CALTECH CORE-COLLAPSE PROJECT (CCCP) OBSERVATIONS OF TYPE II SUPERNOVAE: EVIDENCE FOR THREE DISTINCT PHOTOMETRIC SUBTYPES

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ABSTRACT

We present R-band light curves of Type II supernovae (SNe) from the Caltech Core-Collapse Project (CCCP). With the exception of interacting (Type IIn) SNe and rare events with long rise times, we find that most light curve shapes belong to one of three apparently distinct classes: plateau, slowly declining, and rapidly declining events. The last class is composed solely of Type IIb SNe which present similar light curve shapes to those of SNe Ib, suggesting, perhaps, similar progenitor channels. We do not find any intermediate light curves, implying that these subclasses are unlikely to reflect variance of continuous parameters, but rather might result from physically distinct progenitor systems, strengthening the suggestion of a binary origin for at least some stripped SNe. We find a large plateau luminosity range for SNe IIP, while the plateau lengths seem rather uniform at approximately 100 days. As analysis of additional CCCP data goes on and larger samples are collected, demographic studies of core-collapse SNe will likely continue to provide new constraints on progenitor scenarios.

Key word: supernovae: general

Online-only material: color figures

1. INTRODUCTION

Type II supernovae (SNe) are widely recognized as the end stages of massive H-rich stars and represent the bulk of observed core-collapse SNe (see Filippenko 1997 for a review of SN classifications). Several subtypes of Type II SNe have been observed. Those showing a plateau in their light curve are known as Type IIP events, while those showing a linear decline from peak magnitude are classified as IIL (see Patat et al. 1994 and references therein). A third class of events, Type IIn SNe display narrow lines in their spectra, indicative of interaction between the SN ejecta and a dense circumstellar medium.

Red supergiants (RSGs) have been directly identified as the progenitors of Type IIP SNe for several events (see Smartt 2009 and Leonard 2011 for reviews on this topic and Fraser et al. 2011, 2012 and Van Dyk et al. 2012 for recent results). Such stars have thick hydrogen envelopes that are ionized by the explosion shock wave. As the shocked envelope expands and cools, it recombines, releasing radiation at a roughly constant rate, thus producing a plateau in the light curve (e.g., Popov 1993; Kasen & Woosley 2009). It follows that SNe IIL might be the explosions of stars with less massive H envelopes that cannot support a plateau in their light curve. SN IIb progenitors, then, would contain an even smaller H mass.

However, if SNe IIP–IIL–Ib–Ib progenitors represent merely a sequence of decreasing H envelope mass, one would expect the properties of these SNe to behave as a continuum. Specifically, a gradual transition in light curve shape should be observed when examining a homogeneous sample of events.

The Caltech Core-Collapse Project (CCCP; Gal-yam et al. 2007) is a large observational survey which made use of the robotic 60 inch (P60; Cenko et al. 2006) and Hale 200 inch telescopes at Palomar Observatory to obtain optical BVR photometry and spectroscopy of 48 nearby core-collapse SNe. By providing a fair sample of core-collapse events with well-defined selection criteria and uniform, high-quality optical observations, CCCP allows to study core-collapse SNe as a population rather than as individual events.

Light curves of Type Ib/c SNe from CCCP have been presented and analyzed by Drout et al. (2011). Type IIn CCCP events are treated by Kiewe et al. (2012). Here we present photometry of 21 non-interacting Type II SNe with well-observed light curves collected through CCCP. We present R-band data for most of the events to simplify the comparison of their light curve shapes. A more detailed multi-color analysis will be presented in a forthcoming paper.
We note that distinguishing between the cIIb and eIIb subclasses without direct progenitor detections requires observations during the very early stages of the explosion, nebular spectra or radio and X-ray observations (Chevalier & Soderberg 2010). Such data are not available for the Type IIb events in our sample. We therefore do not distinguish between cIIb and eIIb SNe in this work, and refer to them collectively as SNe IIb.

