Super Luminous Supernova and Gamma Ray Bursts

Shlomo Dado$^1$ and Arnon Dar$^1$

**ABSTRACT**

We use a simple analytical model to derive a closed form expression for the bolometric light-curve of super-luminous supernovae (SLSNe) powered by a plastic collision between the fast ejecta from core collapse supernovae (SNe) of types Ib/c and IIn and slower massive circum-stellar shells, ejected during the late stage of the life of their progenitor stars preceding the SN explosion. We demonstrate that this expression reproduces well the bolometric luminosity of SLSNe with and without an observed gamma ray burst (GRB), and requires only a modest amount ($M < 0.1 M_\odot$) of radioactive $^{56}$Ni synthesized in the SN explosion in order to explain their late-time luminosity. Long duration GRBs can be produced by ordinary SNe of type Ic rather than by 'hypernovae' - a subclass of superenergetic SNeIb/c.

*Subject headings:* gamma-ray burst: general, supernovae: general

1. Introduction

The progenitor stars of core-collapse supernovae of type Ib/c, are stripped of their envelope through strong winds and/or major eruptions during the final stages of their life before their explosion (e.g., Pastorello et al. 2010; Quimby et al. 2011, and references therein). The ejected massive shells in these eruptions sweep up slower stellar winds, which were blown before these eruptions, and create a matter-clean space surrounding the progenitor star. The interaction of the radiation from the SN explosion with such slowly moving circumstellar (CS) shells often produces delayed emission of narrow lines, which stops when the SN ejecta collide with the CS shell (Chugai 1990,1992).

Light from the progenitor star back-scattered by CS shell(s) into the matter-free space around the progenitor star produces a glory - a halo of scattered light surrounding the progenitor star. In the cannonball (CB) model of gamma ray bursts (GRBs), long duration GRBs are produced by inverse Compton scattering of glory photons by the electrons in...
the 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 (e.g., Dar & Rújula 2000,2004; Dado et al. 2009). In this scenario, SN explosions that produce long GRBs (SNe-GRB) are ordinary core-collapse SNe of type Ic where the kinetic energy of the ejecta is typically a few $10^{51}$ ergs, rather than ‘hypernovae’ - hypothetical super energetic core collapse SNIc explosions, where the kinetic energy of the ejecta exceeds a few $10^{52}$ ergs and their bolometric light-curve is powered by the radioactive decay of $M \gg 0.1 M_{\odot}$ of $^{56}$Ni synthesized in the explosion (e.g., Iwamoto et al. 1998; Nakamura et al. 2001). So far, the CB model has been very successful in predicting/reproducing the main observed properties of long duration GRBs (e.g., their rate, location in star formation regions, association with core collapse SNe of type Ib/c, typical photon energy, multi-pulse structure, pulse shape and duration, spectral evolution of the individual pulses and large photon polarization) and the observed correlations between them (see, e.g., Dado et al. 2009; Dado & Dar 2012, and references therein).

The CB model scenario implies that in SNeIc the fast SN ejecta may collide with a slowly expanding massive CS shell ejected some time before the explosion. Such a collision may produce a very luminous SNIc and even super-luminous (SLSN), which are powered mainly by the collision rather than by a large mass of $^{56}$Ni synthesized in the explosion. Because of relativistic beaming, most of the GRBs that are produced in SNeIc and SLSNe are beamed away from Earth and are not observed. Indeed, most SNeIc and SLSNe are not accompanied by an observed GRB. The first discovered SLSN without an associated GRB was SN1999as (Knop et al. 1999) at a redshift $z=0.127$, which was much more luminous than the very bright SNe of type Ib/c that produced observed GRBs such as SN1998bw (Galama et al. 1998), that produced GRB 980425 (Soffitta et al. 1998, Pian et al. 2000), SN2003dh (Stanek et al. 2003; Hjorth et al. 2003) that produced GRB 030329 (Vanderspek et al. 2003), and SN2006aj (Campana et al. 2006; Pian et al. 2006; Sollerman et al. 2006) that produced GRB 060218 (Cusumano et al. 2006). More recently, transient surveys that were monitoring many square degrees of the sky every few nights have discovered several additional SLSNe in the nearby Universe without an observed GRB. The first one was SN2005ap (Quimby et al. 2007). The absence of hydrogen in its spectrum, its very broad lines, and its energetics led Quimby et al. (2007) to propose that SN2005ap could have been produced by the same mechanism that produces SNe with an observable GRB. Other discoveries of SLSNe without an observed GRB include SN2003ma behind the Large Magellanic Cloud at $z =0.289$ by the SuperMACHO microlensing survey (Rest et al. 2011), SN2006gy (Smith et al. 2008,2010), SN2007bi (Gal-Yam et al. 2009), SN2008am (Chatzopoulos et al. 2011), SN2010hy (Kodros et al. 2010; Vinko et al. 2010), SN2010gx (Pastorello et al. 2010), SN 2010jl (Stoll et
al. 2011), and SCP 06F6 (Quimby et al. 2011).

