Observable fractions of core-collapse supernova light curves brightened by binary companions

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ABSTRACT

Many core-collapse supernova progenitors are presumed to be in binary systems. If a star explodes in a binary system, the early supernova light curve can be brightened by the collision of the supernova ejecta with the companion star. The early brightening can be observed when the observer is in the direction of the hole created by the collision. Based on a population synthesis model, we estimate the fractions of core-collapse supernovae in which the light-curve brightening by the collision can be observed. We find that 0.19 per cent of core-collapse supernova light curves can be observed with the collisional brightening. Type Ibc supernova light curves are more likely to be brightened by the collision (0.53 per cent) because of the high fraction of the progenitors being in binary systems and their proximity to the companion stars. Type II and IIb supernova light curves are less affected (∼10−3 and ∼10−2 per cent, respectively). Although the early, slow light-curve declines of some Type IIb and Ibc supernovae are argued to be caused by the collision with the companion star (e.g. SN 2008D), the small expected fraction, as well as the unrealistically small separation required, disfavour the argument. The future transient survey by the Large Synoptic Survey Telescope is expected to detect ∼10 Type Ibc supernovae with the early collisional brightening per year, and they will be able to provide information on supernova progenitors in binary systems.

Key words: binaries: general – supernovae: general – supernovae: individual: SN 2008D.

1 INTRODUCTION

Core-collapse supernovae (SNe) are explosions of massive stars. Massive stars do not explode as they are born. During their evolution to their death, which takes millions of years, the internal structures of the stars dramatically change and their masses can be reduced because of mass-loss. They can also be affected by their binary companions. Sana et al. (2012) found that more than 70 per cent of massive stars which can eventually explode are once in close binary systems. The effect of stellar duplicity on the stellar evolution has been studied (see Langer 2012 for a review). Especially, core-collapse SNe with little or no hydrogen (SNe III/Ib/Ib/Ic) have been suggested to come from binary systems (e.g. Podsiadlowski, Joss & Hsu 1992; Podsiadlowski et al. 1993; Maund et al. 2004; Eldridge, Izzard & Tout 2008; Yoon, Woosley & Langer 2010; Follati et al. 2014; Eldridge et al. 2015). SN light-curve (LC) modelling also supports this idea (e.g. Nomoto et al. 1993; Utrobin 1994; Woosley et al. 1994; Blinnnikov et al. 1998; Bersten et al. 2012, 2014; Fremling et al. 2014).

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When a SN explosion occurs in a binary system, the SN and the companion star can both be affected by the explosion (e.g. Wheeler, Lecar & McKee 1975; Fryxell & Arnett 1981; Chugai 1986; Livne, Tuchman & Wheeler 1992; Marietta, Burrows & Fryxell 2000; Pakmor et al. 2008; Chevalier 2012; Liu et al. 2013; Hirai, Sawai & Yamada 2014; Maeda, Kutsuna & Shigeyama 2014; Sabach & Soker 2014; Tauris 2015). Several SN properties can be strongly affected by the existence of the companion. In particular, Kasen (2010, hereafter K10) showed that the binary companion can alter the early X-ray/ultraviolet/optical SN LCs. The early optical brightness is increased because of the extra heating provided by the collision between the SN ejecta and the companion star.

