

# The Flavours of SN II Light Curves

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**Abstract.** We present *R*-Band light curves of Type II supernovae (SNe) from the Caltech Core Collapse Program (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 distinct classes: plateau, slowly declining and rapidly declining events. The latter 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. We present also host galaxy trends from the Palomar Transien Factory (PTF) core collapse SN sample, which augment some of the photometric results.

**Keywords.** supernovae: general

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## 1. Introduction

Type II supernovae (SNe) are widely recognized as the end stages of massive H-rich stars. Together with Type Ib/c events, they represent the bulk of observed core collapse SNe (see Filippenko 1997 for a review of SN classifications). Several sub-types 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. A third class of events, Type IIb, characterized by its spectral rather than its photometric properties, develops prominent He features at late times. Finally, 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 (see Smartt 2009 for a review). 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 can not support a plateau in their light curve. SN IIb progenitors, then, would contain an even smaller H mass.

However, if SNe IIP-IIL-IIb 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 Program (CCCP) is a large observational survey which made use of the robotic 60-inch (P60) and Hale 200-inch telescopes at Palomar Observatory to obtain optical *BVRI* photometry and spectroscopy of 48 nearby core collapse SNe.

Light curves of Type Ib/c SNe from CCCP have been presented and analyzed by Drout *et al.* (2011). Type IIIn CCCP events are treated by Kiewe *et al.* (2012). Here we present the *R*-Band photometry of 21 non-interacting Type II SNe with well observed light curves collected through CCCP.

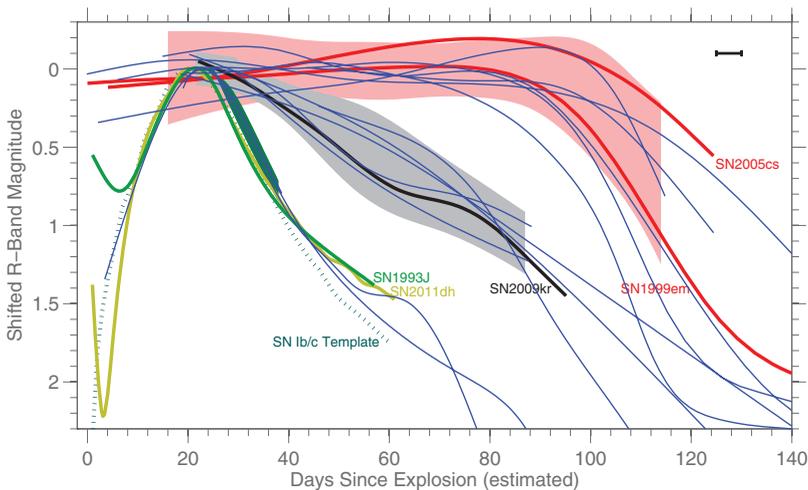
## 2. Photometry

Our light curves are produced using image subtraction via the CPM method (Gal-Yam *et al.* 2008a) for PSF matching. Due to incomplete data for three of the events, we use photometry published in the literature. The light curve of SN2004fx is taken from Hamuy *et al.* (2006), that of SN2005ay from Gal-Yam *et al.* (2008b) and that of SN2005cs from Pastorello *et al.* (2009).

