BINARY SYSTEMS OF CORE-COLLAPSE SUPERNOVAE POLLUTING A GIANT COMPANION

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ABSTRACT

We examine binary systems where when the more massive star, the primary, explodes as a core-collapse supernova (SN), the secondary star is already a giant that intercepts a large fraction of the ejecta. The ejecta might pollute the secondary star with newly synthesized elements such as calcium. We use Modules for Experiments in Stellar Astrophysics to calculate the evolution of such SN-polluted giant (SNPG) binaries. We estimate that on average at any given time tens of SNPGs are present in the Galaxy, and \( \approx 10 \) SNPG objects are present in the Magellanic Clouds. We speculate that the high calcium abundance of the recently discovered evolved star HV 2112 in the Small Magellanic Cloud might be the result of an SNPG with a super-AGB stellar secondary of mass \( \approx 9 \, M_\odot \). This rare SNPG scenario is an alternative explanation to HV 2112 being a Thorne–Żytkow object.

Key words: binaries: close – stars: AGB and post-AGB – stars: evolution – stars: individual (HV 2112) – stars: massive – stars: peculiar

1. INTRODUCTION

In a recent work Schaffenroth et al. (2015) suggested that the extreme runaway star HD 271791 was polluted by gas from a core-collapse supernova (CCSN). The observed enrichment indicates that HD 271791 had been ejected by a supernova (SN) explosion of a very massive compact primary, probably a Wolf–Rayet star. To avoid engulfment during the giant phase of the CCSN progenitor, the polluted star cannot be too close to the CCSN. Hence, to intercept a large fraction of the newly synthesized elements in the CCSN, the companion should be a giant. We here study some aspects of the evolution of such binary systems. We set aside the question whether the CCSN ejecta actually removes a large part of the giant, and no pollution occurs, as claimed by Hirai et al. (2014).

Such a pollution might account for the presence of rare stars with peculiar abundances, e.g., HV 2112 (Papish et al. 2015b). Levesque et al. (2014) found the evolved star HV 2112 in the Small Magellanic Cloud (SMC) to have peculiar abundances. They suggested that the star is a red supergiant (RSG) star and that the peculiar abundances can be understood if HV 2112 is a Thorne–Żytkow object (TZO). TZOs are RSG stars that have a neutron star (NS) at their center (Thorne & Żytkow 1975, 1977). The star is powered by accretion onto the NS and/or by nuclear burning in a region away from the NS. The most likely formation scenario for a TZO in this case is an NS that inspired inside the envelope of an RSG star, down to the core. The NS then destroyed the core and replaced the core as the central dense object. Part of the destroyed core formed a temporary accretion disk around the NS.

Tout et al. (2014) examined whether HV 2112 is a TZO or perhaps a super asymptotic giant branch (SAGB) star. SAGB stars are stars with a typical initial mass range of \( \approx 7–11 \, M_\odot \) (with dependence on the convective overshoot treatment; Eldridge & Tout 2004; Siess 2006) with an oxygen/neon core undergoing thermal pulses with third dredge-up. Tout et al. (2014) argued that SAGBs can synthesize most of the elements that are used to claim that HV 2112 is a TZO through s-process, e.g., molybdenum, rubidium, and lithium. However, they found no way for an SAGB star to synthesize calcium. They suggested that the observed high calcium abundance can be attributed to its synthesis in the temporary accretion disk around the NS, composed of the destroyed core material in the TZO formation process. In such an accretion disk temperatures and densities are high enough for calcium nucleosynthesis (Metzger 2012). The kinetic energy of the disk wind that is required to spread calcium in the giant has enough energy to unbind the envelope, and thus Tout et al. (2014) postulated that the outflow is collimated and hence most of it escapes from the star.

However, it is not clear whether a TZO can form at all. Based on earlier studies of common envelope (CE) ejection by jets (Armitage & Livio 2000; Soker 2004; Chevalier 2012), Papish et al. (2015b) studied the removal of the CE that supposedly leads to the formation of TZOs. Papish et al. (2015b) found that the jets are launched by the accretion disk while the NS is still in a Keplerian orbit around the central part of the core that is still intact. Therefore, they argued, the jets are not well collimated, and the envelope and a large part of the core will be ejected. Papish et al. (2015b) speculated that the calcium in HV 2112 comes from an explosion of an SN while HV 2112 was already a giant star and hence could intercept a large fraction of the SN ejecta. The exploding star was just slightly more massive than HV 2112 when they both were on the main sequence. In such massive close-mass binary systems the lighter star expands to become a giant before the more massive star explodes.

