Constraining the Progenitor of the Type Ia Supernova SN 2012cg

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ABSTRACT

The nature of the progenitors of Type Ia supernovae (SNe Ia) is not yet fully understood. In the single-degenerate (SD) scenario, the collision of the SN ejecta with its companion star is expected to produce detectable ultraviolet (UV) emission in the first few days after the SN explosion within certain viewing angles. It was recently found that the \( B - V \) colour of the nearby SN Ia SN 2012cg at about sixteen days before the maximum \( B \)-band brightness was about 0.2 mag bluer than those of other normal SNe Ia, which was reported as the first evidence for excess blue light from the interaction of normal SN Ia ejecta with its companion star. In this work, we compare current observations for SN 2012cg from its pre-explosion phase to the late-time nebular phase with theoretical predictions from binary evolution and population synthesis calculations for a variety of popular progenitor scenarios. We find that a main-sequence donor or a carbon-oxygen white dwarf donor binary system is more likely to be the progenitor of SN 2012cg. However, both scenarios also predict properties which are in contradiction to the observed features of this system. Taking both theoretical and observational uncertainties into account, we suggest that it might be too early to conclude that SN 2012cg was produced from an explosion of a Chandrasekhar-mass white dwarf in the SD scenario. Future observations and improved detailed theoretical modelling are still required to place a more stringent constraint on the progenitor of SN 2012cg.

Keywords: supernovae: general - binaries: close - stars: evolution

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are important cosmological probes that led to the discovery of the accelerating expansion of the Universe (Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999). However, the nature of SN Ia progenitors and the physics of their explosion mechanisms are still a mystery (e.g. Hillebrandt & Niemeyer 2000; Maoz, Mannucci & Nelemans 2014, for a review). There is a general consensus that SNe Ia arise from thermonuclear explosions of white dwarfs (WDs) in binary systems (Hoyle & Fowler 1960; Nomoto 1982). Depending on the nature of the companion star, the most popular progenitor scenarios of SNe Ia fall into three general categories: (i) a carbon-oxygen (CO) WD accretes matter from a non-degenerate companion, potentially a main-sequence (MS), subgiant (SG), red giant (RG), or even helium (He) star, to trigger an explosion when its mass reaches the Chandrasekhar-mass (Ch-mass) limit. This is the single-degenerate (SD) scenario (Whelan & Iben 1973; Han & Podsiadlowski 2004), (ii) explosions are caused by the merger of two CO WDs. This is the double-degenerate (DD) scenario (Iben & Tutukov 1984; Webbink 1984), (iii) the WD accretes material from a He-burning star or a He WD to lead to a Sub-Chandrasekhar-mass (Sub-Ch-mass) explosion when the He-shell accumulation reaches a critical value of about 0.02–0.2 \( M_\odot \). This is the double-detonation scenario (Livne 1990; Woosley & Weaver 1994).

On the one hand, some narrow absorption signatures of circumstellar material (CSM) have been detected in some SNe Ia (Pate et al. 2007; Sternberg et al. 2011; Dilday et al. 2012), the absence of H/He features in the nebular spectra of SNe Ia (Leonard 2007; Lundqvist et al. 2013, 2015; Shappee, Kochanek & Stanek 2013; Maguire et al. 2016), the lack of radio and X-ray emission around peak brightness (Bloom et al. 2012; Brown et al. 2012; Chomiuk et al. 2012; Horesh et al. 2012; Margutti et al. 2014), and the absence of a sur-
vivin companion star in SN Ia remnants (Kerzendorf et al. 2009; Schaefet & Pagnotta 2012).

It has been widely proposed that very early-time observations of SNe Ia can be used to place strong constraints on their progenitor systems (e.g., Kasen 2010; Nugent et al. 2011; Rabinak, Livne & Waxman 2012, hereafter RLW12; Brown et al. 2012; Cao et al. 2015; Olling et al. 2015; Marion et al. 2016). In particular, Kasen (2010) suggested that the strong excess emission can arise from the collision of SN ejecta with its companion star in the SD progenitor system, and it should be detectable in the ultraviolet (UV) and blue optical bands in the first few hours to days after the SN explosion under favorable viewing angles. Therefore, early UV observations are proposed as a direct way to test progenitor models of SNe Ia. The analysis of observed early light-curves has been carried out for many nearby SNe Ia to look for evidence of these shock emissions (Hayden et al. 2010; Brown et al. 2012; Cao et al. 2015; Marion et al. 2016; Olling et al. 2015), but only a subluminous SN Ia (iPTF14atg, Cao et al. 2015) and one normal event (SN 2012cg, Marion et al. 2016) have been reported as likely detections of the signatures of the interaction between SN ejecta and a stellar companion. Interestingly, Marion et al. (2016) have shown that the analytical model of Kasen (2010) with a 6.0 $M_\odot$ MS companion star could provide an explanation for the excess blue luminosity detected in SN 2012cg at about three days after the explosion. They therefore reported that this was the first evidence for emission from the interaction of SN ejecta with a stellar companion star for normal SNe Ia, supporting the SD scenario.