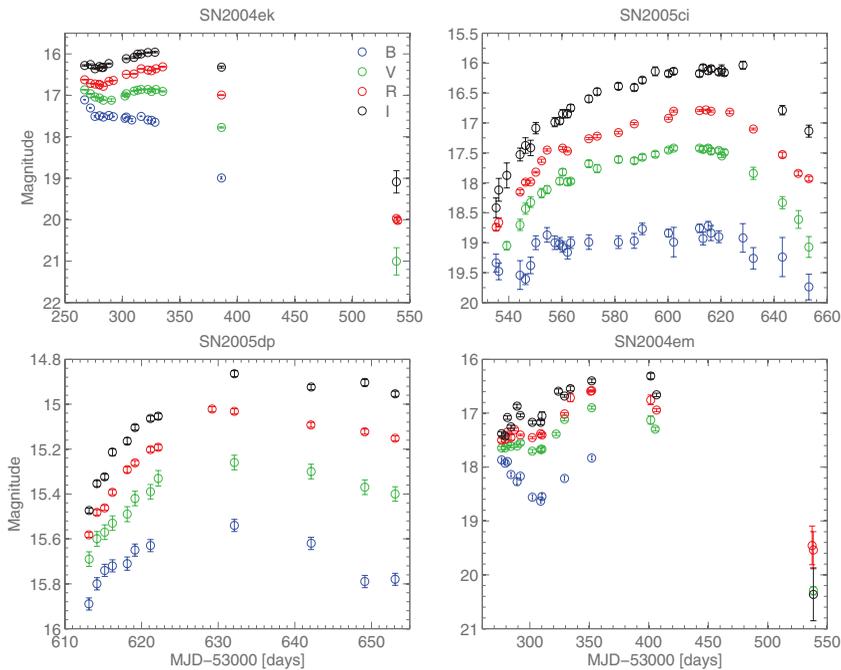
## 3. Results and Discussion

We plot the *R*-Band light curves of 15 Type II events normalized to peak magnitude in Figure 1. Rather than forming a continuum, we find that the light curves group into three distinct sub-classes: plateau, slowly declining (1-2 Mag/100 days) and initially rapidly declining (5-6 Mag/100 days) events. 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).

Three events (SN2004ek, SN2005ci and SN2005dp; Figure 2) 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).



**Figure 1.** *R*-band light curves of 15 Type II SNe from CCCP, normalized in peak magnitude (SN2004fx data taken from Hamuy *et al.* 2006; SN2005ay data taken from Gal-Yam *et al.* (2008b); SN2005cs data taken from Pastorello *et al.* 2009). Reference SNe are shown for comparison (SN1999em from Leonard *et al.* 2002; SN2009kr from Fraser *et al.* 2010; SN1993J from Richmond *et al.* 1994; SN2011dh from Arcavi *et al.* 2011). We also overplot the SN Ib/c template derived by Drout *et al.* (2011). The data have been interpolated with spline fits (except for SN2005by, where a polynomial fit provided a better trace to the data). The shaded regions denote the average light curve  $\pm 2\sigma$  of each subclass. The typical 5-day uncertainty in determining the explosion times is illustrated by the interval in the top right corner.



**Figure 2.** *BVRI* light curves of the CCCP events not included in Figure 1. Three events (SN2004ek, SN2005ci, SN2005dp) show long rise times, while one peculiar event (SN2004em) changes behavior from flat to rising around three weeks after explosion.

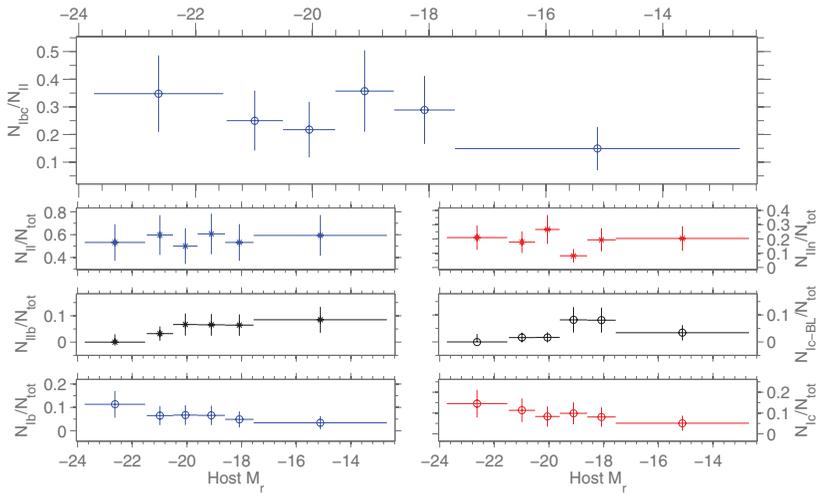
Finally, one event (SN2004em; Figure 2) displays a very peculiar photometric behavior. For the first few weeks it is similar to a Type IIP SN, while around day 25 it suddenly changes behavior to resemble a SN1987A-like event.

