate with observations of normal-bright SNe Ia such as SN 1994D, it is not consistent with the observations of SN 2005hj.

The Si ii 6355 line seen in SN 2005hj is narrow, and during the plateau phase the wings do not change, the depth does not change, and the velocity of the minimum does not change to within the errors. The data require a narrow distribution of Si ii in velocity space, and we suggest this may be explained by an interaction that compresses the Si- rich layers as predicted by merger and pulsating delayed detonation models. The shell models are also consistent with the velocity drop seen after the plateau because a significant amount of Si is located below the shell (Khokhlov et al. 1993; Höflich & Khokhlov 1996).

In Figure 10 we show general properties of these models. As discussed in the papers above, to first order, the observational signatures of the shell depend on the mass of the shell $M_{\text{shell}}$. Almost the entire WD is burned, and momentum conservation determines the amount of high-velocity matter that can pile up in the expanding shell. With increasing shell mass, more material of the SN envelope is slowed down. As a consequence, the velocity of the shell $v_{\text{shell}}$ decreases with $M_{\text{shell}}$. Because it will take longer for the photosphere to recede into the lower velocity matter, the time until the beginning of the plateau phase, $t_{\text{ph}}$, increases with $M_{\text{shell}}$. The optical depth increases with $M_{\text{shell}}$. Duration of the plateau, $\Delta t_{\text{plateau}}$, also increases, the temperature gradient becomes steeper, and the photosphere becomes cooler (i.e., $B - V$ increases) with increasing $M_{\text{shell}}$ (Khokhlov et al. 1993; Höflich & Khokhlov 1996). The duration of the plateau, $\Delta t_{\text{plateau}}$, is defined by the velocity spread $\Delta v$ around $v_{\text{shell}}$ with $\Delta v = 500 \text{ km s}^{-1}$, which puts the end of the plateau phase safely into the parts of a rapidly declining $v_{\text{ph}}$. We choose a larger value than in the observations to avoid amplitudes due to discreteness, which, in some of the models, is of the order of $0.1 \text{ km s}^{-1}$. By increasing $\Delta v$ from 200 to 500 km s$^{-1}$ the nominal duration is increased by $\approx 1$ day. However, we also note that the actual width depends on the velocity spread in the shell (see § 4).

Given the model predictions, we can use different observational indicators to test which $M_{\text{shell}}$ is consistent with SN 2005hj (Fig. 10). All three parameters, $v_{\text{shell}}$, $t_{\text{ph}}$, and $t_{\text{ph}}$ suggest $M_{\text{shell}} \approx 0.2 M_{\odot}$, with the allowed ranges specifically bracketed by $0.15 - 0.25$ and $0.1 - 0.25 M_{\odot}$ for the plateau length, shell velocity, and plateau onset, respectively, taking the observed errors into account. The comparison between the $B - V$ color as a function of $v_{\text{shell}}$, $t_{\text{ph}}$, or $t_{\text{ph}}$, however, shows only marginal consistency between the observations and the models if we assume only foreground reddening by the Galaxy. We note, that the intrinsic $B - V$ color of the models is uncertain by about $0.05 - 0.1$ mag at maximum light. The two best-fitting models, pd23 and d et2env2, show a peak brightness, $M_F$, of $-19.42$ and $-19.41$ mag, respectively, with an uncertainty of $\pm 0.1$ mag (Höflich & Khokhlov 1996), versus a typical DD model with $-19.2$ mag (Höflich et al. 2002), i.e., they are brighter by about 20%, mostly due lower escape probability of $\gamma$-rays that results when the $^{56}$Ni layers are slowed down because of the interaction (Höflich et al. 1991).

4. DISCUSSION AND CONCLUSIONS

We have presented photometric and spectroscopic data for SN 2005hj, a slightly overluminous Type Ia. The most striking feature is an apparent plateau in the expansion velocity evolution,
which we derive from the Si $\lambda6355$ line. The velocities remain at about 10,600 km s$^{-1}$ for about 3 weeks starting slightly before maximum light, and this plateau is bracketed by preceding and succeeding decelerations. We find that Si is confined to a relatively narrow velocity region. Analysis of the detailed observations in concert with published models suggest there may be some physical distinction between SN 2005hj and other normal-bright SNe Ia that may systemically affect their use as distance indicators if not properly taken into account.