Alternative mechanisms which were invoked in order to explain the observed luminosity of SLSNe include:

I. Radioactive decay of large amounts (several $M_{\odot}$) of radioactive $^{56}$Ni produced in pair-instability explosions of extremely massive stars (Rakavy & Shaviv 1967; Barkat et al. 1967; Heger & Woosley 2002; Waldman 2008; Gal-Yam et al. 2009; Yoshida & Umeda 2011), which are efficiently mixed in the SN ejecta.

II. Efficient conversion of kinetic energy of the SN ejecta into thermal energy in SN explosions inside optically thick winds (Falk & Arnett 1973, 1977; Ofek et al. 2007; Smith & McCray 2007; Smith et al. 2010; Balberg & Loeb 2011; Chevalier & Irwin 2011, 2012; Moriya et al. 2012; Chatzopoulos et al. 2012; Ginzburg & Balberg 2012; Ofek et al. 2012).

III. Collision(s) of the fast SN ejecta with slowly expanding dense circum-stellar shell(s) ejected by the progenitor star sometime before the SN explosion (Grassberg et al. 1971; Moriya et al. 2012), supplemented by energy release in the radioactive decay chain $^{56}$Ni $\rightarrow ^{56}$Co $\rightarrow ^{56}$Fe of $M(^{56}$Ni) $\ll M_{\odot}$ synthesized in the explosion.

The rapid decay of the bolometric light-curve of SLSNe such as SN2010gx, and the very large mass, $\sim 10 M_{\odot}$, of $^{56}$Ni needed to explain its peak luminosity, however, indicate that the pair instability mechanism where a large mass of $^{56}$Ni is produced (scenario I) is unlikely to be its power source (Pastorello et al. 2010). In scenario II, the progenitor star explodes into a dense wind, and the strong shock that presumably explodes it breaks out into the wind. This strong shock is assumed to convert the kinetic energy which it imparts to the ejecta in SN explosions into internal thermal energy of the wind. Numerical simulations of core-collapse SNe, however, so far have not produced consistently strong enough shocks that can reproduce the observed SNe where the typical kinetic energy of the debris is a few $10^{51}$ ergs. But, by adjusting the wind parameters and the energy deposited in it, and by introducing many simplifying assumptions, Ginzburg and Balberg (2012) were able to calculate bolometric light curves for some SLSNe, which look like those observed. Scenario III has not been studied yet in detail with numerical hydrodynamical codes (Ginzburg & Balberg 2012). However, scenario III is strongly suggested by observations of SNn of type Ib/c and by the success of the CB model of GRBs in predicting the main observed properties of long GRBs produced in SNe of Type Ic.

In this letter we use a simple analytical model based on only a few general assumptions to derive a closed form expression for the bolometric luminosity of SLSNe in scenario III. It involves only few adjustable parameters. We use it to demonstrate that collisions between the fast ejecta from core collapse SNe of types Ib/c and their massive circum-stellar shells, which were ejected in eruptions of their massive progenitors in the years preceding their SN
explosion, together with a modest amount of radioactive isotopes, which were synthesized in the SN explosion and deposited in the ejecta, can reproduce quite well the bolometric light-curves of both the supernovae that were observed in association with GRBs and those of the recently discovered SLSNe without an observed GRB. We conclude with a short discussion of the implications for SN explosions and GRBs.

