Wind Roche Lobe Overflow as a way to make type Ia supernova from the widest symbiotic systems

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ABSTRACT
Symbiotic stars are interacting binaries with one of the longest orbital periods. Since they can contain a massive white dwarf with a high accretion rate they are considered a promising type Ia supernovae (SNe Ia) progenitors. Among symbiotic binaries there are systems containing a Mira donor, which can have orbital periods of a few tens of years and more. This subclass of symbiotic stars due to their very large separation usually was not considered promising SNe Ia progenitors. We analysed evolution of one of the well studied symbiotic star with a Mira donor, V407 Cyg. We showed that the standard evolution model predicts that the system will not become a SN Ia. However, by simply adding a Wind Roche Lobe Overflow as one of the mass transfer modes we predict that the white dwarf in V407 Cyg will reach the Chandrasekhar limit in 40–200 Myr.

Key words: supernovae: general – stars: evolution – binaries: symbiotic – binaries: close – stars: individual: V407 Cyg

1 INTRODUCTION
Type Ia supernova (SN Ia) is a thermonuclear outburst of a carbon–oxygen (CO) white dwarf (WD). Many scenarios have been proposed for progenitors of SNe Ia, which include a single-degenerate (SD) scenario, where WD is accreting mass from a companion until it reaches a Chandrasekhar mass ($M_{\text{CH}}$) and as a result explodes as a SN Ia (e.g. Whelan & Iben 1973; Wang 2018). A double-degenerate (DD) scenario involves a merger of two WDs (Iben & Tutukov 1984; Webbink 1984). Similarly, in the core-degenerate (CD) scenario the SN Ia outburst is due to a common-envelope phase of a binary with a WD and an asymptotic giant branch (AGB) star, which leads to a merger of the WD and a degenerate core of the AGB star (e.g. Soker 2013; Wang et al. 2017). There are also scenarios involving SN Ia on a sub-$M_{\text{CH}}$ WD. In one of the scenarios the SN Ia is triggered by a helium shell detonation (Jiang et al. 2017). It is also speculated that SN Ia can also be produced by a single, isolated WD when it transfers from a liquid to the solid state (Chiosi et al. 2015). Unfortunately, there are no observations of systems that produced SN Ia before the explosion, hence none of the scenarios is directly confirmed trough observations. Moreover, each of the scenarios has its problems and most probably more than one scenario is responsible for the observed SN Ia population. Possible progenitors of SN Ia, together with their advantages and disadvantages are presented e.g. in Maoz et al. (2014), Livio & Mazzali (2018) and Patat & Hallakoun (2018).

Symbiotic stars (SySt) are long-period interacting binaries with a red giant (RG) as a mass donor. Most commonly a white dwarf is an accretor, but in some systems a neutron star (NS) is observed (see Mikolajewska 2012 for a recent review of SySt). Since some of them contain a massive WD with a high accretion rate, they have been proposed as possible SN Ia progenitors (see e.g. Hachisu et al. 1999; Lu et al. 2009; Booth et al. 2016; Mikolajewska & Shara 2017, Liu et al. 2017). SySt can be considered as SN Ia progenitors both in the SD scenario, as well as in the DD scenario, in which case the RG evolves into WD, leading to a WD+WD binary. Dilday et al. (2012) showed that the evolution of the SN Ia PTF 11kx outburst was consistent with a symbiotic nova progenitor, although other scenarios for this outburst have been proposed as well (Soker et al. 2013). A review of most promising SN Ia progenitors among SySt is presented in Mikolajewska (2013).
Kepler's Supernova Remnant, a remnant of SN Ia, has dust features consistent with a SD scenario and a massive AGB donor (Williams et al. 2012). It’s progenitor could have been very similar to the SySt V407 Cyg (Chiottelis et al. 2012; Mikolajewska 2013). V407 Cyg is a SySt containing a massive Mira donor on AGB (Tatarnikova et al. 2003a,b) and a massive WD (e.g. Hachisu & Kato 2012) – a system almost identical to the speculated progenitor of Kepler’s supernova. The presence of the Mira providing a vast amount of dust into the system V407 Cyg implies that it belongs to the D-type (dusty) SySt, which have the widest orbits among SySt with expected orbital periods of the order of a few tens of years and more (e.g. Gronadzki et al. 2009).