While early SN optical LCs are brightened by a collision, they are presumed to decline much more slowly than those without a collision (K10). Relative to a normal, e.g. single-star, SN, the LC describing a collision between SN ejecta and a companion star is brighter (K10). Energy from the collision counteracts adiabatic cooling after the shock breakout, thus slowing the LC decline. The LC of SN Ib 2008D was related to a collision because of the extremely slow LC decline during the 5 d after the explosion (Dessart et al. 2011). SN LC simulations show that the early LC declines in SNe Ib caused by the adiabatic cooling in the SN ejecta only.
last about 1 d because their progenitors are compact (Wolf–Rayet stars). The LCs then become flat for several days because of helium recombination if a sufficient amount of helium is in the progenitors (Dessart et al. 2011). The declining phase of the LC of SN 2008D lasted for about 5 d and is difficult to explain with standard compact Wolf–Rayet progenitors. Because many SN Ibc progenitors are suggested to be in binary systems, Dessart et al. (2011) proposed that the slow decline can be related to the collision of the SN ejecta with the binary companion. However, Bersten et al. (2013) argued that the separation required to explain the early luminosity of SN 2008D is unrealistically small (∼R⊙) and it is not likely caused by the collision. They suggested that the 56Ni mixing to the outermost layers of the SN ejecta lead to the early, slow LC decline rather than the collision. Other plausible explanations for the slow LC decline include a large progenitor radius (e.g. Chevalier & Fransson 2008; Nakar & Piro 2014) and the existence of an extended dense circumstellar medium (e.g. Balberg & Loeb 2011; Svirski & Nakar 2014).

While a large fraction of core-collapse SN progenitors may be affected by the binary companion during their evolution, whether we can observe brightening in the early LCs is not obvious even if the progenitors are in binary systems. This is because not only the progenitors need to be in binary systems but also observers need to be within certain limited viewing angles from which the brightening can be observed (K10, Fig. 1). In this paper, we investigate the expected fractions of core-collapse SNe whose observed LCs are brightened by the collision based on a population synthesis model. Our predicted fractions can be tested with future transient surveys.

The rest of this paper is organized as follows. In Section 2, we summarize our population synthesis model and the general SN properties predicted from the model. Then, we estimate the fractions of SNe in which the early LC brightening by the collision is observable in Section 3. We discuss our results in Section 4 and conclude in Section 5.

2 POPULATION SYNTHESIS

In this section, we briefly summarize our population synthesis modelling. We discuss the general SN properties predicted by our population synthesis model. We also discuss the uncertainties in our predictions.

2.1 Method

We model stellar evolution with the binary evolution code BINARY_C/NUCSYN (Izzard et al. 2004b, 2006, 2009) which is a modified and updated version of that presented by Hurley, Tout & Pols (2002). We refer to these papers for the detailed physics and assumptions in the binary evolution model. Of the key parameters in binary-star evolution, we set the common-envelope ejection efficiency, αCE, to 1 by default and use the fits to detailed models describing the envelope binding energy parameter, λ (Dewi & Tauris 2001; Tauris & Dewi 2001). αCE is constrained to be around ∼0.1–1 for low- and intermediate-mass stars (e.g. Zorotovic et al. 2010; De Marco et al. 2011; Davis, Kolb & Knigge 2012). Wind mass-loss is taken into account by following the prescription summarized in Izzard et al. (2006). A SN is assumed to occur when the carbon–oxygen core mass reaches a given maximum mass (see Hurley, Pols & Tout 2000 for details). When a star explodes in a binary system, the companion star is assumed to receive a kick velocity from a Maxwellian distribution with a dispersion of 190 km s⁻¹, as is assumed in Hurley et al. (2002).

Our stellar populations are modelled by a three-dimensional parameter space of the primary mass, secondary mass, and orbital period. The primary mass is distributed according to the initial mass function of Kroupa (2001), and the secondary mass is chosen to be flat in the mass ratio q = M2/M1. The period distribution follows that of Sana et al. (2012) for O-type primary stars in excess of 16 M⊙, Raghavan et al. (2010) for solar-like primary stars with mass below 1.15 M⊙, and a fitting function interpolated linearly in primary mass between these two limiting masses. We evolve systems with primary masses from 3 to 80 M⊙, mass ratios between 0.1 M⊙/M1 and 1.0 and orbital periods between 0.1 and 10¹⁰ d. All our stars have metallicity Z = 0.02 and start in circular orbits.

The fraction of stars in binary systems in our stellar populations is based on Raghavan et al. (2010). All the stars which are O-type or B-type at the zero-age main sequence are assumed to be in binary systems initially. Therefore, the initial binary fraction of our SN progenitors is essentially 100 per cent. Observations indicate that the fraction of OB stars in binary systems are more than 70 per cent (Raghavan et al. 2010; Sana et al. 2012). Single stars in these observations may be observed as single because they are merged stars or their companion stars have already exploded. Thus, the actual initial binary fractions are not well known and we simply assume the 100 per cent binary fraction in this study.