2. Collision of the SN ejecta with a dense CS shell

The observed narrow lines in SNeIc indicate that the dense circumstellar shells (CSS) that emit them are expanding with a velocity of a few hundreds km/s at a typical distance of $R \sim 3 \times 10^{16} \pm 1$ cm from the exploding star, and have a typical baryon density $n \sim 10^{8} \pm 2$ cm$^{-3}$ and a typical mass $M_{css} \sim 1 - 10 M_{\odot}$. The SN ejecta of mass $M_{ej}$ that have a much faster velocity, $v_{ej} \sim 10^{4}$ km s$^{-1}$, overtake the slower massive CSS typically within $R/(v_{ej} - v_{css}) \sim 10^{1.5}$ days.

We assume that the collision between the SN ejecta and a CS shell is a plastic collision. Then, energy-momentum conservation implies that the center of mass (CM) energy $\mu v^{2}/2$ is converted to internal energy, where $\mu = M_{ej} M_{css}/(M_{ej} + M_{css})$ is the reduced mass of the colliding shells and $v = v_{ej} - v_{css} \approx v_{ej}$ is their relative velocity. This internal energy is roughly a fraction $M_{css}/(M_{ej} + M_{css})$ of the kinetic energy of the incident ejecta, typically a few $10^{51}$ ergs. For a patchy CS shell, or a clumpy SN ejecta, that covers a solid angle $\eta 4 \pi$, $M_{ej}$ must be replaced by $\eta M_{ej}$. The thermal expansion speeds of the SN and CS shells are negligible compared to their radial velocities and their merger is completed within relatively a short time.

Consider now the collision in the rest frame of the CS shell. Most of the kinetic energy of the SN ejecta is carried by atomic nuclei of mass $\sim A m_{p}$ and charge $Z e$. For $\beta = v/c \sim 1/30$, their typical kinetic energies is $A m_{p} \beta^{2} c^{2}/2 \sim A/2$ MeV. In SNeIc, the CS shells consists mainly of the hydrogen and helium layers, which were stripped off from the progenitor star sometime before the SN explosion. The SN ejecta from such a massive star stripped off of its hydrogen and helium layers, consists mainly of nuclei heavier than helium nuclei. Such nuclei lose their kinetic energy in the CS shell mainly by Coulomb interactions with electrons (ionization and scattering off free electrons) at a rate which is given approximately by the Bethe-Bloch energy loss rate of sub-relativistic nuclei in matter. For ejecta with velocity $v \sim 10^{4}$ km/s, $dE/dx \sim 1.35$ MeV $Z^{2} \beta^{-2}$ cm$^{2}$ g$^{-1}$, they lose their energy in the CS shell within $\leq 10^{-4}$ g cm$^{-2}$, whereas the typical column density of CS shells is a few g cm$^{-2}$. Consequently, the kinetic energy deposition is mainly near the interface of the colliding shells, and it lasts relatively a very short time. This energy is converted almost
instantaneously to thermal (black body) radiation \( a T^4 \gg n k T \) by bremsstrahlung and multiple scattering of the knocked on electrons, and is transported from the collision zone to the entire CS shell by diffusion and shock wave. This thermal radiation escapes into the interstellar medium (ISM) from a depth with an opacity \( \tau_{\text{opt}} \sim 1 \). If the opacity of the entire ionized shell is \( \tau_{\text{opt}} = N_e \sigma_T > 1 \) where \( N_e \) is the electron column density of the shell, and \( \sigma_T \approx 0.67 \times 10^{-24} \text{ cm}^2 \) is the Thomson cross section for Compton scattering, then the photons that the thermal radiation from the collision cross the CS shell by ‘random walk’ in a typical time \( t_r \approx \Delta R^2/\lambda c = \tau_{\text{opt}} \Delta R/c \) where \( \Delta R \) is the width of the CS shell whose density becomes nearly uniform for \( R \gg \Delta R \).

The radioactive (ra) decay chain \(^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe} \) in the collision zone releases there additional energy at a rate,

\[
\dot{E}_{\text{ra}} = 7.76 \times 10^{43} \frac{M(^{56}\text{Ni})}{M_\odot} \left[ e^{-t/8.77\text{d}} + 0.227 e^{-t/111.4\text{d}} \right] \text{ erg s}^{-1},
\]

For \( t > 14 \text{ d} \), the decay of \(^{56}\text{Co} \) dominates the radioactive energy release.

