Analysis of Late–time Light Curves of Type IIb, Ib and Ic Supernovae

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ABSTRACT

The shape of the light curve peak of radioactive–powered core–collapse "stripped–envelope" supernovae constrains the ejecta mass, nickel mass, and kinetic energy by the brightness and diffusion time for a given opacity and observed expansion velocity. Late–time light curves give constraints on the same parameters, given the gamma–ray opacity. Previous work has shown that the principal light curve peaks for SN IIb with small amounts of hydrogen and for hydrogen/helium–deficient SN Ib/c are often rather similar near maximum light, suggesting similar ejecta masses and kinetic energies, but that late–time light curves show a wide dispersion, suggesting a dispersion in ejecta masses and kinetic energies. It was also shown that SN IIb and SN Ib/c can have very similar late–time light curves, but different ejecta velocities demanding significantly different ejecta masses and kinetic energies. We revisit these topics by collecting and analyzing well–sampled single color and quasi–bolometric light curves from the literature. We find that the late–time light curves of all stripped–envelope core collapse supernovae are heterogeneous. The peak behavior is a poor predictor of the late–time light curve. The values for ejecta mass and energy derived from the peak nearly always predict too steep a late–time decline. The physics of the late–time light curves is fairly simple, so the discrepancies may lie in the physics of the peak. These discrepancies may point the way to asymmetries on small or large scales that alter the gamma–ray deposition near peak light or to time–dependent optical opacities that are not captured in simple models.

Subject headings: supernovae: general – physical processes: diffusion, opacity, radiative transfer

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1. Introduction

Ensman & Woosley (1988) made the first detailed quantitative models of SN Ib light curves based on helium cores from massive stellar models. Their models produced less peak–to–tail contrast than the observations. Clocchiatti & Wheeler (1997) noted several apparent properties of “stripped–envelope” supernovae: (1) Some events completely trap gamma–rays for hundreds of days. The only known examples of these slow light curves were SN Ib. (2) Some events display a similar photometric evolution with an intermediate later time rate of decline, similar to SN 1993J, despite their spectral variety, SN IIb, SN Ib, SN Ic. (3) Some events decline especially rapidly from maximum, show an especially large peak to tail contrast, but show a slope comparable to those of the intermediate slope class (point 2) at very late times, over 100 days after maximum. These events all seemed to be SN Ic. Drout et al. (2011) found that the behavior of the light curve peaks of stripped–envelope events were rather similar, with SN Ib and SN Ic having statistically indistinguishable decline rates up to $\sim 40$ days after maximum, implying similar ejecta mass and energy. Taddia et al. (2014) find that SN Ic and SN Ic–BL have shorter rise times than SN IIb and SN Ib, but that the post–peak declines are similar for all categories. Similar decline rates shortly after peak, with some dispersion, were also noted by Cano (2013) and Lyman et al. (2014). This evidence for similar post–peak decline rates belies the long–standing evidence for late–time light curve dispersion. Here, we compile light curve data for late–time light curves of stripped–envelope supernovae and re–investigate the uniformity of the late–time behavior. We concentrate here on light curve properties. See Modjaz et al. (2014) for a recent compilation of spectral properties. Section 2 defines the analytical basis of our analysis. Section 3 presents the data. Section 4 gives some discussion and our conclusions.

2. Peaks and Tails

We analyze data from the literature on the light curves of stripped–envelope supernovae. We did our own compilation, but see Cano (2013) for an independent compilation, including some long–term data of the same events we present here. We estimate the ejecta mass and energy from the observed rise time and photospheric velocity near peak light, and an effective opacity, assumed to be constant. Following Arnett (1982) we write

$$M_{ej} \sim \frac{1}{2} \frac{\beta c}{v_{ph,g}^2} = 0.77 \, M_\odot \left(\frac{\kappa}{0.1 \, \text{cm}^2 \, \text{g}^{-1}}\right)^{-1} \left(\frac{v_{ph,g}}{10^9 \, \text{cm} \, \text{s}^{-1}}\right)^2 \left(\frac{t_r}{10 \, \text{d}}\right)^2,$$

