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Light Curve Modeling of Superluminous Supernovae

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Abstract. Origins of superluminous supernovae (SLSNe) discovered by recent SN surveys are still not known well. One idea to explain the huge luminosity is the collision of dense CSM and SN ejecta. If SN ejecta is surrounded by dense CSM, the kinetic energy of SN ejecta is efficiently converted to radiation energy, making them very bright. To see how well this idea works quantitatively, we performed numerical simulations of collisions of SN ejecta and dense CSM by using one-dimensional radiation hydrodynamics code STELLA and obtained light curves (LCs) resulting from the collision. First, we show the results of our LC modeling of SLSN 2006gy. We find that physical parameters of dense CSM estimated by using the idea of shock breakout in dense CSM (e.g., Chevalier & Irwin 2011, Moriya & Tominaga 2012) can explain the LC properties of SN 2006gy well. The dense CSM's radius is about 10^{16} cm and its mass about 15 $M_{\odot}$. It should be ejected within a few decades before the explosion of the progenitor. We also discuss how LCs change with different CSM and SN ejecta properties and origins of the diversity of H-rich SLSNe. This can potentially be a probe to see diversities in mass-loss properties of the progenitors. Finally, we also discuss a possible signature of SN ejecta-CSM interaction which can be found in H-poor SLSN.

Keywords. supernovae: general, supernovae: individual (SN 2006gy, SN 2006oz), stars: mass loss, circumstellar matter

1. Introduction

There are several suggested ways to explain the huge luminosity of superluminous supernovae (SLSNe), e.g., large production of ^{56}Ni (Gal-Yam *et al.* 2009, Moriya *et al.* 2010), interaction between dense circumstellar medium (CSM) and SN ejecta (or ejecta from stellar surface) (e.g., Woosley *et al.* 2007), magnetar spin-down (e.g., Kasen & Bildsten 2010), fallback (e.g., Dexter & Kasen 2012), etc. Most of SLSNe II (see, e.g., Gal-Yam 2012 for a review of the SLSN classification) show narrow lines which are expected to appear from dense CSM and it is natural to think they are coming from the interaction.

2. Shock Breakout for Superluminous Supernovae

Here, we investigate an SLSN model in which a SN explosion occurred in dense CSM and the SN gets superluminous because of the deceleration by the dense CSM. To explain the huge luminosities of a SLSN in this model, the dense CSM needs to be so dense that we need to take the effect of the shock breakout into account (Chevalier & Irwin 2011, Moriya & Tominaga 2012). From the shock breakout model, we can estimate two observable timescales,

$$t_d \simeq \begin{cases} \frac{R_o}{v_s}\left[\left(\frac{c/v_s + x^{1-w}}{c/v_s+1}\right)^{\frac{1}{1-w}} - x\right] & (w \neq 1), \\ \frac{R_o}{v_s}\left(x^{\frac{1}{1+c/v_s}} - x\right) & (w = 1). \end{cases} \tag{2.1}$$

$$t_s = \frac{R_o - xR_o}{v_s}, \tag{2.2}$$

where t_d is the diffusion timescale in the dense CSM after the shock breakout which corresponds to the SLSN LC rising time, t_s is the time required for the shock wave to go through the entire CSM, R_o is the CSM radius, v_s is the shock velocity, c is the speed of light, xR_o is the radius of the shock breakout, and w is the CSM density slope ($\rho \propto r^{-w}$). For the best observed SLSN 2006gy, $t_d \simeq 70$ days and $t_s \simeq 200$ days (Smith *et al.* 2010) and we can estimate CSM properties for given w and v_s. Estimated CSM structures reproduces SN 2006gy properties very well, as reported in Moriya *et al.* (2013b). What is particularly interesting is that the steady mass loss model could not reproduce the SN 2006gy LC. We also note that the shell shocked diffusion model suggested by Smith & McCray (2007) does not work for SN 2006gy (Moriya *et al.* 2013a).

