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What is the role of wind mass transfer in the progenitor evolution of Type Ia supernovae?

Carlo Abate

Argelander-Institut für Astronomie – Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany, e-mail: cabate@uni-bonn.de

Abstract. Type Ia supernovae (SNe Ia) are thermonuclear explosions of carbon-oxygen white dwarfs (WDs) that accrete mass from a binary companion, which can be either a non-degenerate star (a main-sequence star or a giant) or an other WD in a binary merger (single- and double-degenerate scenario, respectively). In population-synthesis studies of SNe Ia the contribution of asymptotic giant branch (AGB) stars to either scenario is marginal. However, most of these studies adopt simplified assumptions to compute the effects of wind mass loss and accretion in binary systems. This work investigates the impact of wind mass transfer on a population of binary stars and discusses the role of AGB stars as progenitors of SNe Ia.

Key words. Stars: AGB – Stars: binaries – Stars: wind mass transfer – Binaries: angular-momentum loss – Stars: supernovae Type Ia

1. Introduction

It is generally accepted that type Ia supernovae (SNe Ia) are thermonuclear explosions of carbon-oxygen white dwarfs (Hoyle & Fowler 1960). The explosion occurs when the WD reaches a critical mass close to the Chandrasekhar mass ($\approx 1.4\,M_\odot$ for non-rotating stars) by transferring material from a binary companion. Two main evolutionary paths have been proposed to describe this process. In the *single-degenerate (SD) scenario* the WD steadily accretes mass from a non-degenerate star, such as a main sequence star or a giant (Whelan & Iben 1973; Nomoto 1982). In the *double-degenerate (DD) scenario* two carbon-oxygen WDs merge and their combined mass exceeds the Chandrasekhar mass (Webbink 1984; Iben & Tutukov 1984). Hillebrandt & Niemeyer (2000) provide an exhaustive review of the two scenarios and discuss the discrepancies between modelled and observed properties of SNe Ia.

One problem of the models is that binary population-synthesis (BPS) studies typically predict rates of SNe Ia explosions several times lower than the observations (Toonen et al. 2012; Claeys et al. 2014). In these models, the contribution of asymptotic giant branch (AGB) stars is marginal, for two reasons. First, because Roche-lobe overflow (RLOF) from AGB donor stars is mostly unstable (Paczyński 1965), AGB stars do not efficiently transfer mass on to WDs in the SD channel. Second, in the DD scenario only AGB stars in a relatively narrow range of separations form WDs in orbits sufficiently tight to merge within a Hubble time. Consequently, only about 10% of all possible systems producing a SNe Ia event pass through (at least) one AGB phase (Claeys et al. 2014). However, most BPS models assume spherically-symmetric winds and low wind accretion efficiencies, as predicted by the canonical Bondi-Hoyle-Lyttleton (BHL) model. In contrast, recent hydrodynamical simulations of binary systems with AGB donors show that AGB winds can be very efficiently accreted by the companions in some circumstances (e.g. in the wind-RLOF, or WRLOF, regime described by Mohamed & Podsiadlowski 2012), and that the expelled material can carry a significant amount of angular momentum, in some cases shrinking the orbit significantly (Brookshaw & Tavani 1993).

This study investigates the impact of the high wind-accretion efficiencies and the strong angular-momentum losses on the SNe Ia rate.

2. Models

The BPS code `binary_c/nucsyn` (Izzard et al. 2004) is used to simulate the evolution of binary systems for a wide range of initial primary and secondary masses ($M_{1,\mathrm{i}}$ and $M_{2,\mathrm{i}}$, respectively) and initial orbital separations (a_i). In each simulation the evolution of 150×150×200 binary systems in a $\log M_{1,\mathrm{i}}$–$\log M_{2,\mathrm{i}}$–$\log a_\mathrm{i}$ parameter space is calculated.

The delay-time distribution (DTD), that is the SNe Ia rate as a function of time per unit mass in stars formed in an initial starburst at $t = 0$, is computed as

$$\mathrm{DTD}(t) = \frac{\sum\limits_{M_{1,\mathrm{i}}} \sum\limits_{M_{2,\mathrm{i}}} \sum\limits_{a_\mathrm{i}} \delta_{\mathrm{SNeIa}}\ \Psi_{M_1,M_2,a}\ \delta V}{M_{\mathrm{total}}\ \delta t}, \quad (1)$$

where:

