Are Superluminous Supernovae Powered By Collision Or By Millisecond Magnetars?

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ABSTRACT

Using our previously derived simple analytic expression for the bolometric light curves of supernovae, we demonstrate that the collision of the fast debris of ordinary supernova explosions with relatively slow-moving shells from pre-supernova eruptions can produce the observed bolometric light curves of superluminous supernovae (SLSNe) of all types. These include both, those which can be explained as powered by spinning-down millisecond magnetars and those which cannot. That and the observed close similarity between the bolometric light-curves of SLSNe and ordinary interacting SNe suggest that SLSNe are powered mainly by collisions with relatively slow moving circumstellar shells from pre-supernova eruptions rather than by the spin-down of millisecond magnetars born in core collapse supernova explosions.

Subject headings: supernovae: general

1. Introduction

For a long time, it has been widely believed that the observed luminosity of all known types of supernova (SN) explosions is powered by one or more of the following sources: radioactive decay of freshly-synthesized elements, typically $^{56}$Ni (Colgate and McKee 1969; Colgate et al. 1980), heat deposited in the envelope of a supergiant star by the explosion shock (Grassberg et al. 1971), and interaction between the SN debris and the circumstellar wind environment (Chevalier 1982). Recently, however, a new type of SNe, superluminous SNe (SLSNe) whose peak luminosity exceeds $10^{44}$ ergs per second, much brighter than that of the brightest normal thermonuclear supernovae (type Ia) and core collapse supernova (types Ib/c and II) was discovered by modern supernova surveys. The first discovered SLSNe was SN2006gy (Quimby 2006; Quimby et al. 2007) in the Texas Supernova Search (Quimby et al. 2005) and followed by Smith et al. (2007,2008) and by Ofek et al. (2007). A few more

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SLSNe were discovered in the Texas Supernova Search and many more in deeper and wider surveys with the Palomar Transient Factory (PTF, Rau et al. 2009), the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS, Kaiser et al. 2010), the Catalina Real-time Transient Survey (CRTS, Drake et al. 2009), and the La Silla QUEST survey (Hadjiyska et al. 2012). In analogy to the spectroscopic classification of ordinary SNe, Gal-Yam (2012) has recently classified SLSNe into two distinct groups, Hydrogen-rich events (SLSN Type II) and events lacking spectroscopic signatures of hydrogen (SLSNe Type I), which was further divided into a minority of events whose luminosity appears to be dominated by radioactivity (SLSN-R) and a majority that require some other source of luminosity (SLSN-I).

Following the discovery of SN2006gy, Woosley, Blinnikov and Heger (2007) suggested that it is a pair-instability supernova explosion (Rakavy and Shaviv 1967; Barkat et al. 1967) of a very massive star whose luminosity was powered by radioactive \( ^{56}\text{Ni} \) (see also, Kasen et al. 2011) synthesized in the SN explosion. However, the peak luminosity of SN2006gy, \( L_p \approx 3 \times 10^{44} \, \text{erg s}^{-1} \) at peak-time \( t_p \approx 70 \, \text{d} \) (Smith et al. 2007; Ofek et al. 2007), would have required the synthesis of more than 40 \( M_\odot \) of \( ^{56}\text{Ni} \) (See Eq. (6)), which is highly implausible. Consequently, Smith and McCray (2007) suggested that the light-curve of SN2006gy was produced by an SN blast wave that breaks free of an opaque circumstellar shell into a surrounding wind.

An alternative power-source of the luminosity of SLSNe that has been suggested more recently is the spin-down of a millisecond magnetar born in SN explosions of massive stars (Kasen & Bildsten 2010; Woosley 2010).\(^1\) Magnetars were suggested before to power soft gamma repeaters (Katz 1982; Thompson and Duncan 1995; Kouveliotou et al. 1998), anomalous X-ray pulsars (Thompson and Duncan 1996) and gamma ray bursts (Usov 1992; Zhang and Meszaros 2001). However, despite their popularity, there are unresolved problems with magnetar models (e.g., Katz 2013), which were realized long ago and led to alternative conventional explanations for the rapid spin down of slowly rotating neutron stars, their energy source, and the observed properties of soft gamma-ray repeaters (SGRs), anomalous X-ray pulsars (AXPs), and gamma ray bursts (GRBs). E.g., rapid braking of neutron stars can be due to emission of relativistic particles/wind/jets along their open magnetic field lines (e.g., Marsden et al. 1999; Dar and De Rújula 2000a) rather than by magnetic dipole radiation. Their bursts and steady state emission can be powered by a sudden or gradual local or global phase transition/contraction to a more condensed state (Dar and De Rújula 2000a). More-