In this work, by comparing theoretical predictions from detailed binary evolution calculations and binary population synthesis (BPS) models for a variety of progenitor systems of SNe Ia (such as pre-explosion companion properties, early-time UV emissions, stripped H/He mass, and so on) to different observations of SN 2012cg, we try to place some constraints on its possible progenitor system.

2 SN 2012cg

SN 2012cg was spectroscopically classified as a SN Ia (Cenko et al. 2012; Silverman et al. 2012). It was discovered on 2012 May 17 (UT) in the nearby spiral galaxy NGC 4424 (15.2 ± 1.9 Mpc, Cortés, Kenney & Hardy 2006) by the Lick Observatory Supernova Search (Filippenko et al. 2001). By fitting early-time data of SN 2012cg, Silverman et al. (2012) obtained that it reached the maximum B-band brightness on 2012 June 2.0 ± 0.75, and the peak magnitude in the B-band was $m_B = 12.09 ± 0.02$ mag, which corresponds to an absolute magnitude of $M_B = −19.73 ± 0.30$ mag. However, by measuring the rise and initial decline of the light curve of SN 2012cg in the B, V, R, and I filters, Munari et al. (2013) found the $B$-band luminosity of SN 2012cg peaked on 2012 June 4.5 with an absolute magnitude of $M_B = −19.55$ mag (after corrections for a reddening of $E(B−V) = 0.18$ mag). In addition, it was found that the light curve of SN 2012cg was slightly narrower than that of a typical normal SN Ia, namely SN 2011fe (Silverman et al. 2012). They also estimated the explosion date of SN 2012cg to be May 15.7 (UT), which is consistent with the explosion time of MJD=56062.5 (May 15.5 UT) estimated by Marion et al. (2016).

3 THE PRE-EXPLOSION PROGENITOR

WDs can only be observed directly in our own Milky Way and several very nearby galaxies because they would be faint. We therefore do not expect to generally detect the pre-explosion progenitors in the DD scenario. In the SD scenario, however, the companion stars are non-degenerate which generally play a major role in determining the pre-explosion luminosities of progenitor systems. Therefore, analyzing pre-explosion images at the SN position provides a direct way to put constraints on the nature of the progenitor companion star (e.g., McCully et al. 2014; Foley et al. 2014). However, no progenitors of normal SNe Ia have yet been directly observed, even for the relatively nearby events, SN 2011fe (Li et al. 2011) and SN 2014J (Kelly et al. 2014), although the probable progenitor system of a SN Iax SN 2012Z (i.e., SN 2012Z-S1) has been recently discovered (McCully et al. 2014).

By analyzing pre-explosion archival WFPC2 images of NGC 4424 in F606W and F814W band from the Hubble Space Telescope (HST), Graur et al. (2016) found no source within a 2” radius of the location of SN 2012cg down to limits of $M_V = −6.0$ and $M_R ≈ −5.4$ mag, and thus excluded most supergiants as potential binary companions of the progenitor of SN 2012cg. By taking into account Galactic and host-galaxy extinctions for these filters, they place an upper-limit on the luminosity of pre-explosion progenitor of SN 2012cg of $< 840 L_\odot$.

In our previous study, we have predicted pre-explosion companion signatures of different SD progenitor scenarios by performing detailed binary evolution calculations with the STARS code (Liu et al. 2015). Here, to place constraints on the possible progenitor of SN 2012cg, we directly use the predicted results in
Liu et al. (2015) to compare with its pre-explosion HST observations in Fig. 1. As shown, most of the companion stars in the He-rich donor Ch-mass scenario are more luminous than the upper-limit constraint on the progenitor luminosity of SN 2012cg. Therefore, the He donor Ch-mass scenario can be excluded from the possible progenitor of SN 2012cg.

Here, we note that our previous calculations (Liu et al. 2015) focused on subluminous SNe Iax, in which all WDs were assumed to trigger weak pure deflagration explosions (as proposed by Fink et al. 2014) when they increase their masses to get close to the Ch-mass explosion limit. However, because the WD are treated as a point mass in our binary evolution calculations, it is impossible to determine the exact ignition condition of the Ch-mass WD. No matter whether the Ch-mass CO WD undergoes a delayed-detonation explosion that matches normal SNe Ia or a weak deflagration explosion of SNe Iax, the progenitor properties at the moment of SN explosion are the same in our binary evolution calculations. Therefore, to directly take the predictions from Liu et al. (2015) for the comparison of SN 2012cg in Fig. 1 is reasonable.

