TIDALLY ENHANCED STELLAR WIND: A WAY TO MAKE THE SYMBIOTIC CHANNEL TO TYPE Ia SUPERNOVA VIABLE

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1. INTRODUCTION

Type Ia supernovae (SNe Ia) are used as distance indicators for cosmology. From SNe Ia, we deduce that the expansion of the universe is accelerating (Riess et al. 1998; Perlmutter et al. 1999). They are also crucial for the study of Galactic chemical evolution because they expel iron. However, the exact nature of their progenitors remains unclear and it is still uncertain whether a double-degenerate (DD) or a single-degenerate (SD) scenario dominates. In the DD scenario, two carbon–oxygen (CO) white dwarfs (WDs) can produce an SN Ia while merging if their total mass is larger than 1.38 M⊙. In the SD scenario, a WD explodes as an SN Ia if its mass reaches 1.38 M⊙ while accreting from a non-degenerate companion such as a main-sequence (MS) star or slightly evolved subgiant in the WD+MS channel, a giant star in the WD+RG channel or the symbiotic channel, or a helium star (van den Heuvel et al. 1999; Han & Podsiadlowski 2004).

A progenitor model can be tested by comparing the predicted distribution of the time between star formation and SN Ia explosion with that observed. This ranges from less than 108 yr to more than 3 Gyr. A significant number of SNe Ia have occurred after the latter timeframe (Botticella et al. 2008; Totani et al. 2008; Schawinski 2009). Though the DD scenario can reproduce such delays, the SD scenario cannot, except in the study by Hachisu et al. (2008) who assumed that the wind from the WD strips the outer layers of the red giant (RG) at a high rate (their mass-stripping effect). They showed that symbiotic stars are likely progenitors of SNe Ia with long delays. Gilfanov & Bogdán (2010) have claimed that supersoft X-ray (SSX) fluxes in early-type galaxies are much smaller than expected if the SD scenario were to dominate SNe Ia production. However, Hachisu et al. (2010) argue that this SSX flux is actually rather strong evidence in favor of the SD scenario in early-type galaxies and that the progenitors are symbiotic stars.

There are at least four recurrent symbiotic novae, such as RS Oph or T CrB, that have very massive WDs. They are thought to have RG companions of mass \( M < 1 M_\odot \) (Anupama & Mikolajewska 1999). It is difficult to reproduce these systems in standard binary evolution because dynamical instability in mass transfer sets in when the giant fills its Roche lobe. Hachisu et al. (1999a) systematically studied binary evolution and established WD+MS and WD+RG paths to SNe Ia by introducing three new physical effects: (1) the wind from the RG acts like a common envelope to reduce the separation for very wide binaries with separations up to about 30,000 R_\odot, (2) the WD loses much of the transferred mass in a massive optically thick wind, and (3) their mass-stripping effect. They produced SNe Ia at a rate comparable to that observed. Since then the only work to produce sufficiently high SN Ia rates with long delay times was Hachisu et al. (2008), who implemented all three effects. Other works adopted the above effects except mass stripping in their population syntheses and found smaller SN Ia rates.

The concept of a compact object accreting from the stellar wind of a companion was used by Davidson & Ostriker (1973) to explain X-ray pulses in massive X-ray binaries. It is now generally included in population synthesis calculations such as those by Hurley et al. (2002), though Hachisu et al. (1999a) did not include any wind accretion in their model. The surfaces of RG stars are not tightly bound and so it is relatively easy to drive a cool wind. Such winds might be enhanced by tidal or other interaction with a companion (Tout & Eggleton 1988a) and so could remove significant mass and angular momentum from the giant’s envelope before Roche lobe overflow (RLOF) begins. Tout & Eggleton (1988a) introduced this concept of companion reinforced attrition (CRAP) to explain mass inversion in RS CVn binaries and it has since been widely used to explain phenomena related to giant star evolution in binary systems, such as DD objects, post-asymptotic giant branch (AGB) stars, barium stars, cataclysmic variable stars, and bipolar planetary nebulae (see, for example, Han 1998; van Winckel 2003; Bonacic et al. 2008). As potential progenitors of SNe Ia, symbiotic stars (Kenyon & Webbink 1984) gain two advantages from CRAP. First, the WD may grow in mass substantially by accretion from stellar wind before RLOF and second mass transfer may be stabilized because the mass ratio \( M_{\text{giant}}/M_{\text{WD}} \) can be much reduced at the onset of RLOF. So the distribution of masses and periods from which SNe Ia arise through the symbiotic channel is enlarged.

