Synthetic light curves of shocked dense circumstellar shells

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ABSTRACT

We investigate numerically the light curves (LCs) of shocked circumstellar shells, which it has been suggested might reproduce the observed LC of superluminous SN 2006gy analytically. In the previous analytical model, the effects of recombination and bolometric correction on LCs were not taken into account. To see these effects, we perform numerical radiation hydrodynamic calculations of shocked shells using STELLA, which can treat multigroup radiation transfer numerically with realistic opacities. We show that the effects of recombination and bolometric correction are significant and that the analytical model should be compared with the bolometric LC rather than a single-band LC. We find that shocked circumstellar shells having a rapid LC decline initially because of adiabatic expansion, rather than luminosity increase, and these shocked shells fail to explain the LC properties of SN 2006gy. However, our synthetic LCs are qualitatively similar to those of superluminous SN 2003ma and SN 1988Z and the latter objects may be related to shocked circumstellar shells.

Key words: supernovae: general – supernovae: individual: SN 1988Z – supernovae: individual: SN 2003ma – supernovae: individual: SN 2006gy.

1 INTRODUCTION

The origin of superluminous supernovae (SLSNe), the existence of which was recognized only recently (see Gal-Yam 2012 for a review), is still a mystery. Several mechanisms to explain their extremely high luminosities have been suggested so far (e.g. Smith et al. 2007; Woosley, Blinnikov & Heger 2007; Blinnikov & Sorokina 2010; Kasen & Bildsten 2010; Chatzopoulos, Wheeler & Vinko 2012; Dexter & Kasen 2012; Moriya et al. 2013; Ouyed et al. 2012). At least for the subclass of SLSNe named ‘SLSN-II’ in Gal-Yam (2012), ejecta–circumstellar medium (CSM) interaction is likely to be a main power source, because most of them show narrow emission lines that are supposedly related to the existence of a dense circumstellar shell (see e.g. Filippenko 1997). SNe can be very bright at their early epochs when they have dense circumstellar shells, since the kinetic energy of SN ejecta can be efficiently converted to radiation due to interaction.

Dense circumstellar shell causing SLSNe are likely to be dense enough to cause shock breakout in the shell (e.g. Moriya et al. 2013). There are two possible locations at which shock breakout can occur in a dense shell. The two cases are clearly summarized in Chevalier & Irwin (2011). In one case, the optical depth of a dense shell is high enough to keep photons in the forward shock until they come near the surface of the dense shell. In other words, shock breakout occurs near the surface of the dense shell. On the other hand, if the optical depth is low, then shock breakout can occur within the shell well before the shock reaches the vicinity of the shell surface. In this case, photons emitted from the shock diffuse in the remaining shell after shock breakout. LCs from the latter cases have been investigated numerically and they are found to be consistent with the LC of SN 2006gy (Moriya et al. 2013; Ginzburg & Balberg 2012).

Smith & McCray (2007, SM07 hereafter) investigate a SLSN LC model resulting from a circumstellar shell through which a shock wave has passed. This model basically corresponds to the former picture of shock breakout, i.e. shock breakout at the surface of a dense shell. In other words, SM07 consider a dense shell from which photons start to emit after the passage of a shock wave. They
apply the LC model of adiabatically cooling SN ejecta formulated by Arnett (1980). By simply comparing the shape of the model LC with the R-band LC of SN 2006gy, SM07 concluded that SN 2006gy can result from a shocked circumstellar shell.

However, there are many simplifications involved in the SM07 model that have not been discussed so far. The existence of a recombination wave in a shocked H-rich CSM is presumed to affect the LC, as in the case of Type IIP SNe (e.g. Grassberg, Imshenik & Nadyozhin 1971; Falk & Arnett 1977; Kasen & Woosley 2009; Bersten, Benvenuto & Hamuy 2011). In addition, SM07 compare a bolometric LC obtained from their model with the R-band LC of SN 2006gy. As the shocked shell should have a temperature close to $10^4$ K at the beginning to explain the observed properties of SN 2006gy (Smith et al. 2010), a large proportion of emitted photons are not in the R band and bolometric correction should be considered.

To see the importance of these neglected effects in the SM07 analytic model, we numerically follow the system suggested to explain SN 2006gy in SM07 by using the numerical radiation hydrodynamics code STELLA. STELLA is a one-dimensional radiation hydrodynamics code; it can treat multifrequency radiation and the opacity is calculated based on the physical parameters under the assumption of local thermodynamic equilibrium. This assumption is a good approximation by which to obtain a LC from a shocked shell because of its large density and optical depth. Thus, STELLA is a suitable code to see the effects of bolometric correction and recombination, which are not taken into account in the SM07 analytic model. For details of STELLA, we refer the reader to other articles (e.g. Blinnikov & Bartunov 1993; Blinnikov et al. 2000, 2006; Blinnikov & Tolstov 2011).

