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Monte Carlo simulations of the formation channels of SNeIb

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We present a Monte Carlo simulator of the population of binary stars within the solar neighborhood. We have used the most updated models for stellar evolution, a complete treatment of the Roche lobe overflow episodes, as well as a full implementation of the orbital evolution. Special emphasis has been placed on processes leading to the formation of binary systems in which one of the members is a white dwarf. As a preliminary application of our Monte Carlo simulator we have performed a statistical study of the scenarios leading to type Ib supernovae events within our Galaxy.

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1. Introduction

A wide variety of interesting astrophysical problems, with relevance to many current and planned terrestrial and space-borne observatories like Chandra and XMM-Newton — which are devoted to study X-ray binaries — LIGO and LISA — which will study gravitational radiation sources — or Swift — whose main aim is to study gamma-ray burst progenitors — require extensive population synthesis studies. Additionally, several other interesting problems require modelling the Galactic populations of Type Ia supernova progenitors, binary systems containing a white dwarf and a neutron star and double white dwarf binary systems. Including the selection and observational biases in these kind of studies is of the largest importance and can only be reliably done using a Monte Carlo simulator. Here we describe the preliminary results of such a simulator.

2. The Monte Carlo simulator

The basic ingredient of any Monte Carlo simulator is a generator of random variables and for that purpose we have used a random number generator [1] which provides an uniform probability density within the interval $(0,1)$ and ensures a repetition period of $\gtrsim 10^{18}$, which is virtually infinite for practical simulations. For the stellar ingredients of each one of the components of binary system we have adopted the analytical fits to the stellar evolutionary tracks of Ref. [2]. The masses of each of the components were obtained using a standard initial mass function [3]. We have only considered stellar masses less than 20 $M_\odot$. Also, an exponentially decreasing star formation rate [4] was adopted. Finally, a disk age of 11.5 Gyr was assumed. In addition, orbital separations have been randonmly drawn according to a logarithmic probability distribution [5]. The eccentricities were also randomly drawn according to a thermal distribution [6], $f(e) = 2e$ for $0 \le e \le 0.9$. Finally, we have computed the orbital evolution of the binary taking into account circularization and synchronization [7, 8, 9]. Mass-losses through stellar winds were not considered.

The Roche lobe radius have been modelled according to the prescription of Ref. [10] and during the overflow episodes both rejuvenation and ageing have been taken into account. Likewise, we have performed the overflow treatment following the formalism of Ref. [11], although for the first common envelope episodes gravitational radiation losses and magnetic braking have been disregarded. Within this formalism the following mass–radius exponents can be defined:

$$\begin{aligned}
\zeta_{\rm L} &= \frac{d\ln R_{\rm L,donor}}{d\ln M_{\rm donor}} \\
\zeta_{\rm ad} &= \frac{d\ln R_{\rm ad}}{d\ln M_{\rm donor}} \\
\zeta_{\rm eq} &= \frac{d\ln R_{\rm eq}}{d\ln M_{\rm donor}}
\end{aligned}$$

where $\zeta_{\rm L}$ represents the response of the Roche lobe itself, $\zeta_{\rm ad}$ is the adiabatic hydrostatic stellar response and $\zeta_{\rm eq}$ is the thermal-equilibrium stellar response. It follows that when $\zeta_{\rm ad} < \zeta_{\rm L}$ a dynamical mass transfer ensues, when $\zeta_{\rm eq} < \zeta_{\rm L} < \zeta_{\rm ad}$ a thermal mass transfer takes place, whereas nuclear evolution only occurs when $\zeta_{\rm L} > \zeta_{\rm ad}, \zeta_{\rm eq}$. Finally the fraction of mass accreted has been modelled acoording to the expression:

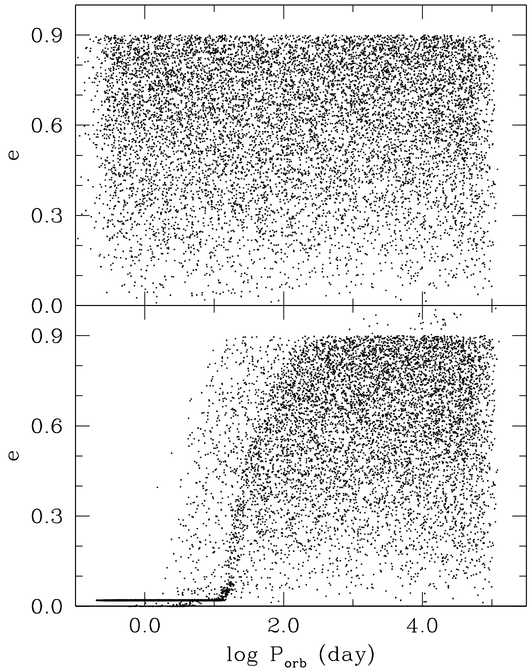

Figure 1: Initial (top panel) and final (bottom panel) distributions of eccentricities as a function of the period of the binary system.

$$f = \min\left(\frac{t_{\mathrm{KH,donor}}}{t_{\mathrm{KH,accretor}}}, 1\right)$$

which takes into account the Kelvin-Helmholtz timescales of both the donor and the accretor.

3. Testing the model

3.1 Tidal evolution: circularization and synchronization

The evolution of orbital parameters driven by tidal interactions of the binary has been computed in the standard equilibrium–tide, weak–friction approximation [7, 8] and following closely the treatment of Refs. [9] and [12]. The results are shown in Figure 1. In the top panel of this figure we show the initial distribution of eccentricities as a function of the period, whereas the bottom panel panel displays the final distribution. As can be seen, the tidal effects are significant for roughly 25% of the binary population. In particular, those binary systems with orbital periods shorter than about 10 days end up with orbits which are circularized and synchronized. Nevertheless, we stress that with our treatment any binary system which suffers Roche–lobe overflow is instantly synchronized and circularized.

3.2 Overflow statistics

A total of $\sim 9.0\times10^4$ binary systems were generated. Of these binary systems $\sim 4\%$ underwent Roche–lobe overflow during the main sequence phase (a case A mass–transfer episode), $\sim 10\%$ binaries overflown its Roche lobe before He ignition (case B) and $\sim 8\%$ did it before C