\(^1\)Ordinary magnetars are slowly rotating neutron stars with observed periods \( P \sim 2 - 12 \, \text{s} \) and \( \dot{P} \sim 10^{-13} - 10^{-10} \), whose internal magnetic fields are believed to be \( B \sim 10^{14} - 10^{15} \) Gauss in excess of the quantum critical value \( B_{\text{QED}} = 4.4 \times 10^{13} \) Gauss. Their huge magnetic field energy was inferred from the assumption that their observed spin-down rate is due to magnetic dipole radiation.
over, recent measurements of the period derivatives of SGRs 0418+5729 and 1822-1606 (Rea et al. 2010, 2012, respectively), and 3XMM J185246.6+003317 (Rea et al. 2013), imply that their dipole magnetic fields are well in the range of ordinary radio pulsars and challenge the magnetar model of SGRs and AXPs. In fact, magnetars are needed to explain the observed properties neither of SGRs and AXPs nor of GRBs, and may just be a fiction.

Long duration GRBs and their afterglow are very well explained by the cannonball (CB) model of GRBs (e.g., Dar & Rújula 2004; Dado et al. 2009 and references therein). In the CB model, long duration GRBs are produced by inverse Compton scattering of glory\(^2\) by highly relativistic bipolar jets of plasmoids (cannonballs) of ordinary matter, which presumably are ejected in mass accretion episodes of fall-back material on the newly formed central object (neutron star or black hole) in stripped-envelope supernova explosions. Such a circumstellar (cs) surroundings of stripped-envelope core collapse SN explosions can explain (Dado and Dar 2012) the bolometric light-curves of both SLSNe-I and SLSNe-II as a plastic collision between the fast debris from core collapse SN explosions of types Ic (SNeIc) and IIn (SNeIIn) and the slower massive circumstellar shells (Dado and Dar 2012): SLSNe of types I and II could simply be ordinary SNeIb/c and SNeIIn, respectively, which become superluminous by such collisions. Moreover, Dado and Dar (2012, 2013) have demonstrated that the bolometric light curves of SNeIb, SLSNe-I, SNeIb/c and SLSNe-Ib/c can all be well described by a simple analytic expression (a universal master formula) for the light curves of supernova explosions powered by an ordinary amount of radioactive \(^{56}\text{Ni}\) and dominated by the collision of the SN debris with pre-supernova ejecta.

Recently, however, Inserra et al. (2013) and Nicholl et al. (2013) have demonstrated that using a spinning-down millisecond magnetar as a power-source in the master formula derived by Dado and Dar (2013) for the bolometric light curves of SN explosions, they could reproduce quite well the bolometric light curves of SLSNe-Ic\(^3\). They concluded that the light-curves of all known SLSNe-Ic may be explained by spinning down millisecond magnetars. But so far the magnetar model has not been demonstrated to be able to explain multi-peak bolometric light-curves or fast decline light curves of some SLSNe-Ic as well as SLSNe-II.

In contrast, in this letter we demonstrate that a mass of radioactive \(^{56}\text{Ni}\) similar to that synthesized in ordinary SNeIc/b and SNeIIn explosions plus collision of the fast SNe debris

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\(^2\)The glory is a light halo around the progenitor star, a Wolf Rayet (WR) or large blue variable (LBV), formed by stellar light scattered from circumstellar shells blown from the progenitor star in eruptions prior to its SN explosion.