2.2 Supernova properties

The population synthesis model described in the previous section predicts several SN properties. The total core-collapse SN rate of the Galaxy predicted from the model is (0.93–1.99) × 10⁻² yr⁻¹, assuming a Galactic star formation rate of 0.68–1.45 M⊙ yr⁻¹ (Robitaille & Whitney 2010) and the average stellar mass from

![Figure 1. Schematic picture of important parameters in our model. When the SN ejecta collides with the companion star with radius R⋆ at a separation a, a hole with the half-opening angle of θh ≃ arctan(2R⋆/a) is created by the collision. The early LC brightening because of the collision can be observed when the observer is in the direction of the hole (K10).](https://academic.oup.com/mnras/article-abstract/450/3/3264/1075714/1075714)
the Kroupa initial mass function (0.83 M⊙). This rate is consistent with the estimated Galactic core-collapse SN rate from recent surveys [e.g. (2.30 ± 0.48) × 10−2 yr−1; Li et al. 2011b].

We determine the SN type of the exploding stars based on the stellar composition. While there exist many types of core-collapse SNe, we only consider three SN types (II, Ib, and Ibc) for simplicity. If hydrogen remains in SN progenitors, the SNe are classified as Type II or Ib. We try to identify Type Ib because several SN Ib progenitors are suggested to be in binary systems (e.g. Maund et al. 2004; Bersten et al. 2012; Follatelli et al. 2014; Fox et al. 2014). The difference between the progenitors of the two SN types is presumed to be in the remaining hydrogen-rich envelope mass, but the exact mass dividing the two types is not well constrained. In our standard model, we classify the progenitors with the hydrogen-rich envelope mass smaller than 4.5 M⊙ as Type Ib and the other hydrogen-rich progenitors as Type II. The dividing mass 4.5 M⊙ is chosen so that the Type Ib fraction in our model is similar to the observed fraction (~10 per cent; Smith et al. 2011; Eldridge et al. 2013). However, the dividing mass 4.5 M⊙ is higher than the 2 M⊙ used in other progenitor studies (e.g. Heger et al. 2003; Groh et al. 2013) or those estimated from observational properties (~0.5–0.1 M⊙; e.g. Nomoto et al. 1993; Podsiadlowski et al. 1993; Woosley et al. 1994; Blinnikov et al. 1998; Elmhamdi et al. 2006; Bersten et al. 2012). We also show the results with the dividing mass of 2, 0.5, and 0.1 M⊙. As is shown in the following sections, the SN Ib fractions in core-collapse SNe are affected by the dividing mass but the observational fractions of the early LC brightening because of the collision are not much. If a SN is hydrogen free, it is classified as Type Ibc. Because the differences in the progenitors of Type Ib and Ic SNe may not simply come from the remaining helium mass and they are not well known (e.g. Dessart et al. 2012; Hachinger et al. 2012), we do not sub-divide the hydrogen-free SNe.

The fractions of each SN type are shown in Table 1. The fractions of hydrogen-rich SNe (Type II and Ib) and the hydrogen-free SNe (Type Ibc) obtained from our population synthesis model match the observations reasonably (Type II including all the sub-types ~70 per cent and Type Ib ~30 per cent; Arcavi et al. 2010; Li et al. 2011a; Smith et al. 2011; Eldridge et al. 2013), although Type Ibc SNe are slightly overproduced (see also discussion on uncertainties in Section 2.3). When the dividing mass between Type II and Type Ib is set to 2, 0.5, and 0.1 M⊙, the SN Ib fractions become 2.9, 2.2, and 2.0 per cent, respectively (see also Claeys et al. 2011). The fraction of hydrogen-free SNe is not affected by the dividing mass of the two hydrogen-rich SN types.