In this study we use population synthesis models to predict the fate of V407 Cyg and its viability as a SN Ia progenitor in the frame of the SD scenario. In particular, we study importance of including formulae for mass transfer through wind accretion and through Roche lobe overflow (RLOF). We expanded the code by adding the wind Roche lobe overflow (WRLOF; Mohamed & Podsiadlowski 2012). In order to implement WRLOF we adopted the prescription in eq. 9 of Abate et al. (2013):

\[ \beta_{\text{acc}} = \min \left( \frac{25}{9} q^2, -0.284 \left( \frac{R_d}{R_d} \right)^2 + 0.918 \frac{R_d}{R_L} - 0.234 \right) , 0.5 \]  

(1)

where \( \beta_{\text{acc}} \) is the ratio between the mass accreted by the secondary star and the mass lost by donor star per unit of time, \( q = M_{\text{secondary}}/M_{\text{donor}} \). \( R_d \) is the dust formation radius and \( R_L \) is Roche-lobe radius of the mass donor. The dust formation radius can be calculated with eq. 4 of Hönker (2007):

\[ R_d = \frac{1}{2} \left( \frac{T_d}{T_{\text{eff}}} \right)^{-\frac{2}{3}} \]  

(2)

where \( R_\star \) is the mass donor radius, \( T_d \) is the dust condensation temperature and \( p \) is a parameter characterising wavelength dependence of the dust opacity. We assumed dust consisting of amorphous carbon grains, for which \( T_d = 1500K \) and \( p = 1 \) (Höfner 2007). In our model we calculated mass accretion rate at each time step using the WRLOF and the standard Bondi & Hoyle (1944) accretion, and used the larger value from these two as the mass accretion rate.

Typically, when a WD is accreting matter recurrent nova outbursts are expected. During a nova outburst large amount of matter is ejected from the WD. It remains controversial whether the WD is accreting more mass during a nova cycle than it losses during outburst, i.e. how much (if any) of the accreted mass is retained. In principle, the theoretical and observational considerations show that at least
in some cases the WD mass can grow (Yaron et al. 2005; Nomoto et al. 2007; Mikolajewska & Shara 2017). In our study, in the case of CO WD we used mass accumulation formulae from Ivanova & Taam (2004). Namely, in the case of mass accretion rate lower than $10^{-11} \text{M}_\odot \text{yr}^{-1}$ all accreted mass is ejected in nova explosions, in the case of mass accretion rate between $10^{-11}$ and $10^{-9} \text{M}_\odot \text{yr}^{-1}$ the fraction of accreted mass retained on the WD is interpolated from Pringle & Kovetz (1995) models, and in the case of mass accretion rate grater than $10^{-8} \text{M}_\odot \text{yr}^{-1}$ all of the accreted mass is retained on the WD. Moreover, we adopted $M_{\text{CH}}=1.40 \text{M}_\odot$ (e.g. Hillman et al. 2015). In the case of ONe WD we used the same accumulation formulae as in the case of CO WD (Belczynski et al. 2008).

In order to study V407 Cyg we evolved a single star from the Main Sequence (MS) to the RG stage. We stopped the single star evolution when the star met the parameters of the RG star adopted in our model, i.e. the mass, effective temperature and luminosity (section 2.1). Subsequently, we modelled a binary with a RG with the same structure as the one obtained from the single star evolution. The second star in the binary was a WD on a circular orbit consistent with the accepted orbital period. In order to fully explore the adopted parameter space we chose a range of masses on the MS by trial and error until we found the range for which the RG could evolve to the desired mass, luminosity and effective temperature. Using this procedure we were able to model systems with the RG mass in a range 4.00–7.30 M$_\odot$. Stars with masses higher than 7.30 M$_\odot$ did not reach the desired luminosity and effective temperature in a single star evolution models. We carried out calculation in a grid of models covering 300 stars evenly spaced in the zero age MS mass space. The second part of the grid consisted of 100 WDs evenly spaced in the current mass ranging from 1.0 M$_\odot$ up to 1.399 M$_\odot$. The prior evolution, leading to the SySt phase is beyond the scope of this paper. Our method is similar to that adopted by Lin et al. (2011) to study X-ray binaries evolution.

### 3 RESULTS

The Roche-lobe filling factor of the RG in V407 Cyg, defined as the ratio of the stellar radius to the volume Roche-lobe radius, is presented in Fig. 1. This ratio is small in all our models, exactly as expected for a D-type SySt. This means that no other channel proposed to enhance mass accretion rate in SySt, such as tidally enhanced RG wind (e.g. Lü et al. 2009), is applicable in the case of V407 Cyg.

In Fig. 2 the calculated mass accretion rate is presented. Using only standard wind accretion (left panel) the mass accretion rate is over two orders of magnitude lower than when WRLOF is included (right panel). This indicates that WRLOF can be important mass transfer mode for systems such as V407 Cyg. Moreover, since WRLOF is based on more realistic estimates than the simple estimates of the standard wind accretion (Mohamed & Podsiałowski 2012) its inclusion enables to perform more realistic predictions about evolution of such systems.