3. The bolometric light-curve

Let \( t = 0 \) be the explosion time and \( t_c \) be the collision time after the explosion. Let us approximate the behaviour of the CS shell by that of a container in thermal equilibrium with a black body radiation of temperature \( T \), energy density \( u = a T^4 \), and pressure \( p = u/3 \), whose radius \( R \) expands at a constant rate \( V = (m_{ej} v_{ej} + m_{css} v_{css})/(m_{ej} + m_{css}) \) but whose width \( \Delta R \) remains nearly constant. Energy conservation implies that its photospheric luminosity \( L = 4 \pi R^2 \sigma T^4 / \tau_{\text{opt}} \) satisfies approximately

\[
t_{\text{opt}} \dot{L} + L = \dot{E}_{\text{ra}},
\]

where \( t_{\text{opt}} = 4\pi \Delta R \tau_{\text{opt}} / c \) as long as it is opaque \( (\tau_{\text{opt}} > 1) \) and cooling by adiabatic expansion of the CS shell was neglected compared to radiative cooling. If the CS shell is patchy and covers only a solid angle \( \eta 4\pi \) where \( \eta < 1 \), then the bolometric luminosity \( L = 4 \pi \eta R^2 \sigma T^4 \) still satisfies Eq.(2) and yields a photospheric effective radius smaller than the true radius by a factor \( \eta^{1/2} \).

The general solution of Eq.(2) for \( t > t_c + t_{\text{rw}} \) is given by \( L = L_c + L_p \) where \( L_c(t) = L_c(t - t_c - t_{\text{rw}}) e^{-(t - t_c - t_{\text{rw}})/\tau} \) is the general solution of the homogeneous part \( \dot{L} + L / \tau_{\text{opt}} = 0 \) of Eq. (2), and \( L_p(t) \) is a particular solution of the entire equation,

\[
L_p(t) = 7.76 \times 10^{43} \frac{M(^{56}\text{Ni})}{M_\odot} \left[ \frac{e^{-t/\tau_{\text{Ni}}}}{(1 - \tau / \tau_{\text{Ni}})} + 0.227 \frac{e^{-t/\tau_{\text{Co}}}}{(1 - \tau / \tau_{\text{Co}})} \right] \text{ erg s}^{-1}.
\]
The light curve after the collision can be approximated by

\[ L(t > t_c) \approx [1 - e^{-(t-t_c)^2/t^2}] [L_c(t-t_c) + L_p(t)] \]  

where the first term on the RHS is roughly the fraction of the volume of the CS shell which is transparent to the radiation (approximately \(1/\tau_{opt} \propto t^2\) for \(\tau \gg 1\) and 1 for for \(\tau \lesssim 1\)), and where we have neglected the spread in arrival times (\(\sim R/c\)) of photons emitted simultaneously in the SN rest frame from different points of the photosphere of the CS shell. The bolometric luminosity predicted by Eqs. (3) and (4) for a single collision involves five parameters, \(M(^{56}\text{Ni})\) that was synthesized in the SN explosion, \(E_{cm} = \mu v^2/2\), and \(t_c\), \(t_r\), and \(t_d = t_{opt}\), which depend on the unknown mass-loss history (\(\dot{M}\), angular distribution and chemical composition) of the progenitor star during the years preceding its SN explosion. The time-integrated luminosity satisfies \(\int L \, dt = \mu v^2/2 + 2.31 \times 10^{50} M(^{56}\text{Ni})/M_\odot\), and can be used to determine the center of mass energy of the colliding shells. The product \(\eta R(t)^2\) can be determined from the measured luminosity and black body temperature of the photosphere. If after the collision the merged shell overtakes another CS shell, then the additional luminosity after the second collision is also described by Eq. (4) but with \(t_c(2), t_r(2), E_k(2)\) and \(\tau(2)\) corresponding to that collision.

4. Comparison with observations

In Figures 1-3 we compare the bolometric light-curves of three representative SLSNe and their light-curves as predicted by Eqs. (3) and (4).