We start by showing the initial conditions of the models that are constructed based on SM07 in Section 2 and then show the numerical results in Section 3. A discussion is presented in Section 4 and we conclude in Section 5. We apply the same distance to the host galaxy (73.1 Mpc) and extinctions (Galactic $A_K = 0.43$ mag + host $A_K = 1.25$ mag) as in Smith et al. (2007) to the observed LC of SN 2006gy.

2 MODELS

The initial conditions of our numerical calculations are constructed based on SM07 at first. We do not follow shock propagation in shells, to make the initial conditions the same as those of SM07. The initial conditions are supposed to result from shock passage in a dense circumstellar shell. Since we do not treat the shock wave, the smearing term in the STELLA code that affects the conversion efficiency from kinetic energy to radiation discussed in Moriya et al. (2013) does not affect the results obtained in this paper.

Table 1 lists our initial conditions. The initial radius of the SM07 model suggested for SN 2006gy is $2.4 \times 10^{15}$ cm. The mass of the shocked shell in the model is $10 M_\odot$. We assume that the system is homologously expanding and the outermost layer velocity is $4000 \text{ km s}^{-1}$, as assumed in SM07. The initial temperature is set constant in the entire shell. We try two temperatures for the SM07 system, namely $10^4$ K (model 01 or M01) and $4 \times 10^4$ K (M02). The composition is solar in these models.

We also investigate several configurations other than those suggested in SM07. M03 has the same velocity but the initial radius is three times larger than that of the SM07 model. The temperature is set to $1.7 \times 10^4$ K to match the observed luminosity of SN 2006gy. The mass is increased to $20 M_\odot$ in M03 to keep the shell optically thick. M04 and M05 have the same density structure as M03 but the velocity is 0.5 and 2 times that of M03, respectively. We also show the results of M06, which is more compact than the SM07 model. The composition is solar in M03–M06. M07 has 50 per cent carbon and 50 per cent oxygen, while its other properties are the same as in M03.

| Name | $v_{ini}^a$ km s$^{-1}$ | $M_{shell} b$ $M_\odot$ | $R_{ini}$ $c$ cm | $T_{ini} d$ $10^4$ K | Composition |
|------|-------------------|-------------------------------|----------------|---------------------|-------------|
| M01  | 4000              | 10                            | 2.4            | 1                   | solar       |
| M02  | 4000              | 10                            | 2.4            | 4                   | solar       |
| M03  | 4000              | 20                            | 7.2            | 1.7                 | solar       |
| M04  | 2000              | 20                            | 7.2            | 1.7                 | solar       |
| M05  | 8000              | 20                            | 7.2            | 1.7                 | solar       |
| M06  | 4000              | 20                            | 0.72           | 13                  | solar       |
| M07  | 4000              | 20                            | 7.2            | 1.7                 | C 50 per cent + O 50 per cent |

$^a$Velocity of the outermost layer of the shell.
$^b$Mass of the shell.
$^c$Radius of the shell.
$^d$Initial temperature of the shell.

3 SYNTHETIC LIGHT CURVES

Fig. 1(a) shows the bolometric LCs of M01–M03. At first glance, we find that no LCs are consistent with that of SN 2006gy. Furthermore, the R-band LCs shown in Fig. 1(b) are found to be even more different from the R-band LC of SN 2006gy. This indicates the importance of bolometric correction. We discuss the LC behaviour in this section, but most of our discussion can be found in previous studies; see e.g. Grassberg et al. (1971) and Falk & Arnett (1977).

The bolometric LCs start with the initial peak. The peak bolometric luminosity is $4\pi R_s^2\sigma T_4^4$, where $\sigma$ is the Stefan–Boltzmann constant. At first, the bolometric luminosity decreases due to adiabatic expansion of the shell. If we assume that the homologously expanding shell is radiation-dominated at early phases, then the bolometric luminosity should decrease $\propto t^{-2}$. This rapid decrease in bolometric luminosity appears in our numerical models.

SM07 suggest that the bolometric LC of shocked shells would rise $\propto t^2$ at first because shocked materials expand homologously and a shocked shell is just an expanding blackbody. However, if we take into account the decrease in the blackbody temperature of the shell due to adiabatic expansion and the lack of any heat sources, the effect of temperature decline on bolometric luminosity ($\propto t^{-4}$ in radiation-dominated shells) is larger than the effect of radius increase ($\propto t^2$). In fact, our synthetic LCs do not show a luminosity increase and the luminosity simply declines.

