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Barium star population synthesis with an improved TP-AGB model

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Abstract. We explore the formation of barium stars by carrying out stellar population synthesis, using a rapid synthetic binary star evolution code which includes nucleosynthesis and an up-to-date treatment of AGB evolution. Similarly to other studies, we find that the orbital period distribution and eccentricities predicted for the systems are in disagreement with observations. In search of a solution for this, we discuss some ingredients that may be missing in the current binary interaction models, especially the possibility of mass accretion during the common envelope phase and additional energy sources that may help to expel the common envelope.

1. Introduction

Barium stars are G or K-type giants with abnormally large abundances of heavy *s*-process elements, most prominently of barium, up to 1.2 dex above solar (Jorissen et al., 1998). These heavy elements are synthesized during the thermally pulsing asymptotic giant branch (TP-AGB) phase in low and intermediate mass stars, but the barium stars are not evolved enough to have reached this stage yet. Ba stars are in binary systems with periods between about 10^2 and 10^4 days, and have a white dwarf (WD) companion (McClure, Fletcher & Nemec, 1980; McClure, 1983; McClure & Woodsworth, 1990). They are formed when an unevolved star accretes mass enriched with *s*-process elements from its evolved companion, when the latter becomes a TP-AGB star (Jorissen et al., 1998). Thus, if their evolutionary history can be reliably modelled, Ba stars become probes of the nucleosynthesis processes occurring in TP-AGB stars and provide information about the physical processes involved in the stellar interaction in wide binary systems. However, barium stars present orbital properties, such as period distribution and eccentricities, that cannot be explained by standard binary stellar evolution (BSE) models as we show in § 3 (see also Pols et al. 2003). This problem is also present in other binary stellar systems, such as low metallicity carbon stars and binaries with a post-AGB star component (van Winkel et al., 1997; Jorissen et al., 1998, and references therein), which show evidence of a similar kind of mass transfer to that which has occurred in Ba star systems.

2. Population synthesis

In order to see if binary evolution models are capable of reproducing the observed data, both individually and statistically, stellar population synthesis has to be done. For this purpose rapid synthetic evolution codes are needed. Hurley et al. (2002, hereafter H02) developed a compre-

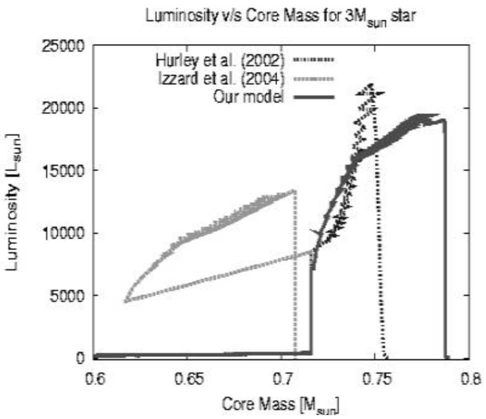

Fig. 1. Luminosity-core mass (LCM) relation for a 3 $M_{\odot}$ star with metallicity $Z = 0.02$. During the E-AGB phase, the hydrogen-exhausted core mass remains constant at 0.67 $M_{\odot}$. In our model the core mass at the start of the TP-AGB is the same as in the H02 model, which is greater than in the I04 model. However, we keep the more accurate LCM relation from I04.

Table 1. Grid of initial conditions used for carrying out Ba star population synthesis. The primary masses, M_1, are weighted by the initial mass function from Kroupa, Tout & Gilmore (1993). The distribution of initial mass ratios, $q = M_1/M_2$, and of eccentricities, e, is constant, and the distribution from Duquennoy & Mayor (1991) is used for the initial separations, a. All initial points are spaced logarithmically, except for the eccentricity, which has a linear spacing.