4 SEARCHING FOR STRIPPED HYDROGEN

In the DD scenario, the donor star is another CO WD, which can naturally explain the lack of H or He in the SN Ia spectra and the absence of a surviving companion star in SN remnants (SNRs). In the SD scenario, however, the non-degenerate companion is a H- or He-rich star. After the SN explosion, the companion star is significantly hit and shocked by the SN ejecta, causing some H-rich or He-rich material to be removed from outer layers of the companion star, though the companion star survives the explosion (e.g., Wheeler, Lecar & McKee 1975; Marietta, Burrows & Fryxell 2000; Pakmor et al. 2008; Liu et al. 2012, 2013b; Pan, Ricker & Taam 2012). Depending on the removed masses and the distances to observed SNe Ia, the signatures of removed H or He may be detectable in late-time nebular spectra of some nearby SNe Ia. Therefore, searching for Hα emission due to removed H-rich material in late-time spectra of SNe Ia is a way to identify the SD or DD progenitor scenario. Unfortunately, no such signature of swept-up H has been detected so far. This further places a stringent upper-limit on the removed H-mass of 0.001 – 0.058 $M_\odot$ (e.g., Mattila et al. 2005; Leonard 2007; Shappee et al. 2013; Lundqvist et al. 2013, 2015; Maguire et al. 2016).

Most interestingly, Maguire et al. (2016) constrained the removed H-mass in SN 2012cg to be $\lesssim 0.005 – 0.008 M_\odot$, which is much less massive than the removed H-rich mass predicted from recent hydrodynamical simulations for the MS and RG donor scenario ($\geq 0.1 M_\odot$ with a typical velocity of $\lesssim 1000$ km s$^{-1}$, e.g., Liu et al. 2012, 2013a; Pan, Ricker & Taam 2012). This poses a serious challenge to the MS/RG donor binary system as the progenitor of SN 2012cg. However, only several specific binary systems have been studied in these hydrodynamical simulations, and the parameter surveys in the simulations have shown that the amount of removed companion mass strongly decreases as the binary separation increases. Different binary systems evolve to different evolutionary stages and have different binary parameters when the WD explodes as an SN Ia. Consequently, the companion radii and binary separations of systems are expected to differ significantly from the MS or RG companion star models used in hydrodynamical impact simulations. Therefore, a comparison between the observational upper-limit on the removed H-mass for SN 2012cg and the predicted distribution of removed H-rich masses from binary population synthesis (BPS) calculations for the MS and RG donor scenario is required.

To predict the early UV luminosity distribution due to the interaction of SN ejecta with a stellar companion star, we have performed BPS calculations for the MS, RG and He donor Ch-mass scenario of SNe Ia (Liu, Moriya & Stancliffe 2015, hereafter...
LMS15\(^1\)). Taking the data from LMS15, the distribution of the ratio of binary separation ($a$) to the companion radius ($R_2$), $a/R_2$, at the moment of SN Ia explosion is shown in Fig. 2. Based on the distribution of $a/R_2$, we further calculate the distribution of removed H-rich mass due to ejecta impact in the MS and RG donor scenario by adopting the power-law relations between the removed H-rich mass and binary separation from past hydrodynamical impact simulations for the MS (Eq. 2 of Liu et al. 2012) and RG (Eq. 4 of Pan, Ricker & Taam 2012) donor scenario. As shown in Fig. 2, the peaks of removed H-rich mass in the MS and RG donor Ch-mass scenario are about 0.15 $M_\odot$ and 0.60 $M_\odot$ respectively. These peak values are larger than the observed upper-limit of SN 2012cg by a factor of around 20–100. Therefore, non-detection of removed H in late-time nebular spectra of SN 2012cg indicates that the MS or RG donor binary system is unlikely to be its possible progenitor.

Here, we point out that single fitting parameters of the power-law relations are used when we calculate the distributions of the removed H-rich masses by the SN explosion, which means that the effect of companion structures on the fitting parameters of the power-law relations are ignored. Even for the same progenitor scenario, it was found that fitting parameters are also dependent on the details of the structure of the companion star due to the history of mass transfer (Liu et al. 2012). For example, for the MS donor scenario, the fitting parameters could be slightly different if the detailed structures of the MS companion star are somewhat different (see Table 3 of Liu et al. 2012). However, we expect that the peak of removed H-rich mass in Fig. 2 can only be shifted by about a factor of two due to the uncertainties of fitting parameters among different MS (or RG) companion stars.

5 EARLY-TIME EXCESS LUMINOSITY

Marion et al. (2016) presented early-time photometry of SN 2012cg, showing that blue excess light is seen at about 16 days before maximum $B$-band brightness. They reported that this blue early-time excess is consistent with predicted early-time emission of shocked gas that was proposed by Kasen (2010), suggesting SN 2012cg was generated from a binary system in the SD Ch-mass scenario. Here, we discuss the possibility of different origins of the early excess blue luminosity of SN 2012cg.

