CALTECH CORE-Collapse Project (CCCP) Observations of Type IIn Supernovae: Typical Properties and Implications for Their Progenitor Stars

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ABSTRACT

Type IIn supernovae (SNe IIn) are rare events, constituting only a few percent of all core-collapse SNe, and the current sample of well-observed SNe IIn is small. Here, we study the four SNe IIn observed by the Caltech Core-Collapse Project (CCCP). The CCCP SN sample is unbiased to the extent that object selection was not influenced by target SN properties. Therefore, these events are representative of the observed population of SNe IIn. We find that a narrow P-Cygni profile in the hydrogen Balmer lines appears to be a ubiquitous feature of SNe IIn. Our light curves show a relatively long rise time (\textgreater{}20 days) followed by a slow decline stage (0.01–0.15 mag day\textsuperscript{-1}), and a typical V-band peak magnitude of $M_V = -18.4 \pm 1.0$ mag. We measure the progenitor star wind velocities (600–1400 km s\textsuperscript{-1}) for the SNe in our sample and derive pre-explosion mass-loss rates (0.026–0.12 $M_\odot$ yr\textsuperscript{-1}). We compile similar data for SNe IIn from the literature and discuss our results in the context of this larger sample. Our results indicate that typical SNe IIn arise from progenitor stars that undergo luminous-blue-variable-like mass loss shortly before they explode.

Key words: stars: mass-loss -- supernovae: general -- supernovae: individual (SN 2005bx, SN 2005cl, SN 2005cp, SN 2005db)

Online-only material: color figures

1. INTRODUCTION

For many decades it has been known that hydrogen-rich Type II supernovae (SNe II; Minkowski 1941; see Filippenko 1997 for a review on SN spectroscopic classification) arise from the gravitational core collapse of massive stars (e.g., Arnett et al. 1989; Smartt 2009). Schlegel (1990) recognized that a small subset of SNe II show narrow emission lines and proposed that they constituted a separate subclass (SNe IIn). It has been suggested that the narrow emission lines of SNe IIn originate from photoionized dense wind surrounding the exploding stars (Chugai 1991). It was later noticed that some SNe IIn (e.g., SN 1988Z) show, in addition to a narrow unresolved Hz emission component ($\Delta v < 200$ km s\textsuperscript{-1}), also an intermediate component ($\Delta v \sim 10^3$ km s\textsuperscript{-1}; Stathakis & Sadler 1991). This component has been interpreted as a result of radiative shocks in dense wind clouds (Chugai & Danziger 1994), though other explanations have been suggested (Chugai 2001; Dessart et al. 2009).

Over the years, a specific model has emerged which describes the properties of SNe IIn as a result from a combination of emission from several physically distinct regions (see Smith et al. 2008 for a recent description). In brief, it is assumed that the SN ejecta interact with a massive slower wind blown by the progenitor star, launching a pair of forward and reverse shocks. The interaction decelerates the blast wave from its initial velocity and a dense shell traveling approximately at the shock velocity is formed. Initially, this dense shell is optically thick and obscures the actual electron-scattering photosphere of the SN which lies interior to the shock. At this stage (which can, in principle, have a duration of years), the optical spectrum is dominated by a blue continuum from the shocked material, superposed with emission lines. The emission lines often have a complex profile, including a narrow component from the photoionized, outer unshocked wind, and an intermediate-width component from the shocked dense shell. Later on, as the interaction weakens, the shocked region may become optically thin and the underlying SN photosphere (with its high-velocity absorption-dominated spectrum) may emerge (e.g., Gal-Yam & Leonard 2009). Applying such a model, one can extract the physical properties of the progenitor star (in particular, its mass-loss rate) from the observations (e.g., Salamanca et al. 1998; Gal-Yam & Leonard 2009). Previously derived values (summarized in Table 9) show progenitor wind velocities of 50–1000 km s\textsuperscript{-1} and mass-loss rates that range between $10^{-4}$ and $0.3 M_\odot$ yr\textsuperscript{-1}. These are consistent with a variety of possible massive progenitors, from red supergiant (RSG) stars (typical wind velocities of tens of km s\textsuperscript{-1}, e.g., Smith et al. 2007) and small mass-loss rates ($\lesssim 10^{-5} M_\odot$ yr\textsuperscript{-1}), to stripped Wolf–Rayet (W-R) stars with fast (thousands of km s\textsuperscript{-1}) and more massive winds ($\sim 10^{-4} M_\odot$ yr\textsuperscript{-1}), up to luminous blue variable stars (LBVs) which have the most extreme mass-loss rates (up to $\sim 10^{-2} M_\odot$ yr\textsuperscript{-1}) and intermediate-velocity winds (a few hundreds of km s\textsuperscript{-1}; e.g., Humphreys & Davidson 1994).

The connection between SNe IIn and LBVs was brought into focus by studies of SN 2005gl. Gal-Yam et al. (2007b) analyzed pre-explosion images of this SN IIn, and detected a possible progenitor, whose extreme luminosity ($L_V > 10^6 L_\odot$) suggested an LBV identification (the only stars of comparable
properties known in our galaxy are LBVs). Gal-Yam et al. (2007b) also noted that the relative rarity and spectral appearance of SNe IIn could be naturally explained by an origin in very massive LBVs (with $M \gtrsim 80 M_\odot$). Gal-Yam & Leonard (2009) subsequently presented post-explosion Hubble Space Telescope (HST) data of this event that showed the putative progenitor of SN 2005gl had disappeared, providing strong evidence that this SN IIn had indeed originated from a single massive LBV analog. These authors also analyzed the spectra of SN 2005gl and showed that the derived mass-loss rate was consistent with that of eruptive LBVs (e.g., P-Cygni during its sixteenth-century eruption). Other work on additional SNe supports the SN IIn–LBV connection (e.g., Smith et al. 2007; Trundle et al. 2008).

It remains an open question how general the SN IIn–LBV connection is, i.e., are most or all SNe IIn related to LBVs or stars with similar properties? A literature-based study of this question is weakened due to the fact that the sample of SNe IIn published thus far may be highly biased, due to the tendency of authors to preferentially publish extreme or unusual events (this is evident for many of the objects, as summarized in Section 4 and Table 9).