where $\beta = 13.8$ is an integration constant, $c$ the speed of light, $\kappa$ the effective opacity, $v_{ph}$ the velocity at the photosphere and $v_{ph,g}$ in units of $10^9 \, \text{cm} \, \text{s}^{-1}$, and $t_r$ the rise time to maximum light.
light. This equation is based on assumptions of homologous expansion and self-similar diffusion with a power source at the center of spherical ejecta. Two further assumptions are that \( v_{ph} \) is a reasonable proxy for the scaling velocity in the model and that the rise time to maximum light is a reasonable proxy for the effective timescale in the model, \( t_{eff} = \sqrt{2t_d t_h} \), where \( t_d \) is the model diffusion time and \( t_h \) the model hydrodynamical time. In practice, the photospheric velocity will be affected by the distribution of density and opacity and hence may not precisely represent a fixed scaling velocity, the rise time is not exactly equal to \( t_{eff} \) even in the context of the basic model (Chatzopoulos et al. 2013), and the opacity will be constant neither in space nor time.

The corresponding kinetic energy is then

\[
E_{ke} = \frac{1}{2} M_{ej} < v^2 >, \quad (2)
\]

which implicitly defines the mean squared expansion velocity. This velocity cannot be measured directly, so a relation must be adopted between this velocity and the velocity at the photosphere. We adopt the relation for a constant density sphere, \( < v^2 > = 3/5 v_{ph}^2 \). With this relation we can then write

\[
E_{ke} = \frac{3}{10} M_{ej} v_{ph}^2 = \frac{3}{20} \frac{\beta C}{\kappa} v_{ph}^3 t_r^2 = 4.6 \times 10^{50} \text{ ergs} \left( \frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1} v_{ph,9}^3 \left( \frac{t_r}{10 \text{ d}} \right)^2, \quad (3)
\]

so \( E_{ke} \) is proportional to \( v_{ph}^3 \) and hence sensitive to the choice of \( v_{ph} \) and its dispersion among events.

For the late-time tail, we adopt the formalism of Clocchiatti & Wheeler (1997) and define a characteristic timescale

\[
T_0 = \left( \frac{C \kappa \gamma M_{ej}^2}{E} \right)^{1/2}, \quad (4)
\]

where \( C \) is a dimensionless structure constant dependent on the slope of the density profile and is typically \( C \sim 0.05 \), and \( \kappa \gamma \) is the opacity to gamma rays. Using Equation (1) for \( M_{ej} \), this can also be written

\[
T_0 = \left[ \left( \frac{5 \beta C}{3} \right) \left( \frac{C}{v} \right) \left( \frac{\kappa \gamma}{\kappa} \right) \right]^{1/2} t_r = 32 \text{ d} \left( \frac{\kappa \gamma/0.03}{\kappa/0.1} \right)^{1/2} v_{ph,9}^{-1/2} \left( \frac{t_r}{10 \text{ d}} \right), \quad (5)
\]

\(^1\text{Note that there is a typo in Arnett (1982) where the relation between photospheric velocity, kinetic energy and mass is given as } v_{ph}^2 = 3/5(2E_{ke}/M_{ej}). \text{ This error was corrected in Arnett (1996) where the correct relation is given, } v_{ph}^2 = 5/3(2E_{ke}/M_{ej}), \text{ but the error has propagated in the literature in, among other works, Valenti et al. (2008a), Chatzopoulos, Wheeler & Vinko (2012) and Chatzopoulos et al. (2013) who wrote } M_{ej} \sim 3/10 \beta C \kappa t_r^2 \text{ without carefully specifying the prescription for the velocity.}\)
where we take as a fiducial optical opacity $\kappa = 0.1 \text{ cm}^2 \text{ g}^{-1}$ and as a fiducial gamma–ray opacity $\kappa_\gamma = 0.03 \text{ cm}^2 \text{ g}^{-1}$.