To summarize, our population synthesis model reproduces bulk observational properties of core-collapse SNe, namely, the rate and the fraction of the hydrogen-rich and hydrogen-free SNe, reasonably well. Thus, the model is presumed to represent the binary properties of SN progenitors reasonably.

### 2.3 Uncertainties

Because the number of stars used in our population synthesis calculations is sufficiently large, the errors in the estimated fractions below are mainly systematic. To evaluate the systematic uncertainties, we perform the binary population synthesis calculations with several model assumptions. The largest deviation in the predicted fractions we found is by a factor of 1.5 from the standard fraction shown in the next section when we reduce the common-envelope ejection efficiency αCE to 0.5 from the standard value αCE = 1. We also refer to de Mink et al. (2014) and Claeys et al. (2011, 2014) for the recent investigations on the systematic uncertainties in the binary evolution modelling with similar algorithm.

### 3 PREDICTED OBSERVABLE FRACTIONS OF THE EARLY LIGHT-CURVE BRIGHTENING DUE TO THE COLLISION

Based on our population synthesis model, we estimate the expected fractions of core-collapse SNe in which the LC brightening due to the binary collision is observable. Our population synthesis model provides the fractions f s of SNe coming from each simulated progenitor system at the time of the explosion. The total fraction of SNe in binary systems when they explode is expressed as

\[ f_s(\text{binary}) = \sum f_s. \]

The summation in equation (1) is taken for all the SN progenitors which are in binary systems at the time of the explosion. The binary fractions predicted from our population synthesis model are shown in Table 1. The binary fractions are smaller at the time of the explosion than at the time of the birth because a SN progenitor can leave the binary system when its companion star explodes earlier. Stellar mergers also reduce the binary fractions. Because SN II progenitors tend to have longer lifetimes, their binary fraction is more reduced when they explode than that of SN Ibc progenitors. The binary fraction is larger in SNe Ibc because more mass can be lost in the binary systems because of the binary interactions during the evolution, allowing the progenitors in the binary systems to strip the hydrogen-rich envelope more easily. The binary evolution makes the predicted fraction of the stripped SNe close to that observed (e.g. Izzard et al. 2004a; Eldridge et al. 2008; Eldridge, Langer & Tout 2011).

We assume that LC brightening from a binary collision can be observed if the observer is within the half-opening angle θh of the hole created by the collision (K10). Following K10, we set

\[ \theta_h \simeq \arctan \left( \frac{2R_y}{a} \right), \]

where \(R_y\) is the radius of the companion and \(a\) is the separation. Fig. 1 presents a schematic picture of these parameters. If the observer is at a random location, the probability \(p_h\) that the SN is observed within the half-opening angle is

\[ p_h = \frac{\Omega_h}{4\pi} = \frac{1 - \cos \theta_h}{2}. \]

![Table 1. Fractions predicted from our population synthesis model. See Section 2.3 for uncertainties.](https://academic.oup.com/mnras/article-abstract/450/3/3264/1075714)
where $\Omega_h$ is the solid angle of the hole. The fraction of SNe in which the collisional brightening can be observed is

$$f(\text{observable}) = \sum_{\text{binary}} f_h.$$  \hfill (4)

The fractions of SNe in which the LC brightening from a collision is observable are summarized in Table 1: 0.19 per cent of all core-collapse SN LCs are found to be brightened by the collision. The observable fractions in SNe II and Ib are small. The expected fraction for SNe II is $3.8 \times 10^{-3}$ per cent. The fraction is larger in SNe Ib ($1.6 \times 10^{-2}$ per cent for the standard model). The dividing mass between SNe II and Ib is found to have a small effect on the observable fraction ($1.8 \times 10^{-2}$ per cent for 2 M$_\odot$, $1.5 \times 10^{-2}$ per cent for 0.5 M$_\odot$, and $1.4 \times 10^{-2}$ per cent for 0.1 M$_\odot$).