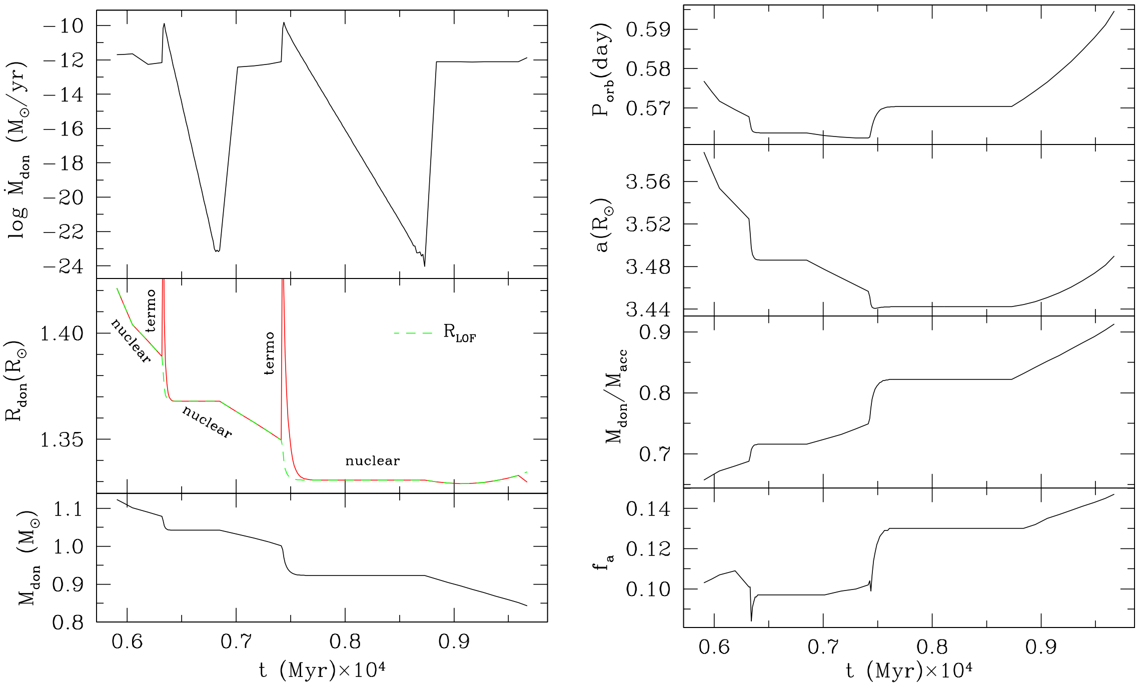

Figure 2: An example of the evolution of a binary system. In the left panel we show from top to bottom the time evolution of the mass–transfer rate, the donor radius and the mass of the donor. In the right panel, also from top to bottom, the period, the orbital separation, the donor–accretor mass ratio and the fraction of mass transfered are shown.

ignition (case C). For those binaries which underwent a case A mass–transfer episode we obtained that the final destiny in $\sim 85\%$ of the cases is the merger of the components, whereas in the remaining $\sim 15\%$ of the cases the binary survives as a detached system at the end of main sequence phase of the donor. However, these systems will most likely merge during the giant phase. For those systems which undergo a case B mass–transfer episode, the final destiny depends on whether the donor is subgiant or giant star. If the donor is a subgiant $\sim 50\%$ of the binaries end up as He–naked star plus a main sequence star, $\sim 45\%$ merge and the remaining $\sim 5\%$ form a He white dwarf plus a main sequence star binary system. If the donor is a giant then it is found that $\sim 61\%$ of the systems end up their lifes as binary systems containing a He white dwarf and a main sequence star, $\sim 25\%$ of them form a binary containing a He–naked star and a main sequence star, $\sim 13\%$ will merge and only $\sim 1\%$ form a double binary white dwarf with He cores. With respect to those systems which undergo a case C mass–transfer episode, in most of the cases ($\sim 89\%$) a system composed by a He–evolved star and a main sequence star is obtained, while in the rest of cases a merger ($\sim 4.9\%$), a He–evolved plus a He–naked ($\sim 4\%$) system, a He–evolved and a He white dwarf ($\sim 2\%$) binary and He–evolved plus a He–evolved ($\sim 0.1\%$) system are obtained.

3.3 An example of mass transfer evolution

Our code follows the time evolution of the orbital parameters of every binary system. For illustrative purposes, in Figure 2 the time evolution of the full set of relevant parameters of a particular system during the different mass–transfer episodes is shown. At the onset of the first mass–transfer episode ($t \simeq 5.8 \times 10^3$ Myr since the ZAMS) the binary is characterized by $M_{\rm donor} =$

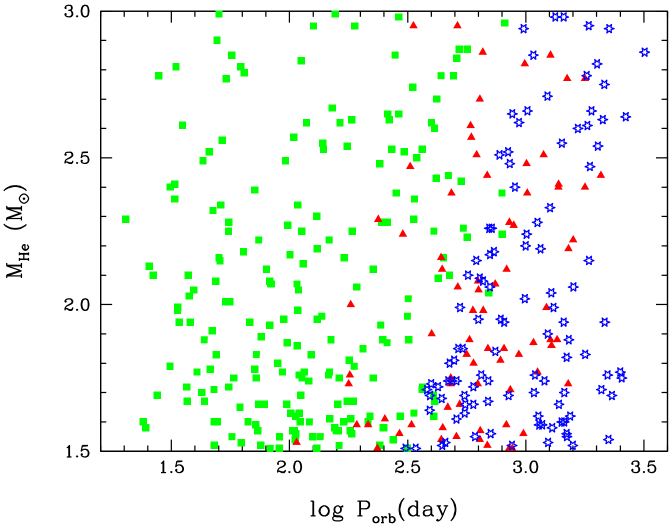

Figure 3: Distribution of masses of Helium stars as a function of the orbital periods. See text for details.

$1.13 M_\odot$, $M_{acc} = 0.74 M_\odot$, $a = 3.60 R_\odot$ and $P_{orb} = 0.58$ days. The overflow episodes take place during the main–sequence phase of both the donor and the accretor. Mass transfer proceeds in a nuclear timescale with the exception of two episodes with a thermal timescale, as clearly seen in the middle plot of the left panel of Figure 2. As a consequence, the mass transfer rate is highly non–conservative as shown in the bottom plot of the right panel of Figure 2. At the end of the the main–sequence phase of the donor the system is detached and has $M_{donor} = 0.84 M_\odot$, $M_{acc} = 0.77 M_\odot$, $a = 3.49 R_\odot$ and $P_{orb} = 0.59$ days. The second overflow occurs before He ignition in the degenerate core of the primary. Afterwards, a common envelope phase will occur, leading to a merger.