5.1 SN ejecta-companion interaction

In LMS15, we filter the expected early UV luminosity distribution for different SD progenitor systems by applying the BPS results to the analytical model of Kasen (2010). Using the same method, the expected early luminosity distributions of shocked gas in the uvm2 band for the MS, RG and He donor Ch-mass scenario are compared to an early-time light curve of SN 2012g in the same band (Figs. 3 and 4) to place constraints on the possible progenitor system. Here, an ejecta mass of $M_{ej} = 1.4 M_\odot$ and an explosion energy of $E_{ej} = 1.0 \times 10^{51}$ erg are used for our calculation. These typical values correspond to a mean expansion velocity of ejecta of $\approx 10^4$ km s$^{-1}$. Also, the magnitudes are calculated in the AB magnitude system here.

Kasen (2010) showed that the emission due to the interaction of SN ejecta with a companion star dominates the early-time (few days after explosion) light curves of SNe Ia within certain viewing angles. At later epochs, this shock flux becomes weak and the light curve is dominated by the flux of the SN itself. Also, this early-time excess emission should be brightest in the UV band and become subordinate at longer optical wavelengths although it can still cause a blue colour evolution in the optical light curve (Kasen 2010; Marion et al. 2016). Therefore, only predictions for the uvm2 filter (the uvw1 and uvw2 filters have an extended red tail) of the Swift/UVOT is shown as an example. For a given binary progenitor system, the maximum excess emission should be observed when the viewing angle is $\theta = 0^\circ$, i.e., the companion star lies directly along the line of sight between the observer and the SN explosion. On the other hand, the excess emission detected for viewing angle $\theta = 180^\circ$ should be negligible, corresponding to a geometry in which the SN Ia lies directly in the line of sight between the observer and the companion star.

As shown in the left panel of Fig. 3, the expected upper-limit luminosity at around three days after the explosion in the He donor Ch-mass scenario (black dotted line) is much lower than the observed value of SN 2012cg at a similar epoch. We therefore conclude that the early-time blue excess luminosity detected in SN 2012cg was unlikely to arise from the interaction of the SN shock with a companion star in the He donor Ch-mass scenario. Here, we would also like to mention that binary separations at the moment of SN explosions in the He star donor Sub-Ch-mass scenario are generally closer than those of the He star donor Ch-mass scenario, leading to early-time UV emission in this scenario being too weak to explain the early-time blue excess flux observed in SN 2012cg. Therefore, both the Sub-Ch-mass and Ch-mass He star donor scenario could be ruled out if the early-time excess flux of SN 2012cg was indeed produced from the SN-companion interaction.

On the other hand, it is found that the expected upper-limit UV luminosity at three days after the explosion in the MS donor Ch-mass scenario decreases to a value below the observed excess luminosity of SN 2012cg as the viewing angle increases to a value of $\theta \approx 150^\circ$ (Fig. 3), suggesting that early-time emissions of the SN-companion interaction with a viewing angle of $\theta = 0^\circ - 150^\circ$ in this scenario would possibly provide an explanation for the early blue excess luminosity of SN 2012cg. Meanwhile, Fig. 4 shows that the expected lower-limit luminosity of shocked gas (right panel) in the RG donor scenario with a viewing angle larger than about $90^\circ$ is still higher than the observation of SN 2012cg. This indicates that the viewing angle should be $90^\circ \leq \theta \leq 170^\circ$ (left panel of Fig. 4) if the early-time blue excess luminosity of SN 2012cg was indeed caused by the interaction of the SN shock with a RG donor star in the Ch-mass scenario.

\(^1\) Here, we point out that the effect of the accretion disk of a WD is not considered in our binary evolution and population synthesis calculations because it is not clear whether a disk instability can occur (see Kato & Hachisu 2012).
5.2 Cooling of shock-heated CSM

In the SD scenario, CSM is generally expected to be present around the progenitor due to pre-explosion mass loss in a binary system (Patat et al. 2007; Sternberg et al. 2011; Dilday et al. 2012). Also, some recent studies have suggested that a significant mass of CSM might be formed in the DD scenario:

(i) Tidal tail ejection. Prior to the coalescence of two WDs, Raskin & Kasen (2013) found that about $10^{-2} - 10^{-3} M_\odot$ of material could be tidally ejected with a typical velocity of about 2000 km/s. They further suggested that the interaction of the SN ejecta with the ejected tails could lead to detectable shock emission at radio, optical/UV, and X-ray wavelengths, and produce relatively broad Na I D absorption features at late times.

(ii) The double-detonation scenario. Shen, Guillochon & Foley (2013) suggested that a total of $3-6 \times 10^{-5} M_\odot$ of material can be ejected from a CO WD + He WD binary system to the local environment with a initial velocity of $\approx 1500$ km/s.