Fig. 2 shows the distributions of $\theta_h$ for each SN type in our standard model. Although the binary fractions are similar in SNe II and Ib in our population synthesis model, SN Ib progenitors have larger $\theta_h$, making the observable fraction larger. This is because hydrogen-rich SN progenitors in closer binary systems can lose their envelope more easily by the binary interaction during the evolution. Compared to the hydrogen-rich SNe, SNe Ib have a much larger observable fraction, 0.53 per cent, thanks to the larger binary fraction and the flatter distribution of $\theta_h$ (Fig. 2). In other words, we expect to observe the brightening in about 5 out of 1000 SNe Ib with early discoveries.

4 DISCUSSION

We have shown that the fractions of core-collapse SNe in which the LC brightening from the binary collision can be observed are very small. The predicted small observational probabilities disfavour the argument that the early slow LC decline observed in SN Ib 2008D is because of the collision with the binary (Dessart et al. 2011), given the total number of the well-observed SN Ib LCs is about 100 (e.g. Drout et al. 2011; Li et al. 2011a; Bianco et al. 2014; Lyman et al. 2014; Taddia et al. 2015). Bersten et al. (2013) argued that the separation needs to be $a \simeq 10^{11}$ cm to explain the early LC of SN 2008D by the collision based on their estimates of the SN properties. Our population synthesis result indicates that the systems with $a \simeq 10^{11}$ cm in SNe Ib are extremely rare (Fig. 3), because this separation is the typical radius of Wolf–Rayet stars.

This further suggests that the early slow LC decline is not likely because of the collision. Other mechanisms are likely to be related to the mysterious slow LC decline of SN 2008D in its early epoch.

Except for SN 2008D, there are no reported SNe Ib with the clear early slow LC decline (e.g. Drout et al. 2011; Li et al. 2011a; Bianco et al. 2014; Lyman et al. 2014; Taddia et al. 2015). This is consistent with the estimates from our population synthesis. SN Ib LCs with the observations early enough to see the collisional effect are still rare. Our prediction that 0.53 per cent of SNe Ib are brightened by the collision can be tested by future large SN surveys. For example, the Large Synoptic Survey Telescope expects $10^4$ SN Ib discoveries per year (LSST Science Collaboration et al. 2009) and it will find $\sim$10 SNe Ib with the early brightening by the collision per year if they are detected early enough. The Zwicky Transient Facility is also likely to be capable of detecting such events thanks to their emphasis on the early SN discovery (Bellm 2014).

On the contrary, the early slow LC declines of SNe Ib are frequently observed (e.g. Bufano et al. 2014) and the observed SN fraction with the early slow LC decline is presumed to be much larger than the fraction estimated here. Dessart et al. (2011) argued that the extremely large radii required to explain the early slow LC decline observed in SNe Ib (e.g. $\gtrsim 630 R_\odot$ for SN 1993J; Blinnikov et al. 1998) may indicate that they are actually brightened by the binary collision. However, the predicted fractions in our model to observe the collisional brightening in SNe Ib ($\sim 0.01$ per cent) are even smaller than those in SNe Ib ($\sim 0.1$ per cent). Thus, the slow LC declines often observed in SNe Ib are presumed to be mostly from another cause, e.g. the extended early cooling phase caused by the large progenitor radii.

It is interesting to note that SNe Ib are suggested to come from both compact and extended progenitors (Chevalier & Soderberg 2010). If we can identify the compactness of SN Ib progenitors by multivwavelength observations like the radio observations demonstrated by Chevalier & Soderberg (2010) and the early slow declines are associated with the compact progenitors, the early slow declines are more likely to be related to the collision because of the rapid adiabatic cooling of the compact SN ejecta. In our standard population synthesis model, about 10 per cent of SNe Ib have progenitors with radii smaller than 10 $R_\odot$. This fraction increases as the dividing mass decreases because closer binary systems tend to
lose more envelope mass. When the dividing mass is 0.1 M⊙, about 60 per cent of the SN IIb progenitors have the radii smaller than 10 R⊙. This kind of information in SNe IIb may be used to understand the physics involved in the binary evolution (cf. Stancliffe & Eldridge 2009; Claeys et al. 2011). An interesting feature of the LCs affected by the collision is the strong dependence of the luminosity on the separation (K10). The early isotropic bolometric luminosity L_{c,iso} by the collision observed within θ_{h} is formulated by K10 as