In the present paper we examine in more detail the scenario proposed by Papish et al. (2015b). In this SN-polluted giant (SNPG) scenario we specifically study binary systems of two stars that are massive, \( \approx 8.5–20 \, M_\odot \), and are very close in initial masses, \( M_{1,0}–M_{2,0} \approx 0.5–1 \, M_\odot \). The SN explosion of the primary star might pollute the secondary if the two stars are not too far apart. The secondary stars on the lower end of this range, \( M_{2,0} \lesssim 11 \, M_\odot \), will become SAGB stars with enhanced newly synthesized elements, whereas the more massive secondary stars will result in peculiar RSG stars. Therefore, we also examine a sub-group of binaries where the secondary also qualifies as an SAGB star, \( M_{2,0} \approx 8.5–11 \, M_\odot \), and examine the ejecta fraction that might be intercepted by the secondary star.
In Section 2 we study the binary evolution of such systems. We further discuss a sub-group of such systems and propose a possible explanation for the calcium enrichment in HV 2112 (Section 2.1). We also predict additional anomalous abundances expected by the SNPG scenario (Section 2.2). In Section 3 we estimate the birthrate of such systems. Our summary is in Section 4.

2. BINARY EVOLUTION

We examine the evolution of massive binary systems where on the zero-age main sequence (ZAMS) the primary of mass $M_{1,0}$ is slightly more massive than the secondary of mass $M_{2,0}$, as schematically presented in the first row of Figure 1. We are interested in primary stars that end as CCSNe, which implies an initial primary mass of $M_{1,0} \gtrsim 9 M_\odot$. To intercept a large fraction of the newly synthesized elements in the CCSN of the progenitor, the companion should be an evolved giant while the explosion of the primary takes place (third row in Figure 1). The ejecta from the exploding primary star pollutes the secondary, which becomes an SNPG (fourth row in Figure 1), as has been suggested, for example, for the hyper-runaway star HD 271791 (Schaffenroth et al. 2015). We found that for primary stars in the mass range of $M_{1,0} \approx 9-20 M_\odot$ the secondary must be in the mass range of $M_{1,0} > M_{2,0} \gtrsim M_{1,0} - 1 M_\odot$, to allow for the SNPG scenario (more details in Section 3).

The initial orbital separation cannot be too small since we must avoid the possibility that the secondary would be engulfed by the primary during the primary giant phase. Yet we point out that for the case of close binaries it is possible for the primary to fill its Roche lobe during its red giant branch (RGB) phase and transfer some of its outer envelope to its less massive companion (second row of Figure 1). We find that for our close systems $(q \equiv M_2/M_1 \approx 1)$ Roche lobe overflow (RLOF) occurs for $R_{1,\text{RGB}}/a_0 \lesssim 0.4$ (Eggleton 1983), where $R_{1,\text{RGB}}$ is the maximum radius of the primary on the RGB. Hence, assuming that the initial orbital separation of the system is $a_0 \lesssim 2.5 R_{1,\text{RGB}}$, the primary might fill its Roche lobe and transfer the outer layers of its envelope to the secondary star, while the latter is still on the MS. From the radius of the primary star on the RGB we find the cutoff separation for RLOF to range from $a \approx 800 R_\odot$ for a $9 M_\odot$ primary, to $a \approx 2500 R_\odot$ for a $20 M_\odot$ primary. Due to the close initial mass of the stars, in case of mass transfer the post-transfer (PT) primary continues to evolve with a lower-mass envelope, and the PT secondary evolves as a star slightly more massive than the initial primary, $M_{1,\text{PT}} < M_{2,\text{PT}}$. Moreover, since the stars are of close initial masses, as the secondary grows to be the more massive star in the system, the orbital separation grows and the mass transfer might cease, at least for some period. We do not go into details of such an early RLOF phase since it has little importance to the pollution of the secondary and the SNPG outcome. In addition, it is possible that later the secondary will fill its Roche lobe before the primary explodes. If this occurs, we might form a CE. Although the RLOF process is not studied here further, it should be kept in mind, e.g., for population synthesis studies, that an RLOF is an evolutionary route SNPGs might take.