(iii) The violent merger scenario. It has been suggested that the violent merger of a CO WD with either the core of a giant star or another CO WD star might eject some material (about $0.1 - 0.5 M_\odot$) and show some signs of CSM if the SN Ia explodes soon after the common envelope phase (Soker et al. 2013; Ruiter et al. 2013).

(iv) Mass outflows during rapid accretion. Dan et al. (2011) found that some material ($\approx 10^{-2} - 10^{-3} M_\odot$) can be lost through the Lagrangian point with a possible velocity of about 1000 km/s during the rapid accretion phase of two WDs.

(v) Disk winds. Ji et al. (2013) found that a fraction of the disk
(≈ 10⁻³ M⊙) which forms before the SN explosion if the WD-WD system fails to promptly detonate could be lost with a velocity of around 2600 km s⁻¹ due to a magnetically driven wind.

Recently, Piro & Morozova (2015) have shown that the presence of CSM around a progenitor system can lead to significant shock cooling emission during the first few days after the explosion, which can affect the early time rising light curve of a SN Ia. Depending on the degree of nickel mixing in the WD and the exact configuration of the extended material, this shock cooling emission can lead to early-time colour evolution similar to that caused by the ejecta interaction with a companion star (Piro & Morozova 2015). Therefore, the interaction of the SN shock with the CSM might provide an alternative explanation for the early blue colour seen in SN 2012cg (Marion et al. 2016). Here, we adopt the analytical CSM-interaction model used in Cao et al. (2015) to calculate the radius and mass of the CSM to examine the possibility of the early UV excess of SN 2012cg having CSM-interaction as its origin.

As shown in Marion et al. (2016), the Swift measurements for SN 2012cg for the B- and V-band filters at about -16 days (MJD=56065.8) can fit those of SN 2011fe (or a 2⁺ model), but measurements for SN 2012cg in the uvm1-, uvm2-, uvw2- and U-band are well above the observed values of SN 2011fe at the similar phase. If SN 2011fe can be used as a template which only contains emissions from the SN itself (i.e., without any extra emissions), then subtracting the flux of SN 2011fe from that of SN 2012cg at a similar epoch should give us the flux of the SN-CSM interaction. Subsequently, one could calculate the total UV luminosity (LUV) due to the SN-CSM interaction by summing the excess flux (i.e., the flux of SN 2012cg minus that of SN 2011fe at the similar epoch) over the uvm1-, uvm2-, uvw2- and U-band filters. With this method, we obtain an approximate excess UV luminosity of LUV ≈ 4.0 × 10^{40} erg s⁻¹ at about 3.3 days after the explosion by using the total UV luminosity of SN 2012cg on MJD=56065.8 and subtracting that of SN 2011fe on MJD=55799.96. Here, an explosion date for SN 2012cg of MJD=56062.5 (i.e., May 15.5 UT, Marion et al. 2016) is adopted, and the flux of SN 2011fe has been calibrated to the distance of SN 2012cg which is 15.2 Mpc. Also, it should be kept in mind that we assume the actual explosion date of SN 2011fe was indeed on MJD=55796.696 (Nugent et al. 2011) through this study. Given this estimated excess UV luminosity, following Cao et al. (2015) one can further calculate a spherical radius of the CSM of RCSM ≈ 1.0 × 10¹⁶ cm (or RCSM ≈ 9.0 × 10¹⁵ cm), assuming a gas temperature of 15000 K (or 20000 K), leading to a CSM mass of MCSM ≈ 1.2 M⊙ (or MCSM ≈ 0.83 M⊙). Comparing all these values to theoretical predictions on properties of the CSM from different progenitor scenarios of SNe Ia, a value of MCSM ≈ 0.8 M⊙ at a distance of about 10¹⁶ cm is larger than what most SD and DD scenarios predict (Patat et al. 2007; Sternberg et al. 2011; Chomiuk et al. 2012; Raskin & Kasen 2013; Shen, Guillochon & Foley 2013; Soker et al. 2013; Ruiter et al. 2013; Margutti et al. 2014). This seems to indicate that the CSM-interaction as an origin of the observed early UV excess of SN 2012cg is quite unlikely. Here, instead of estimating the gas temperature by modelling the spectral energy distribution from the photometry and spectrum of SN 2012cg, we simply adopt a gas temperature of 15000 K (or 20000 K) in our calculation. By modelling the near-UV to optical spectra of SN 2011fe with a Monte Carlo radiative transfer code, Mazzali et al. (2014) obtained that the photospheric temperature of the photospheric blackbody at -16 days is about 10800 K. In addition, adding a blackbody emission with a temperature of about 10000 K to the spectra of SN 2011fe at about -16 days, Marion et al. (2016) derived that the resulting continua can fit that of SN 2012cg at a comparable phase (see their figure 9). Therefore, adopting a gas temperature of 15000 K–20000 K should be safe for our calculations.