The models considered include delayed detonations, deflagrations, pulsating delayed detonations, and tamped detonation/merger scenarios. In order to explain the narrow Si $\lambda6355$ line and its plateau in velocity, we suggest an early interaction that forms a dense shell as predicted by merger and PDD models. The spectral and photometric peculiarities are consistent with respect to the velocity, duration, and onset of the plateau, and marginally consistent with the maximum light color, for models that have shells of about 0.2 $M_{\odot}$. As indicated by earlier works (Kokhlov et al. 1993; Höflich & Kokhlov 1996), the mass of the interacting shell has been found to be the parameter that dominates the details of these observational signatures independent of how this shell may form. The tight predicted relation between each of $v_{\text{shell}}$, $t_{\text{shell}}$, and $t_0$ may provide a stable means to separate SN 2005hj-like events from regular Branch-normal SNe Ia. Although the agreement between the shell models and the observations is good, the predictions are not necessarily unique and other possibilities may exist. For example, we have not considered three-dimensional models such as the detonation from a failed deflagration scenario recently examined by Kasen & Pleva (2007). For SN 2005hj, then, the agreement of the plateau velocity and its duration to that predicted by shell models may simply be a fluke, and in such case this concordance should then not hold for other SNe with similar Si $\lambda6355$ evolution. Given the data and models considered, we suggest that either PDDs or merger events are responsible for SN 2005hj, and this implies the existence of two different progenitor channels.

It is important to understand how these two progenitor channels, which may occur in relatively varying fractions as a function of redshift, will impact studies using SNe Ia as distance indicators. Li et al. (2001b) estimate that 20% of SNe Ia in their sample are either 1991T-like or 1999aa-like. These SNe show spectral features and a velocity plateau similar to SN 2005hj. Branch (2001) found five 1999aa-like events in the Li et al. (2001b) sample out of 20 total SNe Ia that were observed early enough to show 1999aa-like spectral features, and one that was 1991T-like; however, in the pre-LOSS sample they do not classify any of the seven SNe Ia with early spectra as 1999aa-like. These nearby samples are constructed from targeted galaxy searches that have different selection biases than the deep cosmological surveys, but we will assume a uniform 2005hj-like rate of 25% for all SNe Ia. SNe Ia that appear spectroscopically similar to SN 2005hj in a single epoch could none the less arise from different progenitors, and the mass of the low-density envelope around PDDs or mergers may effect their peak magnitudes and/or light-curve shapes, but we will further assume that all such events deviate uniformly from the LWR of Branch normal SNe Ia. Höflich et al. (1996) calculated the relation between peak $V$ band magnitudes, $M_{V}$, and the fading between maximum light and +20 days, $dM_{V}(20)$, for a variety of theoretical models and found that shell models produced $dM_{V}(20)$ that were 0.2–0.3 mag smaller than for (in vacuum) delayed detonations reaching the same peak magnitude. Therefore using the same LWR for shell models will result in corrected peak magnitudes systematically offset by 0.1–0.2 mag. Also, the observed peak magnitudes of SNe Ia are usually corrected for absorption along the line of sight using the observed $B-V$ color at maximum light and a reddening law. For events that are intrinsically red, this will increase the estimated peak magnitude above its already overluminous intrinsic value. Cosmological studies may therefore need to remove or at least separately handle SN 2005hj-like events to avoid systematic errors in distance.