After an initial rapid luminosity decline, bolometric LCs start to be affected by photons diffused in the shell and begin to follow the diffusion model of Arnett (1980). From this point, the SM07 analytic model begins to work. M01, which has an initial temperature ($10^4$ K) close to the blackbody temperature of SN 2006gy at the LC peak, is too faint at this epoch to explain SN 2006gy because of the initial rapid luminosity decline due to adiabatic expansion. With the initial configuration suggested by SM07, the temperature should be around $4 \times 10^4$ K (M02) to explain the luminosity of SN 2006gy, but this is inconsistent with the observed blackbody temperature (Fig. 2). M03 has a larger radius than M01 and M02. Thus, the required temperature to obtain the same luminosity is low ($1.7 \times 10^4$ K) and close to the observed values.

Although the bolometric LCs at these epochs seem to follow the observed bolometric LC, we should be careful because the...
The bolometric LC of SN 2006gy is obtained through the R-band LC without bolometric correction. We need to compare LCs in the R band (Fig. 1b). We find that the numerical R-band LCs do not match the observed R-band LC even in those models that give a good fit in Fig. 1(a). This is simply because of high temperatures in the shell and most of the emitted photons are not in the R band. We note that the strong Hα line observed in SN 2006gy is in the R-band and thus direct comparison between our numerical R-band LCs and the observed R-band LC can be inappropriate. However, the Hα luminosities of SN 2006gy at the epochs we are interested in are $\sim 10^{41}$ erg s$^{-1}$ (Smith et al. 2010) and the bolometric correction therefore remains important.

Another unavoidable and important consequence of the SM07 model, which is not discussed in SM07, is the existence of a recombination wave in the shocked shell. In the SM07 model, there are no energy sources in the shell because the shock has already passed the shell and the shocked shell simply cools down. At one epoch, the temperature should reach the recombination temperature as is the case for Type IIP SNe. This is not the case for continuous ejecta-CSM interaction models because there remains an energy source (shock waves) that can keep the shell ionized until the shock wave passes through the dense shell.

The effect of recombination can be seen by comparing M03 and M03co in Fig. 1(a). M03 is calculated with our standard opacity table, which takes recombination into account. M03co (M03 constant opacity) is calculated by forcing the scattering opacity of the system to be 0.34 cm$^2$ g$^{-1}$, which corresponds to fully ionized solar composition materials. At first, when the shell is above the recombination temperature, the two LCs follow almost the same track. Then the two LCs start to deviate when the outermost layer reaches the recombination temperature at around 40 d after the LC peak (Fig. 2). The recombination wave, and thus the photosphere, move inside (in a Lagrangian sense) after this epoch. They eventually reach the bottom of the shell and the LC suddenly drops. On the other hand, the LC with constant opacity continues to decline monotonically, roughly following the SM07 analytic model. Fig. 3 shows the photospheric radii of the models and the effect of recombination therefore is clear.

Another important consequence caused by the existence of recombination is the strong dependence of LCs on the shell velocity. The epoch when the outermost layers reach recombination temperature and the recession velocity of the recombination wave in the shell are affected by the shell velocity. This is simply because adiabatic cooling becomes more efficient in faster shells. M04 and M05 have slower and faster shells, respectively, than M03 and their LCs are presented in Fig. 4. At first, the LCs are expected to differ when recombination starts to play a role in shells. However, the difference at this epoch is not significant according to our calculations. The time of the drop in the LCs clearly differs and faster shells have earlier drops due to a faster recombination wave.
4 DISCUSSION

4.1 Model with initial $R$-band luminosity increase

All the models we have presented so far do not have a phase with luminosity increase and the luminosity just declines. However, it is possible to have a rising phase in optical LCs from a shocked shell. Fig. 5 shows one example of a LC obtained from M06. The bolometric LC and optical LCs as well as the $R$-band LC of SN 2006gy are shown in the same figure for illustrative purposes. The evolution of the bolometric LC does not differ so much from the previous models but optical LCs of M06 have a rising phase. This is because of the initial small radius and high temperature. The optical luminosities are low at the beginning due to the initial high temperature. Then, as adiabatic cooling is efficient due to the initial small shell radius, the shell cools quickly and optical luminosities increase accordingly. The $R$-band LC can be similar to that of SN 2006gy, although the photospheric temperature is much higher in M06 and it is inconsistent with SN 2006gy observations.