However, the above results are given with an explosion date for SN 2012cg of May 15.5 UT (MJD=56062.5, Marion et al. 2016). If we assume that the actual explosion date of SN 2012cg was one day earlier or later than May 15.5 UT, the date of MJD=56065.8 in SN 2012cg would correspond to 4.3 or 2.3 days after the explosion, rather than the 3.3 days used above. We then adopt the above method to re-calculate the total excess UV luminosity due to the SN-CSM interaction by using the flux of SN 2012cg on MJD=56065.8 and subtracting that of SN 2011fe at around 4.3 (MJD=55800.996, i.e., case A) or 2.3 (MJD=55798.996, i.e., case B) days after the explosion, respectively. As a result, for case A, we obtain an approximate UV luminosity of LUV ≈ 1.0 × 10^{40} erg s⁻¹, a radius of RCSM ≈ 2.5 × 10¹⁵ cm (or RCSM ≈ 2.0 × 10¹⁵ cm) and a CSM mass of MCSM ≈ 0.07 M⊙ (or MCSM ≈ 0.05 M⊙) for a gas temperature of 15000 K (or 20000 K), respectively. These values are consistent with predictions from most SD progenitor scenario (Sternberg et al. 2011; Margutti et al. 2014). As discussed by Cao et al. (2015), the SN shock has a typical velocity between 5000 km s⁻¹ and 20000 km s⁻¹. Hence, four days after the explosion, the SN shock was traveled to RCSM ≈ 10¹⁶ cm, this is also consistent with our calculated results. Comparing with the expected pre-explosion ejected mass from different DD scenarios presented above, the amount of ejected ma-

![Figure 5](image-url)
The progenitor of SN 2012cg

Table 1. Summary of the constraints on the possible progenitor of SN 2012cg.

| Observational constraints | MS donor (Ch-mass) | RG donor (Ch-mass) | He star donor (Ch-mass) | He star donor (Sub-Ch-mass) | He WD donor (Sub-Ch-mass) | DD scenario | References |
|--------------------------|-------------------|-------------------|------------------------|---------------------------|--------------------------|-------------|------------|
| Pre-explosion observations | Yes               | No                | Yes                    | Yes                       | Yes                      | Yes         | [1]        |
| Early excess luminosity:  |                   |                   |                        |                           |                          |             |            |
| (i) Ejecta-star interaction | Yes              | Yes               | No                     | No                        | -                        | -           | [2]        |
| (ii) Ejecta-CSM interaction | Possible         | Possible          | Possible               | No                        | Unlikely                 | Possible    | [3]        |
| No stripped Hydrogen      | No                | No                | Yes                    | Yes                       | Yes                      | Yes         | [4]        |
| Deep radio observations   | Possible          | Unlikely           | Possible               | Possible                  | Possible                 | Possible    | [5]        |
| Late $^{57}$Co decay fitting | Yes             | Yes               | Yes                    | No                        | No                      | No          | [6]        |
| Narrow blueshifted absorption lines | Possible | Possible          | Possible               | Possible                  | Possible                 | Possible    | [7]        |

References: [1] Graur et al. (2016); Li et al. (2011); Liu et al. (2015), [2] Kasen (2010); Liu, Moriya & Stancliffe (2015); Marion et al. (2016), [3] Cao et al. (2015); Piro & Morozova (2015), [4] Mattila et al. (2005); Leonard (2007); Shappee, Kochanek & Stanek (2013); Lundqvist et al. (2013); Maguire et al. (2016); Marietta, Burrows & Fryxell (2000); Liu et al. (2012, 2013b); Pan, Ricker & Taam (2012), [5] Chomiuk et al. (2012, 2015), [6] Graur et al. (2016), [7] Maguire et al. (2013).

teral from the He WD donor scenario ($3 - 6 \times 10^{-5} M_\odot$, see Shen, Guillochon & Foley 2013) is much less than our estimated CSM mass ($\approx 0.05 M_\odot$), which seems to suggest that the cooling of shock-heated CSM in the He WD donor scenario is unlikely to be the origin of the early blue excess flux in SN 2012cg. However, all other DD scenarios are possible, as they depend on the exact radius of the CSM (which is determined by the exact ejected velocity and the delay times between the mass ejected and the SN explosion). Unfortunately, both the ejected velocity and the delay time in the DD scenario are still poorly constrained.

In contrast, a calculation for case B gives a much more massive CSM mass and a larger CSM radius, making the CSM-interaction as an origin of the early excess UV flux of SN 2012cg more unlikely. Therefore, whether the CSM interaction could provide a possible explanation for the early excess UV flux in SN 2012cg depends on the exact explosion date. Piro & Nakar (2013) suggested that the SN may have a dark phase, which could lead to the explosion date inferred from a simple light curve extrapolation being different from the actual explosion date.