The evolutionary scheme presented in Figure 1 is significantly different from those in Sabach & Soker (2014), as there is no reverse evolution, the primary experiences a CCSN explosion, and the secondary is a giant when the primary ends its evolution; these do not hold in the scenarios discussed in Sabach & Soker (2014).

To follow the evolution of each star from ZAMS, we use the Modules for Experiments in Stellar Astrophysics (MESA), version 7184 (Paxton et al. 2011), for non-rotating stars. We specifically run models with initial primary masses of $M_{1,0} = 9.5 M_\odot$, $10 M_\odot$, $13 M_\odot$, $15 M_\odot$, $18 M_\odot$, and $20 M_\odot$. For the lower mass range of the systems studied here, $M_{1,0} \lesssim 15 M_\odot$, we were able to evolve the stars until the formation of an ONe core. We encountered some numerical difficulties at very late evolutionary stages because off-center burning flames make the computation numerically expensive. The omission of the final core collapse has no consequences for our study.

Figure 2 shows the evolution of a representative binary system evolving according to our assumptions in the higher mass range, $15 M_\odot \lesssim M_{1,0} \lesssim 20 M_\odot$, where we later show that the secondary must be in the mass range of $M_{1,0} > M_{2,0} \gtrsim M_{1,0} - 1.2 M_\odot$ (Section 3).

The initial primary and secondary masses are $M_{1,0} = 20 M_\odot$ and $M_{2,0} = 19 M_\odot$, respectively. The system was evolved from ZAMS with a metallicity of $z = 0.02$ and until the explosion of each star. It is evident that once the primary explodes, the secondary is already a red giant. It is also apparent that during the giant phase of the primary star mass transfer is possible via RLOF, depending on the initial separation of the system (see above). This possibility is not presented here as there is little significance to the SNPG outcome.

We note that there are uncertainties as to whether SN ejecta can enrich a giant companion star. Hirai et al. (2014) find in
recent numerical simulations that the shock propagating through the secondary by the SN ejecta can heat the companion. This might lead to the removal of up to 25% of the companion mass by the excess energy in case of a close binary and could rule out the proposed model. This difficulty might be overcome by non-spherical SN ejecta with a large concentration of calcium and other synthesized elements ejected toward the companion. Another process that can overcome the difficulties posed by the results of Hirai et al. (2014) and allow large quantities of calcium and other heavy elements to be accreted onto the companion is if the newly synthesized elements from the core of the SN expand in dense clumps. Such clumps can penetrate deeper into the star and stay bound. An estimation of the overall ejecta fraction intercepted by the secondary star for the case of an SAGB companion and a prediction of additional anomalous abundances expected by the SNPG scenario are shown next.

2.1. HV 2112 as an SAGB Star

We examine a sub-group of SNPGs where the mass of the secondary during the explosion of the primary is in the range of \( \approx 8.5-11 M_\odot \), in order to qualify as an SAGB star (Eldridge & Tout 2004; Siess 2006). We present here a representative case for such systems that might account for HV 2112 being an SAGB star. For the SMC metallicity \((Z \approx 0.004; \text{Diago et al. 2008})\) Doherty et al. (2015) find that SAGB stars are in an initial mass range of \( 7.1-8.8 M_\odot \). Accordingly, we chose the initial primary and secondary masses, as shown in Figure 3, to be \( M_{1,0} = 9.5 M_\odot \) and \( M_{2,0} = 9 M_\odot \), respectively. We evolved each star with an SMC metallicity of \( z = 0.004 \) using MESA.

The initial stellar masses were chosen according to four criteria: (1) the primary is massive enough to explode as a CCSN (triggered by electron capture); (2) the stars must be of close initial masses for the secondary to be an RGB star during the explosion of the primary; (3) the secondary must qualify as an SAGB star at late stages; and (4) the evolved SAGB secondary must agree with the properties of HV 2112, e.g., luminosity of \( \approx 4.6 \times 10^9-1.1 \times 10^5 L_\odot \) (Levesque et al. 2014; Tout et al. 2014).

We note the that during the final \( (\text{few} \times 10^3 \text{yr}) \) stages of evolution the stars seem to exceed the Eddington luminosity. One should take into account that in the calculated model the opacity is much lower than that of electron scattering. Since the classical Eddington luminosity is for electron scattering
opacity, we find the Eddington luminosity limit in our model to be higher than what textbooks give. Namely, the star does not reach the Eddington luminosity at the photosphere. Above the photosphere electron scattering might dominate, and the mass-loss rate must be very high. Our simulations do not include such an enhanced mass-loss rate, but this is what we expect to occur.