We take the radiated power to be

$$L_{in} = L_{\text{decay}} \left(1 - e^{-\left(T_0/t\right)^2}\right),$$

where $L_{\text{decay}}$ is the total input from gamma–rays and positrons from the radioactive decay of $^{56}\text{Ni}$ and $^{56}\text{Co}$ according to

$$L_{\text{decay}} = A\left[e^{-t/t_{\text{Ni}}} + 0.21 \times e^{-t/t_{\text{Co}}}\right],$$

where $A$ is a scaling constant that depends on the initial mass of $^{56}\text{Ni}$, $t_{\text{Ni}} = 8.8 \text{ d}$ is the decay time of $^{56}\text{Ni}$ and $t_{\text{Co}} = 111 \text{ d}$ is the decay time of $^{56}\text{Co}$. For this work, we neglect the difference in the deposition functions of gamma-rays and positrons, but comment on the separate effect of positrons below. Figure 1 gives simple model bolometric light curves with various degrees of gamma–ray leakage as determined by the timescale $T_0$. Values of $T_0$ estimated from Equation 4 and determined from observations for a sample of stripped–envelope supernovae are presented in Table 1.

Fig. 1.— Model light curves for a range of the gamma-ray trapping timescale $T_0$ (arbitrary normalization). A trapping timescale of infinity corresponds to total trapping of gamma-rays from radioactive $^{56}\text{Ni}$. In these figures, positrons are assumed to have the same effective opacity as gamma-rays.
Table 1. Estimated vs. Observed Timescale of Late–Time Decay of Stripped–Envelope Supernovae

| Event | Type | $v_{ph}$ $10^3 km/s^{-1}$ | $t_{rise}$ M | $E_{ke}$ $10^{51}$ erg | $T_0$ Est.(d) | $T_0$ Obs.(d) | Band |
|-------|------|-----------------|-----------------|-----------------|-----------------|-----------------|------|
| 83N   | Ib   | 7.8             | [16]            | 1.5             | 0.56            | 36              | 166 ± 16       | V    |
| 83V   | Ic   | 14              | [20]            | 4.3             | 5.0             | 54              | 151 ± 7        | B    |
| 84L   | Ib   | 10              | [20]            | 3.1             | 1.8             | 64              | 660 ± 109      | V    |
| 90B   | Ic   | 11              | [20]            | 3.4             | 2.4             | 61              | 113 ± 5        | R    |
| 93J   | IIb  | 7.5             | 17              | 1.7             | 5.6             | 63              | 135 ± 5        | Bol  |
| 94I   | Ic   | 11.5            | 9               | 0.72            | 0.57            | 27              | 115 ± 6        | R    |
| 96cb  | IIb  | 9               | 25              | 4.3             | 2.1             | 85              | 152 ± 15       | R    |
| 98bw  | Ic   | 14              | 14.4            | 2.2             | 2.6             | 39              | 192 ± 6        | R    |
| 99dn  | Ib   | 10              | [15]            | 1.7             | 1.0             | 48              | 220 ± 14       | R    |
| 02ap  | Ic   | 15              | [9]             | 0.94            | 1.3             | 24              | 186 ± 8        | Bol  |
| 03jd  | IIb  | 14              | [20]            | 4.3             | 5.0             | 54              | 237 ± 81       | R    |
| 04aw  | Ic   | 16              | [35]            | 15              | 23              | 89              | 206 ± 123      | R    |
| 07Y   | Ib   | 9               | 15              | 1.6             | 0.75            | 51              | 114 ± 1        | r'   |
| 07gr  | Ic   | 6.4             | 15              | 1.1             | 0.27            | 60              | 157 ± 4        | R    |
| 08D   | Ib   | 10              | 20              | 3.1             | 1.8             | 64              | 107 ± 3        | R    |
| 08ax  | Ib   | 8               | 22              | 3.0             | 1.1             | 79              | 175 ± 11       | Bol  |
| 09bb  | Ic   | 25              | [9]             | 1.6             | 5.8             | 18              | 57 ± 20        | R    |
| 09jf  | Ib   | 10              | 25              | 4.6             | 2.8             | 79              | 315 ± 24       | R    |
| 11bm  | Ic   | 7.5             | 45              | 12              | 3.9             | 170             | 308 ± 41       | R    |
| 11dh  | IIb  | 6.9             | 22              | 2.5             | 7.3             | 85              | 210 ± 10       | R    |
3. Analysis