5.3 Cooling of the shock-heated WD

After SN Ia explosion, radiation energy deposited in the shock-heated outer layers of the SN ejecta immediately diffuses out and contributes to the SN brightness after the shock breakout (RLW12). The diffusion of radiation from the shock-heated ejecta in the explosion is thought to be a contributor to the excess luminosity of SNe in addition to the luminosity generated by nickel heating. This shock breakout model has been used to put considerable constraints on the radius of the progenitor star by detecting the early shock luminosity (Nugent et al. 2011; Bloom et al. 2012).

In Fig. 5, we compare the early-time observations of SN 2012cg in the $uvmt2$-band to the predicted early-time light curves from the analytical model of RLW12 to examine the possibility that the early excess luminosity detected in SN 2012cg was produced from cooling of the shock-heated WD. Here, we assume an explosion energy of $10^{51}$ erg, an ejecta mass of $1.4 M_\odot$, a form factor of 0.05, and an electron scattering opacity $0.2 \text{ cm}^2 \text{ g}^{-1}$ (Bloom et al. 2012). As shown in Fig. 5, to account for the early-time excess flux in SN 2012cg, a progenitor radius of $\approx 2.0 R_\odot$ is required. This is much larger than the typical progenitor radius which is an isolated WD, in both the SD and DD scenarios, although some recent hydrodynamical studies suggested that the envelope of the exploding WD could spread out to a radius of $\approx 0.1 R_\odot$ in the violent merger model (Tanikawa et al. 2015). Therefore, one can conclude that the diffusion of radiation from the shock-heated ejecta in the shock breakout model of RLW12 is unlikely to be the contributor of the early excess luminosity seen in SN 2012cg.

6 LATE-TIME PHOTOMETRY

Seitenzahl, Taubenberger & Sim (2009) suggested that significant contributions from the slow decay of $^{57}$Co and $^{55}$Fe can lead to a slow-down in the decline of the light curve of a SN Ia at very late times (> 900 days after the explosion). Because different progenitor scenarios predict different amounts of $^{57}$Co and $^{55}$Fe during the explosion, different declines of late-time light curves should occur. For instance, the delayed-detonation model of a Ch-mass WD produces more $^{57}$Co and $^{55}$Fe than those in the violent merger model of two WDs (Röpke et al. 2012). Therefore, comparing the observed late-time light curves with the predictions has been suggested to be a potential way to constrain the progenitors of SNe Ia.

The late-time photometry of SN 2012cg has been followed using the HST by Graur et al. (2016). They found its late-time light curve exhibits a similar behavior to that predicted by the decay of $^{57}$Co of a near Ch-mass explosion model, suggesting it favors the SD scenario. However, these authors also pointed out that the observed colour and light-curve shape at late times can also be explained by extra flux of a light echo. Therefore, future follow-up observations are needed to study whether its late-time photometry would still follow the slow decay of elements predicted from the Ch-mass WD explosion. This may help to exclude a light echo as an extra contributor to the late-time light curve of SN 2012cg and thus disfavor the DD scenario.
7 DISCUSSION

We summarise the constraints on the possible progenitor of SN 2012cg in Table 1. For a comprehensive discussion, the results from other studies such as the deep radio observations of Chomiuk et al. (2015), the detection of blueshifted Na I D (Maguire et al. 2013) and the late-time photometry observations (Graur et al. 2016) for SN 2012cg are also included in this table. As given in Table 1, the Ch-mass He donor and RG donor scenario are likely to be ruled out as the possible progenitor of SN 2012cg. Also, the Sub-Ch-mass scenario struggles to explain the excess blue luminosity seen in SN 2012cg. Meanwhile, current studies for the Sub-Ch-mass scenario found that this model still cannot reproduce the observational characteristic features of SNe Ia well (Kromer et al. 2010; Woosley & Kasen 2011), although the details of this model still require future development and numerous complications remain to be solved in such a model. This scenario therefore can also be excluded.

Consequently, it seems that only the MS donor Ch-mass scenario and the merger of two CO WDs are likely to be the possible progenitor of SN 2012cg. However, both scenarios still have their own problems with explaining the observations. The MS donor Ch-mass scenario predicts that a large amount of H-rich material (which is higher than the observational upper-limit of around 0.005$M_\odot$ by a factor of 20) can be removed from outer layers of the companion star by the SN explosion, posing a serious challenge to the fact that no evidence of $H_a$ emission in late-time spectra has been detected. However, as discussed by Maguire et al. (2016), the observed flux at the position of $H_a$ was converted to the mass with one-dimensional models by Mattila et al. (2005), and Lundqvist et al. (2013) who performed spectral synthesis modelling based on the earliest two-dimensional impact simulation of Marietta, Burrows & Fryxell (2000), which might lead to some uncertainties of the results. To place a more stringent constraint on the upper-limit mass for non-detection of swept-up H in late-time spectra of SNe Ia, future multi-dimensional radiative transfer modelling with ejecta structures obtained from updated three-dimensional impact simulations such as those of Liu et al. (2012) and Pan, Ricker & Taam (2012) is still needed.