As the primary star explodes, it chemically pollutes the secondary star, now an RGB star with a radius of \( \approx 230 R_\odot \). The polluted secondary continues to evolve into an SAGB star. To account for the calcium abundance in HV 2112, Papish et al. (2015b) assumed that the giant secondary star intercepted a large enough fraction of the ejecta. We here demonstrate that this is possible. Tout et al. (2014) estimate the calcium mass in HV 2112 to be \( \approx 10^{-4} M_\odot \) from the line ratios presented by Levesque et al. (2014) for the SMC metallicity. For massive stars, \( 9 M_\odot \lesssim M_1 \lesssim 20 M_\odot \), with a metallicity of \( z = 0.02 \) exploding as a CCSN the ejected \( ^{40}\text{Ca} \) mass is \( \approx \text{few} \times 10^{-3} - 10^{-2} M_\odot \) (Woosley & Weaver 1995; Rauscher et al. 2002; Chieffi & Limongi 2013). This is up to 100 times the calcium mass estimated in HV 2112. We note that the Ca abundance in the lower range of massive stars \( 8 M_\odot \lesssim M_1 \lesssim 11 M_\odot \), exploding as CCSNe, has not been studied thoroughly for the metallicity of the SMC; hence, we use the above estimations of the ejecta in our calculations.

Overall a fraction of \( f \approx 0.01 \) of the SN ejecta must be accreted onto the secondary. For an accretion efficiency \( \eta \) we have
\[
f = \frac{1}{4} \left( \frac{R_2}{a} \right)^2 \eta = 0.01, \tag{1}
\]
where \( a \) and \( R_2 \) are the separation of the system and the secondary radius during the SN explosion, respectively. To account for \( \approx 10^{-4} M_\odot \) of \( ^{40}\text{Ca} \) in HV 2112 requires that \( \eta \approx 0.25 \). In cases where RLOF is avoided at an earlier stage (see Section 2), \( R_2/a \gtrsim 0.4 \) and hence \( \eta \gtrsim 0.25 \).

### 2.2. Additional Anomalous Abundances

We further expect additional anomalous abundances according to the SNPG model. We can estimate these by comparing the ejected mass in an SN explosion and the composition in a relevant region, with respect to Ca. For the solar neighborhood we use the present-day solar composition (Anders & Grevesse 1989; Goswami & Reddy 2010) and the SN yields for a metallicity of \( z = 0.02 \) found by Woosley & Weaver (1995), Rauscher et al. (2002), and Chieffi & Limongi (2013). Taking all these into account, we find Ar to be similar to Ca in both solar abundance (up to a factor of 2) and the ejected mass in an SN explosion. We therefore estimate the Ar overabundance to be similar, or slightly smaller, compared to Ca. Si, S, Fe, and Ni are ejected in a mass up to 10 and even 20 times larger than that of Ca, yet from the solar abundance we expect no Fe overabundance. We note that Levesque et al. (2014) find no Fe overabundance. We do expect a comparable or even slightly higher overabundance in S, and a larger Ni overabundance, compared to Ca. As to the Si overabundance, we cautiously predict a low yet non-negligible overabundance.

We follow the same procedure for the SMC. Chieffi & Limongi (2004) presented similar yields for the case of an exploding star of metallicity \( z = 0.02 \) and \( z = 0.006 \). We also direct the reader to the work of Nomoto et al. (2006), who presented estimations on the SN yields for a metallicity of \( z = 0.004 \), though we find a large deviation between their estimations for \( z = 0.02 \) and those we have referred to previously. We point out that we did not find a detailed source to the composition in the SMC, yet we estimate the ratio of the composition of the different elements to that of Ca to be the same as in the solar neighborhood (Venn 1999). Hence, we deduce that the same overabundances are expected to be found for SNPGs in the SMC as in the solar neighborhood. Overall, we expect SNPGs to possess Ca, Ar, S, and Ni overabundance, and perhaps also a low Si overabundance.