### 3.1. Declining SNe

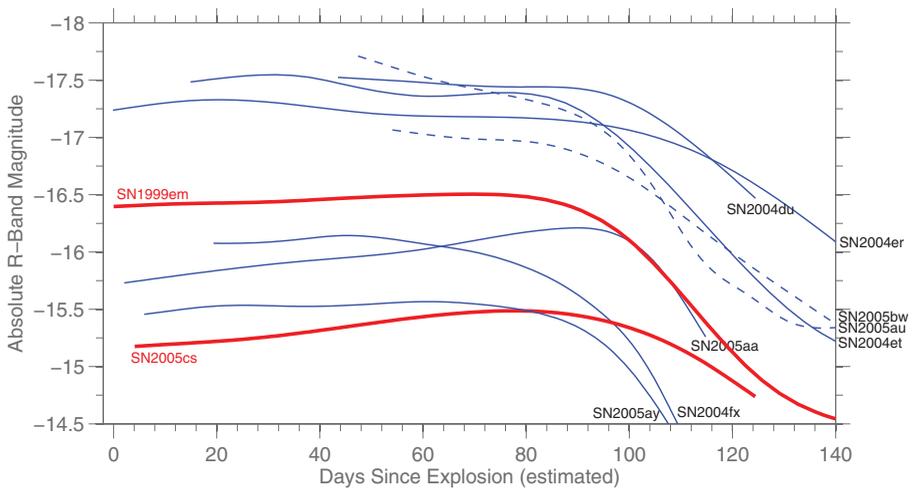
Aside from establishing a different rate of decline for SNe Iib compared to SNe IIL, Figure 1 suggests that the IIP, IIL and Iib subtypes do not span a continuum of physical parameters, such as H envelope mass. Rather, additional factors should be considered. Specifically, Type Iib events might arise 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, Van-Dyk *et al.* 2011). The similarity of the Type Iib light curves to those of Type Ib events (in addition to the known spectral similarities at late times) suggests that these two types of events might come from similar progenitor systems. Metallicity might be an important factor driving some of the systems to explode as Ib SNe and others as Iib's (Fig. 3; Arcavi *et al.*, in prep.).

### 3.2. Plateau SNe

The *R*-Band light curves of the Type IIP SNe, on an absolute magnitude scale, can be seen in Figure 4. 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



**Figure 3.** Core collapse SN fractions as a function of host galaxy luminosity, considered as a proxy for metallicity (Tremonti *et al.* 2004), for 369 events discovered and followed through the Palomar Transient Factory (PTF; Rau *et al.* 2009, Law *et al.* 2009).



**Figure 4.** *R*-band light curves of 9 Type IIP SNe from CCCP (SN2004fx data taken from Hamuy *et al.* 2006; SN2005ay data taken from Gal-Yam *et al.* (2008b); SN2005cs data taken from Pastorello *et al.* 2009) with respect to their estimated explosion time (except for SN2005au and SN2005bw, marked by dashed lines, for which the explosion date is not known to good accuracy). SN1999em (Leonard *et al.* 2002) is shown for comparison. Spline fits were applied to the data

plateau lengths, however, seem rather uniform at  $\sim 100$  days (with the sole exception of SN2004fx, displaying a shorter plateau)<sup>†</sup>.

The scarcity of observed short plateaus and the possibly related sharp distinction between IIP and IIL light curves is evident. Such a pronounced absence of intermediate

<sup>†</sup> 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

events might suggest that Type IIL SNe are powered by a different mechanism than that associated with SNe IIP (e.g., Kasen & Bildsten 2010).

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## Discussion

CHORNOCK: Can you comment on the peak luminosities of the objects you have classified as SNe IIL / slow decliners?

ARCAVI: We do not have the peaks resolved for all these events, but they seem to be confined to the  $-16$  to  $-17$  magnitude range.

CHORNOCK: What about SN 1979C?

ARCAVI: SN 1979C, known as the canonical Type IIL, does not fit into any of the three subtypes we identify in Fig. 1. SN 1979C was exceptionally bright and it is still debated whether it was an interacting event. We therefore choose not to include it in the analysis.

SMITH: You showed different behavior of SNe IIb vs. Ib with host galaxy luminosity (and presumably metallicity). Have you looked for a similar trend with the location within the host galaxy?

ARCAVI: The location within the host galaxy can serve as a proxy for progenitor mass, and is therefore an excellent complementary parameter to check. We hope to be able to conduct this analysis in the future, especially for the very faint host galaxies in the PTF sample (most of which require the resolution of *HST*).

KATZ: Is there a continuous spectrum between SNe Ib and IIb?

ARCAVI: Yes, in fact at late times, the two events have identical spectra (which is why multi-epoch spectroscopy is required to correctly classify them).

Additional discussion points were incorporated into the text.