4.2 Possible corresponding supernovae

LCs of shocked shells obtained by our numerical calculations have an initial rapid decline followed by a relatively long plateau. Although these features are not seen in SLSN 2006gy, SLSN 2003ma (SLSN-II) shows qualitatively similar features (Rest et al. 2011). The LC of SN 2003ma is different from those of other known SLSNe. The LC of SN 2003ma has a quick rise and quick decline followed by a long plateau phase that lasts for about 100 d, while other SLSNe evolve more slowly. Then the LC drops by about 1 mag in the optical and the luminosity stays almost constant for about 1000 d after the drop. The initial rise and decline as well as the plateau phase, which lasts for about 100 d, can be seen in some synthetic optical LCs obtained in this study (e.g. Fig. 1b), but the plateau phase after the drop, which lasts for about 1000 d, requires another emission mechanism such as continuous CSM interaction.

SN 1988Z has similar features to SN 2003ma, although the luminosity is about 3 mag smaller (e.g. Turatto et al. 1993; Aretxaga et al. 1999). Because of the LC similarity, SN 1988Z could also be related to shocked shells (see also Chugai & Danziger 1994). Depending on e.g. radii and temperatures of shocked shells, their luminosities can vary. There may be many other similar SNe with a variety of luminosities and plateau durations, depending on the shell properties.

4.3 Other effects

4.3.1 Shell of carbon and oxygen

We examine a LC from a shocked shell with 50 per cent carbon and 50 per cent oxygen. A subclass of SLSNe is known to have no hydrogen features in its spectra and a composition likely to be dominated by carbon and oxygen (e.g. Quimby et al. 2011). Fig. 6 shows the results. As the opacity decreases significantly compared with the cases with solar composition, the LC declines much faster. In addition, due to the high recombination temperature of carbon and oxygen, the effect of recombination is less significant than in the cases with solar composition. However, we do see a significant drop in the LC due to recombination if we compare it with the LC model (M07) with constant opacity ($0.1 \text{ cm}^2 \text{ g}^{-1}$). Thus, we should also be cautious about the applicability of the SM07 model when we try to apply it to carbon- and oxygen-dominated systems.
We also investigate the effect of the different opacity tables adopted in STELLA (Fig. 7). The detailed descriptions about the three opacity tables adopted here can be found in Tominaga et al. (2011).

In one opacity table (‘inner shell’ in Fig. 7), the inner-shell photoionization is additionally taken into account. The opacity table used so far in this paper assumes that all atoms and ions, except for hydrogen, are in the ground state to obtain the opacity from bound–free absorptions as in Eastman & Pinto (1993). In the other opacity table used in this section (‘bound free’ in Fig. 7), excited levels are also taken into account in bound–free absorptions.

As can be seen in Fig. 7, in which LCs from the three opacity tables are shown, the difference caused by the different opacity tables is small. Thus, the effects of inner-shell photoionizations and excited levels in bound–free absorption on LCs are negligible in the system we are interested in in this paper.

5 CONCLUSIONS

We investigate numerically the LC properties of shocked shells, which it has been suggested can account for SN 2006gy analytically through SM07. We show that shocked shells fail to explain the rising part of the SN 2006gy LC because of adiabatic cooling. In addition, in the declining part we show the importance of the effects of bolometric correction and recombination, which are not taken into account in SM07. SM07 compare their analytic bolometric LCs with the observed R-band LC of SN 2006gy, but the high temperature of the shell estimated from spectral observations is against this assumption and the R-band LCs of shocked shells become flatter than the bolometric LCs. Recombination also makes the LCs flatter than those suggested analytically in SM07.

We also show the effect of the expansion speed of shocked shells. This affects the propagation velocity of the recombination wave in the shells and changes the duration of the LCs. The composition of the shells alters the opacity and is shown to change the LCs greatly. Although we show that the LC of SN 2006gy is not consistent with the shocked circumstellar shell model, this kind of system can exist. We suggest that SLSN 2003ma and SN 1988Z may come from a shocked shell because of their qualitative LC similarity to our numerical results. In addition, our numerical modelling indicates that shocked shells can be bright (sometimes more than $\sim-23$ mag in the optical) and their luminosities can drop more than 1 mag in the optical within 1 d (M03). This kind of object could be observed in future transient surveys and could fill the bright and fast-declining part of explosive transient phase space (e.g. Kulkarni 2012). The existence of such transients from a shocked shell indicates the existence of explosive mass loss just before explosions of some kinds of star, a fact currently not well-known, and they can provide us with a clue to understanding such mass loss.
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