ABSTRACT

In the symbiotic (or WD+RG) channel of the single-degenerate scenario for type Ia supernovae (SNe Ia), the explosions occur a relatively long time after star formation. The birthrate from this channel would be too low to account for all observed SNe Ia were it not for some mechanism to enhance the rate of accretion on to the white dwarf. A tidally enhanced stellar wind, of the type which has been postulated to explain many phenomena related to giant star evolution in binary systems, can do this. Compared to mass stripping, this model extends the space of SNe Ia progenitors to longer orbital periods and hence increases the birthrate to about 0.0069 yr^{-1} for the symbiotic channel. Two symbiotic stars, T CrB and RS Oph, considered to be the most likely progenitors of SNe Ia through the symbiotic channel, are well inside the period–companion mass space predicted by our models.
when CRAP is taken into account. Here we study this for SNe Ia with CRAP instead of Hachisu et al.’s (1999a) mass-stripping effect. Although both processes may occur in real systems we only include CRAP so as to isolate its effects.

2. BINARY EVOLUTION CALCULATIONS
AND RESULTS

We evolve about 2000 population I (with metallicity $Z = 0.02$) close WD+MS binary stars with Eggleton’s stellar evolution code (Eggleton 1971; Pols et al. 1998). Their CO WD masses $M_{\text{WD}}$ are 0.6, 0.65, 0.8, 1.0, and 1.1 $M_\odot$, the initial orbital periods are between 10 and 10,000 days spaced at intervals of $\Delta \log_{10}(P/\text{days}) = 0.1$, and the companion, secondary masses $M_2$ in the range from 0.8 to 7.0 $M_\odot$. The tidally enhanced mass-loss rate from the secondary $\dot{M}_{2w}$ is modeled by Reimers’ (1975) formula with the extra tidal term included by Tout & Eggleton (1988b) so that

$$M_{2w} = -4 \times 10^{-13} \frac{\eta (L/L_\odot)(R/R_\odot)}{(M_2/M_\odot)} \times \left[1 + B_w \min \left( \frac{1}{2}, \frac{R}{R_L} \right)^6 \right] \ M_\odot \ \text{yr}^{-1}, \quad (1)$$

where $R$ and $L$ are the radius and luminosity of the giant secondary, $R_L$ is its Roche lobe radius, and $\eta$ is Reimers’ wind coefficient. We set $\eta = 0.25$. We set the wind enhancement parameter $B_w$ to 10,000 as required to fit Z Her (Tout & Eggleton 1988a). Thus, the mass-loss rate $|\dot{M}_{2w}|$ could be 150 times larger than Reimers’ rate when the star more star than half fills its Roche lobe.

Some of the mass lost in the stellar wind of the giant may be accreted by the WD at a rate (Boffin & Jorissen 1988) so that

$$\dot{M}_{2a} = -\frac{1}{\sqrt{1-e^2}} \left( \frac{G M_{\text{WD}}}{v^2_w} \right)^2 \frac{\alpha_{\text{acc}} \dot{M}_{2w}}{2a^2(1 + v^2_{\text{orb}}/v^2_w)^{3/2}}, \quad (2)$$

where $v_{\text{orb}} = \sqrt{G(M_2 + M_{\text{WD}})/a}$ is the orbital velocity, $G$ is Newton’s gravitational constant, $a$ is the semi-major axis of the orbit, and $e$ is its eccentricity. We take $e = 0$ because we expect orbits to have circularized by this time. The coefficient $\alpha_{\text{acc}}$ is an accretion efficiency and we set $\alpha_{\text{acc}} = 1.5$. We fix the wind velocity $v_w$ to 5 km s$^{-1}$ and discuss this later. If $v_w$ or $a$ is small, the right-hand side of Equation (2) becomes large and so we add the limit $\dot{M}_{2a} \leq -\dot{M}_{2w}$. That part of the wind which is not accreted carries off the specific angular momentum of the donor star.