Here we present and analyze four SNe IIn observed by the Caltech Core-Collapse Project (CCCP; Gal-Yam et al. 2007a; A. Gal-Yam et al. 2011, in preparation). The CCCP SN sample is unbiased in the sense that essentially every young core-collapse SN that was observable from Palomar Observatory during the project was followed up, without preference. Thus, these objects should fairly represent the population of observed SNe IIn. Typical wind velocities and mass-loss rates can therefore be derived, which may help constrain the properties of the progenitor stars. We organize the paper as follows. In Section 2 we present our observations, and derive physical parameters for the sample in Section 3. We present an exhaustive literature review of SNe IIn in Section 4, and discuss our results in Section 5. We conclude with a summary in Section 6.

## 2. Observations

The observations reported here were taken as part of the CCCP (Gal-Yam et al. 2007a; A. Gal-Yam et al. 2011, in preparation). The CCCP obtained photometric (optical and near-IR) and spectroscopic observations of 50 core-collapse SNe. The program is designed to provide a fair sample of core-collapse events, with well-defined selection criteria and uniform, high-quality optical/IR observations. One of the goals of the CCCP is to characterize the little-studied properties of core-collapse SNe as a population. Four SNe IIn are included in the CCCP SN sample.

### 2.1. Discovery

SN 2005bx was discovered by Rich (2005) on 2005 April 27, and was absent on 2005 April 11. It was thus discovered within 16 days of explosion. The host galaxy MCG +12-13-19 is at $z = 0.031218$ (NASA/IPAC Extragalactic Database (NED)). Bommaud et al. (2005) identified SN 2005bx as an SN IIn based on a spectrum taken on 2005 May 1; our earlier spectrum from April 30 (Gal-Yam et al. 2005) confirms this identification.

Pugh & Li (2005) reported the discovery of SN 2005cl by the Lick Observatory Supernova Search (LOSS; Filippenko et al. 2001). The SN was detected on 2005 June 2 (marginal) and 12, and was absent on 2005 May 23, so it too was discovered rather young. The host galaxy MCG -01-53-20 is at $z = 0.025878$ (Huchra et al. 1993, via NED). A spectrum taken by Modjaz et al. (2005a) on 2005 June 13 demonstrates that SN 2005cl was an SN IIn.

Lee et al. (2005) reported the LOSS (Filippenko et al. 2001) discovery of SN 2005cp on 2005 June 20. Spectroscopy by Modjaz et al. (2005b) on 2005 June 30 indicated a young age and IIn classification. The host galaxy,UGC 12886, is at $z = 0.022115$ (Giovanelli & Haynes 1993, via NED). Our light curve confirms that this was a young SN found on the rise (see Figure 3 below).

SN 2005db was discovered by Monard (2005) on 2005 July 19, and was absent on 2005 July 2, so it was discovered rather early. The host galaxy, NGC 214, is at $z = 0.015124$ (Humason et al. 1956, via NED). Blanc et al. (2005) identified this event as a Type IIn based on a spectrum taken on 2005 July 20. Our light curve confirms that this was a young SN found on the rise (Figure 4).

### 2.2. Photometry

We obtained optical photometry with the 1.5 m robotic telescope at the Palomar Observatory (P60; Cenko et al. 2006) using a $2048 \times 2048$ pixel CCD in the Johnson–Cousins $BVRI$ bands. All images were pipeline-reduced by the automated P60 software, applying standard bias and flat-field correction, as well as an astrometric solution.

We derived light curves using the image-subtraction-based photometry routine mkdiffle (Gal-Yam et al. 2004), implemented within IRAF. This pipeline performs image registration followed by reference image subtraction using the common point-spread function (PSF) method (Gal-Yam et al. 2008), relative calibration with respect to local standards, and error calculation.

Field calibration was carried out relative to stars near the SN location with absolute photometry determined in two ways. In the fields of SN 2005cl and SN 2005db, Sloan Digital Sky Survey (SDSS) cataloged $gri$ magnitudes of nearby stars were transformed to the $BVRI$ Vega-based system using the equations of Jordi et al. (2005). The fields of SN 2005bx and SN 2005cp are not within the SDSS footprint. For those we obtained standard photometric calibration using Landolt standards taken by the P60 on photometric nights. Additional discussion of photometric calibration, as well as finding charts for the nearby calibration stars used for the four SN fields in this work, are given in the Appendix.

Photometry of all SNe was corrected for Galactic extinction (Schlegel et al. 1998, via NED). The final light curves were also corrected for extinction in the host galaxy by first estimating the equivalent width (EW) of the Na D absorption feature in our spectra using the IRAF splot routine and then calculating the excess color $E(B-V)$ from the EW using the formula of Turatto et al. (2003). In two cases (SN 2005cl and SN 2005bx) an apparently unrelated noise fluctuation falls close to the Na D feature in our best spectra. We also calculate an upper limit on the extinction assuming this apparent noise feature is due entirely to Na D absorption. We view this upper limit as very conservative. Therefore, we corrected the light curves shown for the most likely estimate reported in the table. In the mass-loss calculations below we adopt the average between the likely estimate and upper limit as our extinction value, and

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7 See http://nedwww.ipac.caltech.edu.

8 IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under cooperative agreement with the National Science Foundation.
propagate the range bracketed between these values in the mass-loss error calculations. The adopted extinctions are given in Table 1.

Late images (mid–end 2005 November) of SN 2005db do not show signal from the SN. An upper limit on its luminosity was therefore calculated by introducing artificial point sources of decreasing flux at the SN location and using the SExtractor software (Bertin & Arnouts 1996) to determine when the artificial object was detected at 3σ confidence. These values are adopted as the reported upper limits.

The photometric light curves of all four SNe are presented in Figures 1–4 and the data points are listed in Tables 2–5. The errors include photometric errors due to non-perfect image subtraction and Poisson errors (derived by mkdifflc), extinction uncertainty errors, zero-point calibration errors, and distance modulus errors taken from NED, which usually dominate the errors in peak absolute magnitudes (∼0.15 mag). We determined peak magnitudes and dates from low-order polynomial fits to the data (example fits to the R-band data are presented). Rise times were estimated using our data combined with reported non-detections, assumed to have been obtained in bands closely matching the R band (Section 2.1). Post-peak decay slopes were determined from linear fits. SN 2005cl showed a clear break in the decline rate, so a broken linear fit was used. The BVRI peak values, dates, rise times, and decline rates are listed in Table 6.

2.3. Spectroscopy

Spectroscopic observations were carried out using the double-beam spectrograph (Oke & Gunn 1982) mounted on the 5 m Hale telescope at the Palomar Observatory. We used the D55 dichroic, with 600/158 line/mm grisms in the blue/red sides, respectively. We obtained a continuous spectrum covering the wavelength range 3400–9400 Å. The instrumental resolution was 4.88 Å per pixel in the red and 1.08 Å per pixel in the blue.
Figure 2. BVRI light curves of SN 2005cl. Our data trace a slow rise to peak magnitude, followed by a slow decay, with an obvious break to a steeper decline around MJD-53625 day. The blue vertical lines mark the spectroscopic observation epochs of SN 2005cl.