	lower	upper	# of points
M_1	$1.0M_{\odot}$	$5.0M_{\odot}$	25
M_2	$0.8M_{\odot}$	M_{primary}	25
a	$100R_{\odot}$	$30000R_{\odot}$	25
e	0	0.99	10

hensive evolutionary synthetic code for binary stellar evolution, based on detailed models by Pols et al. (1998, hereafter P98), which include convective core overshooting. However, the P98 detailed models do not undergo thermal pulses on the late AGB. To model the TP-AGB, the same luminosity-core mass relation as in the early-AGB (E-AGB) phase is assumed in H02. The TP-AGB section of the H02 code was improved by Izzard et al. (2004 hereafter I04), with a synthetic code based on the detailed model calculations by Karakas et al. (2002, hereafter K02), which undergo thermal pulses and follow the nucleosynthesis of many elements. However, the K02 detailed models do not consider convective overshooting. This means the transition from the E-AGB to the TP-AGB phase is not self-consistent in the I04 code, leading to discontinuities in the evolution of the core mass, the luminosity and the radius of the AGB star.

In order to perform population synthesis of Ba stars with a more self-consistent code, we have made some modifications to the I04 code. These consist basically in assigning, at the beginning of the TP-AGB phase, the (bigger) core mass calculated by the H02 model to the end of the E-AGB phase. However, we maintain the luminosity-core mass relation for the TP-AGB phase given in I04, which is more reliable (see Figure 1).

Thus, using the I04 code with the modifications mentioned above, we carried out Ba star population synthesis calculations, on a grid of 25 × 25 × 25 × 10 points (described in Table 1), with metallicity $Z = 0.008$. The binary interaction model is described in detail in H02. It includes the effect of tidal forces, mass transfer via Roche lobe overflow (RLOF), wind accretion, common envelope (CE) evolution and stellar wind mass loss on the AGB as described by Vassiliadis & Wood (1993). Wind accretion is calculated following the Bondi & Hoyle (1944, hereafter BH) prescription, with efficiency α_W (see equation 6 of H02). In our model we have assumed $\alpha_W = 1.5$. In the case of unstable RLOF, the system enters a CE situation, during which no net mass transfer is assumed to take place, which is a standard assumption in most evolutionary models. The energy to expel the CE is taken from the orbit, with efficiency α_{CE} (see H02, equation 71), and from a fraction, f_{ion}, of the energy released by recombination of ions. For these free parameters, we have assumed the values $\alpha_{CE} = 1$ and

f_{ion} = 0.03. The criterion used to discriminate whether a star becomes a Ba star is that it must be in the (first) giant branch phase and that its barium overabundance exceeds 0.2 dex.

3. Comparison of results with observations and discussion

The results from our population synthesis are compared to the observational data gathered by Jorissen et al. (1998). Notice that the observational data plotted in Figure 2 are a subsample, for which the *s*-process overabundance has been measured (Jorissen et al., 1998), and the whole sample is plotted in Figure 4.

3.1. Overabundances and periods

In Figure 2, the output of the model appears divided into longer-period (LP) systems, which have periods from around 1500 to 300000 days, and shorter-period (SP) systems, which have periods from around 10 to 800 days. The LP systems have been formed only by wind accretion, which can easily explain the shape of the envelope of LP systems in Figure 2, given that the more separated the components are, the less *s*-process element enriched mass can be accreted, according to the BH prescription. The SP systems have been formed after mass transfer via RLOF, which is generally unstable, given that the star accreting mass is less massive, and leads to a CE phase. Since the energy needed for expelling the envelope is mainly taken from the orbit, the orbital period is shortened. This explains the gap existing between the LP and SP systems, given that for periods around 2000 days an AGB star just fills its Roche lobe at maximum radius.

In order to reproduce the highest observed overabundances for LP systems, a large BH wind accretion efficiency parameter is needed. However, this leads to two problems. First, there are too few SP systems predicted in comparison with the LP systems to reproduce the data. And second, there are too many Ba stars predicted in very long period systems ($\gtrsim$ 4000 days). In addition to this, it is clear that the overabundance predicted for SP systems is low compared to the observed one, even using the high wind accretion efficiency parameter implemented here. This implies that the approximation of a constant wind accretion efficiency might not be good, but rather the efficiency should decrease with orbital period. Further studies are needed of the effect of the wind structure close to an AGB star on the accretion rate. In addition to this, given the large atmospheric scale height of AGB stars, it is difficult to define an accurate radius for them. In binaries with an AGB component, the marked difference between wind accretion and accretion via RLOF may disappear and the possibility of a smooth transition between the two regimes must be considered, as hydrodynamical simulations by Nagae et al. (2004) also suggest.