Figure 1 compares the bolometric light-curve of SN1998bw (Galama et al. 1998; Nakamura et al. 2001; Fynbo et al. 2000) which produced GRB 980425 (Pian et al. 2000) and the light-curve predicted by Eqs. (3) and (4), assuming it was powered by a single collision between the SN debris and a CS shell ejected sometime before the SN/GRB event and by the decay of \(^{56}\text{Ni}\) synthesized in the explosion. The best fit parameters are reported in Table 1. The late-time decay of the bolometric light curve could be powered by 0.06 \(M_\odot\) of \(^{56}\text{Ni}\) that was synthesized in the explosion, if the merged shell is opaque to \(\gamma\) rays.

Figure 2 compares the bolometric light-curve of the ultra-luminous SN 2010gx (Pastorello et al. 2010) and the light-curve predicted by Eqs. (3) and (4) for a collision between the SN ejecta and a massive CS shell. The best fit parameters are reported in Table 1. The lack of late-time data does not allow determination of the mass of \(^{56}\text{Ni}\) synthesized in the explosion.

Figure 3 compares the bolometric light-curve of the ultra-luminous SN 2006gy (Smith et al. 2008,2010) and the light-curve predicted by Eqs. (3) and (4) for a collision between the SN ejecta and a CS shell, followed by an encounter between the merged SN-CS shells with a wind or a second CS shell downroad around \(\sim\) day 140. The best fit parameters are reported
in Table 1. The data do not allow a reliable determination of the time of the second collision or of the amount of $^{56}$Ni synthesized in the explosion.

5. Discussion and conclusions

Very large photospheric velocities were inferred from the early-time broad line spectra of SNe associated with an observed long GRB (SNe-GRB) such as SN1998bw, SN2003dh, and SN2003lw. Also unusual large quantities of $^{56}$Ni synthesized in these explosions were inferred from both their bolometric lightcurves and spectra (e.g., Nakamura et al. 2001; Mazzali et al. 2001, 2006). The unusual large value of the kinetic energy of the SN explosion that was inferred from the very large early-time photospheric velocities led Iwamoto et al. (1998) and the above authors to conclude that SNe-GRB belong to a class of hyper-energetic SNe ("hypernovae"), where the kinetic energy of the ejecta is typically $5 \times 10^{52}$ ergs, and the synthesized mass of $^{56}$Ni is $\sim 0.5 \, M_\odot$.

However, the early time-photospheric velocity that was inferred, e.g., from the broad lines in the spectrum of SN1998bw (Patat et al. 2000) decreased by a factor 4 from $\sim 40,000$ km s$^{-1}$ to $\sim 10,000$ km s$^{-1}$ within the first 30 days after the explosion. If these velocities were the bulk motion c.m. velocities of the whole SN ejecta, such a deceleration would have required collision with a mass $M \sim 3 \, M_{ej} \sim 30 \, M_\odot$ enclosed within $R \sim 5 \times 10^{15}$ cm. But, a typical ISM baryon density of $1 \, \text{cm}^{-3}$, yields an ISM mass $M \sim 4\pi m_p R^3/3 \sim 1 \times 10^{-10} \, M_\odot$ within such a radius, while a wind environment will have typically only $\dot{M} \, R/V \lesssim 10^{-3} \, M_\odot$ within $R \sim 5 \times 10^{15}$ cm. Hence, either the observed velocity was only of thin photospheric layer of the SN shell which decelerated rapidly by collision with a massive wind/shell (while the mean velocity of the SN shell was its $\sim 5000$ km/s) or the broad absorption lines were

Table 1. The best fit values of the parameters used in reproducing the measured bolometric light curve of several SLSNe. Times are measured in days after the SN explosion.