(A color version of this figure is available in the online journal.)

Figure 3. BVRI light curves of SN 2005cp. The SN exhibits a slow rise to peak, followed by an extended decline stage of constant slope. The blue vertical lines mark the spectroscopic observation epochs of SN 2005cp.

(A color version of this figure is available in the online journal.)

All data were obtained at the parallactic angle (Filippenko 1982). The typical exposure time was between 10 and 30 minutes, see Table 7 for more details.

Spectroscopic reduction was performed using the CCCP spectroscopic pipeline, which is based on IRAF and IDL scripts as described, e.g., in Matheson et al. (2000) and Gal-Yam et al. (2007b). In brief, to derive the total-flux spectrum, we extracted the one-dimensional sky-subtracted spectra optimally (Horne 1986) in the usual manner. The spectra were then wavelength and flux calibrated and corrected for continuum atmospheric extinction and telluric absorption bands (Wade & Horne 1988; Bessell 1999; Matheson et al. 2000).

Our resulting spectroscopic time series are presented in Figures 5–11 and all data are publicly available in digital form from the Weizmann Experimental Astrophysics Spectroscopic Database.9 We discuss each object separately below.

2.3.1. SN 2005bx

We present our spectroscopy of SN2005bx in Figure 5. The continuum shape was initially blue, and reddened with time. Except for the Balmer emission lines, there are no other strong

http://www.weizmann.ac.il/astrophysics/wiseass/
Figure 4. BVRI light curves of SN 2005db. The SN has an initially rapid rise followed by a broad peak. Following the peak, there is a period of 30–40 days in which the SN magnitude is almost constant. This is followed by a slow decline, which is faster in bluer bands, that eventually turns into a sharp drop in the SN luminosity, traced by the upper limits marked by downward-facing triangles. This magnitude drop can be evaluated in the VRI bands to be between 1–2 mag within 4–9 days. This sharp drop in magnitude may be indicative of a CSM distribution with a sharp cutoff, leading to an abrupt luminosity decrease as the ejecta emerge from the previously ejected mass shell and the interaction effectively stops. The dashed blue lines mark the spectroscopic observation epochs of SN 2005db.

(A color version of this figure is available in the online journal.)

Figure 5. Spectral evolution of SN2005bx. The intermediate component evident in the first spectrum fades away in later observations.

(A color version of this figure is available in the online journal.)

features. The intermediate-width component of the Hα line is evident in the first spectrum, which we decompose in Figure 13 below, and disappears in later spectra. None of our spectra exhibit P-Cygni profiles in the narrow lines.

2.3.2. SN 2005cl

We present our spectroscopy of SN2005cl in Figure 6, showing the spectral evolution of the SN. One can see the
null
October spectrum was also analyzed and provides consistent results.

3. PHYSICAL PARAMETERS OF CCCP SNe IIn

3.1. Wind Velocity Calculation

We measured the widths of the intermediate and narrow components of the Hα emission line in our SN spectra and calculated the corresponding velocities using the Doppler formula. For each event the spectrum where the intermediate component was most evident was analyzed.

In order to measure the line widths, the Hα feature was decomposed using the following steps, implemented within MATLAB. First, the linear continuum surrounding of the line feature was removed. Next, a nonlinear least-squares script solved for the best-fit multi-Gaussian decomposition. Input parameters consisted of the number of components and an initial guess for the FWHM, height, and center of each Gaussian, no other constraints were imposed. The scripts provide the user with the best-fit Gaussian width, height, and center for each component as well as their corresponding errors. The errors are propagated into the wind velocity error. Line profile decompositions are shown in Figures 13–16. In all cases the best fits required both a narrow and an intermediate-width component. In some cases a broad component was also required. When appropriate, narrow P-Cygni profiles were smoothed. The measured velocities are reported in Table 8.

3.2. Mass-loss-rate Calculation

The calculation is done via the following formula that relates the mass-loss rate of the progenitor with the luminosity resulting from the ejecta–wind interaction (Chugai & Danziger 1994):

\[ L_{\text{Hα}} = \frac{1}{2} \epsilon_{\text{Hα}} M v_{\text{shock}} \frac{v_{\text{shock}}}{v_{\text{wind}}} \]

We assume an efficiency factor \( \epsilon_{\text{Hα}} = 0.1 \), which is appropriate for young SNe (Salamanca et al. 1998) and compatible with previous studies. \( v_{\text{shock}} \) is extracted from the intermediate component in the Hα feature (following the interpretation presented in Section 1; but see Chugai 2001; Dessart et al. 2009) and \( v_{\text{wind}} \) is extracted from the narrow component and/or the blue edge of the narrow P-Cygni profile (see below).

To derive the absolute Hα flux we performed synthetic photometry on the relevant spectra using the methods of Poznanski et al. (2002), compared the resulting R-band magnitude with our photometry (see above, interpolated as needed), and scaled the spectrum to match the absolute photometry. The resulting correction factors ranged between 1.7 and 3.2. The luminosity was then extracted by integrating over the intermediate-width feature in the SN spectrum and accounting for the distance to the SN (obtained from NED). All measured values are reported in Table 8.

Following previous works, the shock velocity was taken as the FWHM of the intermediate-width component. The errors derived from the Gaussian decomposition of the Hα profile are...
Figure 6. Spectral evolution of SN2005cl. One can see that the intermediate component of the Balmer lines fades away in the later observations. Note the narrow P-Cygni profile in the first four Balmer lines in the earliest spectrum.

(A color version of this figure is available in the online journal.)