4. Results: the formation channels for SNIb

As one of the multiple results that can be derived from the analysis of the binary population we studied, as a preliminary result of our code, the main channel that leads to the formation of type Ib supernovae. Type Ib supernovae are believed to have an origin nearly identical to type II supernovae, in which a massive star suffers collapse at the core. However, the progenitor star of a Type Ib supernova has expelled its outer, convective, H–rich envelope before the explosion. Hence, the most probable astrophysical scenario involves a mass–transfer episode in a binary system. We thus start with a main sequence binary. The primary evolves to form a system composed by a giant and a main sequence star. The giant overflows its Roche lobe and the system evolves through a common envelope phase to form a helium star plus a main sequence star if the donor has a non–degenerate He core ($M > 2\ M_\odot$). The He star will not be evolved if the common envelope phase occurs before He ignition and the binary may be observed as a subdwarf with a main sequence companion. The second Roche–lobe overflow happens when the helium star has finished helium core burning. Again in this case a second common envelope episode occurs. However, some of these stars have already gone through all the relevant burning phases of nuclear burning and explode as supernovae. We have found that helium stars of masses smaller than 3 $M_\odot$ and larger than 1.5 $M_\odot$ are likely to produce type Ib supernovae.

In Figure 3 we show the distribution of masses of helium stars as a function of the orbital periods of the systems for all the possible progenitors. Subgiants in the Herztsprung Gap (HG) are

	Case B		Case C	Total
	HG progenitor	GB progenitor	EAGB progenitor	
1^{st} Overflow	1.4%	1.6%	7.3%	10.3%
SNIb	0.2%	0.1%	0.1%	0.4%

Table 1: Summary of the results of the frequency of binary systems which lead to type Ib supernovae events.

shown as green squares, giant branch (GB) progenitors are plotted using red triangles and early Asymptotic Giant Branch (EAGB) progenitors are displayed as blue stars. As can be seen, helium stars evolving from subgiant progenitors are very likely to become SNIb events and, besides, they exhibit a wide range of orbital periods. EAGB progenitors have long periods ($\log P_{\rm orb} > 2.5$) and the same occurs for giant progenitors, although they also occupy a region of somewhat smaller periods. We have found that, on average, two SNIb events are expected to occur every 100 yr in the whole Galaxy. The final results are summarized in Table 1, where the relative frequencies can be found. As can be seen, the three channels of formation of SNIb contribute to the total rate, although He stars with subgiant progenitors are more likely to occur than other channels. In fact, their probability is twice that of giant progenitors and early AGB progenitors. We estimate that 2 SNIb events are expected every 100 yr.

5. Conclusions

We have presented the preliminary results obtained using a Monte Carlo simulator of the binary population of our Galaxy. We have checked that our model correctly follows the tidal evolution of the simulated binaries, including circularization and synchronization of the orbits, and the overflow and mass transfer episodes — either A, B, and C cases — and we have presented detailed results for a typical binary system. Given that our tests were satisfactory we have used our Monte Carlo code to assess the relative frequencies of the scenarios conducting to the formation of type Ib supernovae. We have found that He stars produced in a binary system composed of a massive main sequence star and a less massive companion can account for all the events. We have also found that the most probable channel for the formation of these supernovae is the one in which the primary is a subgiant which fills its Roche lobe while still is in the Hertzsprung gap. The other two channels of formation of SNIb, namely those in which a giant star or an early AGB star are involved, are equally probable, but their respective probabilities are half of that in which a subgiant is involved. In a near future we plan to extend our Monte Carlo simulations to other interesting astrophysical problems in which binary systems are involved. In particular, one of the cases we want to study in depth is the population of double white dwarf binaries and that of binary systems in which the components are a white dwarf and a neutron star. Both kinds of systems are guaranteed sources for LISA [13, 14, 15] and, therefore, a correct modelling of their respective populations deserves further attention.

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