| SN        | $t_c$ | $t_{max}(L) - t_c$ | $t_r$ | $t_d$ | $M(^{56}\text{Ni})$ | $\chi^2$/dof |
|-----------|-------|-------------------|-------|-------|---------------------|--------------|
| SN1998bw  | 0.52  | 7.52              | 39.7  | 0.06  | $M_\odot$           | 0.34         |
| SN2010gx  | 23.52 | 41.77             | 12.97 | $< 0.10 \, M_\odot$| 1.40         |
| SN2006gy  | 5.54  | 60.97             | 35.14 |       |                     | 1.00         |
|           | 147.5 | 57.22             | 79.15 |       |                     |              |
due to line broadenig e.g., by Compton scattering inside an optically thick the SN shell). In both cases the kinetic energy of the explosion should have been estimated from the late-time nebular velocity of $M_{ej} + M_{css}$ rather than from modeling the early time photospheric velocity (Nakamura et al. 2001; Mazzali et al. 2001, 2006). The typical observed expansion velocities, 5000 km/s, during the nebular phase of SNe associated with observed long duration GRB imply kinetic energy release of only $\sim 2.5 \times 10^{51} (M_{ej} + M_{css})/10M_\odot$ erg typical to ordinary SN explosions and do not support an "hypernovae" origin of SN-GRBs.

Also the true values of the mass of $^{56}$Ni which were synthesized in SN1998bw and other SN-GRBs may be much smaller than inferred, e.g., by Nakamura et al.(2001) and Mazzali et al.(2001,2006). These large masses were inferred mainly from the peak-luminosity in the photospheric phase, while in our model, and in reality, a large part of it could be supplied by the collision between the SN shell and the CS shell. The inferred mass from the nebular phase is highly model dependent since it depends on the fraction of the radioactive energy release that is absorbed in the SN shell that depends on the unknown mass of the shell and its density distribution as function of time, and on the density distribution of $^{56}$Ni within it: The fraction of the total $\gamma$-ray energy that is absorbed in the SN shell is $1 - 1/\tau_\gamma + e^{-\tau_\gamma}/\tau_\gamma$. For nearly-transparent SN shells, $\tau_\gamma \ll 1$, and only a fraction $\tau_\gamma/2 \ll 1$ of the total $\gamma$-ray energy is deposited in the SN shell. Hence, in the models of Mazzali and collaborators, a much larger mass of $^{56}$Ni was required in order to power the observed luminosity of SNe-GRB in both the photospheric and nebular phases. However, because the radius of of the SN shell expands like $R \approx V_{ej} t$, $\tau_\gamma$ decreases like $t^{-2}$. Neglecting other losses, the luminosity powered by the decay of $^{56}$Co must decline then like $t^{-2} e^{-t/111.4d}$. The observed bolometric lightcurve of SN1998bw during the time interval 300-778 day, however, displayed an exponential decay consistent with that of $^{56}$Co without the $t^{-2}$ modulation. This is possible if either the CS shell is opaque to both the $\gamma$-rays and the positrons from the decay of $^{56}$Co, or opaque only to the positrons. In our model the SN shell deposits its radio-isotopes at the bottom of a CS shell. If the lightcurve of SN1998bw is powered also by the SN shell collision with a CS shell, which is nearly opaque to both the $\gamma$-rays and the positrons from the decay of $^{56}$Co it implies a rather small, $\sim 0.06 M_\odot dot$ (i.e., normal).

SLSNe are probably stripped-envelope SNe, most of which are SNeIc and SNeIIn (e.g., Pastorello et al. 2010; Quimby et al. 2011 and references therein). Their luminosity is powered mainly by plastic collision between their fast ejecta and slowly expanding massive circum-stellar shells formed in eruptions during the final stage of their life before their explosion. SLSNe may also produce GRBs, but like SNeIc-GRBs, most of them are not observed because they are beamed away from our line of sight to the SN explosion.

The CS environments of core-collapse SNe provide evidence of massive winds and ejec-
tion episodes of massive shells, probably in thermonuclear eruptions preceding their SN explosion. Although it defies current paradigms of stellar evolution theory, perhaps the expulsion of a large fraction of the stellar mass by winds and thermonuclear eruptions preceding the SN explosion of massive stars make it possible for the energy deposition by the shock and the neutrinos from their collapsing core to unbind the left-over external mass and impart to it a kinetic energy of the order of $E_k \sim$ several $10^{51}$ ergs.