### 3. BIRTHRATE ESTIMATION

To estimate the Galactic and Magellanic Clouds (MCs) birthrates of the studied SNPG systems, as well as the fraction of all potential progenitors of CCSNe, we proceed as done by Sabach & Soker (2014). For the initial mass function of the relevant primary we take (Kroupa et al. 1993)
\[
dN/dM = AM^{-2.7}, \quad \text{for} \quad 1.0 M_\odot < M, \tag{2}
\]
where \( A \) is a constant. For the systems studied here we demand that the initial stellar mass must be
\[
M_{i,0} > M_{2,0} \gtrsim M_{i,0} - \Delta M = M_{2,0,\text{min}}.
\]
We also assume that the secondary mass distribution is constant in the allowed range \( dN_2 = dM_2/M_1 \) for \( M_1 > M_2 > 0 \). The number of relevant binary systems is given by
\[
N_b \approx \int_{M_{i,0}}^{1.0} \int_{M_{i,0} - 0.6 M_\odot}^{M_{2,0}} \left( \frac{M_{i,0} - M_{2,0,\text{min}}}{M_{i,0}} \right) dM_{1,0} \tag{3}
\]
We find that for primary stars with initial mass of \( 15 M_\odot \gtrsim M_{i,0} \gtrsim 9 M_\odot \) the secondary must be in the mass range of \( M_{i,0} > M_{2,0} \gtrsim M_{i,0} - 0.6 M_\odot \), to allow our evolutionary scenario. For primary stars with initial mass of \( 20 M_\odot \gtrsim M_{i,0} \gtrsim 15 M_\odot \) the secondary must be in the mass range of \( M_{i,0} > M_{2,0} \gtrsim M_{i,0} - 1.2 M_\odot \). This gives
\[
N_b \approx \int_{9 M_\odot}^{15 M_\odot} \int_{0.6 M_\odot}^{M_{i,0}} \left( \frac{M_{i,0}}{M_1} \right) dM_{1,0} + \int_{15 M_\odot}^{20 M_\odot} \int_{1.2 M_\odot}^{M_{i,0}} \left( \frac{M_{i,0}}{M_1} \right) dM_{1,0} = 6 \times 10^{-4} AM_\odot^{-1.7}. \tag{4}
\]
For the progenitors of CCSNe we take all stars with initial mass \( M \geq 9 M_\odot \), for which integration gives \( n_{\text{CCSN}} = 0.014 AM_\odot^{-1.7} \).

Raghavan et al. (2010) estimate a lower limit of 75% for O-type stars to have companions. We take a typical fraction \( f_0 \approx 0.8 \) of O-type stars to be in binary systems with an orbital separation less than 700 AU, and the relevant binary population of massive stars to span over a range of four orders of magnitude (from \( a_{\text{min}} \approx 0.1 \) to \( a_{\text{max}} \approx 1000 \) AU) with an equal probability in the logarithmic of the orbital separation. For the pollution of the secondary by the primary to take place, the relevant orbital separation distribution is \( a \approx 2-6 R_\odot \approx 500-1500 R_\odot \) (as we cannot completely rule out some mass transfer, accounting for the lower limit). We find the orbital separation distribution to span over \( \approx 0.5 \text{dex} \).
Accordingly, the probability of a binary system to be in the desired orbital separation is \( f_s \approx 0.5/4 = 1/8 \). This is a crude estimate as we took an order-of-magnitude value for the relevant orbital separation range. We also note that if the eccentricity of the system is considered, the initial separation range is even larger.

The fraction of the SNPG systems studied here to the number of CCSN progenitors is

\[
\frac{N_{\text{Systems}}}{N_{\text{CCSN}}} \approx \frac{N_h}{N_{\text{CCSN}}} f_s f_i \approx 4.3 \times 10^{-3}. \tag{5}
\]

Using the CCSN rate in the Galaxy \( \approx 0.014 \, \text{yr}^{-1} \) (Cappellaro et al. 1997), we estimate the Galactic birthrate of such systems to be \( \approx 6 \times 10^{-5} \, \text{yr}^{-1} \). From the lifetime of the polluted secondary stars studied here from the primary explosion to the secondary explosion, \( \approx 10^6 \, \text{yr} \) (Figure 2), we estimate that on average \( \approx 60 \) such SNPG systems exist in the Galaxy at any given time. Maoz \& Badenes (2010) estimate the SN (SN Ia + CCSN) rate in the MCs to be \( 2.5-4.6 \times 10^{-3} \, \text{yr} \) and the CCSN rate to be \( \approx 2.5 \) times more than the SN Ia rate. From the lifetime of the polluted secondary star we estimate that on average \( \approx 10 \) such systems exist in the MCs at any given time.