Table 7
Log of Spectroscopic Observations

| Supernova | UT Date   | Exposure Time (s) | Observers     | Comments           |
|-----------|-----------|-------------------|---------------|--------------------|
| 2005bx    | 2005 Apr 30 | 900               | Sand & Cenko  |                    |
|           | 2005 Jun 4  | 1200              | Gal-Yam & Sand|                    |
|           | 2005 Jul 16 | 1200              | Gal-Yam & Sharon | slightly cloudy    |
| 2005cl    | 2005 Jul 16 | 600               | Gal-Yam & Sharon |                   |
|           | 2005 Aug 13 | 1800              | Cenko         |                    |
|           | 2005 Sep 8  | 1800              | Leonard       | clear sky, poor seeing |
| 2005cp    | 2005 Jul 16 | 600               | Gal-Yam & Sharon | clear sky         |
|           | 2005 Aug 13 | 1800              | Cenko         |                    |
|           | 2005 Sep 8  | 1800              | Leonard       | clear sky, poor seeing |
|           | 2005 Oct 24 | 1800              | Gal-Yam       |                    |
|           | 2005 Dec 24 | 1800              | Sand          |                    |
|           | 2006 Jan 8  | 1800              | Cenko & Ballmer|                   |
|           | 2006 Jan 20 | 1800              | Moon          |                    |
| 2005db    | 2005 Aug 14 | 1200              | Sand          |                    |
|           | 2005 Sep 8  | 900               | Leonard       |                    |
|           | 2005 Oct 24 | 900               | Gal-Yam       | clear              |
|           | 2005 Dec 24 | 1800              | Sand          | poor seeing        |
|           | 2006 Jan 8  | 1800              | Cenko & Ballmer|                   |
|           | 2006 Jan 20 | 1800              | Moon          |                    |

Table 8
Wind Velocities and Mass-loss Rates of SNe 2005bx, 2005cl, 2005cp, and 2005db

| Supernova | Shocked Wind Velocity (km s⁻¹) | Unshocked Wind Velocity via Gaussian Fitting (km s⁻¹) | Unshocked Wind Velocity via P-Cygni Profile (km s⁻¹) | Unshocked Wind Velocity used for Mass Loss (km s⁻¹) | Mass Loss Rate (M⊙ yr⁻¹) |
|-----------|--------------------------------|------------------------------------------------------|-----------------------------------------------------|---------------------------------------------------|-------------------------|
| SN2005cl  | 3188 ± 67                      | 1520 ± 111                                           | 1318 ± 223                                          | 1475 ± 65                                          | 0.12 ± 0.02             |
| SN2005cp  | 2290 ± 30                      | 611 ± 112                                            | 632 ± 225                                           | 610 ± 110                                          | 0.026 ± 0.005           |
| SN2005db  | 2237 ± 37                      | 850 ± 113                                            | 1113 ± 65                                          | 958 ± 220                                          | 0.057 ± 0.024           |
| SN2005bx  | 4122 ± 66                      | 813 ± 133                                            | N/A                                                 | 813 ± 133                                          | 0.037 ± 0.019           |
Figure 7. Hα emission line in our first spectrum of SN2005cl shows a clear P-Cygni profile. The red arrow marks the velocity offset of the blue edge of the absorption feature used to estimate the progenitor wind velocity.

(A color version of this figure is available in the online journal.)

Figure 8. Zoomed-in section of the 2005 September 8 spectrum of SN 2005cl. Note that the blue continuum bump is partially resolved into multiple narrow P-Cygni profiles of H, Fe II, and Ca II.

(A color version of this figure is available in the online journal.)

provided by the least-squares script output. Running the script with a different number of components (larger or smaller) turned out to provide poorer decompositions.

The unshocked wind velocity was derived from the half-width at zero intensity (HWZI) of the narrow component. In addition to the error calculation procedure described above, the errors in the unshocked wind velocity also account for the uncertainty in the level of the continuum that translates to an uncertainty in the flux zero point when measuring the HWZI. All the errors were propagated linearly into the velocity errors. The unshocked wind velocity was also calculated via the measurement of the P-Cygni profile, while taking the width as the difference between the Hα or Hβ feature peak and the blue edge of the absorption feature (Figures 7, 10, 12). The errors of the P-Cygni velocities are calculated according to our instrumental resolution, and the measured values are also corrected for the instrumental resolution—4.88 Å pixel$^{-1}$ in the red band and 1.08 Å pixel$^{-1}$ in the blue band, following Alexander et al. (1999). These measurements are also reported in Table 8.

For SN 2005cl and SN 2005cp, the unshocked-wind-velocity values used in the mass-loss-rate calculation include the range of values consistent with both the Gaussian fitting and the
Figure 9. Spectral evolution of SN2005cp. Broad, intermediate, and narrow components are prominent in the August 13 spectrum (second from top). The blue continuum in early spectra is not resolved into individual lines, and narrow P-Cygni features appear only in the Hα feature in a late spectrum. A strong Hα emission line dominates the spectrum at late times.

(A color version of this figure is available in the online journal.)

P-Cygni profile values. The average of the values in this range was taken as the unshocked wind velocity and the edges of this range determined the velocity error. For SN2005db, there was no overlap between the velocities derived by the two methods, so we considered the entire range of values defined by both methods (from the lower value of the Gaussian fitting to the top value of the P-Cygni profile). The final results can be seen in Table 8.

The mass-loss rates derived from Equation (1) using the values derived above and their respective errors are reported in the final column of Table 8.

Figure 10. Hα emission line in our January 8 spectrum of SN2005cp shows a clear P-Cygni profile. The red arrow marks the velocity offset of the blue edge of the absorption feature used to estimate the progenitor wind velocity.

(A color version of this figure is available in the online journal.)

4. PREVIOUSLY STUDIED SNe IIn

SNe IIn are rare (2%–9% of all core-collapse SNe; Cappellaro et al. 1997; Li et al. 2011). We have found only 15 SNe IIn for which progenitor mass-loss rates have been estimated in the literature, and few other events are discussed in detail (Table 9). For a single event (SN 2005gl) the progenitor was identified as an LBV-like star (Gal-Yam et al. 2007b; Gal-Yam & Leonard 2009) via pre-explosion images. SNe IIn exhibit a wide range of wind velocities and mass-loss rates (Table 9).
Figure 11. Spectral evolution of SN2005db. Composite profiles of the Balmer lines are evident, with narrow P-Cygni profiles. The October spectrum shows emerging intermediate-width P-Cygni profiles of Fe\textsc{ii}, He\textsc{i}, and the Ca\textsc{ii} IR triplet. The last three spectra appear to be dominated by the host galaxy light, similar to a starburst template spectrum from Kinney et al. (1996).

(A color version of this figure is available in the online journal.)

Figure 12. Zoom-in on the H\textbeta feature from a spectrum taken on 2005 September 8, showing a narrow P-Cygni profile. The red arrow marks the velocity offset of the blue edge of the absorption feature.

(A color version of this figure is available in the online journal.)

In addition to conventional SNe IIn, there are other SNe that exhibit IIn characteristics. One group are the Ia/IIn Hybrids, also known as SNe Ia (Deng et al. 2004). There is an argument whether these are explosions of white dwarfs interacting with circumstellar medium (Hamuy et al. 2003; Aldering et al. 2006) or the result of a core-collapse in massive stars (Benetti et al. 2006).