\(^3\)Inserra et al. (2013) obtained the master formula that was derived by Dado and Dar 2013, by combining Eqs. 31, 32, and 36 of Arnett 1982.
with slowly expanding dense circumstellar shells formed by eruptions before the SN explosion can explain well the observed bolometric light curves of all types of SLSNe, including those with a multipeak structure (two or more peaks) such as SN2006oz (Leloudas et al. 2012) and PTF12-dam (Nicholl et al. 2013), or with a sudden fast late-time decline such as that of SN2006gy (Smith et al. 2008). Such bolometric light-curves that look similar to those of ordinary interacting SNeIb/c and SNeIIn, such as SN2005bf (Folatelli et al. 2006), SN2009ip (Pastorello et al. 2013; Margutti et al. 2013) and SN2010mc (Ofek et al. 2013) are shown in this letter to be well explained as interacting SNe. This suggests that SLSNe types I and II can simply be ordinary SNeIb/c and SNeIIn, respectively, which are powered by the decay of an ordinary amount of $^{56}$Ni and become superluminous mainly by the interaction of their fast SN debris with massive circumstellar shells.

2. The master equation for supernova light curves

Dado and Dar (2013) have derived a simple master formula for the bolometric luminosity $L_b(t)$ of SN explosions approximated by a fireball with homologous expansion and photon escape by random walk to its surface,

$$L_b(t) = \frac{e^{-t^2/2t_r^2}}{t_r^2} \int_0^t t e^{t^2/2t_r^2} \dot{E} \, dt. \quad (1)$$

where $t$ is the time after shock break out, $\dot{E}(t)$ is the energy deposition rate in the SN fireball, and the mean escape time of optical photons by diffusion has the approximate time-behaviour, $t_{\text{diff}} = t_r^2/t$ with a diffusion time scale (the time when $t_{\text{diff}} = t_r = t$),

$$t_r \approx \left[\frac{3 M f_e \sigma_T}{8 \pi c V}\right]^{1/2}, \quad (2)$$

where $M$ is the expanding mass, $V$ is its expansion velocity, $f_e$ is the fraction of free (ionized) electrons in $M$ and $\sigma_T$ is the Thomson cross section.

Assuming that the 3s and 3p electrons outside the neon-like closed shells core of intermediate mass elements, such as Mg, Si, and S, are ionized, one obtains $f_e(Si) \approx 0.285$ whereas, e.g., for cobalt the 4s and 3d electrons outside the argon-like closed shell core, are ionized yielding $f_e(Co) = 0.333$. For $f_e \approx 0.31 \pm 0.03$ we expect $t_r \approx (9 \pm 1) (M/M_\odot)^{1/2}$ day.

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4 In many distant SLSNe, where only a modest mass of $^{56}$Ni is synthesized in the explosion, the initial SNe may not be bright enough to be visible or resolved from the SLSNe light curve.
3. The power supply in interacting SNe

For the sake of simplicity, let us assume that SLSNe are powered by the radioactive decay chain $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, which begins at $t=0$, and by plastic collision that begins later at time $t_c > 0$ between the expanding fireball and a circumstellar mass, which was blown off from the progenitor star sometime before the explosion and expands with velocity $V_{cs} \ll V$. Hence $\dot{E} = \dot{E}_r + \dot{E}_c$ and $L_b(t) = L_r(t) + L_c(t)$, where the subscripts $r$ and $c$ denote radioactivity and collision, respectively.

**Radioactive Power:** Energy deposition by Gamma-rays and positrons emitted in the decay chain $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ can power SN light-curves at a rate $\dot{E}_r = \dot{E}_{\gamma} + \dot{E}_{e^\pm}$, where,

$$\dot{E}_{\gamma} = \frac{M(^{56}\text{Ni})}{M_\odot} [A_{\gamma}(\text{Ni}) 7.85 \times 10^{43} e^{-t/8.76d} + A_{\gamma}(\text{Co}) 1.43 \times 10^{43} [e^{-t/111.27d} - e^{-t/8.76d}]] \text{ erg s}^{-1}. \quad (3)$$