Before RLOF begins stellar wind is the only way to transfer material to the WD so the mass-transfer rate $\dot{M}_t = \dot{M}_{2a}$. During RLOF the mass is transferred in both a stream and the wind so that $\dot{M}_t = \dot{M}_{2a} + |\dot{M}_{2\text{RLOF}}|$, where $\dot{M}_{2\text{RLOF}}$ is the mass-transfer rate by RLOF.

We continue the practice of limiting the rate at which the WD can accrete (Han & Podsiaiidowski 2004; Meng et al. 2009; Wang et al. 2009) by the prescription of Hachisu et al. (1999b). This accounts for the limited rate at which hydrogen can burn and for mass loss in both hydrogen and helium novae. Thus,

$$\dot{M}_{\text{WD}} = \eta_{\text{H}} \eta_{\text{He}} \dot{M}_t. \quad (3)$$

Hydrogen accretion is controlled by

$$\eta_{\text{H}} = \begin{cases} M_{\text{cr}}/|M_t|, & |M_t| > M_{\text{cr}}, \\ 1, & M_{\text{cr}} \geq |M_t| \geq M_{\text{low}}, \\ 0, & |M_t| < M_{\text{low}}, \end{cases} \quad (4)$$

where $M_{\text{low}}$, equal to $\frac{1}{8} M_{\text{cr}}$, is the accretion rate below which hydrogen novae expel most of the material and $M_{\text{cr}}$ is the critical accretion rate above which hydrogen cannot burn as it is accreted but is instead expelled in an optically thick wind. Helium accretion is then further controlled by

$$\eta_{\text{He}} = \begin{cases} -0.175 (\log_{10}(M_{\text{He}}/M_\odot \ \text{yr}^{-1}) + 5.35)^2 + 1.05, & -7.3 < \log_{10}(M_{\text{He}}/M_\odot \ \text{yr}^{-1}) < -5.9, \\ 1, & -5.9 \leq \log_{10}(M_{\text{He}}/M_\odot \ \text{yr}^{-1}) < 0, \end{cases} \quad (5)$$

where $M_{\text{He}} = \eta_{\text{H}}|M_t|$. That part of the mass transferred but ultimately not accreted carries off the specific orbital angular momentum of the WD.

In Figure 1, we show the evolution of a binary system which ends as an SN Ia. Initially, $M_{\text{WD}} = 0.8 M_\odot$, $M_2 = 1.5 M_\odot$, and $\log_{10}(P/\text{days}) = 1.9$. The wind enhancement factor $B_w = 10,000$. We see three phases of CO WD growth to 1.378 $M_\odot$ at which carbon ignites degenerately. First, wind accretion becomes important at about $4.7 \times 10^6$ yr when the accretion is sufficient for hydrogen to burn as it accretes. Stable mass transfer dominates for a short time of around $1.02 \times 10^7$ yr. Finally, wind accretion continues after the system has detached because the orbit grows faster than the giant. The supernova occurs when the secondary’s mass has fallen to $0.353 M_\odot$ just as it is about to leave the RG branch and shrink to a WD.

At $2.673 \times 10^9$ yr ($t \approx 7 \times 10^9$ yr in Figure 1), the enhanced mass-loss rate reaches its maximum of 150 times Reimers’ rate. In this case, the WD is able to accrete all the wind and $\dot{M}_{2a} = -\dot{M}_{2w}$. This is an extreme case of small $P^c$. 

![Figure 1](image-url)
corresponding to the short orbital period edge of the space that leads to SNe Ia for an initially 0.8 $M_\odot$ CO WD (see Figure 2 below). At longer initial periods, the WD reaches 1.378 $M_\odot$ before RLOF occurs so there is no stable mass-transfer phase. For much wider systems and for more massive secondaries, that ignite helium non-degenerately and consequently do not grow very large on their first ascent of the giant branch, similar evolution occurs when the secondary is on the AGB.