Another group that technically resembles SNe IIn are faint events that exhibit very narrow emission lines. These are often understood as LBV super-eruptions that leave the star intact (so-called SN impostors; Van Dyk 2006; Maund et al. 2006). We will not discuss these further here.

A review of literature events follows.

1. SN 1987F is probably the first well-observed SN IIn, and thus predates the recognition of the class (and its definition) by Schlegel (1990). Spectroscopic observations were reported by Filippenko (1989) and Wegner & Swanson (1996). The event shows both narrow and intermediate-width components. The spectroscopic evolution of this
Figure 13. Decomposition of the Hα feature in the 2005 April 30 spectrum of SN 2005bx.
(A color version of this figure is available in the online journal.)

Figure 14. The decomposition of the Hα feature (post-smoothing) in the 2005 July 16 spectrum of SN 2005cl.
(A color version of this figure is available in the online journal.)

object is quite similar to that of SN 2005cp in our sample (comparing Figure 2 from Filippenko 1989 with our Figure 9). Photometric data have been presented by Filippenko (1989), Cappellaro et al. (1990), Wegner & Swanson (1996), and Tsvetkov (1989). The object was discovered after peak, but its reported magnitude ($M_V = -18.3$ mag; Filippenko 1989) is similar to that of SN 2005cp (and the average value of our CCCP sample), while the $V$-band decline rate reported by Cappellaro et al. (1990) and Wegner & Swanson (1996; $\sim 0.01$ mag day$^{-1}$) is also similar to that of SN 2005cp. Chugai (1991) derives a pre-explosion mass-loss rate using a formula similar to Equation (1) of $M = 10^{-3} M_\odot$ yr$^{-1}$, assuming an unshocked wind velocity of 10 km s$^{-1}$. Replacing this with the measured value of the narrow-line width from Wegner & Swanson (1996; 150 km s$^{-1}$) would drive this value up to $M \approx 10^{-2} M_\odot$.

2. SN 1988Z is the first extensively studied event and is frequently mentioned in the literature. It was discovered post-maximum, and early photometric and spectroscopic observations are presented by Statidakis & Sadler (1991), Turatto et al. (1993b), Filippenko (1997), and Aretxaga et al. (1999). Chugai & Danziger (1994) estimate the pre-explosion mass-loss rate to be between $7 \times 10^{-4}$ and $1.5 \times 10^{-2} M_\odot$ yr$^{-1}$.

3. SN 1994W is a well-studied event discovered before maximum light and extensively followed. The general properties of this SN closely resemble our observations.
of SN 2005cl, with a similar spectral shape, absolute magnitude, and rise and decline rates (Sollerman et al. 1998). These authors measure the unshocked wind velocity from the blue edge of the narrow P-Cygni profile to be 1000 km s$^{-1}$. Chugai et al. (2004) present an extensive analysis of additional observations and derive a very high mass-loss rate of 0.3 $M_\odot$ yr$^{-1}$ using similar procedures to those we have employed. Interestingly, Dessart et al. (2009) have recently suggested that this event may have resulted from a collision between consecutive shells ejected by the progenitor, without the final core-collapse SN having occurred yet.

4. SN 1994aj was studied by Benetti et al. (1998). Its spectra show some similarity to those of SN 2005cp, but its light curve decays significantly more rapidly ($\sim 0.04$ mag day$^{-1}$), though this decline rate slows down by factor of 10 or so at late times. Estimating the unshocked wind velocity to be $\sim 1000$ km s$^{-1}$ from the observed narrow P-Cygni profile and the shock velocity to be around 3700 km s$^{-1}$ from the HWZI of the H$\alpha$ emission line, these authors derive a mass-loss rate of $\sim 10^{-3}$ $M_\odot$ yr$^{-1}$ using Equation (1).

5. SN 1995G is another well-observed event. Pastorello et al. (2002) present extensive photometric and spectroscopic observations. Even though the peak was not observed, the
data provided by these authors show that this event appears to be similar to SN 2005cl in terms of its estimated peak magnitude (\(M_V = -18.5\) mag) and its initial decline rate (\(\sim 0.01\) mag day\(^{-1}\)). At later times the decline slows down substantially. The spectra are similar to those of SN 2005cl presented above, including the blue continuum “bump” which is partially resolved into individual narrow P-Cygni profiles of numerous lines. Pastorello et al. (2002) estimate a moderate mass-loss rate (\(\sim 2 \times 10^{-3} M_\odot \text{yr}^{-1}\)) using Equation (1). However, replacing their assumptions with values consistent with our methodology (efficiency \(\sim 0.1\) and wind velocity estimated from the blue edge of the narrow P-Cygni profile, which would be \(\sim 1200\) km s\(^{-1}\) for this object) would drive the deduced mass-loss rate to very high values (\(>1 M_\odot \text{yr}^{-1}\)). Indeed, more sophisticated modeling of the same data set by Chugai & Danziger (2003) explains the properties of SN 1995G with an explosive mass ejection a few years before the SN and leads to a mass-loss rate of \(\sim 0.1 M_\odot \text{yr}^{-1}\).

6. SN 1995N occurred in a very nearby galaxy (24 Mpc), but was discovered long after explosion. Late-time optical and UV observations of SN 1995N are presented by Fransson et al. (2002). These authors measure the unshocked wind velocity to be \(<500\) km s\(^{-1}\), and estimate the intermediate-width component velocity to be around 5000 km s\(^{-1}\), but do not estimate the mass-loss rate of the progenitor. Zampieri et al. (2005) use X-ray data to estimate a mass-loss rate of \(2 \times 10^{-4} M_\odot \text{yr}^{-1}\). Earlier observations verbally described by Baird et al. (1998) were apparently never published.

7. SN 1996L is described by Benetti et al. (1999). Its light curve declines rapidly (\(\sim 0.05\) mag day\(^{-1}\)), though this decline rate slows down by factor of five or so at late times. Observations began after maximum light, but these authors estimate a peak magnitude similar to that of SN 2005cp. Estimating the unshocked wind velocity to be \(\sim 1600\) km s\(^{-1}\) from the observed blue edge of the narrow P-Cygni profile and the average shock velocity to be around 4800 km s\(^{-1}\), these authors derive a mass-loss rate of \(\sim 10^{-3} M_\odot \text{yr}^{-1}\) using Equation (1).