$A_{\gamma}(\text{Ni})$ and $A_{\gamma}(\text{Co})$ are the attenuation coefficients of the $\gamma$-rays from the decay of $^{56}\text{Ni}$ and $^{56}\text{Co}$, respectively, in the SN fireball. $A_{\gamma} \approx 1 - e^{-\tau_{\gamma}}$, where $\tau_{\gamma}(t) \approx R \Sigma_i \rho_i \sigma_i$ is the fireball opacity and the summation extends over all its particles. For a composition dominated by intermediate mass elements and iron group elements, $\rho_i \lambda_i \approx 13 g cm^{-2}$ for the $\gamma$ rays with $<E_{\gamma}> \approx 0.54$ MeV from the decay of $^{56}\text{Ni}$ and larger by a factor $\approx 5/3$ for $\gamma$-rays with $<E_{\gamma}> \approx 1.32$ MeV from the decay of $^{56}\text{Co}$ (see Hubbell 1982). Hence, $\tau_{\gamma} = R \rho / \rho_i \lambda_i \approx t_{\gamma}^2/t^2$ where $t_{\gamma}^2 \approx 3 M/4 \pi V^2 \rho_i \lambda_i$, and $t_{\gamma}(\text{Ni}) \approx 35 (M/M_\odot)$ d while $t_{\gamma}(\text{Co}) \approx 22 (M/M_\odot)$ d.

The positrons from the $\beta^+$-decay of $^{56}\text{Co}$ (and the $e^\pm$ from the decay of other relatively long lived radioactive isotopes that were synthesized in the thermonuclear explosion) are presumably trapped by the turbulent magnetic field of the SN fireball. Presumably, they lose their kinetic energy before the $e^+e^-$ annihilation into two 0.511 MeV $\gamma$-rays. Their energy deposition rate is given approximately by

$$\dot{E}_{e^\pm} = \frac{M(^{56}\text{Ni})}{M_\odot} A_e (1 + 6.22 A_{\gamma}) \ 1.43 \times 10^{43} [e^{-t/111.27d} - e^{-t/8.76d}] \text{ erg s}^{-1}. \quad (4)$$

where $A_e = 0.034$ is the ratio between the energy released in the radioactive decay of $^{56}\text{Co}$ as kinetic energy of $e^+$ and that released directly in $\gamma$-rays. The kinetic energy deposition dominates the radioactive power supply when the fireball becomes highly transparent to $\gamma$-rays, i.e., when $t \gg t_{\gamma}(\text{Co})$.

As long as $\dot{E}$ changes rather slowly with time relative to the fast rise with time of the factor $t e^{t^2/2t^2}$, it can be factored out of the integration in Eq. (1) to yield

$$L_r(t) \approx [1 - e^{-t^2/2t^2}] \dot{E}_r. \quad (5)$$
Hence, the contribution of radioactivity to bolometric luminosity initially rises approximately like $L_r \approx (t^2/2 \tau_r^2) \dot{E}_r$, has a peak value $L_r(t_p) \approx \dot{E}_r(t_p)$, and a late-time asymptotic behaviour $L_r \approx \dot{E}_r$.

If the bolometric luminosity of an SLSN is powered by the radioactive decay chain $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, and if its luminosity peak time $t_p \gg \tau(\text{Ni}) = 8.76$ d, then its peak luminosity satisfies (Dado and Dar 2012)

$$L(t_p) = \dot{E}_r \approx 1.43 \times 10^{43} \left[\frac{M(^{56}\text{Ni})}{M_\odot}\right] A_\gamma(\text{Co}) e^{-t_p/111.27} \text{ erg s}^{-1}. \quad (6)$$

E.g., if the bolometric luminosity of SN2006gy was powered by the synthesis of $^{56}\text{Ni}$, then its observed peak value $L_p(70\text{d}) \approx 3 \times 10^{44}$ erg s$^{-1}$ would have required $M(^{56}\text{Ni}) \geq 40M_\odot$!