To estimate $M_{ej}$, $E_{ke}$, and $T_0$, we use data from the literature. Some of the supernovae that we discuss here have estimated UBVRI quasi–bolometric light curves, but not all. We have used the R–band as a proxy that allows us to treat most of the events in a somewhat homogeneous way, but also compare to bolometric data where it is available. For events with only R–band data, we neglect bolometric corrections and assume that the R–band light curves are proxies of the bolometric luminosity to within a constant scaling factor (See Lyman et al. 2013 for a discussion of estimating bolometric corrections for stripped–envelope supernovae). Figure 2 gives a comparison of the R–band and UVOIR light curves of three events, Type IIb SN 1993J, and two broad–lined SN Ic, SN 1998bw, and SN 2002ap, normalized at peak light. This figure shows that, for these events, the R–band is a reasonable representation of the quasi–bolometric light curve to times of hundreds of days. We have ignored reddening corrections for our R–band light curves, but such corrections have been made by the original authors who present the quasi–bolometric data. It seems unlikely that the results we present here are simply the result of variance in reddening. In some cases of sparse or absent R–band data, we employ V–band or other available data.

The sample for which there is good rise time data as well as long–time tail data is still sparse. The peak is used to estimate the rise time, $t_r$. For many of the more recent events and for some earlier nearby events, there is pre–maximum photometry. In the best cases, there are reasonably accurate estimates of the time of explosion (SN 1993J, Richardson et al. 1994; SN 2008D, Malesani et al. 2009, Modjaz 2009). In other cases, the earliest data are up to two weeks prior to peak and thus are a good representation of the rise time (SN 1998bw, Patat et al. 2001; SN 1994I, Richardson et al. 1996; SN 1999dn, Benetti et al. 2011; SN 2007Y Stritzinger et al. 2009; SN 2007gr, Valenti et al. 2008a; SN 2009jf, Sahu et al. 2011; SN 2011bm, Valenti et al. 2012; SN 2011dh, Ergon et al. 2014, Marion et al. 2014). Note that even in these cases, the R–band peak may be delayed from the bolometric peak by several days. We have used the time to R–band peak in most cases, but recognize that some ambiguity is introduced in this way.

In yet other cases there is some pre–maximum data, but not as extensive as the previous cases. For cases where there is pre–maximum data more than a magnitude dimmer than maximum, we use the time from first observation to the peak in R–band as an estimate for the rise time. This is an underestimate by perhaps several days, or typically 10 – 20%. Examples are SN 1983N (FES data; Clocchiatti et al. 1997), SN 1996cb (Qui et al. 1999), SN 2002ap (Tomita et al. 2006), SN 2004aw (Taubenberger et al. 2006), and SN 2009bb (Pignata et al. 2011).

In other cases, there is little or even no pre–maximum data. In these cases, we make
Fig. 2.— Comparison of R–band and quasi–bolometric light curves for three supernovae: SN 1993J (upper left panel); SN 1998bw (upper right panel); SN 2002ap (lower panel). Data are from Barbon et al. (1995); Richmond et al. (1994); Zhang et al. (2004) (SN 1983J); Patat et al. (2001) (SN 1998bw); and Tomita et al. (2006) (SN 2002ap).

estimates based analogies to other events (SN 1983V, Clocchiatti et al. 1997; SN 1984L, Swartz & Wheeler 1991) or on the decline from maximum and estimate the time to decline by a magnitude from peak (SN 1990B, Clocchiatti et al. 2001). The light curves of the stripped–envelope events are typically asymmetric around the peak with more rapid rise than decline, so this post–maximum decline timescale almost surely overestimates the rise time. In these various cases, we have put our estimates in square brackets in Table 1 to highlight the uncertainty. The rise time comes in squared in the estimates of the mass and energy, so these estimates should be considered with caution.