### 2. PHOTOMETRY

Our light curves are produced using image subtraction with respect to P60 reference imaging obtained approximately one year or later after explosion. We employ the Common Point Spread Function (PSF) method (Gal-Yam et al. 2008b) for PSF matching using the mkidiff routine (Gal-Yam et al. 2004) implemented in IRAF.\(^{14}\) Our photometry is calibrated to Sloan Digital Sky Survey (SDSS) stars near the SN—themselves magnitudes converted to the Johnson–Cousins systems using the equations of Jordi et al. (2005). For objects outside the SDSS footprint, we used Landolt standards observed at the same night as the SN field for calibration. Our measurements are presented in the natural system (see Kiewe et al. 2012 for more details) with typical photometric errors of ~0.1 mag. The photometry is corrected for Galactic extinction using the Schlegel et al. (1998) maps retrieved via the NASA/IPAC Extragalactic Database (NED). The distance moduli to the SN host galaxies are taken from NED, if available, or calculated from spectroscopic redshifts assuming a cosmological model with \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\) otherwise. We adopt a distance modulus of 29.62 for SN 2005cs, based on the distance estimate of Vinkó et al. (2012).

Due to incomplete data for three of the events, we use photometry published in the literature for them. The light curve of SN2004fx is taken from Hamuy et al. (2006), that of SN2005ay from Gal-Yam et al. (2008a), and that of SN2005cs from Pastorello et al. (2009).

For each SN, we constrain the explosion date to a window between the last non-detection and first detection. For a few events, this window is wider than 14 days, but the SN was detected before peak brightness or the first spectrum taken displayed a blue continuum, known to be indicative of a young event (e.g., Gal-Yam et al. 2011). We treat these cases as if a non-detection existed 14 days prior to the first detection. The explosion date window dates are noted in Table 1. Two events with poorly constrained explosion dates did not display blue featureless spectra upon first detection. These are SN2005au and SN2005bw (both SNe IIP) and we include them only to study absolute plateau luminosities.

### 3. RESULTS AND DISCUSSION

We plot the smoothed R-band light curves of 15 Type II events normalized to R-band peak magnitude in Figure 1 (top panel). The measured data and the smoothed fit used in Figure 1 is shown in Figures 2 and 3. Rather than forming a

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**Table 1**

| SN       | Type       | Peak/Plateau Mag | ΔM15\(_g\) | Distance Modulus | Distance Modulus Source | Explosion MJD | Discovery Reference |
|----------|------------|------------------|------------|------------------|-------------------------|---------------|---------------------|
| SN2004du | Plateau    | −17.46 (0.055)   | 34.26      | NED              |                         | 53229 (2)     | IAUC 8387           |
| SN2004er | Plateau    | −16.69 (0.077)   | 33.39      | NED              |                         | 53273 (2)     | IAUC 8412           |
| SN2004et | Plateau    | −17.48 (0.088)   | 28.80      | NED              |                         | 53268 (4)     | IAUC 8413           |
| SN2004fx | Plateau    | −16.087 (0.038)  | 32.60      | NED              |                         | 53300 (3)     | IAUC 8431           |
| SN2005aa | Plateau    | −15.824 (0.134)  | 34.83      | Redshift         |                         | 53402 (5)     | IAUC 8476           |
| SN2005au | Plateau    | −17.069 (0.141)  | 34.07      | NED              |                         | 53407 (1)     | IAUC 8496           |
| SN2005ay | Plateau    | −16.447 (0.119)  | 31.21      | NED              |                         | 53452 (4)     | IAUC 8500/2         |
| SN2005bw | Plateau    | −16.945 (0.150)  | 35.15      | Redshift         |                         | 53470 (7)     | IAUC 8503           |
| SN2005cs | Plateau    | −15.400 (0.079)  | 29.62      | Vinkó et al. 2012|                         | 53548 (2)     | IAUC 8553           |
| SN2005Z  | Slow decline | <−17.5          | 0.135      | 34.61            | Redshift                | 53391 (5)     | IAUC 8476           |
| SN2005ab | Slow decline | <−15.2          | 0.405      | 34.14            | Redshift                | 53406 (7)     | IAUC 8478           |
| SN2005an | Slow decline | <−17.0          | 0.170      | 33.39            | Redshift                | 53430 (7)     | CBET 113            |
| SN2005ba | Slow decline | −17.4           | 0.202      | 35.60            | Redshift                | 53450 (7)     | IAUC 8503           |
| Quest SN1| Slow decline | −16.5           | 0.181      | 33.63            | Redshift                | 53256 (7)     |                    |
| SN2004ex | Rapid decline | −17.2          | 0.751      | 34.41            | Redshift                | 53289 (1)     | IAUC 8418           |
| SN2005bp | Rapid decline | <−16.8          | 0.926      | 35.41            | Redshift                | 53477 (7)     | IAUC 8515           |
| SN2005by | Rapid decline | −17.5          | 0.750      | 35.39            | Redshift                | 53482 (6)     | IAUC 8523           |

