Mem. S.A.It. Vol. 88, 294

Memorie della

The binary channels to electron capture supernovae

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Abstract. Due to the second dredge-up and expected strong mass loss during the thermally pulsing super-AGB phase, the mass range for single stars to evolve as electron capture supernova (ECSN) is very narrow. In this short contribution, we briefly review alternative binary channels and present recent case A & B mass transfer simulations. In these models, the envelope is removed during Roche lobe overflow (RLOF), preventing the occurrence of the second dredge-up and the reduction of the H-free core below the Chandrasekhar mass. The newly formed helium star can then ignite carbon and may end its life as ECSN.

Key words. Stars: abundances – Stars: binaries – Stars: evolution – Stars: supernovae

1. Introduction

Super AGB stars have a mass ranging between $\sim 7\,M_\odot$ and $11\,M_\odot$ depending on the metallicity and input physics (mainly the treatments of mixing processes and mass loss). The evolution of their structure is characterized by the off-center ignition of carbon followed by the propagation of a carbon burning flame towards the center and the formation of an ONe core. Subsequently, during the thermally pulsing super-AGB (TP-SAGB) phase, the core may grow due to mass accretion from the burning shells and reach the critical mass $M_{\rm EC} = 1.37\,M_\odot$ (Nomoto 1984) beyond which electron capture reactions on the abundant ^{20}Ne become energetically favorable. The reduction of the electron number induces the collapse of the core and the explosion of the star in the so-called electron capture supernova (ECSN). Stellar evolution calculations indicate that unless mass loss is drastically reduced, a very small fraction of SAGB stars will evolve into ECSN. The estimated mass range is $\approx$ 0.1-0.3 $M_\odot$ width (for a recent review, see Doherty et al. 2017). The reason why it is so difficult for single stars to go ECSN is because (*i*) the wind developing during the TP-SAGB phase is powerful enough to remove the envelope before the core can grow up to $M_{\rm EC}$ and (*ii*) the second dredge-up (2DUP), which occurs after central helium burning, can significantly reduce the mass of the H-depleted core (Fig. 1). In massive stars, the 2DUP does not have time to operate and the CO core can grow above the Chandrasekhar mass when the He burning shell moves outward. As a consequence, their nuclear evolution will proceed up to the formation of an iron core and they will explode as core collapse SN.

With binaries, new evolutionary routes towards ECSN become possible because the degenerate ONe core can grow by accretion from a companion. Several scenarios have been devised, depending on the chemical composition of the accreted matter. The first scenario is similar to the one advocated to explain the formation of cataclysmic variables except that in this case we have a SAGB progenitor and a low mass companion. In this accretion induced collapse scenario, the SAGB star fills its Roche lobe during the TP-SAGB phase. The system then enters a common envelope phase and after the spiral-in and removal of the SAGB envelope, the ONe white dwarf and main sequence (MS) companion end up in a short period system. Subsequently H-rich material is transferred to the ONe WD and providing the accretion rate is in the right range, the mass of the WD can increase up to $M_{\rm EC}$.

The merger of two CO WDs can also lead to ECSN. The formation of these systems involve two phases of common envelope. In this scenario, the lower mass WD, which has a larger radius, transfers CO-rich material on the companion. Saio & Nomoto (1985) showed that carbon ignites off-center and a deflagration front propagates to the center, converting the massive CO WD in an ONe core. If the total mass exceeds $M_{\rm EC}$ then an ECSN may occur. However, recent models by Schwab et al. (2016) show that silicon can ignite off center before EC reactions start, potentially affecting the mode of explosion. In case of the merger of a ONe + CO WD, a similar scenario applies: the CO WD is tidally disrupted and the accreted C-rich material is recurrently ignited at the edge of the O+Ne core until the mass of the accretor reaches $M_{\rm EC}$.

Nomoto (1984) and Habets (1986) showed that He stars in the mass range 2 and 2.5 $M_\odot$ can evolve toward ECSN. Helium stars are a very common by-product of binary evolution and can be formed as a result of Roche lobe overflow (like in stable case A and B mass transfer) or a common envelope (CE) if the system does not merge. In both case, the envelope of the most massive stars is removed and the naked primary is a He star. A good illustration of these different possibilities is given by

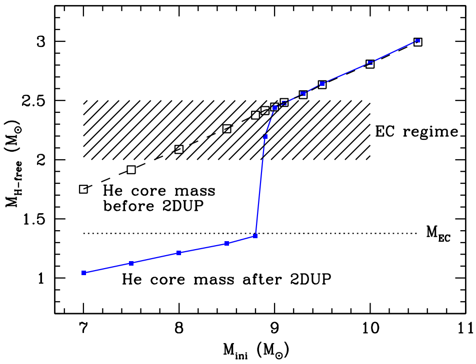

Fig. 1. Mass of the H-depleted core before (dashed lines with open squares) and after (solid line with filled squares) the 2DUP as a function of initial stellar mass (data for solar metallicity models taken from Siess 2007). The shaded area shows the mass range where, according to Nomoto (1984), helium stars go ECSN.