Taddia et al. (2014) give a table containing observed R–band rise times. Most of these agree with our choices, but there are some discrepancies. We chose 17 days for the rise for SN 1993J versus 22.53 days for Taddia et al. Our estimate is measured from the
early minimum in the light curve, ignoring the initial fireball decline phase. We assume the subsequent rise is more representative of other events that were not caught so early and of the diffusion time we are attempting to constrain. We chose 15 days for SN 2007Y from Stritzinger et al. (2009), versus the 21 days assigned by Taddia et al. The latter seems to involve some extrapolation even beyond the early V-band data, but our value is surely a lower limit.

Estimates of velocity are taken from photospheric velocities given in the literature. For uniformity, we have tried to select whenever possible the velocity of the P Cygni absorption minimum of Fe II λ5169 measured at R-band maximum. While this line may be relatively free of blending, as may affect estimates based on Si II, there are still issues. In particular, the velocity measured in this way often declines rather rapidly from pre-maximum to post-maximum epochs. Velocities at bolometric maximum several days earlier would usually have been somewhat higher and there is the general concern as to whether any velocity measured in this way properly represents the scale velocity of the underlying model. Such considerations come in especially sensitively in estimates of the energy. Cano (2013) and Lyman et al. (2014) also give compilations of photospheric velocities. In general, our estimates agree with theirs to within 20%. Exceptions are SN 2004aw where we determined 16,000 km s$^{-1}$, Cano gave 11,800 km s$^{-1}$ and Lyman et al. give 11,000 km s$^{-1}$, and SN 2009bb, for which we determined 25,000 km s$^{-1}$, Cano gave 15,000 km s$^{-1}$, and Lyman et al. gave 17,000 km s$^{-1}$.

The rise time and photospheric velocity are used to estimate the ejecta mass and kinetic energy from Equations 1 and 2. These quantities, especially the energy, are sensitive to the velocity, as noted above. The rise time and photospheric velocity are also used to estimate the decay parameter, but, from Equation 4 the value of $T_0$ only depends linearly on the rise time and on the square root of the velocity. Uncertainty in these parameters are relatively unimportant to that particular quantity. The effects in which we are interested are typically factors of several in $T_0$, as illustrated in Table 1.

We also use the late-time light curves to directly determine an estimate of $T_0$ and one standard deviation error bars by minimizing the $\chi^2$ of the fit of Equation 6 to the data. To minimize the effect of scatter in the peak data, we only use the data after 50 days from maximum to determine the observed value of $T_0$. Table 1 also gives the measured and estimated values of the various parameters. The error given for SN 2007Y is especially, and probably artificially, low because there is sparse late-time data that is easy to fit.

For some objects in the sample here, Clocchiatti et al. (2008) also estimated values of $T_0$ from UBVRI quasi-bolometric light curves. Comparing the values derived here (first numbers, R-band; the numbers in parentheses are our estimate of the value based on quasi-bolometric data) with those given by Clocchiatti et al. (second numbers) we find: SN 1994I,
115 d vs. 65 d; SN 1998bw, 192 (283) d vs. 120 d; SN 2002ap, 186 (202) d vs. 142 d; SN 1990B, 113 d vs. 88 d. There are differences of 10 to 30% with our estimates somewhat on the high side, but again we are interested in discrepancies of factors of several. SN 1994I seems the most discrepant, but since it suffers an especially rapid decline at first and relatively slower later, the fits may not be done in precisely the same way. See also Figure 7.

Figures 3, 4, and 5 give the light curves we have compiled. For comparison purposes, the light curves have been shifted in time to a common peak and have been normalized to an arbitrary magnitude of 15.

Fig. 3.— R–band light curves of a sample of SN IIb. Note the similar behavior around maximum and the very similar late–time light curves of SN 1993J and SN 2011dh for nearly 250 days, but the variation in the decline rate manifested by SN 1996cb (slower) and SN 2003jd (faster after peak, but comparable to SN 1993J later). The dot–dash line represents the total trapping of the energy of radioactive decay. Data are from Barbon et al. (1995); Richmond et al. (1994); Zhang et al. (2004) (SN 1993J); Qiu et al. (1999) (SN 1996cb); Valenti et al. (2008b) (SN 2003jd).