\[ L_{c,iso} \simeq 2 \times 10^{45} \left( \frac{a}{10^{13} \text{ cm}} \right) \left( \frac{M_{ej}}{10 \text{ M}_\odot} \right) \left( \frac{v_{ej}}{10^8 \text{ cm s}^{-1}} \right)^{2/3} \times \left( \frac{\kappa_e}{0.2 \text{ cm}^2 \text{ g}^{-1}} \right)^{-7/3} \left( \frac{h}{d} \right)^{-1/2} \text{ erg s}^{-1}, \]

(5)

where M_{ej} is the SN ejecta mass, v_{ej} is the SN ejecta velocity colliding to the binary star, κ_e is the electron scattering opacity in the SN ejecta, and t is the time since the explosion. The luminosity is proportional to the separation because the collisional heating at longer separations is less affected by the subsequent adiabatic cooling (K10). In Fig. 3, we plot the fraction distribution of the SN Ibc progenitors in binary systems at the time of the explosion. The angle θ_{h} is plotted versus the separation. The angle indicates the probability for the system to be observed within the hole created by the collision (equation 3). The most probable systems to be observed have a_{13} = 0.1–1. This indicates that the early luminosity affected by the collision is most likely to be \sim 10^{42–43} erg s^{-1} for SNe Ibc with a typical ejecta mass of 2 M⊙ (Drout et al. 2011). Because the binary configuration of the most probable systems is similar to the system with which the LC brightening is simulated by K10 in terms of the ratio of the separation to the companion radius (a factor of a few), the SN Ibc LCs with the collisional brightening are presumed to be similar to those in K10. For SNe II and Iib, the separations of the systems with the highest observable probabilities are \sim 10^{14} cm. Thus, the typical early time luminosities from the collision can be \sim 10^{42} erg s^{-1} with M_{ej} = 10 M⊙, although this is rarely observed.

5 CONCLUSIONS

We investigate the expected fractions of core-collapse SNe in which the LC brightening due to the collision between the SN ejecta and the companion star is observable by performing population synthesis simulations with binary stellar evolution. The brightening of the LCs is assumed to be observable if an observer is within the direction of the hole created by the collision (K10, Fig. 1).

The expected fractions are summarized in Table 1. We find that only 0.53 per cent of SN Ibc LCs can be observed with the brightening because of the binary collision, although 61 per cent of them are in binary systems when they explode. The observable fractions in hydrogen-rich SN LCs are much smaller because of the smaller fractions of the progenitors in binary systems at the time of the explosions and the larger separations (\sim 10^{13} per cent in SNe II and \sim 10^{12} per cent in SNe Ibb).

The very small predicted fractions disfavour the interpretation that the early slow LC decline observed in SN Ibb 2008D is due to the binary collision. The separation required to explain the early LC is also unrealistically small (Fig. 3; see also Bersten et al. 2013). We find that the most probable systems to be observed with LC brightening have a = 10^{12–10^{15}} cm (SNe Ibc) and a \sim 10^{14} cm (SNe II and Ibb). Thus, the expected luminosities of the LCs affected by the collision are \sim 10^{42–10^{43}} erg s^{-1} (SNe Ibc) and \sim 10^{44} erg s^{-1} (SNe II and Ibb).

The small expected fractions indicate that the slow LC declines observed so far are likely to be caused by other mechanisms than the collision. However, future large transient surveys such as the Large Synoptic Survey Telescope or the Zwicky Transient Facility will be able to observe SN LCs with the collisional brightening. The Large Synoptic Survey Telescope is expected to detect \sim 10 SNe Ibc with the early brightening due to the collision per year. The Zwicky Transient Facility is also capable of detecting such events with their emphasis on early SN discovery.

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