Tauris & van den Heuvel (2006) in their review of the formation and evolution of compact X-ray sources (see in particular their Fig. 12 and 15). Recently Tauris et al. (2015) investigated the evolution of peculiar systems composed of a neutron star and a He star companion. Their simulations show that depending on the initial period, ECSNs occur provided the He star has a mass between 2.6 – 2.95 $M_\odot$.

As mentioned previously, the 2DUP leads to a dramatic reduction of the He core mass that prevents the star from evolving towards ECSN. However, as suggested by Podsiadlowski et al. (2004), the occurrence of the 2DUP depends on the presence of the extended convective envelope and can be avoided if the SAGB envelope is removed as a result of binary interactions. As can be seen from Fig. 1, the initial mass range for ECSN increases substantially from 8.8-9.0 $M_\odot$ to 7.8-9.0 $M_\odot$ if the 2DUP is absent. Using dedicated models, we now explore in more detail this scenario.

2. Case A and B mass transfer

To investigate the evolution of He stars formed during stable RLOF, we computed a series of binary evolution models with the BINSTAR code (Siess et al. 2013). By default, we assume the orbits are circular, the mass transfer conservative and the stars synchronized with the orbital period. We also include a moderate core overshooting ($f_{\rm over}$ = 0.01) and disable wind mass loss which is negligible anyway. The evolution of the primary is followed until neon ignition or end of carbon burning (in the WD outcome). To estimate the fate of the He star, we have different criteria based on the ONe core mass at the end of C burning and on the evolution of the central temperature and density.

Figure 2 illustrates a typical case A mass transfer through the evolution of a 11.5+9 $M_\odot$ system with an initial period of 2 days. During case A mass transfer (MT), the primary starts filling its Roche lobe on the MS and the envelope is removed in two episodes: a first main episode (case A) during which the mass ratio is reversed, briefly interrupted when H burning moves in a shell in the primary, followed a case AB (e.g. Pols 1994). The system eventually detaches when helium ignites at the center of the donor star. In this example, the companion has accreted ≈ 10 $M_\odot$ and now evolves much faster than the primary. Eventually the secondary leaves the core He burning phase before the primary and its expansion following central He exhaustion leads to a new phase

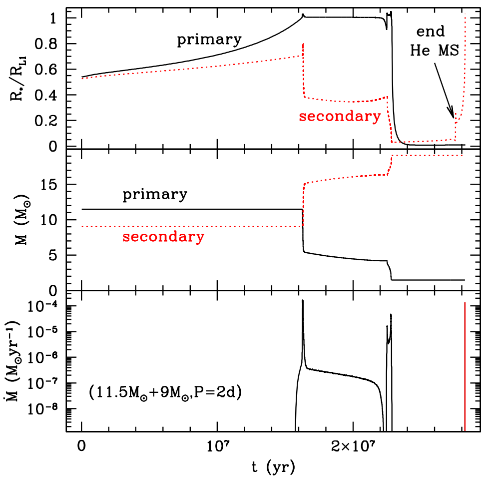

Fig. 2. Evolution of a case A 11.5+9 $M_\odot$ system with an initial period of 2 d. From top to bottom, the panels show the evolution of the Roche filling factor, stellar masses and mass transfer rate.

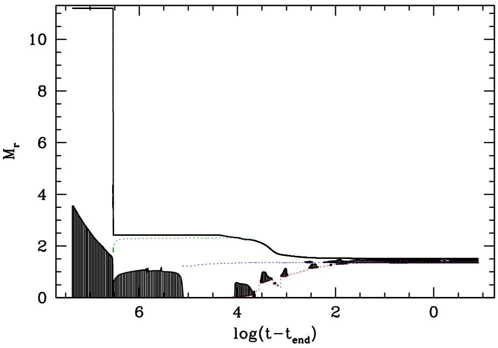

Fig. 3. Kippenhahn diagram of the primary star of a 11.2+9 $M_\odot$ binary with an initial period of 4 d. The colored dotted lines indicate the locus of maximum nuclear energy production associated with H, He and C burning. Time is counted backward from the last computed model.

of MT. However, at this stage a merger is a likely outcome because of the extreme mass ratio ($q = M_2/M_1 \approx 13.5$). Our simulations reveal that very few case A systems will go ECSN because of this reverse MT when the secondary overtakes the primary's evolution.