Figure 8 gives a sample of 4 SN IIb. They are all rather similar near peak, with similar rise times and early declines, but substantial departures from homogeneity set in beginning about 30 days after maximum. The long–term light curves of these events are distinctly steeper than that given by full trapping of gamma-rays from $^{56}$Co decay. There is a clear dispersion of the late–time decay times despite the similarity of the light curves near peak and the common spectral class. SN 1993J and SN 2011dh show very similar late–time light curves for nearly 350 days. SN 2003jd falls more steeply around 30 days after peak, but has a similar rate of decline at later times. SN 1996cb is slower at late time than the others. Its
decay after 100 days is similar to that of total trapping, but a contribution from circumstellar interaction cannot be ruled out.

Fig. 4.— R–band light curves of a sample of SN Ib. Note the significant dispersion in the decline rate at late time. The dot–dash line represents the total trapping of the energy of radioactive decay. Data are from Clocchiatti et al. (1996) (SN 1983N); Swartz & Wheeler (1991) (SN 1984L); Benetti et al. (2011) (SN 1999dn); Stritzinger et al. (2009) (SN 2007Y); Sahu et al. (2011) (SN 2009jf).

Figure 5 gives a sample of 7 SN Ib. We have plotted V–band data for SN 1983N, r’–band data for SN 2007Y, and bolometric data for SN 2008D and SN 2008ax. These seven events again are rather similar on the rise. SN 1984L flattens to be comparable to the radioactive decay slope, but SN 1984L was a late–time radio emitter, so there might be some contribution to the light curve from collision with a circumstellar medium. SN 1999dn and SN 2009jf are similar on the tail for the first 100 days. SN 2009jf subsequently falls at a rate roughly comparable to cobalt decay until at least 250 days, but SN 1999dn falls more steeply at 300 to 400 days. SN 1983N, SN 2007Y, SN 2008D and SN 2008ax fall at somewhat steeper and very similar rates at late times, with SN 2008D being the steepest of this group.

Figure 5 gives a sample of 9 SN Ic. We have plotted B–band data for SN 1983V. There appears to be some true dispersion in the early peak widths. SN 2011bm has a distinctly wider peak. SN 1994I falls especially rapidly. SN 2009bb nearly rivals SN 1994I in terms of steepness of post–maximum decline. There is clearly a large dispersion in the rate of decay of the late–time tails. SN 2011bm continues to decline slowly, with a late–time decay very comparable to that expected for $^{56}$Co decay. The late–time light curves of the broad-line Type Ic SN 1998bw and SN 2002ap are very similar, with SN 2004aw declining somewhat
Fig. 5.— R–band light curves of a sample of SN Ic. The data for SN 1983V are V–band. Note the distinct rapid rise and decline of SN 1994I and the slower rise and decline of SN 2011bm. The post–peak decay of SN 2011bm closely follows the radioactive decay line. Otherwise, the relative homogeneity of the peaks leads to a large dispersion of late–time tails. The dot–dash line represents the total trapping of the energy of radioactive decay. Data are from Clocchiatti et al. (1997) (SN 1983V); Clocchiatti et al. (2001) (SN 1990B); Clocchiatti et al. (2008) (SN 1994I); Patat et al. (2001) (SN 1998bw); Tomita et al. (2006) (SN 2002ap); Taubenberger et al. (2006) (SN 2004aw); Pignata et al. (2011) (SN 2009bb); Valenti et al. (2012) (SN 2011bm).
more slowly and SN 1990B somewhat more rapidly. The light curve of SN 1994I flattens at very late times (300 days), which may have to do with partial trapping of positrons (Clocchiatti et al. 2008).

Figure 6 gives a selected sample of light curves that seem, by eye, to fall into two categories in terms of late–time tails. One group has a decline roughly comparable to $^{56}$Co decay, and the other is significantly steeper. Type Ib SN 1984L, Type Ic SN 2011bm, and perhaps Type Ib SN 2009jf are the only examples in our sample of late-time light curves that track $^{56}$Co decay (corresponding to very large values of $T_0$). As remarked above, the late–time light curves of the Type Ib SN 1999dn and SN 2009jf are very similar up to 100 days with SN 1999dn perhaps tracking $^{56}$Co decay. Later data on SN 1999dn fall below this early common trend. Most stripped–envelope supernovae decay considerably faster than expected for complete trapping of $^{56}$Co, as expected for rather low–mass, rapidly–expanding ejecta.