**Collision Power:** For simplicity, consider a plastic collision between a fast expanding SN fireball and a slowly moving circumstellar shell (CS) with a density profile $\rho(R) = 0$ for $R < R_c$, $\rho(R) = \rho_0 R_c^2/R^2$ for $R_c \leq R \leq R_e$, and $\rho(R) = 0$ for $R > R_e$. Such a shell could have been formed by mass ejection at a constant rate $\dot{M}$ during an eruption time $\Delta t$ sometime before the SN explosion, yielding $\rho_0 R_c^2 = \dot{M}/4 \pi V_{cs}$. Hence, for $t_c \leq t \leq t_e$, and $V \gg V_{cs}$, the energy deposition rate in the SN fireball is

$$\dot{E}_c(t) = \frac{\dot{M} (V - V_{cs})}{2 V_{cs}} \approx \frac{\dot{M} V^3}{2 V_{cs}}. \quad (7)$$

The matter swept-up by the expanding SN fireball decelerates the SN expansion. For a relatively low $V_{cs}$, momentum conservation yields for $t_c \leq t \leq t_e$

$$V(t) \approx V_c \left[1 + b \left(t - t_c\right)\right]^{-1/2}, \quad (8)$$

where $V_c = V(t_c)$ and $b \approx 8 \dot{M} V_c/3 M V_{cs}$.

During the collision, $\dot{E}_c$ changes with time rather slowly relative to the fast rise of the exponential factor in the integrand on the right hand side of Eq. (1), which can be approximated by

$$L_c(t) \approx \left[1 - e^{-(t-t_c^2)/2t_c^2}\right] \dot{E}_c \approx \left[1 - e^{-(t-t_c)^2/2t_c^2}\right] \dot{M} V^3/2 V_{cs}. \quad (9)$$

Hence, the contribution of a collision with a circumstellar shell/wind to the bolometric luminosity rises approximately like $L_c \approx (t - t_c)^2/2 t_c^2 \dot{E}_c(t)$, and has a peak value $L_c(t_{pc}) = \dot{E}_c(t_{pc})$ at the peak time $t_{pc}$ of the collision luminosity and a late-time asymptotic behaviour $L_c(t) \approx \dot{E}_c(t)$ as long as $t \leq t_e$. Beyond $t_e$, where $\dot{E}_c(t) = 0$, Eq. (1) yields

$$L_c(t > t_e) = L_c(t_e) \exp^{-[t-t_c^2-(t_e-t_c)^2]/2t_c^2}. \quad (10)$$
Note that during the collision, \([t_r]^2\) as given by Eq. (2) increases with time roughly like \(M V_0/V^2\).

The generalization of the above formulae to SN explosion expanding into a pre-supernova wind or colliding with a sequence of circumstellar shells is straightforward. The bolometric light-curve during a collision with a continuous wind is obtained by setting \(t_c\) to be the beginning time of the explosion. For expansion into a multi-shell environment, each SN-shell collision is still described by Eqs. (8)-(10) with \(t_c\) and \(t_e = t_c + dt_c\) being, respectively, the beginning and end times of the collision of the expanding SN with the specific shell.

The pre-supernova history of the progenitors of SNe-Ib/c SNeIIn, and consequently their environments, are poorly known. The assumed constant rate of mass ejection during mass ejection episodes and their assumed sharp step-like beginning and decline are surely over simplifications, which were introduced in order to minimize the number of adjustable parameters in our fitted bolometric light curves of SLSNe dominated by collisions. If, however, the SN expansion velocity \(V(t)\) is known from the time-dependent profiles of SN absorption and emission lines, then Eq. (9) may be used to extract roughly the pre-supernova history of mass ejection.

4. Colour temperature for collision dominated lightcurve

During the photospheric phase, when the SN fireball is optically thick, its continuum spectrum is approximately that of a black body, with an effective photospheric temperature that satisfies the Stefan-Boltzmann law. Consequently,

\[
T \approx \left[ \frac{L_b}{4 \pi V^2 t^2 \sigma} \right]^{1/4}
\]

where \(\sigma = 5.67 \times 10^{-5}\) erg s\(^{-1}\) cm\(^{-2}\) K\(^{-4}\). Thus, if radioactivity can be neglected during the collision, then \(T \propto [V/2t_r^2]^{1/4}\) for \((t - t_c)^2 \ll t_r^2\), while \(T \propto V^{1/4} (t - t_c)^{-1/2}\) for \((t - t_c)^2 \gg t_r^2\). The two behaviours can be combined roughly into a simple interpolation formula,

\[
T \propto [V/[2t_r^2 + (t - t_c)^2]]^{1/4}.
\]

This formula is valid until the SN enters the nebular phase.