For the sub-case of SAGB polluted giants the recurrence of objects such as HV 2112 is smaller since the SAGB lifetime is a few times \( 10^5 \, \text{yr} \) (Figure 3; Doherty et al. 2015). We estimate that only one to three objects will be found in the SMC. If a large number of such objects will be found, probably neither our model nor the TZO model will be applicable. We note that the uncertainties in our estimates are very large, but nonetheless the conclusion that such SNPG objects are rare is robust.

4. DISCUSSION AND SUMMARY

We have studied some properties of binary systems where the secondary star is already in its giant phase when the primary explodes as a CCSN (Figure 1). For this to occur the initial mass of the secondary star should be only slightly, by about 5% or less, below the initial mass of the primary.

From the results of Section 3 this case occurs in about 2% of all CCSNe. This implies that observations of the post-explosion site can reveal that a giant star still exists there. With better sky coverage and more SNe in relatively close galaxies, such cases must be eventually detected.

We then discussed a specific type of such systems where the orbital separation is such that the secondary star can intercept a large fraction, about 1%, of the SN ejecta. If the secondary envelope is not completely ablated by the ejecta, the secondary becomes polluted with metals from the SN; we term this an SNPG scenario. In Section 3 we estimated that the SNPG scenario might occur in about 0.4% of all CCSNe. The secondary then lives for some time before it explodes. We estimated that at any given time there are about 60 SNPG stars in the Galaxy and about 10 SNPG stars in the MCs. If we allow for a lower chemical pollution, then the orbital separation can be larger and the number of SNPG systems increases.

We used the SNPG scenario to address the large calcium abundance of the evolved star HV 2112 in the SMC. Tout et al. (2014) find that an SAGB star can account for the peculiar abundances of HV 2112 besides that of calcium. Levesque et al. (2014) and Tout et al. (2014) argued that the high calcium abundance is best explained if HV 2112 is a TZO.

Papish et al. (2015b), on the other hand, argued that it is impossible to bring an NS to the center of a giant star since the entire envelope and part of the original core will be ejected by the jets that are launched by the NS as it inspirals (Armitage \& Livio 2000; Soker 2004; Chevalier 2012). Instead, Papish et al. (2015b) speculated that the high calcium abundance might be explained by pollution (enrichment) from a more massive companion that had already exploded as a CCSN. Based on our proposed alternative to the TZO scenario and on studies that suggest that an NS can launch jets that remove the CE, we call into question the interpretation of HV 2112 as a TZO. We further expect additional anomalous abundances according to the SNPG model by comparing the ejected mass in an SN explosion and the composition in a relevant region, with respect to Ca. Overall, we expect SNPGs to possess Ca, Ar, Si, and Ni overabundance, and perhaps also a low Si overabundance.

The evolutionary routes discussed here and in Papish et al. (2015b) have potential relation to some exploding and erupting astrophysical objects.

1. Explosion with jets. The process by which the inspiraling NS launches jets and ejects the envelope and core is very rapid and will be observed as an explosion (Chevalier 2012). In light of the failure of the recent neutrino mechanism to reach the desired explosion energy of CCSNe (Papish et al. 2015a), we hold the view that it is quite likely that all CCSNe have exploded by jets launched by the newly formed NS (or black hole) at their center, as in the jittering-jet mechanism (Papish \& Soker 2014; Gilkis \& Soker 2014). Hence, the NS-core merger might be wrongly attributed to a CCSN with large pre-explosion mass loss (Chevalier 2012).

2. Intermediate-luminosity optical transient (ILOT) 1. If the NS ejects the entire envelope but does not merge with the core of the RSG star, then the outburst will be much less energetic. The total energy will be of the order of the binding energy of the envelope. The luminosity of the outburst will be much below that of an SN, but more than that of a nova. The outburst will be classified as an ILOT event. We note that the inspiraling of a WD companion to the core of a giant star can also lead to an ILOT event (Sabach \& Soker 2014). Tylenda et al. (2013) already suggested that the transient OGLE-2002-BLG-360 is an ILOT (which they termed a red transient) in the process of a final merger of a CE evolution.

3. ILOT 2. If an early stage of RLOF takes place once the primary is a red giant, the mass transfer from the more evolved star to the secondary star occurs in an unstable manner over a short time, tens of years and less; this event can be classified as a luminous blue variable major event, or as an ILOT (Kashi \& Soker 2010). The points here are that (1) a massive secondary star (almost as massive as the primary) can accrete at a very high rate from the primary star to form an ILOT, and (2) some ILOTs of massive stars might turn into SNPGs.