Fig. 6.— Light curves of a selected sample of SN IIb, Ib, and Ic with similar late–time decay rates. Note the relative homogeneity of the peaks and the bifurcation (in this small sample) of the late–time light curves into two groups. The slower–declining group has only SN Ib, but the more rapidly–declining group contains SN IIb, SN Ib and SN Ic, including high–velocity SN Ic. The dot–dash line represents the total trapping of the energy of radioactive decay. References to data are given in previous captions.

The assortment of light curves of other SN Ib, SN Ic, including some broad–line SN Ic, and SN IIb in Figure 6 are also rather similar, but with a distinctly different, steeper slope. Interestingly, this group comprises 11 of our sample of 20 events. This group includes SN 1983V, but we note that the data are B–band, so the decline rate may be exaggerated.
The light curves of SN 1983V in both V–band and B–band were very similar to those of SN 1993J in the respective bands (Clocchiatti et al. 1997), and the light curve we plot here is very similar to that of SN 1993J in R–band at late times, but it is appropriate to regard this comparison with some caution. There appears to be some dispersion in peak width for this particular subsample. Figure 6 illustrates that neither spectral type nor similar peak light curves determine the slope of the late–time tail, and that events of different spectral type can have remarkably similar late–time tails, as emphasized by Clocchiatti et al. (1996, 1997). The spectra and light curves of SN Ib/c at maximum light are not sufficient to classify them. Figure 7 presents data for two events that decay more rapidly at late times than most. Both are SN Ic. SN 1994I seems to fall more rapidly from peak than SN 1990B.

Fig. 7.— Light curves of two stripped-envelope supernovae with rather steep late–time decay rates, both SN Ic. The dot–dash line represents the total trapping of the energy of radioactive decay. References to data are given in previous captions.

We have fit the late–time data to determine the value and one standard deviation uncertainty of the parameter $T_0$ for each of the events we consider here. To make the fitting more efficient, we have only considered data on the tail after 50 days from maximum. These values are presented in Table 1. For illustration, we have also made an analytic fit to the group of 11 events that form a nearly common locus in Figure 6. Restricting the analysis to more than 50 days from maximum, we can neglect the contribution of the $e^{-t/T_0}$ term in Equation (7). Anticipating that $T_0$ is fairly large, then at 50 days the term $e^{-(T_0/t)^2}$ in Equation (7) is essentially zero and can also be neglected. Making those two assumptions, one can write the magnitude $M = -2.5 log L + K$ at the two epochs, 50 days and 400 days, where the similar track in Figure 6 passes through about magnitude 17 and 22.5, respectively.
Using these values, the resulting parameter is $T_0 = 158$ days, a reasonable estimate to the range of values for these 11 events presented more formally in Table 1.

Table 1 gives for our sample of events, the observed values of $v_{ph}$, $t_r$, and $T_0$, along with the derived values of $M_{ej}$, $E_{ke}$, and the value of $T_0$ estimated from them. This exercise shows clearly that the values of $M_{ej}$ and $E_{ke}$ derived from the peak behavior are poor predictors of the late–time behavior. The discrepancies are not subtle. The directly measured values of $T_0$ occasionally agree within a factor of two of those estimated from the peak properties, but the discrepancies are routinely factors of 2 to 4, and can be as much as a factor of 10 (SN 1984L). In no case is the estimate of $T_0$ from the peak properties greater than that determined from direct observations of the late–time tail.

4. Conclusions

We confirm that the late–time light curves of stripped–envelope core–collapse supernovae are heterogeneous. The peak behavior is a poor predictor of the late–time light curve. The values for ejecta mass and energy derived from the peak and the parameters that determine them essentially always predict too steep a late–time decline. The physics of the late–time light curves is fairly simple, so the discrepancies may lie in the physics of the peak, despite the similarity of post–peak decline determined by Drout et al. (2011), Cano (2013), Taddia et al. (2014) and Lyman et al. (2014). These discrepancies may point the way to asymmetries on small or large scales that alter the gamma–ray deposition near peak light. Care must be taken with values of the ejecta mass and kinetic energy derived with simple estimates based only on the properties of the peak.