Figure 2 shows the results of our binary evolution calculations in an initial-period–secondary-mass plane for various initial WD masses. No SNe Ia arise when $M_{i,WD} = 0.6 M_\odot$. Whether a CO WD reaches the critical mass to explode as an SN Ia depends on both the amount of mass transferred and the efficiency at which this can be accreted by the CO WD. In each panel, contours enclose the progenitors of SNe Ia. Only for the very high initial WD masses, of 1.1 $M_\odot$, can a massive secondary star drive an SN Ia. These stars ignite helium non-degenerately and so do not grow large enough to transfer sufficient mass while on their first ascent of the giant branch. Thus, only those initially massive enough to retain enough envelope mass to transfer via a wind on the first ascent of the giant branch are able to reach SNe Ia. In this case, the initial mass of the secondary ought not to be larger than the progenitor of the WD. This determines our upper limit for the upper region in panel (d) and explains why this region is absent for lower-mass WDs. The other regions are more interesting because they are more populated by virtue of the stellar mass function. For these the low secondary mass boundary is due to the limited amount of mass available for transfer from the lower-mass companions. The long period boundary is due to the efficiency of burning and accumulating the transferred material. The high secondary mass and low period boundary are both due to the onset of RLOF and dynamically unstable mass transfer because CRAP has not removed enough mass. Carbon burning then begins more gently in the heated outer layers of the WD and a supernova is avoided.

To examine the effect of CRAP in more detail, we repeated our calculations for an initially 1 $M_\odot$ WD with 0 < $B_w$ < 10,000 (see Figure 3). As $B_w$ decreases, the progenitor region shrinks and vanishes as $B_w$ → 0. This is consistent with the claim of Iben & Tutukov (1984) that there is no symbiotic channel to
Figure 4. Contours enclosing progenitors of SNe Ia, now in the final-period–secondary-mass plane just before explosion for various initial WD masses and also the triangle for Hachisu et al.’s (1999a) mass-stripping scenario. Filled stars and circles are the current positions of two symbiotic binary stars, T CrB and RS Oph. To plot these we have assumed that both the CO WDs have a mass of 1.378 M⊙ so that the secondary mass for T CrB is 0.71 M⊙ according to Hachisu et al. (1999a) or 0.823 M⊙ derived from the mass ratio of about 0.6 determined by Belczyński & Mikolajewska 1998 and for RS Oph 0.68–0.8 M⊙ according to Brandi et al. (2009). As in panel (d) of Figure 2, the contour for 1.1 M⊙ has two parts but the upper region is off this figure.

SNe Ia. For comparison, the progenitor region found by Hachisu et al. (1999a) is also shown in this figure. Our model extends the possible progenitor periods by almost a factor of 5–6. The velocity v near the companion’s wind is important because it strongly affects M. However, the growth rate of the CO WD MWD is not always sensitive to v because MWD is limited by M at the mass accretion rate is large enough (Equation (4)). Thus, once M is larger than about 10^{-6} M yr^{-1} the dependence of M on v becomes small because only about 10% or less of M is required for the CO WD mass to increase at M. When M is closer to 10^{-7} M yr^{-1}, the CO WD may not increase at all if v is large. Our choice of v ≈ 5 km s^{-1} is an estimate of the lower limit to the poorly modeled wind velocity. We choose it to demonstrate that such a channel to SNe Ia can exist but note that our progenitor region would shrink in places if v were larger.4

Figure 4 shows the regions in the final-period–secondary-mass plane at which the WD reaches 1.378 M⊙ for various initial CO WD masses. The region for a 1 M⊙ CO WD calculated with the mass-stripping effect (Hachisu et al. 2008) is superimposed in the figure. As for the initial systems, these regions extend to longer orbital periods. Two symbiotic stars, that are considered possible progenitors of SNe Ia, T CrB and RS Oph, with orbital periods 228 days (Belczyński & Mikolajewska 1998) and 454 days (Brandi et al. 2009), are plotted under the assumption that MWD ≈ 1.378 M⊙. Both are located well inside the region of SNe Ia progenitor regions for our models but lie on the edge of what might be expected with mass stripping.