We calculated the amount of mass that is accumulated onto a WD before the RG evolves into a degenerate object (Fig. 3). In the models where only the standard Bondi & Hoyle (1944) wind accretion is included the WD has to have essentially a mass equal to the Chandrasekhar limit in order to explode as SN Ia or experience AIC. When we consider models with WD masses larger than 1.2 M$_\odot$ (Mikolajewska 2010) only 7% of the models, that have the most massive WDs, reach M$_{\text{CH}}$. Moreover, none of the WDs with masses in range $M_{\text{WD}} = 1.35 - 1.37 \text{M}_\odot$ (Hachisu & Kato 2012), estimated from the modelling of the evolution of the nova outburst, are massive enough to reach M$_{\text{CH}}$. On the contrary, when the WRLOF is included in modelling, as much as 90% and 97% of the models exhibited SN Ia or AIC for the 1.2 M$_\odot$ lower limit (Mikolajewska 2010) and the $M_{\text{WD}} = 1.35 - 1.37 \text{M}_\odot$ estimate (Hachisu & Kato 2012) respectively. Moreover, even models with the least massive RGs systems with WD masses as low as 1.15 M$_\odot$ could exhibit SN Ia or AIC. This shows that WRLOF dramatically changes the predicted system evolution and including this mass transfer mode to population synthesis of the D-type SySt is crucial for estimating their plausibility as SN Ia or AIC system progenitors. The WD in this scenario reached the Chandrasekhar limit in 40–200 Myr. In the case of most massive WDs and evolution including WRLOF, only the models with most massive RGs did not exhibit SN Ia outburst or AIC. This is because such a massive RG, after reaching the temperature and luminosity of the RG in V407 Cyg, evolves towards core collapse, supernova II and NS formation, aborting mass accumulation onto WD and ending the system evolution as a WD+NS binary.

Prolonged RLOF accretion onto WD in close binary system may lead to the formation of a low mass black hole. If accretion induced collapse of WD to NS does not disrupt or significantly widens the binary orbit, the RLOF may continue and provided that the donor star has enough mass NS may eventually collapse to a BH (e.g., fig. 2 of Belczynski & Taam 2004). This process will naturally produce low-mass BHs that may potentially fill the apparent mass gap between known NSs and BHs (the lack of compact objects in mass range 2–5 M$_\odot$; e.g. Bailyn et al. 1998, Özel et al. 2010, Belczynski et al. 2012, Wyrykowski et al. 2016). In our models...
we assumed that the NS will collapse to a BH at $M_{\text{NS}}=2\,M_\odot$ (Belczynski & Taam 2004). The BH in fact was created in the case of 10% models of our models with ONe WDs with masses larger than $1.2\,M_\odot$ (Mikołajewska 2010) an in none of the models with WD masses in range $M_{\text{WD}}=1.35-1.37\,M_\odot$ (Hachisu & Kato 2012). In the models in which the WD experienced AIC and then the resulting NS collapsed into a BH the donor ends its evolution as a WD, which means that V407 Cyg can be considered as a potential progenitor of a WD+BH binary.

For consistency check, we calculated expected nova shell mass. For this calculations we assumed $M_{\text{WD}}=1.2\,M_\odot$ and mass accretion rate $\dot{M}=5\times10^{-8}\,M_\odot/\text{yr}$ (Fig. 2). From fig. 4 in Hillman et al. (2016) one can see that the expected nova cycle duration for assumed parameters is $D=100$ yr. From fig. 1 in Hillman et al. (2016) we see that in this case the effective rate, at which the mass is accumulated onto the WD (i.e. mass that is retained on the WD during a nova cycle divided by a nova cycle duration), is of order of $\dot{M}_{\text{eff}}=1\times10^{-8}\,M_\odot/\text{yr}$. The expected nova shell mass is then $D\times(\dot{M}-\dot{M}_{\text{eff}})\approx4\times10^{-6}\,M_\odot$. This is consistent with the shell mass of $\sim10^{-6}\,M_\odot$ estimated from observations (Abdo et al. 2010; Chomiuk et al. 2012).

4 DISCUSSION

We point out that the scenario in which WRLOF leads to SN Ia is different than the one proposed by Lü et al. (2009), Chen et al. (2011) and Liu et al. (2017). In these works the authors proposed changes in mass-loss from the RG. This is different from the WRLOF, since in order to change mass loss from the RG a strong interaction between a WD and RG is needed. In the case of WRLOF, the stellar wind is originally unaffected by the WD, but then it is funnelled onto WD when the wind itself fills the Roche lobe of the RG. Hence, tidal forces are not needed and the model applies to much wider systems.