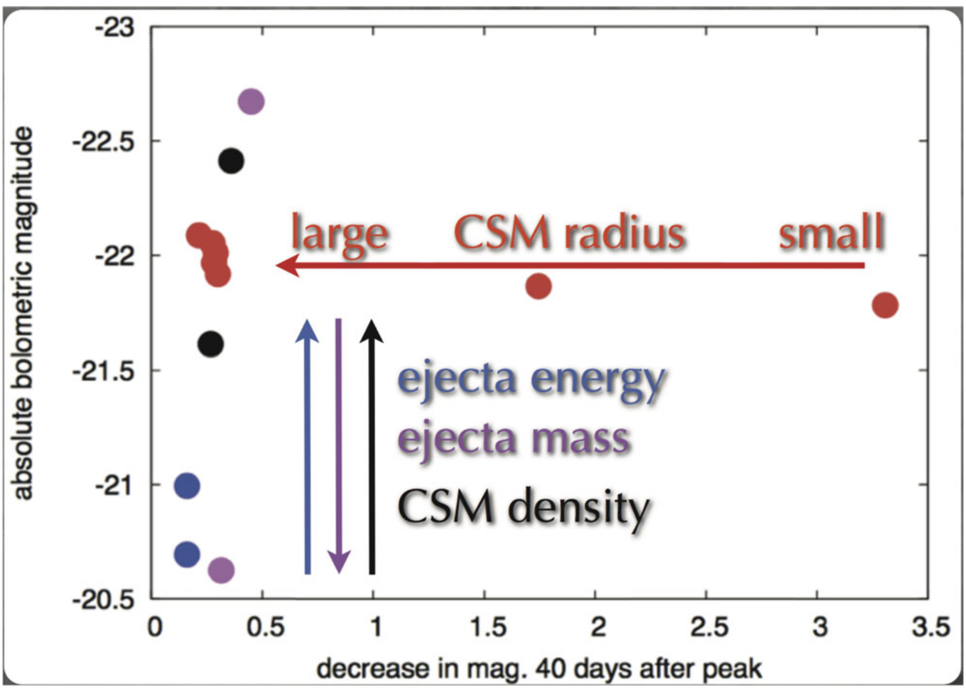

Figure 1. Direction of changes in decline rate-peak luminosity plane.

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3. Diversity of Superluminous Supernovae

Quimby *et al.* (2013) reported the distribution of SLSNe in a decline rate-luminosity plane. Based on the interaction model of SN 2006gy, we can change SN ejecta and CSM properties to see the origin of the diversity. In Figure 1, we show in which directions the SLSN properties move when we change SN ejecta and CSM properties obtained by the preliminary numerical LC calculations. More detailed study will show us the origin of the diversity of SLSNe and the mass loss of the progenitors.

4. 'Dip' in Superluminous Supernova Light Curve

Currently, SLSNe I (e.g., Quimby *et al.* 2011) does not have clear signatures of the physical processes making them superluminous. Leloudas *et al.* (2012) reported the LC observations of a SLSN-I 2006oz. They detected a precursor of the SN and there existed a 'dip' in the LC between the main LC and the precursor. This may indicate the existence of dense C+O CSM around the SN ejecta and SLSN-I may also be related to the SN ejecta-dense CSM interaction (Moriya & Maeda 2012). This 'dip' is also observed in Type IIn SN 2009ip (e.g., Prieto *et al.* 2013), in which the existence of the dense CSM is clear because of the SN type.

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Discussion

Chevalier: You discussed the dip seen in the early light curve of SN 2006oz. What are your thoughts on explaining the plateau before the dip?

Moriya: There can be another CSM component inside the dense CSM powering the main LC and that component may power the plateau before the dip.

Saha, L.: 1. Is there any limit on the mass of the ejecta so that SN could be superluminous or not? 2. How does density gradient help for this kind of SLSN scenario or what are the implications of CSM density gradient for SLSN?

Moriya: 1. Ejecta mass should be similar to or less than the CSM mass. This is because ejecta must be decelerated by CSM to make SLSNe bright. 2. From the LC point of view, the density gradient can affect the LC decline after the peak. The density gradient also affects spectra and I refer Moriya & Tominaga (2012) for details.