Simultaneously, we have shown that the observed early excess blue flux in SN 2012cg could be explained by the SN-CSM interaction (Section 5.2). However, this strongly depends on the exact explosion date. Also, both our estimations for the properties of the CSM in Section 5.2 and calculations by Piro & Morozova (2015) are based on an assumption of a spherical CSM structure. Whether the cooling of non-spherical CSM could still provide a possible explanation for the observed early blue flux of SN 2012cg is unclear. To place strict constraints on the properties of CSM and the observable signatures of the SN shock interacting with the CSM, detailed numerical hydrodynamical simulations for the interaction between the blast wave of the SN and CSM/ISM are required, coupled with different explosion models and the detailed pre-SN mass-loss history, i.e., different configurations of outflow material around progenitor systems. In addition, (Graur et al. 2016) suggested that the decay of $^{57}$Co and $^{55}$Fe produced from current modelling for the two CO WDs merger model have different complexities in explaining the slow-down decline light curve of SN 2012cg at late times. However, they also pointed out that a similar behavior of the late-time light curve of SN 2012cg can be explained by a light echo, which requires future follow-up observations for further confirmation.

7.1 Future observations

The companion stars in the MS donor Ch-mass scenario are expected to survive the explosion and to be significantly heated and shocked due to the interaction with SN ejecta, so that they would show some overluminous signatures (about 20–300$L_\odot$) during their long-term post-explosion evolution (Pan, Ricker & Taam 2012; Shappee, Kochanek & Stanek 2013). As shown in Fig. 6, the surviving MS star would be expected to become more luminous than the SN itself at very late times (around 2000 days). For comparison, a star with a luminosity of 1$L_\odot$ or 10$L_\odot$ is also plotted.
7.2 Spin-up/Spin-down model

In the SD scenario, a WD accretes and retains companion matter that carries angular momentum. As a consequence the WD spins with a short period which leads to an increase of the critical explosion mass. If the critical mass is higher than the actual mass of the WD, the SN explosion could only occur after the WD increases its spin period with a specific spin-down timescale (Di Stefano, Voss & Claey s 2011; Justham 2011). If the spin-down timescale is longer than about 10^6 yrs, the CSM around the progenitor system could become diffuse and reach a density similar to that of the ISM, leading to the lack of radio and X-ray emission which are absent in SN 2012cg (Chomiuk et al. 2015). Also, the MS or RG companion star might shrink rapidly before the SN Ia explosion occurs by exhausting most of its H-rich envelope during a long spin-down (≥ 10^6 yrs) phase, explaining the non-detection of a pre-explosion companion star (Graur et al. 2016) and the absence of swept-up H in the late-time spectra of SN 2012cg (Maguire et al. 2016). However, no (or a very weak) interaction signature from the SN-companion (because of a small companion) or SN-CSM (due to the low density CSM) interaction is predicted in this scenario, making it extremely difficult to explain the early excess UV luminosity seen in SN 2012cg. Also, the exact spin-down timescale of the WD in this model is quite unknown (Maoz, Mannucci & Nelemans 2014).

8 CONCLUSION AND SUMMARY

In this study, using the results from binary evolution and population synthesis calculations for the most likely progenitor scenarios of SNe Ia, we have tried to constrain the possible progenitor of SN 2012cg. We find that the MS donor binary system in the SD scenario and the binary system consisting of two carbon-oxygen white dwarfs are more likely to be the progenitor of SN 2012cg. We solve all these contradictions and thus place a strict constraint on the progenitor system could become di ffuse and reach a density similar to that of the ISM, leading to the lack of radio and X-ray emission which are absent in SN 2012cg (Chomiuk et al. 2015). Also, the MS or RG companion star might shrink rapidly before the SN Ia explosion occurs by exhausting most of its H-rich envelope during a long spin-down (≥ 10^6 yrs) phase, explaining the non-detection of a pre-explosion companion star (Graur et al. 2016) and the absence of swept-up H in the late-time spectra of SN 2012cg (Maguire et al. 2016). However, no (or a very weak) interaction signature from the SN-companion (because of a small companion) or SN-CSM (due to the low density CSM) interaction is predicted in this scenario, making it extremely difficult to explain the early excess UV luminosity seen in SN 2012cg. Also, the exact spin-down timescale of the WD in this model is quite unknown (Maoz, Mannucci & Nelemans 2014).

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