8. SN 1997ab was described by Hagen et al. (1997) and Salamanca et al. (1998). These authors use high-resolution spectroscopy to accurately measure the narrow P-Cygni profiles of the Balmer lines, and derive velocities of 90 km s\(^{-1}\) for the unshocked wind and \(\sim 6600\) km s\(^{-1}\) for the shock. Using Equation (1) they derive a mass-loss rate of \(\sim 10^{-2} M_\odot \text{yr}^{-1}\).

9. SN 1997eg was studied by Salamanca et al. (2002) spectroscopically. Photometric data are not reported. These authors identify a narrow P-Cygni profile in the Balmer lines and use its blue edge to determine the unshocked wind velocity to be approximately 160 km s\(^{-1}\). Estimating the shock velocity to be \(\sim 7000\) km s\(^{-1}\), and using the same analysis used for SN 1997ab (and in our paper), they measure a mass-loss rate of \(8.3 \times 10^{-3} M_\odot \text{yr}^{-1}\). Tsvetkov & Pavlyuk (2004) report a few photometric measurements of this event, while Hoffman et al. (2008) present a model for the star+CSM (circumstellar material) based on spectrophotometric and spectropolarimetric observations.

10. SN 1998S is the most extensively observed SN II and probably among the best-studied SNe of any type. Nearby (\(\sim 17\) Mpc) and luminous, it was one of the brightest SNe of the last few decades and has been observed across the electromagnetic spectrum for many years. Early photometric and spectroscopic observations are reported by Liu et al. (2000), showing the SN peaked at \(M_B = -18.7\), broadly similar to the objects we studied. Its rise time (<20 days) appears short compared to our sample of SNe II, and its decay is among the fastest (\(\sim 0.05\) mag day\(^{-1}\)) measured for SNe II. Its early spectra resemble those of SN 2005cp (Figure 9), in particular in the H\(\alpha\) profile and the broad

### Table 9

| Supernova | Unshocked Wind Velocity (km s\(^{-1}\)) | Shocked Wind Velocity (km s\(^{-1}\)) | Mass-loss Rate (\(M_\odot \text{yr}^{-1}\)) | References |
|-----------|----------------------------------------|--------------------------------------|------------------------------------------|-----------|
| SN 1987F  | 150                                    | 6000                                 | \(10^{-2}\)                                | [1] [2]   |
| SN 1988Z  | \(<200\)                               | 1200–1800                            | \(7 \times 10^{-4} \text{--} 1.5 \times 10^{-2}\) | [3] [4]   |
| SN 1994W  | 1000                                   | \(\sim 4000\)                        | 0.3                                      | [5] [6]   |
| SN 1994aj | 1000                                   | \(\sim 3700\)                        | \(10^{-3}\)                               | [7]       |
| SN 1995G  | \(\sim 1000\)                          | 3000–4000                            | 0.1                                      | [8] [9] [10] |
| SN 1995N  | \(<500\)                               | 2500–5000                            | \(2 \times 10^{-4}\)                     | [11] [12] |
| SN 1996L  | 1600                                   | 4800                                 | \(10^{-3}\)                               | [13]      |
| SN 1997ab | 90                                     | 6600                                 | \(10^{-2}\)                               | [14]      |
| SN 1997eg | 160                                    | 7000                                 | \(8.3 \times 10^{-3}\)                    | [15]      |
| SN 1998S  | 30–100                                 | N/A                                  | \(10^{-4} \text{--} 10^{-3}\)             | [16]–[20] |
| SN 2005Gl | 420                                    | 1500                                 | 0.03                                     | [21]      |
| SN 2005ip | 100–200                                | 1100                                 | \(2.2 \times 10^{-4}\)                    | [22]      |
| SN 2006gg | 200                                    | 4000                                 | 0.1–1                                    | [23] [24] |
| SN 2006ef | 190                                    | 2000                                 | 0.1–4                                    | [25]      |
| SN 2008iy | 100                                    | 5000                                 | 1–2 \(\times 10^{-2}\)                    | [26]      |

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lines on the blue side one to two months after peak. Additional spectroscopy is presented by Anupama et al. (2001), who derive a mass-loss rate of $10^{-4} \, M_\odot \, yr^{-1}$ assuming an unshocked wind velocity of 10 km s$^{-1}$; we note that this value should be corrected upward by a factor of a few given the wind velocities estimated by other authors from detail analyses (e.g., $v_w = 50$ km s$^{-1}$, Leonard et al. 2000; $v_w = 30$ km s$^{-1}$, Bowen et al. 2000). The analysis of Lentz et al. (2001) using synthetic spectroscopy modeling indicates a mass-loss rate of $10^{-3}$–$10^{-4} \, M_\odot \, yr^{-1}$ and wind speeds of 100–1000 km s$^{-1}$. Analysis of the radio and X-ray observations of SN 1998S leads to similar estimates of the mass-loss rate (Pooley et al. 2002). Leonard et al. (2000) present an extensive spectroscopic and spectropolarimetric analysis, while Fassia et al. (2000, 2001) study large optical/IR photometric and spectroscopic data sets. Optical and UV HST observations of SN 1998S are discussed by Bowen et al. (2000) and Fransson et al. (2005). The IR properties of this object are discussed by Gerardy et al. (2000) and Pozzo et al. (2004), and modeling of the spectroscopy is further discussed by Chugai (2001) and Chugai et al. (2002).

11. SN 2005gl was studied by Gal-Yam et al. (2007b) and Gal-Yam & Leonard (2009). This object appears to show a weaker interaction signature than other events discussed above, leading to a moderate peak magnitude ($M_v \sim -17$ mag) and a relatively fast decay ($\sim-0.04$ mag day$^{-1}$; Gal-Yam et al. 2007b), as well as a relatively rapid transition from an interaction-dominated spectrum to one similar to normal SNe II (Gal-Yam & Leonard 2009). Analysis by these authors using methods similar to those used in the current paper leads to estimates of the unshocked wind velocity $v_w = 420$ km s$^{-1}$ (confirmed by Smith et al. 2010 using higher-resolution spectra); the shock velocity is $v_s = 1500$ km s$^{-1}$ and the mass-loss rate is 0.03 $M_\odot \, yr^{-1}$. The analysis of Gal-Yam & Leonard (2009) provides strong evidence that the progenitor of this SN was a luminous LBV star.