5. Comparison with observations

Figure 1 compares the observed bolometric light curve of SN2009ip (Margutti et al. 2013) and that expected from its description as an "ordinary" interacting SNIIn. Similar fits were
obtained for the observed bolometric light-curves of the SN2005fb (Folatelli et al. 2006) and SN2010mc (Ofek et al. 2013) when they were treated as interacting ordinary SNIb/c and SNIIn, respectively. Figs. 2-4 compare the bolometric light curves of the superluminous supernovae 2006oz (Leloudas et al. 2012), PTF 12dam (Nicholl et al. 2013) and PS1-11ap (McCrum et al. 2013) and their description as interacting SNIb/c or SNIIn. Similar fits were obtained for other typical SLSNe, such as SN2006gy (Smith et al. 2008) and SN2010gx (Pastorello et al. 2010). The best fit parameters of all these fits are listed in Table 1. As can be seen from Figs. 1-4 and Table I, the bolometric light curves of all the above representative SNeIc, SNeIn, SLSNe-Ic and SLSNe-II are described well by our master formula for interacting SNe.

6. Conclusions

Models where $^{56}\text{Ni}$ is the power source for the very large luminosities of SLSNe may account for the light curve rise-time and peak-value reasonably well. However, the peak luminosities of SLSNe with a relatively slow-rising light-curve require the synthesis of an implausible amount of $^{56}\text{Ni}$, e.g., $M(\text{^{56}Ni}) \approx 40M_\odot$ in the case of SN2006gy. Such models also fail to fit well the late-time decline of the bolometric luminosities of several SLSNe.

Millisecond magnetars, if born in SNeIc explosions, were shown to be able to produce the observed bolometric lightcurves of SLSNe-Ic (e.g., Inserra et al. 2013, Nicholl et al. 2013) reasonably well. However, it remains to be seen whether magnetar powered SLSNe-Ic, together with a modest amount of radioactive $^{56}\text{Ni}$ synthesized in the explosions, can also explain multipeak light-curves and the observed kinematic and spectroscopic properties of SLSNe-Ic. Moreover, despite their popularity, there are unresolved problems with magnetar models (e.g., Katz 2013), there are observations that challenge the magnetar paradigm (e.g., Rea et al. 2010, 2012, 2013), and there are more conventional explanations for almost all the phenomena that were interpreted with magnetar models.

In this letter, we have demonstrated that SLSNe may be ordinary SNe of types Ib/c and IIn, which interact with the circumburst environment created by their progenitor stars prior to their SN explosion. This is suggested by their similarity to interacting SNe of types Ic and IIn. Our simple master formula (Eq. (1)), which was derived in Dado and Dar 2013 for the bolometric light-curves of SN explosions fit well the bolometric light curves of both interacting SNe and SLSNe, with very few parameters. This success is despite the over-simplified geometry, hydrodynamics and radiation transport used in its derivation: The density, internal energy and velocity profiles of the SN fireball resulting from a collision of the SN debris with a circumstellar shell are surely more complicated than those assumed, and so
are the conversion of kinetic energy into thermal energy via forward and backward shocks and its transport to the SN photosphere from where it escapes freely into space. Nevertheless, as demonstrated in this paper, simple modeling of SLSNe as interacting SNe can reproduce well the observed variety of their bolometric light curves; fast and slowly rising, fast and slowly decaying, single and multi-peak light curves. Moreover, the master formula (1) together with Eqs. (9) and (11) successfully predict the correlated behaviours as a function of time of the observed bolometric luminosity, the colour temperature and the SN expansion velocity inferred from the shapes of absorption and emission lines in several SLSNe, and can be used to extract the eruption history ($\dot{M}/V_{cs}$) of the progenitor star before its SN explosion (Dado and Dar, in preparation). They imply that SLSNe are produced by the explosion of very massive stars, akin to eta Carinae, that have lost tens of solar masses in relatively short emission episodes during a couple of centuries prior to their final SN explosion.