- $M_{1,\mathrm{i}}$, $M_{2,\mathrm{i}}$ and a_i vary in the intervals $[2.5,9.0]M_\odot$, $[1.0,M_{1,\mathrm{i}}]M_\odot$, and $[5,10^5]R_\odot$, respectively,
- $\delta_{\mathrm{SNeIa}} = 1$ if the binary system ends its evolution with a SNe Ia event within the time interval $[t,\ t+\delta t]$, and is zero otherwise.
- $\Psi_{M_1,M_2,a}$ is the initial distribution function of $M_{1,\mathrm{i}}$, $M_{2,\mathrm{i}}$, a_i and is assumed to be separable. Consequently, $\Psi_{M_1,M_2,a} = \psi(M_{1,\mathrm{i}})\phi(M_{2,\mathrm{i}})\chi(a_\mathrm{i})$, where $\psi(M_{1,\mathrm{i}})$ is the solar-neighbourhood initial mass function of Kroupa et al. (1993), $\phi(M_{2,\mathrm{i}})$ is the initial distribution of secondary masses, which is considered to be constant in $q_\mathrm{i} = M_{2,\mathrm{i}}/M_{1,\mathrm{i}}$, and $\chi(a_\mathrm{i})$ is the initial distribution of orbital separation, which is assumed flat in $\log a_\mathrm{i}$ (Öpik & Lukk 1924).
- $\delta V = \delta M_{1,\mathrm{i}}\ \delta M_{2,\mathrm{i}}\ \delta a_\mathrm{i}$ is the volume of a cell in the parameter space of the grid.
- M_{total} is the total mass of stars formed in a grid of synthetic binary systems.

In model set S1 the same physical assumptions are adopted as in the "standard model" of Claeys et al. (2014). The accretion efficiency of wind mass transfer is modelled according to the formulation of the BHL prescription given by Boffin & Jorissen (1988). The wind is assumed to be spherically symmetric (as in Eq. 4 of Abate et al. 2013) and consequently the relation between the angular momentum carried away by the expelled material, $\dot{J}$, the total mass lost by the binary system, $\dot{M}_1 + \dot{M}_2$, and the orbital angular momentum of the system, J_{orb}, can be written as

$$\dot{J} = \gamma \times \frac{J_{\mathrm{orb}}}{M_1 + M_2}\left(\dot{M}_1 + \dot{M}_2\right), \quad (2)$$

where $\gamma = q = M_2/M_1$, that is the mass ratio of the accretor star over the donor star.

To investigate the effect of more efficient wind accretion from AGB donors, model set S2 calculates the wind accretion efficiency according to the WRLOF prescription proposed by Abate et al. (2013, Eq. 9).

Our model set S3 uses the same accretion-efficiency model as set S2. In addition, the angular momentum lost by stellar winds is computed according to Eq. (2) with γ defined as

$$\gamma = \max\{\, q\ ,\ h_{\mathrm{BT93}}\,\}, \quad (3)$$

where h_{BT93} has been determined by O. R. Pols (priv. comm.) from the best fit of the results of the ballistic simulations of Brookshaw & Tavani (1993, hereinafter BT93). The factor h_{BT93} scales approximately as the ratio $(v_{\mathrm{orb}}/v_{\mathrm{wind}})^6$, where v_{orb} and v_{wind} are the orbital velocity of the donor star and the wind velocity, respectively. At wide separations $v_{\mathrm{orb}} \ll v_{\mathrm{wind}}$, the wind barely interacts with the orbit and the spherically-symmetric-wind approximation applies. In contrast, for decreasing orbital separations the ratio between v_{orb} and

Table 1. Wind-accretion efficiency and the angular-momentum prescriptions adopted in each model set.

model set	wind accretion	angular momentum
S1	BHL	isotropic wind
S2	WRLOF	isotropic wind
S3	WRLOF	based on BT93

$v_{\rm wind}$ gradually increases and the angular momentum carried away by the wind becomes progressively larger than in the isotropic-wind case. As a consequence, in model set S3 the binary systems typically widen less (compared to model sets S1 and S2), or even shrink, in response to wind mass loss. Table 1 presents a summary of the wind-accretion and angular-momentum prescriptions adopted in each model set.

3. Results

In Figs. 1a–c the observed DTD (open triangles, recently rederived by Maoz & Graur 2017) is compared with the predictions of model sets S1, S2 and S3, respectively. The individual contributions of different evolutionary paths, namely the SD channel with H-rich and He-rich donor stars and the DD channel, to the total SNe Ia rate (solid line) are shown with the dotted, dashed, and dot-dashed lines, respectively. The SNe Ia countings have been normalised per century and per $10^{10} M_{\odot}$ in stars.