The caveat of our study is that Chomiuk et al. (2012) argued that the environment of V407 Cyg is not typical of SNe Ia. On the other hand, more recently Dimitriadis et al. (2014) showed that the observational constrains on the environment of SN Ia may not apply to systems in which there were classical nova outburst in the past (one of which was observed in V407 Cyg). Moreover, Dimitriadis et al. (2014) showed that the circumstellar medium shaped by nova explosions seem to better reproduce observational features of some SN Ia. We additionally point out that the environment shaped by WRLOF is more complex (Mohamed & Podsiadlowski 2012) then the one in the model used by Chomiuk et al. (2012).

Thus far the main arguments against SySt as promising SN Ia progenitors from existing population synthesis models of SySt (Yungelson et al. 1995; Yungelson et al. 1996; Lü et al. 2006; Yungelson 2010) were that: (i) the typical mass of the accretor is small ($\sim0.5\,M_\odot$), (ii) mass accumulation of matter transferred to the WD is small (see e.g. Kato & Hachisu 1990) and (iii) they often evolve towards dynamically unstable mass transfer and formation of a common envelope. We point out that there are at least a few observed SySt with massive WDs, including four symbiotic recurrent novae (Mikołajewska 2013; Mikołajewska & Shara 2017). Moreover, population synthesis models of SySt are not reproducing the observed distribution of orbital periods (Mikołajewska 2012), which hints that theoretical predictions about the SySt population might be yet inaccurate. In the case of mass accumulation onto the WD, the theoretical predictions are an active field of research, but it seems that the WD can accumulate mass as indicated by both theory (Hillman et al. 2016) and observations (Mikołajewska & Shara 2017). Last but not least, we point out that in such systems as V407 Cyg the binary components separation is too big to reach a common envelope phase. Concluding, our simulations show that, contrary to previous suggestions based mostly on population synthesis models, binary systems like V407 Cyg could be promising SN Ia progenitors.

5 SUMMARY

In this work we analysed predicted evolution of a D–type SySt V407 Cyg. Our analysis showed that in the framework
of Chandrasekhar mass SN Ia explosions, the standard picture may need an update for wide symbiotic systems. In the classical form of wind accretion implementation, the WD would need to have almost exactly Chandrasekhar mass in the present in order to reach a SN Ia. On the other hand, when WRLOF is included as one of the modes of mass transfer, there is 90% probability of encountering a SN Ia when most conservative estimates of the WD mass and a CO WD are adopted. The probability reached 97% for the most accurate WD mass estimate ($M_{\text{WD}} = 1.35 \pm 0.37 M_{\odot}$; Hachisu & Kato 2012). This shows that WRLOF is important factor in studying the D–type SySt evolution. Moreover, WRLOF could be a vital element in evolution of SySt with the longest orbital periods in context of SN Ia. Given the problems of SD scenario (Livio & Mazzali 2018) SySt can alternatively be considered as progenitors of peculiar SN Ia (see e.g. Taubenberger 2017).

Since the distribution of circumbinary material shaped by WRLOF is more complicated than in the simpler models, such as e.g. Bondi & Hoyle (1944) model, the SN Ia produced in the proposed scenario could be interesting in the study of environments of SN Ia. In particular, the large separation of considered binary and complex morphology of circumbinary material could influence lightcurve and spectral evolution of a SN Ia outburst.

We also showed that if the WD in V407 Cyg is a ONe WD and not a CO WD, the WD in the system will probably experience AIC. In the models with the highest initial WD masses the NS after AIC can accumulate enough mass in order to collapse into a BH, which means that V407 Cyg can be considered a potential a progenitor of a WD+BH binary with a low mass BH in the apparent mass gap between known NSs and BHs.

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REFERENCES
Abate C., Pols O. R., Izzard R. G., Mohamed S. S., de Mink S. E., 2013, A&A, 552, A26
Abdo A. A., et al., 2010, Science, 329, 817
Bailyn C. D., Jain R. K., Coppi P., Orosz J. A., 1998, ApJ, 499, 367
Belczynski K., Taam R. E., 2004, ApJ, 603, 690
Belczynski K., Kalogera V., Bulik T., 2002, ApJ, 572, 407
Belczynski K., Kalogera V., Rasio F. A., Taam R. E., Zezas A., Bulik T., Maccarone T. J., Ivanova N., 2008, ApJS, 174, 223
Belczynski K., Wiktorowicz G., Fryer C. L., Holz D. E., Kalogera V., 2012, ApJ, 757, 91
Bondi H., Hoyle F., 1944, MNRAS, 104, 273
Booth R. A., Mohamed S., Podsiadlowski P., 2016, MNRAS, 457, 822
Chen X., Han Z., Tout C. A., 2011, ApJ, 735, L31
Chiosi E., Chiosi C., Trevisan P., Piowan L., Orio M., 2015, MNRAS, 448, 2100
Chiotellis A., Schure K. M., Vink J., 2012, A&A, 537, A139