12. SN 2005ip was studied in detail by Smith et al. (2009). This object was not very luminous, with a peak magnitude of $\sim -17.4$ mag and a relatively rapid decline ($\sim-0.02$ mag day$^{-1}$). The velocity of the unshocked wind is estimated to be 100–200 km s$^{-1}$ and the shock velocity (measured from the intermediate-width component) is about 1100 km s$^{-1}$. The mass-loss rate is estimated to be approximately $2 \times 10^{-4} \, M_\odot \, yr^{-1}$. The spectroscopic analysis supports suggestions concerning dust formation in the ejecta inferred from IR observations of this object by Fox et al. (2009).

13. SN 2006gy attracted intensive attention due to its very high peak luminosity ($M_V \sim -22$ mag), and it seems some late-time studies may still be going on, so a complete review of the literature may be premature. Early results were reported by Ofek et al. (2007), estimating a mass-loss rate of 0.1 $M_\odot \, yr^{-1}$, and Smith et al. (2007), who were more ambiguous about such high mass-loss values. Later analysis by Agnoletto et al. (2009), Smith et al. (2010), and Miller et al. (2010b) does seem to converge on a model invoking an extremely massive star experiencing strong CSM interaction. Smith et al. (2010) estimate the CSM velocity to be around 200 km s$^{-1}$, the shock velocity to be around 4000 km s$^{-1}$, and mass-loss rates on the order of $1 \, M_\odot \, yr^{-1}$.

14. SN 2006ff has been studied by Smith et al. (2008). This SN experienced strong interaction with a very massive CSM, making the event very luminous (the object was caught already in decline, at $M_R \approx -20.8$ mag). Assuming an unshocked CSM velocity of $v_w = 190$ km s$^{-1}$ and a shock velocity of $v_s = 2000$ km s$^{-1}$, these authors estimate very large mass-loss rates, 0.1–0.2 $M_\odot \, yr^{-1}$, several decades prior to explosion, rising to 2.3–4.1 $M_\odot \, yr^{-1}$ a few years before the SN.

15. SN 2008iy was a remarkable event, with an unprecedented rise time of $\sim 400$ days, to its peak magnitude of $M_r = -19.1$ mag (Miller et al. 2010b). These authors measure the unshocked wind velocity to be $\sim 100$ km s$^{-1}$ (perhaps with components extending to 450 km s$^{-1}$) and estimate the shock velocity to be around 5000 km s$^{-1}$. They estimate the mass-loss rate in several ways, getting consistent results of $1-2 \times 10^{-2} \, M_\odot \, yr^{-1}$.

16. A group of objects whose first well-studied member was SN 2002ic (Hamuy et al. 2003) has similarities with SNe IIn in that they show strong CSM interaction, but the nature of the inner explosion (thermonuclear explosion of a white dwarf star or a core-collapse of a massive star) is still debated (e.g., Benetti et al. 2006; Trundle et al. 2008). Members tentatively included in this group are SN 1997cy (García et al. 2000; Turatto et al. 2000), SN 1999e (Rigon et al. 2003), SN 2002ic (e.g., Hamuy et al. 2003; Kotak et al. 2004), and SN 2005gj (Aldering et al. 2006; Trundle et al. 2008). Estimated mass-loss rates are within the same range seen for SNe IIn ($10^{-4}$–$10^{-2} \, M_\odot \, yr^{-1}$; Kotak et al. 2004; Trundle et al. 2008).

17. In addition to the objects listed above, several events are mentioned in the literature, on which little information is provided. These include SN 1978G (Schlegel 1990), SN 1978K (discovered long after explosion), SN 1984E (Gaskel 1984; Dopita et al. 1984; Henry & Branch 1987), SN 1987B (Schlegel 1990; Schlegel et al. 1996), SN 1987C (Schlegel 1990; Schlegel & Kirshner 1998), SN 1988T (Filippenko 1989), SN 1989C (Schlegel 1990; Turatto et al. 1993a), SN 1990S (Hamuy et al. 1993), SN 1994Y (Filippenko 1997; Ho et al. 2001; Tsvetkov & Pavlyuk 1997), SN 1994ak (Filippenko 1997), SN 1996cr (discovered more than a decade after explosion; Bauer et al. 2008; Dwarkadas et al. 2010), SN 1999el (Di Carlo et al. 2002), SN 2007rt (Trundle et al. 2009), SN 2003ma (Rest et al. 2009), and SN 2008Fz (Drake et al. 2010). Some other recently reported events whose connection to SNe IIn is unclear are SN 2008es (Gezari et al. 2009; Miller et al. 2009) and SN 2007od (Andrews et al. 2010).

5. DISCUSSION

5.1. Typical Properties of SNe IIn

SNe IIn are rare, and the first few events noticed received some attention as peculiar SNe II. Following the high-profile work on SN 1988Z and the synthesis paper by Schlegel (1990), coining of the term SNe IIn, these objects became popular subjects of detailed papers throughout the next decade. This trend apparently died out with SN 1999el, and while the number of detected SNe IIn continued to rise, no detailed report on an SN IIn discovered between 1999 and 2003 was published. More recently, several SNe IIn have again been reported, but each of these works was motivated by a perceived peculiarity
or special property of its subject event (extreme luminosity, unusual spectral features, extended light curve, etc.). It thus seems that while the population of SNe IIn reported in earlier papers may be fairly representative of the observed population (but often poorly observed or discovered a long time after explosion), the latest papers (typically with better data) are of obviously non-representative events. It is in this context that the CCCP SN IIn events are quite useful. Since the CCCP targeted every core-collapse SN by design, it likely describes more fairly the SN IIn population detected in nearby galaxies.

In Figure 17, we plot the absolute $R$-band light curves of every SN IIn detected before peak magnitude. As can be seen, the CCCP events provide a substantial increase to this small sample and span the range of photometric properties in terms of peak magnitude of what could be viewed as the “normal” or “typical” population (−19 mag < $M_R$ < −16 mag, i.e., excluding the recently reported very luminous events that were singled out for publication for this reason).

In Figure 18, we replotted the light curve data normalized and shifted so that the peaks coincide. Our new CCCP data significantly increase the number of objects with well-measured rise times, especially if one focused on the above “normal” luminosity range. We can see that SNe IIn typically have long rise times, up to 50 days, and diverse decline rates spanning the range from flat plateau events like SNe II-P to rapidly decaying events like SNe Iib. Since several events show obvious breaks or rapid changes in decline rates, the data suggest that extrapolating the light curves of SNe IIn discovered after explosion backward in order to determine their peak magnitudes may not be a reliable procedure, and that one cannot assume a negligible rise time when estimating explosion dates from near-peak measurements.