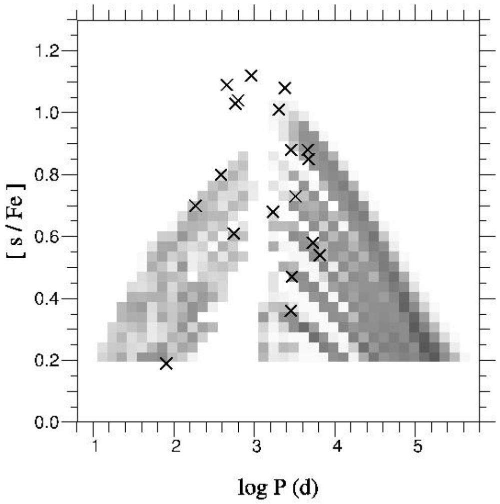

Fig. 2. Overabundance of *s*-process elements in Ba stars , [*s*/Fe], plotted against their period, *P*, in days. The population synthesis output is plotted in gray scale, where a darker shade represents a larger number of Ba star systems expected. The black crosses represent observed Ba star systems for which the overabundance of *s*-process elements has been measured (Jorissen et al., 1998).

Let us point out that the orbital period range of SP systems in the model calculations depends very strongly on the assumptions made for the energy budget during the CE phase. It can be seen in the left panel of Figure 3 that very short periods (of order 10-

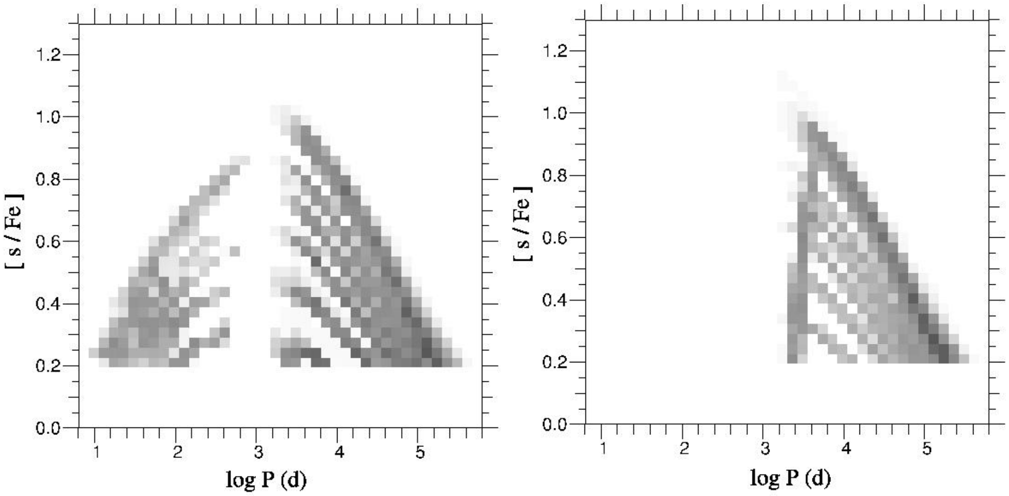

Fig. 3. Both panels plot population synthesis output in the same way as in Figure 2. The left panel shows the expected periods for SP systems (left side of the plot) in the case where all the energy needed for expelling the common envelope is taken from the orbit with 100% efficiency. The right panel shows the periods expected in the case where the energy needed to expel the envelope is taken entirely from sources other than the orbit (in this case, it is the accretion luminosity acting during only 100 years).

100 days) are obtained for the SP systems if the energy needed to expel the envelope is taken entirely from the orbit. On the other hand, in AGB stars with their very distended envelopes, it is easy to expel a CE using other available energy sources, such as the energy released when ions recombine, and the luminosity generated by accretion onto the secondary. The right panel of Figure 3 shows that, if these sources can be tapped efficiently, the orbits hardly shrink during the CE phase, but can remain at the separation where the RLOF started, around period $P \sim 2000$ days.