Our primary goal was not to derive ejecta masses and kinetic energies, rather to caution that these quantities can be sensitive to the way the data is selected and employed. Nevertheless, we can compare these quantities with related work. We note that Drout et al. (2011) employed a measure of the rate of decline to determine estimates of masses and energies, but that this time was in some instances shorter than the observed portion of the rise. The rise times we present in Table 1 are typically a factor of 2–3 larger than those given for the same events by Drout et al. Drout et al. also assigned $v_{ph}$ in only two bins, 10,000 km s$^{-1}$ for SN Ib and normal SN Ic and 20,000 km s$^{-1}$ for SN Ic-BL. This will tend to mute the true dispersion of the physical properties of the supernovae. Also in contrast, Cano (2013) gives mean values for $v_{ph}$ for SN Ib of 8027 km s$^{-1}$, for SN Ic of 8470 km s$^{-1}$, and for SN Ic-BL of 15,114 km s$^{-1}$. Cano does not discriminate between $v_{ph}$ and <$v>$ as we have here. We tend to assign lower values of $M_{ej}$ and $E_{ke}$ than does Cano (for SN 1983N, SN 1999dn, SN 2002ap, SN 2007gr, SN 2008D, SN 2009jf, and SN 2011bm), but agree rather closely in
several cases (SN 1994I, SN 2003jd, SN 2007Y, and SN 2009bb). We assign higher values than Cano for SN 2004aw. We cannot compare directly to Taddia et al. (2014) because their sample was based on SDSS objects not discussed in the general literature. The fits of Taddia et al. were mostly for light curves of less than 60 days after maximum. Their fitting procedure also involved a construction that employed more parameters than do ours. In a sense, the ratio of our values, $T_{0,\text{obs}}/T_{0,\text{est}}$, is another parameter determined by our process. Lyman et al. (2014) also use a measure of the decline rate, rather than the rise, to determine the characteristic light curve “width” and employ a two–parameter fitting procedure similar to that of Taddia et al. to fit light curve properties up to about 80 days after maximum.

The analysis of the light curves of stripped–envelope supernovae has a long history. Ensman & Woosley (1988) invoked clumping as a possible way to address the difficulty of reproducing the peak/tail contrast. Clocchiatti & Wheeler (1997) invoked the possibility that the dynamics were in some fashion “non–homologous” with part of the ejecta remaining in a dense core. Maeda et al. (2003) constructed a two–component model that could fit the data better by dint of having extra parameters. They ascribed the second component to a dense inner region, analogous to the “non–homologous” component of Clocchiatti & Wheeler, to asymmetries in the explosion. Subsequent work has also invoked simple models with more parameters and hence more elaborate fits (Cano et al. 2014; Taddia et al. 2014; Lyman et al. 2014). These models, as ours here, may give hints of the effects of asymmetry in the explosion, but are clearly inadequate to the task of understanding the cause and nature of the asymmetry.

We have emphasized here that similarity of peak light does not necessarily predict similarity of late–time tails of stripped–envelope supernovae. We have also emphasized that explosion parameters derived from the peak are frequently incommensurate with those derived from the tail. Even the subset of events that have similar peaks and tails are discrepant in that regard. Nevertheless, it is striking that this subset exists with similar peaks and similar tails comprising events of all stripped–envelope spectral types, SN IIb, SN Ib, and SN Ic, and with a range of photospheric velocities. Amid the diversity we emphasize, there is a uniformity that demands deeper understanding.

Clocchiatti et al. (1997) emphasized the depths of the conundrum that events with similar late–time tails but different spectral types and different photospheric velocities present. From Equation (4), two events with the same value of $T_{0,\text{obs}}$ must have a (nearly) constant value of $M_{2}^{2}/E_{ke} = 4E_{ke}/<v^{2}>$. The similar late–time light curves would then require some very unexpected correlation between the kinetic energy and ejecta mass and with the mean, and hence presumably photospheric, velocity. Now, as then, the problem posed by the similar light curves and different velocities is not subtle.
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