**Notes.** For the declining SNe, the peak magnitudes and the ΔM15\(_g\) parameter (denoting the magnitude drop at 15 days after peak in the R band) are derived from the smooth fits to the light curves (limits are stated when the rise to peak is not detected in the data). For the plateau events, the average luminosity during the first 50 days is taken as the plateau magnitude (one \(\sigma\) shown in parentheses). The explosion dates assumed in Figure 1 are noted (explosion date window widths shown in parentheses).

\(^{14}\) Photometry from Gal-Yam et al. (2006).

\(^{15}\) Photometry from Gal-Yam et al. (2008a).

\(^{16}\) Photometry from Pastorello et al. (2009).
continuum, we find that the light curves group into three distinct subclasses: plateau, slowly declining (1–2 mag/100 days), and initially rapidly declining (5–6 mag/100 days) events (see also Table 1). We note that the three rapidly declining events are all Type IIb and that they display similar light curve shapes to those of Type Ib/c SNe (Drout et al. 2011). We perform a Kolmogorov–Smirnov test and find that the probability that the measured $\Delta M_{15,R}$ values for the rapid- and slow-decline groups are drawn from a single underlying distribution is 2%.

Three events (SN2004ek, SN2005ci, and SN2005dp; Figure 4) display prolonged rising periods in their light curves. They do not show signs of interaction in their spectra and may be explosions of compact blue supergiant progenitors (Kleiser et al. 2011; Pastorello et al. 2012), as demonstrated directly in the case of SN 1987A (see Arnett et al. 1989 for a review).

Finally, one event (SN2004em; Figure 4) displays a very peculiar photometric behavior. For the first few weeks it is similar to a Type IIP SN, while around day 25 it suddenly changes behavior to resemble an SN 1987A-like event.

The full photometric data set is available online through WISeREP15 (Yaron & Gal-Yam 2012).

3.1. Declining SNe

Aside from establishing a different rate of decline for SNe IIb compared to SNe III, Figure 1 (top panel) suggests that the

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15 http://www.weizmann.ac.il/astrophysics/wiserep
Figure 2. $R$-band photometric data of the plateau CCCP events together with the spline fits shown in Figure 1. The light curve of SN2004fx is taken from Hamuy et al. (2006), that of SN2005ay from Gal-Yam et al. (2008a), and that of SN2005cs from Pastorello et al. (2009).

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

Figure 3. $R$-band photometric data of the declining CCCP events together with the spline fits shown in Figure 1.

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

Figure 4. $BVRI$ light curves of the CCCP events not included in Figure 1. Three events (SN2004ek, SN2005ci, SN2005dp) show long rise times (possibly associated with blue supergiant explosions; Kleiser et al. 2011; Pastorello et al. 2012), while one peculiar event (SN2004em) changes behavior from flat to rising around three weeks after explosion.

(A color version of this figure is available in the online journal.)
IIP, IIL, and IIb subtypes do not span a continuum of physical parameters, such as H envelope mass. Rather, additional factors should be considered. Specifically, Type IIb events might arise from binary systems (as suggested also by recent progenitor studies for SN1993J, Maund et al. 2004; SN2008ax, Crockett et al. 2008; SN2011dh, Arcavi et al. 2011 and Van Dyk et al. 2011). The similarity of the Type IIb light curves to those of Type Ib events (also seen in the Drout et al. 2011 data), in addition to the known spectral similarities at late times and the similar peak radio luminosities (Chevalier & Soderberg 2010), suggests that these two types of events might come from similar progenitor systems. We note that our measured post-peak decline rates are similar to those of both SN2008ax (cIIb; Pastorello et al. 2008; Chornock et al. 2011) and SN1993J (eIIb; Richmond et al. 1994).