As accretion of matter during the CE phase is neglected in our binary stellar evolution code, the *s*-process overabundance in SP systems is mostly due to wind accretion occurring prior to unstable RLOF. However, accretion during the CE phase can prove to be a key ingredient in the scenario. Studies by Hjellming & Taam (1991) show that the net accretion onto a MS component during the CE phase has a tendency to increase with the orbital separation. According to their calculations, the accreted mass can go up to $\sim 0.05 M_\odot$ for systems with final periods around 1 day, which are much shorter than those of Ba stars. The observed overabundances in Figure 2 may be explained if the net accreted mass during CE phase can rise to $\sim 0.1 M_\odot$. This is valid even for low BH wind accretion efficiencies and may help to avoid the orbital period distribution problems explained at the beginning of this sub-section.

3.2. Eccentricities

Within the current standard binary interaction picture, for systems with separations similar to or smaller than the value for which an AGB star fills its Roche lobe at maximum radius, tidal forces are expected to circularize the orbit on timescales shorter than the duration of the CE phase. This can be clearly observed in the output of our model in Fig. 4, where no eccentric Ba star systems are predicted for periods shorter than about 3000 days. However, many observed Ba star systems are eccentric at smaller periods, down to ~ 600 days. This peculiar distribution of the eccentricity is also observed in other intermediate separation binary systems which show evidence of mass transfer, such as those containing a post-AGB component (van Winkel et al., 1997), and in low metallicity CH stars (Jorissen et al., 1998 and references therein). This indicates that there is a (fundamental) physical process which works in opposition to the circularizing action of the tidal forces and that is not taken into account. Karakas et al. (2000), without adding any new physical process, found that in order to reproduce the observed eccentricities with the current models, it is necessary to decrease the commonly accepted strength of tidal dissipation by at least a factor four. However, we find that even a much stronger reduction does not produce eccentric Ba stars below 2000 days. Some people have suggested that an enhancement of mass transfer at periastron might be an explanation, e.g. Soker (2000). It has also been suggested that gravitational interaction with a circumbinary disk may enhance the eccentricity (Artymowicz et al., 1991; Artymowicz & Lubow, 1994; Waelkens et al., 1996 the latter in the case of post-AGB stars). But a massive disk would be needed and although such disks are observed in some post-AGB binaries, their masses tend to be small (Dominik et al., 2003; Soker, 2000 and references therein).

4. Conclusions

Our current model of stellar evolution cannot reproduce, the orbital parameters of the whole sample of Ba stars. In order to do this, a deeper exploration of the processes involved in binary stellar interaction is definitely needed. Among the issues to be investigated is the effect of the structure of the stellar wind at intermediate distances of AGB stars on the accretion process, and the possibility of a smooth transition between RLOF accretion and wind accretion. The overabundances and periods of short-period systems might be reproduced if substantial amount of matter can be accreted during the CE phase, and if additional sources of energy can be used to expel the envelope from the system. The problem of the eccentric short period orbits remains a mystery and indicates that there must be a physical process which enhances the orbital eccentricity that we are missing, and which is very likely fundamental.

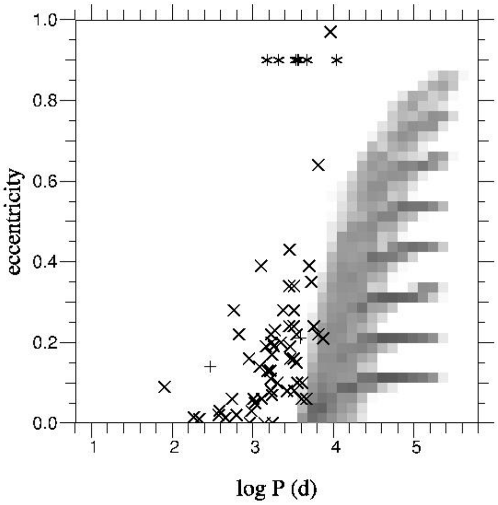

Fig. 4. Eccentricity, *e*, of Ba star systems plotted against their period. The population synthesis output is plotted in gray scale, in the same way as in Figure 2. The systems predicted with $e = 0$ have been omitted for the sake of clarity in the plot. The black +-signs are triple systems and the black asterisks represent lower limits for the period of those systems. The data is a complete sample of Ba stars from Jorissen et al. (1998).

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