As a case for the importance of separating different progenitors, let us consider SN 1999ee. Very similar to SN 2005hj, SN 1999ee shows a plateau with $v_{\text{shell}} = 10, 500$ km s$^{-1}$, a duration of $14 \pm 3$ days, and an onset at day $-3 \pm 1$ relative to maximum (Hamuy et al. 2002; see Fig. 8). The $B-V$ color of SN 1999ee was also quite red at maximum light; $+0.28 \pm 0.04$ mag after correction for galactic extinction (Stritzinger et al. 2002; Krisciunas et al. 2004). Based on the standard brightness decline relation and the corresponding colors, Hamuy et al. (2002) derived reddening in the host galaxy of $0.28 \pm 0.04$, which implies an absolute brightness of $M_{V} = -19.95$ mag, similar to that of SNLS-03D3bb, which Howell et al. (2006) attributed to a super-Chandrasekhar-mass WD. Taking into account the spectroscopic information about the velocity plateau, its length and onset, we attribute a portion of the red color to the intrinsic properties of the supernova. We find that the duration of the velocity plateau, its onset and size are consistent with a shell mass of 0.2 $M_{\odot}$, which suggests an intrinsic color $B-V$ of 0.15 $\pm 0.02$ mag (see Fig. 10). This reduces the reddening in the host galaxy to $\approx 0.13$ mag and the absolute brightness of $M_{V}$ to $-19.53$ mag, which compares favorably to the model predictions of $-19.42$ and $-19.41$ mag for pdd3 and detenv2, respectively, within the model uncertainties. Note that there is an interstellar sodium line in the spectra that implies some degree of reddening within the host. There are some apparent spectral differences when compared to SN 2005hj, namely, SN 1999ee has a slightly broader blue wing in Si ii and stronger absorption around 4900 Å. This may hint toward either different explosions scenarios (i.e., pulsations vs. mergers) or different viewing angles of asymmetric envelopes.

This brings us to the limitation of our studies. Except for the color, SN 2005hj fits remarkably well with the merger and PDD model predictions, but still, it is a single event and the good agreement may be coincidental. We need a large, well-observed sample of similar objects to test and verify or falsify the models and to determine the shell mass distribution. Moreover, three-dimensional effects have been neglected. In reality, we must expect some dispersion. Although pulsating delayed detonation models may be expected to be rather spherical, mergers may be asymmetric with directionally dependent luminosities and colors. In fact, both classes may be realized in nature. As mentioned above, the duration of the plateau, $\Delta t_{\text{shell}}$, is defined by the velocity spread around $v_{\text{shell}}$. The physical width of the shell depends, to first order, on the distance at which the interaction occurs and the density distribution of the interacting expanding media and shell during the hydrodynamical phase of the interaction (Gerardy et al. 2004). For obvious reasons, asymmetries of the shell will increase the velocity gradient seen over the shell. The observations of SN 2005hj indicate a very flat plateau that, in principle, may further constrain the properties of the shell. For SN 2005hj, this may already indicate a rather spherical shell and hint toward the PDD scenario or mergers with an intermediate disk of very large scale heights. However, additional information needs to be taken into account such as detailed line profiles and statistical properties to break this degeneracy between mergers and PDDs.
Whereas the mean velocity of the shell for a given mass is dictated by momentum conservation, the thickness of the shell is limited by the distance of the shell material, the distance sound can travel during the interaction, and the specific density profile within the shell. With increasing distance of the shell, the relative size (and corresponding velocity spread) becomes smaller because the sound speed remains about the same. The intrinsic color will be sensitive to the optical depth of the shell, which is governed by the magnitude of the density jump and thus depends on the distance of the interacting shell from the WD (Gerardy et al. 2004). The blue $B - V$ color for SN 2005hj may hint of a need to modify the distance and structure of the shell. Precise analysis of such “non-stable” features requires detailed model fitting beyond the scope of this paper.

In the recent past, both the scenarios leading to shell-like structures have been discounted. PDD models have been dismissed because three-dimensional deflagration models showed that the WD becomes unbound and thus pulsations would not occur (Röpke et al. 2003; Hillebrandt & Niemeyer 2000). However, it has recently been shown that this solution depends mainly on the ignition conditions, namely, the number and locations of ignition points leading to single or multiple bubble solutions, and mixture of bubble solutions leading to Raleigh-Taylor instabilities. As a result, solutions with fewer bubbles are likely to result in a reduced amount of burning, thus only slightly unbinding the WD and increasing the possibility of PDDs (Livne et al. 2005; Plewa et al. 2004). Similarly, the merging scenario has been dismissed because the WD may undergo burning during the merger and result in an accretion induced collapse (Nomoto & Kondo 1991), and also on the basis of the long merging timescale. However both of these results depend sensitively on the initial conditions, and new pathways to the actual merging may effect the results (Lü et al. 2006). In light of our results, the predicted death of both of these scenarios may be premature, and further studies are needed.

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