REFERENCES

Balberg, S. & Loeb A. 2011, MNRAS, 414, 1715
Barkat, Z., Rakavy, G., & Sack, N. 1967, PRL, 18, 379
Campana, S., et al. 2006, Nature, 442, 1008
Chatzopoulos, E., et al. 2011, ApJ, 729, 143
Chatzopoulos, E., et al. 2012, ApJ, 746, 121
Chevalier, R. A. & Irwin C. M. 2011, ApJ, 729, L6
Chevalier, R. A. & Irwin C. M. 2012, ApJ, 747, L17
Chugai, N. N., 1990, Sov. Astr. Lett., 16, 457
Chugai, N. N., 1992, Sov. Astr. 36, 63
Cusumano, G. et al. 2006, GCN Circ. 4775
Dado, S., Dar, A. & De Rújula, A. 2009, ApJ, 693, 311
Dado, S. & Dar, A. 2012, preprint, arXiv:1203.5886
Dar, A., & De Rújula, A. 2000, arXiv:astro-ph/0008474
Dar, A. & De Rújula, A. 2004, Phys. Rep. 405, 203
Falk, S. W. & Arnett, W. D. 1973, ApJ, 180, L65
Falk, S. W. & Arnett, W. D. 1977, ApJS, 33, 515
Fynbo, J. U., et al. 2000, ApJ, 542, L89
Galama, T. J., et al. 1998, Nature, 395, 670
Gal-Yam, A., et al. 2009, Nature, 462, 624
Ginzburg, S. & Balberg, S. 2012, preprint arXiv:1205.3455
Grassberg, E. K., Inshennik, V. S. & Nadyozhin, D. K. 1971, Ap&SS, 10, 28
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Hjorth, J., et al. 2003, Nature, 423, 847
Iwamoto, K., et al. 1998, Nature, 395, 672
Kodros, J., et al. 2010, CBET 2461
Knop, R., et al. 1999, IAU Circ. 7128
Mazzali, P. A., et al. 2001, ApJ, 559, 1047
Mazzali, P. A., et al. 2006, ApJ, 645, 1323
Moriya, T., et al. 2012, preprint arXiv:1204.6109
Nakamura, T., et al. 2001, ApJ, 550, 991
Ofek, E. O., et al. 2007, ApJ, 659, L13
Ofek, E. O., et al. 2012, preprint arXiv:1206.0748
Pastorello, A., et al. 2010, ApJ, 724, L1
Pian, E., et al. 2000, ApJ, 536, 778
Pian, E., et al. 2006, Nature, 442, 1011
Quimby, R. M., et al. 2007, ApJ, 668, L99
Quimby, R. M., et al. 2011, Nature, 474, 487
Rakavy, G. & Shaviv, G. 1967, ApJ, 148, 803
Rest, A., et al. 2011, ApJ, 729, 88
Smith, N. and McCray, R. 2007, ApJ, 671, L17
Smith, N., et al. 2008, ApJ, 686, 485
Smith, N., et al. 2010, ApJ, 709, 856
Soffitta, P., et al. 1998, IAU Circ. 6884
Sollerman, J., et al. 2006, A&A, 454, 503
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Stoll, R., et al. 2011, ApJ, 730, 34
Vanderspek, R., et al. 2003, GCN Circ. 1997
Vinko, J., et al. 2010, CBET 2476
Waldman, R. 2008, ApJ, 685, 1103
Yoshida, T., & Umeda, H. 2011, MNRAS, 412, L78
Fig. 1.— Comparison between the bolometric light-curve of SN1998bw (Nakamura et al. 2001; Fynbo et al. 2000) and that predicted by Eqs. (3) and (4) assuming it was powered by a plastic collision between the SN ejecta and a CS shell/wind and by the decay of $^{56}\text{Ni}$ synthesized in the SN explosion.
Fig. 2.— Comparison between the bolometric light-curve of SN2010gx (Pastorello et al. 2010) and that predicted by Eqs. (3) and (4) assuming it was powered by the plastic collision between the fast ejecta from the SN explosion and a much slower massive cs shell ejected sometime before the SN explosion.
Fig. 3.— Comparison between the observed bolometric light-curve of SN2006gy (Smith et al. 2011) and that predicted by Eqs. (3) and (4) assuming that it was powered by plastic collisions between the fast ejecta of SN2006gy and a much slower massive circun-stellar shells that were ejected by its progenitor star in two consecutive eruptions sometime before the SN explosion.