Spectroscopically, our sample suggests that intermediate-width components and narrow P-Cygni profiles in the Balmer lines are ubiquitous among SNe IIn, and can usually be detected when a time series of high-quality spectra is examined. Interestingly, combining our data with an extensive literature study, it seems like two spectroscopic groups of SNe IIn seem to manifest. The first, exemplified in our data by SN 2005cl, displays prominent narrow P-Cygni profiles in the Balmer lines that persist with time, and a pointed, sharp profile of the Hα line. Other well-studied members are SN 1994W and SN 1995G. On the other hand, some events, similar to SN 2005cp in our sample, show much weaker narrow P-Cygni profiles in the Balmer series that may only be visible for short periods of time, and have Hα line profiles that are triangular or boxy at late times. Other well-studied members include SN 1987F, SN 1994aj, and SN 1998S. A more complete investigation of the physical reality and nature of this division lies beyond the scope of this work.

Finally, it is interesting to note that only one out of the four events we studied (with similar data) shows a partially resolved pseudo-continuum in the blue (Figure 8; see Smith et al. 2009 for a recent discussion). It is not clear yet if all SNe IIn have blue pseudo-continuum dominated by blended Fe-group lines, which is only resolved in a few cases, or if this phenomenon is rare. It is interesting to note that besides being the only event showing a resolved pseudo-continuum, SN 2005cl is also the SN with the fastest pre-explosion wind velocity and largest mass-loss value in our sample. A systematic study of a larger sample of SNe IIn may also shed light on this aspect.

5.2. Implications for the Progenitor Stars

The mass-loss rates we derive for the CCCP SNe IIn in this work are indicative of progenitor stars with LBV-like behavior (Figure 19), as our values (few $10^{-2}$ to 0.12 $M_\odot$ yr$^{-1}$) are essentially too high for any class of massive stars other than LBVs in the eruptive phase (Humphreys & Davidson 1994). All events also exhibit high wind velocities, which in some cases (1475 ± 65 km s$^{-1}$ for SN 2005cl) are quite extreme compared with most known LBVs (though see the recent measurements by Pastorello et al. 2010 for a counter example). Thus, it is quite possible that the properties of massive stars shortly before they explode do not resemble those of stars seen in our galaxy.
that have not yet reached these late, short-lived stages. While the luminous progenitor of SN 2005gl (Gal-Yam & Leonard 2009) and very high deduced mass-loss rates of some SNe (e.g., SN 2006gy, Smith et al. 2009; SN 2006tf, Smith et al. 2008) suggest that some SNe IIn come from extremely massive stars, it is not clear if this is true for all these events. In this context, our measurements of high mass-loss rates argue against the progenitors of SNe IIn being red supergiant stars, whose wind velocities and mass-loss rates are too low, and the strong hydrogen lines and extended light curves argue against W-R stars, whose atmospheres are expected to be hydrogen-poor and compact (some W-R stars may explain the class of interacting H-poor Ibn SNe; Pastorello et al. 2008). Thus it seems that SNe IIn as a class (if all or most of the objects arise from a single group of massive stars) require a progenitor star that does not fit any of the common classes of massive stars. Such rare progenitor stars are naturally explained by extreme masses, though other explanations are possible.

6. SUMMARY AND CONCLUSIONS

SNe IIn exhibit a wide range of wind velocities and mass-loss rates (Table 9). We have presented our observations of four representative SNe IIn observed by the CCCP project. Our photometry allows us to determine peak magnitudes and rise and decline rates for three events. Our spectroscopic time series are used to measure the pre-explosion wind velocities and mass-loss rates from the progenitor stars of these SNe. We then provide an extensive review of the literature and discuss our results in the context of other well-studied events. Our main results are as follows.

1. SNe IIn are typically luminous compared to other core-collapse SNe (peak $M_V = -18.4$ mag), and have a relatively long rise time (>20 days) followed by a slow decline.

2. SN IIn spectra often show prominent narrow P-Cygni profiles in the Balmer lines and multi-component H$_\alpha$ profiles.

3. We measure fast pre-explosion progenitor winds (600–1400 km s$^{-1}$) and derive large mass-loss rates (0.026–0.12 $M_\odot$ yr$^{-1}$).

4. Our work supports the association between SNe IIn and LBV-like progenitor stars. The strong and massive winds we find are broadly consistent with LBV progenitor stars and unlike those of typical RSGs. This is in accordance with the results from analysis of pre-explosion images of the progenitor of Type IIn SN 2005gl (Gal-Yam & Leonard 2009).

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APPENDIX

PHOTOMETRIC CALIBRATION

In Figure 20 we show finding charts for the SNe and nearby calibration stars, whose magnitudes are given in Table 10.

A.1. SDSS versus Landolt Calibrations

Landolt-derived equations for the observing nights of 2005 August 31 and 2009 April 19 were used to calibrate 15 stars located near four CCCP SNe within the SDSS footprint. The standard Landolt results were compared with magnitudes obtained from the SDSS photometry of these stars as above. The difference between the two calibrations was calculated in each filter for each star as well as the average and the standard deviation of the differences of all the stars. The results from both nights are shown in Table 11.

In all the filters, the scatter in the differences is larger than the mean offsets. We conclude that the two calibration methods are consistent.

### Table 10

| Supernova | Star | R.A. | Decl. | B | V | R | I |
|-----------|------|------|-------|---|---|---|---|
| SN2005bx | 1    | 13:50:36.5 | +68:35:23.0 | 17.18 | 16.15 | 15.64 | 15.17 |
| SN2005cl | 2    | 13:50:54.7 | +68:33:27.0 | 18.06 | 16.72 | 15.99 | 15.35 |
| SN2005cp | 3    | 13:50:33.2 | +68:32:48.3 | 14.76 | 14.07 | 13.63 | 13.26 |
| SN2005db | 4    | 13:50:42.1 | +68:31:57.2 | 14.97 | 14.07 | 13.60 | 13.21 |

A color version of this figure is available in the online journal.
Figure 20. Calibration stars in the fields of the SNe studied in this paper. The SNe are marked by tick marks; stars are circled and numbered (matching Table 10). North is up, east is due left, and a scale bar is provided.

Table 11
Comparison between SDSS Calibration and Landolt Calibrations

|          | 20050831 |          | 20090419 |          |
|----------|----------|----------|----------|----------|
|          | B        | V        | R        | I        |          | B        | V        | R        | I        |
| Average magnitude difference | 0.014    | -0.004   | 0.019    | 0.021    | 0.016    | 0.051    | 0.040    | 0.007    |
| Standard deviation           | 0.076    | 0.021    | 0.045    | 0.048    | 0.109    | 0.080    | 0.049    | 0.025    |

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