Set S1 is the same as the default model of Claeys et al. (2014), hence the features in Fig. 1a are essentially the same as in their Fig. 7. In particular, the contribution of He-rich donors ($\mathrm{SD_{He}}$) is prominent at short delay times ($t < 200$ Myr), whereas the DD channel dominates at delay times longer than about 300 Myr. The contribution of H-rich donors ($\mathrm{SD_H}$) is marginal, as it is essentially restricted to stars on the first giant branch transferring mass on the WDs by stable RLOF.

In set S2, because of the larger range of orbital separations at which the AGB stars can efficiently transfer mass onto the WD com-

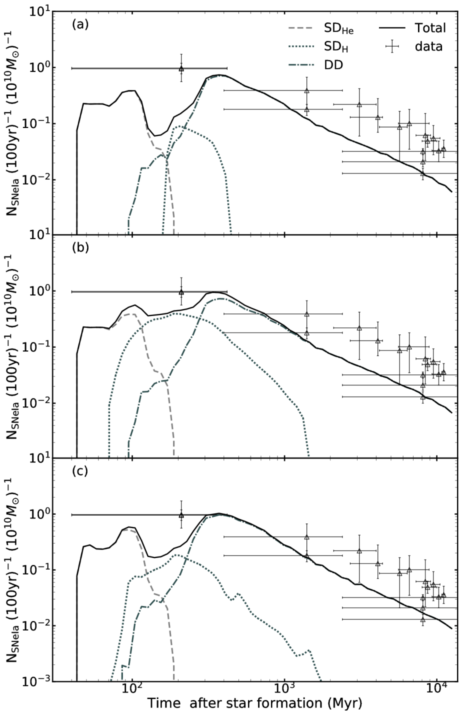

Fig. 1. Delay-time distributions calculated with model sets S1, S2, and S3 (panels a, b, and c, respectively). The dashed and dotted lines represent the contributions to the SNe Ia rate from the SD channel with He-rich and H-rich donor stars, respectively, while the dot-dashed line shows the contribuion of the DD channel. The solid line shows the total predicted SNe Ia rate. The open triangles are the literature data determined by Maoz & Graur (2017).

panions, their overall contribution to the $\mathrm{SD_H}$ channel becomes almost ten times higher. The increase in wind-accretion efficiency has no influence on the $\mathrm{SD_{He}}$ channel, in which mass transfer mostly occurs by RLOF, whereas it produces a small increase of the SNe Ia rate in the DD channel, because when the donor is an AGB star less mass is lost by the systems, hence the orbital separations widen less and consequently a slightly higher proportion of binary systems end up with two WDs that are close enough to merge within a Hubble time. In model set S2, the effect of AGB donors is mostly evident at delay times bewteen 100 and

300 Myr. At later delay times the DD channel dominates, as in set S1, although up to about 1 Gyr a small contribution to the total SNe Ia rate comes from AGB donors within the SD_H channel.

The strong angular-momentum losses predicted by Eq. (3) cause model set S3 to form many more double WDs in close orbits than in sets S1 and S2. Consequently, the SNe Ia rate in the DD channel is about 35% higher than in model S1. The contribution of the SD_H channel is increased compared to model S1 but, in proportion, this channel is less important than in model S2. This occurs because some of the systems, that in model S2 can efficiently transfer material from the AGB donor on to the WD, shrink more in model S3 and consequently accrete less, because of the relation between separation and accretion efficiency in the WRLOF model (see e.g. Fig. 3 of Abate et al. 2013), and hence the WD does not reach the Chandrasekhar mass.

4. Discussion and Conclusions

These results show that a less idealised treatment of wind mass transfer in binary systems significantly increases the contribution of AGB stars in SNe Ia progenitors. In particular, if a WRLOF prescription is adopted for modelling wind accretion, AGB stars are the main donors in the SD channel and their contribution is dominant between about 100 and 300 Myr after the initial burst of star formation. In addition, a larger amount of angular momentum may be lost by the systems if the winds are not ejected isotropically. For example, in model set S3 binary systems up to several thousands of days shrink in response to wind mass loss, consequently more double WDs in close orbits are formed and the contribution of AGB stars to the DD channel increases by a factor of three compared to the default case S1.

It should be emphasised that the simulations of BT93 only include gravitational effects on the wind particles, whereas the hydrodynamical properties of the gas are not taken into account. Consequently, the results obtained with set S3 should be considered as a limit case of strong angular-momentum losses, which have sometimes been invoked to explain the orbital properties of the observed carbon-enhanced metal-poor stars (Abate et al. 2015 and Abate et al. 2017, in prep.).

In conclusion, these results suggest that AGB stars may play a significant role as progenitors of SNe Ia, both in the SD and DD formation scenarios, and detailed hydrodynamical simulations are required to reliably quantify their impact on the total SNe Ia rate.

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