3.2. Plateau SNe

The $R$-band light curves of the Type IIP SNe, on an absolute magnitude scale, can be seen in Figure 1 (bottom panel). We find a wide range of plateau luminosities, but do not have enough statistics to test whether they form a continuous distribution or if there are two distinct underlying types (bright and faint), as previously suggested (Pastorello et al. 2004). The plateau lengths, however, seem rather uniform at $\sim 100$ days (with the sole exception of SN2004fx, displaying a shorter plateau). This is consistent with the plateau length scale given by Popov (1993), which assumes a constant opacity

$$t_p \approx \frac{99^{1/6} M_{10}^{1/2} R_{5000}^{1/6} E_{51}^{1/3} \kappa_{34}^{-1/3}}{\rho_{0.34}^{1/6}} \text{days}$$

(where the radius and mass are expressed in solar units). However, according to this scaling, one would expect to see also longer plateaus (up to $\sim 130$ days for $17 M_\odot$ progenitors). Dessart et al. (2010) predict $\sim 100$ day plateaus for progenitors with masses up to $25 M_\odot$ but they do not consider heating from radioactive decay of $^{56}$Ni in their simulations and state that their plateau durations are thus only lower limits. Kasen & Woosley (2009) show that $^{56}$Ni indeed extends the duration of the plateau ($0.1 M_\odot$ of $^{56}$Ni extends the plateau by $\sim 24\%$ in their models, without greatly affecting the plateau luminosity). We do not find any of these long-duration plateaus in our sample, though a few such events have been observed (e.g., Hamuy 2002).

A scarcity of observed short plateaus and a possibly related distinction between IIP and IIL light curves is apparent. The number of intermediate events expected in such a small sample is difficult to estimate and is highly model dependent. However, if real, this apparent absence might suggest that Type IIL SNe are powered by a different mechanism than that associated with SNe IIP (e.g., magnetars; Kasen & Bildsten 2010) or are produced by a completely different channel (such as electron capture; Swartz et al. 1991). We note that the jet-driven light curves suggested by Young et al. (2005) are too bright to fit our data.

4. SUMMARY

We identify a subdivision of Type II SNe into three main photometric subclasses as well as several peculiar events among the CCCP sample. The distinct subclass division suggests that

16 Note that SN2005au and SN2005bw are plotted only to show their plateau luminosity, their plateau lengths are unknown due the lack of sufficient constraints on their explosion time.

Type IIP, IIb, and IIL SNe might not be members of one continuous class but instead result from different physical progenitor systems: Type IIP from single RSGs while Type IIb (and by association perhaps also Type Ib) from interacting binaries. Binary models have been shown to be very efficient in stripping stars to produce Type IIb and Ib SNe (e.g., Podsiadlowski et al., 1992; Stancliffe & Eldridge 2009). We do not find any Type IIP events with plateaus longer than $\sim 100$ days, in contrast to theoretical expectations (but see Hamuy 2002). Finally, Type IIL SNe could possibly be related to other physical mechanisms such as magnetars.

Our data set can be used to put SNe into context via their light curves. SN2009kkr, for example, clearly belongs to the IIL subclass, as claimed by Elias-Rosa et al. (2010) and does not behave photometrically like a common SN IIP. SN2003ie, on the other hand, is not consistent with being an SN IIIb, but rather fits the IIP subclass (I. Arcavi et al., in preparation).

We present multi-color light curves of three additional long-lasting events, possibly related to the explosions of blue supergiants (Kleiser et al. 2011; Pastorello et al. 2012) and one peculiar SN which displays an abrupt change in its photometric behavior.

We plan to complete the release of CCCP data in a forthcoming paper. Incorporating multi-color light curves and spectroscopic information into the current analysis promises to shed more light on this intriguing subtype division, and consequently on the possible progenitor scenarios leading to the different SN types.

It is clear that statistical analyses of core-collapse SNe as a population are powerful tools to study the gap in the massive-star–SN mapping. With several large-scale transient surveys underway, additional results are expected in the near future. One such survey, the Palomar Transient Factory (Rau et al. 2009; Law et al. 2009), has discovered, classified, and followed over 400 core-collapse SNe to date, more than half of which are non-interacting Type II events. These larger statistics will help test and better quantify the results presented here.

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