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Table 1. Best fit parameters of the bolometric light-curves of a representative sample of interacting supernovae

| SN        | M$_{56}^{\text{Ni}}$ | $t_0$[d] | $t_r$[d] | $t_c$[d] | $dt_c$[d] | $t_{rc}$[d] | $\dot{E}_c(t_c)[\text{erg}]$ | b[d$^{-1}$] | $\chi^2$/dof |
|-----------|----------------------|---------|---------|---------|----------|-----------|----------------|-----------|-------------|
| SN2009ip  | 0.024$M_\odot$      | -5.53   | 23.0    | 48.1    | 14.6     | 6.7       | 3.7E42          | .153      | 0.98        |
|           |                      |         |         |         |          |           | 83.8           | 4.64      | 4.98        |
|           |                      |         |         |         |          |           | 104.9          | 12.2      | 5.02        |
|           |                      |         |         |         |          |           | +3.0E40        | .07       |             |
| SN2006oz  | 0.95$M_\odot$       | -10.56  | 8.28    | 8.66    | 36.9     | 23.1      | 1.23E44         | .035      | 1.08        |
| PTF12dam  | 2.45$M_\odot$       | -66.0   | -64.1   | 70.8    | 62.8     | 1.34E44   | .038           | 0.29      |             |
| PS1-11ap  | 0.072$M_\odot$      | -48.9   | 21.4    | -30.8   | 51.5     | 19.0      | 2.32E43         | .069      | 0.17        |
| SN2005bf  | 0.147$M_\odot$      | -42.4   | 14.7    | -18.8   | 24.9     | 12.9      | 2.1E42          | .038      | 1.34        |
| SN2006gy  | 0.19$M_\odot$       | 2.7     | 5.96    | 5.26    | 82.7     | 41.5      | 8.15E43         | .013      | 0.37        |
|           |                      |         |         |         |          |           | 214.            | +1.5E42   | .0004       |
| SN2010gx  | 0.012$M_\odot$      | -28.1   | 8.27    | -22.5   | 37.5     | 10.3      | 1.04E44         | .06       | 1.12        |
Fig. 1.— Comparison between the rest frame light-curve of the bolometric luminosity of supernova SN2009ip (Margutti et al. 2013) and a best fit light-curve of a supernova powered by the decay of 0.025 $M_\odot$ of $^{56}$Ni synthesized in the explosion and subsequent plastic collisions of the SN debris with a succession of three massive shells after a wind blown by the progenitor star sometimes before its explosion.
Fig. 2.— Comparison between the rest frame light-curve of the bolometric luminosity of the superluminous supernova SN2006oz and a best fit light-curve of a supernova powered by the decay of $0.95 \, M_\odot$ of $^{56}\text{Ni}$ synthesized in the SN explosion followed by plastic collision of the SN debris with a massive shell blown by the progenitor star before its explosion.
Fig. 3.— Comparison of the rest frame light-curve of the bolometric luminosity of the superluminous supernova PTF-12dam (Nicholl et al. 2013) and a best fit light-curve of a supernova powered by the decay of 2.45 $M_\odot$ of $^{56}$Ni synthesized in the SN explosion followed by plastic collision of the SN debris with a massive shell blown by the progenitor star before its explosion.
Fig. 4.— Comparison between the rest-frame bolometric light-curve of the SLSN-Ic ps1-11ap (Nicholl et al. 2013) and the best fit light-curve of a supernova powered by a plastic collision of its debris with a massive shell blown by the progenitor star before the SN explosion.
Fig. 5.— Comparison between the rest frame bolometric light curve of the interacting supernova SN2005bf (Folatelli et al. 2006) and its best fit bolometric light-curve powered by the decay of 0.15 $M_\odot$ of $^{56}\text{Ni}$ synthesized in the explosion and by a subsequent plastic collisions of the SN debris with a sucession of massive shell ejected by the progenitor star before its SN explosion.
Fig. 6.— Comparison between the rest-frame bolometric light-curve of the super-luminous SN2006gy (Smith et al. 2008) and the best fit light-curve of a supernova dominated by two plastic collision of its debris with two massive shells blown by the progenitor star before the SN explosion.
Fig. 7.— Comparison between the rest-frame bolometric light-curve of the super-luminous SN2010gx (Pastorello et al. 2010) and the best fit light-curve of a supernova dominated by a plastic collision of its debris with a massive shell blown by the progenitor star before the SN explosion.