For case B systems, RLOF takes place when the primary is burning H in a shell and proceeds on the thermal timescale of the donor star. When the system detaches at helium ignition, the mass ratio is also very large but contrarily to case A, the primary leaves the core helium burning phase first while the companion is still on the hydrogen MS. Several MT episodes occur when He and carbon shell burning start and contribute to further decrease the mass of the primary. An illustration of the evolution of the donor star of a 11.2+9 $M_\odot$ system with an initial period of 4 days is showed in Fig. 3. While this star ignites neon off-center and likely evolves toward ECSN, the companion is still on the MS.

We then investigated the dependence of the ECSN channel on the initial period. For a fixed secondary mass of 9 $M_\odot$, we find (Fig. 4) that if the period is too short ($P \lesssim 3$ d), most case A systems go into contact either during the primary's MS (because of a too small initial mass ratio or because the secondary is initially too close to filling its Roche lobe) or during reversed mass transfer when the evolution of the secondary has overtaken that of the primary.

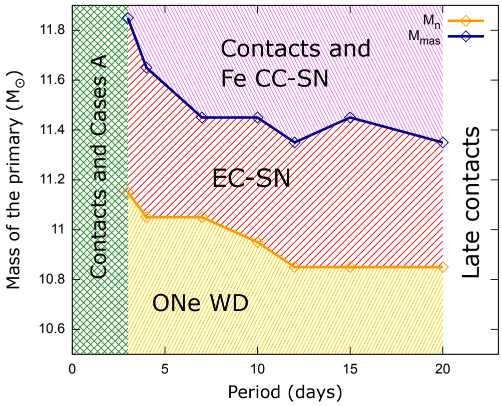

Fig. 4. Fate of the primary star as a function of its mass and initial period for a system with a secondary companion mass $M_2 = 9\,M_\odot$.

With increasing period, the mass transfer also increases because the primary is more evolved when it fills its Roche lobe. In response to a stronger accretion, the companion expands further and our systems (with $M_2 = 9\,M_\odot$) go into contacts for $P \gtrsim 20$ d. Now if primary mass is too small, the He star formed after RLOF is less massive than $M_{\rm EC}$ and ends its life as an ONe WD. Conversely, if the primary is initially too massive it either goes into contact because it is bigger or after RLOF, the He star ignites neon at the center and evolves as a massive star core. So, with our assumptions for angular momentum transfer, we find that the primary mass range for ECSN is not as small as for single stars but is not substantially increased, of the order of $\sim 0.6\,M_\odot$. The decrease of the primary's mass with increasing period results from the fact that with larger initial separation, the He core can grow bigger before RLOF starts so the primary does not need to be initially as massive to go SN.

3. Conclusions

In a conservative evolution, the parameter space for case A systems to host an ECSN progenitor is very limited because of the likely merger outcome resulting from the reverse mass transfer that occurs when the secondary leaves the He MS. On the contrary, case B systems can successfully lead to ECSN. We also showed that in order to avoid contact the period range is restricted to $\approx 3 - 20$ d. We find a weak dependence of this period interval on the secondary's mass. Binary populations synthesis are needed to quantify the fraction of ECSNs that come from binaries. It should also be pointed out that the evolution of binary systems is pledged with large uncertainties associated with stellar and binary interaction modeling. For example, including core overshooting in the stellar models has a dramatic impact on the SAGB mass range and can decrease the initial mass for carbon ignition by up to $2\,M_\odot$. This effect on the primary's mass has a direct impact on the period range for the ECSN channel. As shown by Onno Pols in this proceeding, if mass transfer becomes non conservative, then many case A avoid contact and can evolve towards ECSN. Here again, the effects are very large. A deeper investigation of the parameter space is needed but from these preliminary results, it appears that although the mass range for ECSN in binary systems is larger than for single stars it still remains small with $\Delta M_{\rm EC} \lesssim 0.6\,M_\odot$.

Acknowledgements. LS is senior FNRS research associate.

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