4. Peculiar superluminous CCSNe. In the proposed scenario for SNPGs the secondary is already a giant when the primary explodes. It is quite possible that the secondary will be as bright as the primary. For example, in the binary system presented in Figure 2 the luminosities of the two stars just before the primary explosion are \( L_1 = 1.26 \times 10^5 \, L_\odot \) and \( L_2 = 1.02 \times 10^5 \, L_\odot \). We expect also...
massive CSM, as not all mass is accreted by the secondary. The collision of SN ejecta with the CSM will form a superluminous SN, by channeling much more than $10^{49}$ erg of the kinetic energy to radiation, and hence the SN will be several times as bright as a typical SN. The peculiarity here is that the presence of a post-explosion giant remnant will make it a peculiar CCSN.

Our present study adds to the variety of peculiar astrophysical objects that might be related to peculiar eruptions and explosions.

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REFERENCES

Anders, E., & Grevesse, N. 1989, GeCoA, 53, 197
Armitage, P. J., & Livio, M. 2000, ApJ, 532, 540
Cappellaro, E., Turatto, M., Tsvetkov, D. Y., et al. 1997, A&A, 322, 431
Chevalier, R. A. 2012, ApJL, 752, L2
Chiefi, A., & Limongi, M. 2004, ApJ, 608, 405
Chiefi, A., & Limongi, M. 2013, ApJ, 764, 21
Diago, P. D., Gutiérrez-Soto, J., Fabregat, J., & Martayan, C. 2008, A&A, 480, 179
Doherty, C. L., Gil-Pons, P., Siess, L., Lattanzio, J. C., & Lau, H. H. B. 2015, MNRAS, 446, 2599
Eggleton, P. P. 1983, ApJ, 268, 368
Eldridge, J. J., & Tout, C. A. 2004, MmSAI, 75, 694
García-Beerro, E., Lorén-Aguilar, P., Aznar-Siguán, G., et al. 2012, ApJ, 749, 25
Gilks, A., & Soker, N. 2014, MNRAS, 439, 4011
Goswami, A., & Reddy, B. E. 2010, in Principles and Perspectives in Cosmochemistry (Berlin: Springer)
Hirai, R., Sawai, H., & Yamada, S. 2014, ApJ, 792, 66
Ilkov, M., & Soker, N. 2013, MNRAS, 428, 579
Kashi, A., & Soker, N. 2010, arXiv:1011.1222
Kroupa, P. Tout, C. A., & Gilmore, G. 1993, MNRAS, 262, 545
Levesque, E. M., Massey, P., Zylkowski, A. N., & Morrell, N. 2014, MNRAS, 443, L94
Maoz, D., & Badenes, C. 2010, MNRAS, 407, 1314
Metzger, B. D. 2012, MNRAS, 419, 827
Nomoto, K., Tominaga, N., Umeda, H., Kobayashi, C., & Maeda, K. 2006, NuPhA, 777, 424
Papish, O., Nordhaus, J., & Soker, N. 2015a, MNRAS, 448, 2362
Papish, O., & Soker, N. 2014, MNRAS, 443, 664
Papish, O., Soker, N., & Bukay, I. 2015b, MNRAS, 449, 288
Paxton, B., Bildsten, L., Dotter, A., et al. 2011, ApJS, 192, 3
Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, ApJS, 190, 1
Rauscher, T., Heger, A., Hoffman, R. D., & Woosley, S. E. 2002, ApJ, 576, 335
Sabach, E., & Soker, N. 2014, MNRAS, 439, 954
Schaffenroth, V., Przybilla, N., Butler, K., Irngang, A., & Heuber, U. 2015, arXiv:1501.07816
Soker, N. 2004, NewA, 9, 399
Siess, L. 2006, A&A, 448, 717
Tauris, T. M., & Sennels, T. 2000, A&A, 355, 236
Thorne, K. S., & Zylkowski, A. N. 1975, ApJL, 199, L19
Thorne, K. S., & Zylkowski, A. N. 1977, ApJL, 212, 832
Tout, C. A., Zylkowski, A. N., Church, R. P., et al. 2014, MNRAS, 445, L36
Tylenda, R., Kamiński, T., Udalski, A., et al. 2013, A&A, 555, AA16
Venn, K. A. 1999, ApJ, 518, 405
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181