4 We investigated two alternatives in a little more detail (1) v = 10 km s^{-1} and (2) v = Qv∞, where v∞ is a terminal wind velocity of typically 15 km s^{-1} for a giant star and Qv is calculated according to Yungelson et al. (1995). In both cases, the progenitor regions with the longest period systems not reaching sufficient WD masses to ignite. For example, the upper period boundary moves to log(P/days) ≥ 2.9 for MWD = 1.0 M⊙ and no SNe Ia are predicted at all when MWD = 0.65 M⊙ in case (1).

Table 1

| MWD/M⊙ | Δlog_{10} a | M/A/M⊙ | M/B/M⊙ | Δq | ν/yr^{-1} | ¯ν/yr^{-1} |
|--------|-------------|--------|--------|-----|-----------|-----------|
| 0.65–0.8 | 0.3 × 7/2  | 2.42   | 4.48   | 0.3168 | 0.0013    | 0.0043    |
| 0.8–1.0  | 0.8 × 7/2  | 4.48   | 6.63   | 0.3101 | 0.0001    | 0.0019    |
| 1.0–1.1  | 1.7 × 7/2  | 4.48   | 6.63   | 0.3960 | 0.0028    |           |
| 1.0–1.1  | 1.7 × 7/2  | 6.63   | 7.58   | 0.2576 | 0.0004    | 0.0055    |
| (Lower contour) | 2.0 × 7/2 | 6.63 | 7.58 | 0.3787 | 0.0007 | |
| (Upper contour) | 0.7 × 7/2 | 6.63 | 7.58 | 0.4489 | 0.0003 | |

Notes. For each range of WD masses M, M, and M are the corresponding lower and upper zero-age progenitor masses and Δq and Δlog_{10} a are the typical mass ratio and separation ranges for the regions in Figure 2 which lead to SNe Ia. The frequencies ν and ¯ν are the calculated supernova rates if the extremes of the distribution apply across the whole range and a simple mean of these two extremes. The factors of 2/3 account for the change from period to separation space.

3. FREQUENCY ESTIMATES

Figure 2 shows how the CRAP enhanced symbiotic channel would be very effective if many binary stars with a massive CO WD and an unevolved companion could form with periods between about 100 and 1000 days. However, conventional population synthesis calculations tend to produce such systems either with P < 100 days following the ejection of a common envelope or with P > 1000 days if they have avoided RLOF. On the other hand, we do observe symbiotic stars, such as T CrB and RS Oph, with massive WDs and orbital periods around 1 yr. Hachisu et al. (1999a) describe one way in which these systems, and consequently many like them, could have formed by shrinking a wide orbit in a process similar to common envelope evolution but by interaction with the stellar wind. To obtain the frequency of SNe Ia produced by our channel, we really ought to carry out a full population synthesis from the zero-age main sequence but here we apply the procedure explained by Hachisu et al. (1999a) in their Sections 4.3 and 4.4 so as to get a direct comparison with their rate. We divide the WD masses into the ranges given in our Table 1 and calculate the integral in Equation (1) of Iben & Tutukov (1984),

$$v = 0.2 \text{yr}^{-1} \Delta q \Delta \log_{10} a \int_{M_{A}}^{M_{B}} M^{-2.5} dM,$$

(6)

where M and M are the typical progenitor masses of the WDs at each end of the range. The integral then accounts for the initial mass function. We calculate the initial range of mass ratios, Δq, for a given WD mass by

$$\Delta q = \frac{M_{A} - M_{1}}{M_{B}} - \frac{M_{1}}{M_{B}},$$

(7)

where M and M are the upper and lower limits to the SNe Ia progenitor regions identified directly from Figure 2. By formula (6) we assume that the mass ratio is uniformly distributed between 0 and 1. With the quantity Δlog_{10} a, we assume that the initial period distribution is flat in log P and that this difference is unchanged by the evolution up to the point of Figure 2 so that we may read it from the figure directly for the particular WD mass. We then calculate a simple mean rate ¯ν of
the two extremes. Our total SNe Ia rate is 0.0069 yr\(^{-1}\), significantly larger than that calculated by Hachisu et al. (1999a) with their mass stripping. This rate is very uncertain and probably overestimated because we, as did they, have used cuboid-shaped regions in the initial parameter space, but it is not dissimilar to the actual observed rate for a galaxy like our own.

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