Mem. S.A.It. Vol. 81, 1034
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Memorie della

White dwarf kicks and implications for barium stars

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Abstract. The barium stars have caused much grief in the field of binary stellar evolution. They are often eccentric when they should be circular and are not found to have periods longer than 10^4 days even though wind accretion should still be efficient at such separations. We address both these problems by introducing a kick to white dwarfs when they are born, thus solving the eccentricity problem, and imposing strong orbital angular momentum loss to shrink barium-star binaries down to the observed periods. Whilst our angular momentum prescription is hard to justify for the barium stars it shows that strong angular momentum loss is necessary to reproduce the observed period-eccentricity distribution. We are investigating whether this can be obtained from a circumbinary disc.

Key words. Stars: binaries – Stars: chemically peculiar – Galaxy: stellar content – Nucleosynthesis

1. Introduction

The barium stars show barium absorption lines in their spectra yet have not gone through the asymptotic giant branch (AGB) phase of stellar evolution, i.e. they are dwarf or first giant branch stars, so cannot have made the barium themselves. They are all in multiple systems (McClure & Woodsworth 1990) and the canonical picture of their evolution suggests they accreted their barium from the wind of a companion thermally-pulsing AGB (TPAGB) star which has long since turned into a white dwarf.

While the wind-accretion scenario is generally accepted, it does not explain the period-eccentricity ($P-e$) distribution of the barium stars. Short-period binary barium stars with $P \lesssim 500$ days are in circular orbits[1] as predicted by tidal circularization theory (e.g. Zahn 1977). Most of the rest have periods between 500 and 10^4 days and eccentricities $0 \leq e \lesssim 0.5$ (Jorissen et al. 1998). Binary population synthesis models predict that these systems should have circuliarized and that the only eccentric barium stars should have periods in excess of about 5000 days (Pols et al. 2003). Binaries with $P \gtrsim 10^4$ days are difficult to detect but most known barium stars have measured periods so it appears there is a problem with our understanding of the relevant binary-star physics rather than with the observations.

Several models have been proposed to explain the large eccentricities of the barium

[1] One has non-zero eccentricity but is in a triple system.

stars. It could be that tides are less efficient than predicted but the theory has been tested in other stars and seems to work well (e.g. Claret & Cunha 1997). Eccentricity pumping during the TPAGB phase is the presently favoured model. Certainly the mechanism that pumps the eccentricity of the barium stars must be active on the TPAGB because post-AGB stars show a $P - e$ distribution strikingly similar to the barium stars. Of the many ideas that abound, the most popular include mass-transfer at periastron (Soker 2000; Sepinsky et al. 2009), interaction with a circumbinary disc (Frankowski & Jorissen 2007, Dermine et al. *in prep.*) and eccentricity pumping because of wind-Roche-lobe-overflow hybrid mass transfer (Bonačić Marinović et al. 2008). These models all have their problems and none have been shown to convincingly reproduce the $P - e$ distribution of the barium stars.

We investigate a scenario which has support from observations of globular clusters: white dwarf kicks. Young white dwarfs are observed to have an extended radial distribution in the globular cluster NGC 6397 compared to main-sequence stars and old white dwarfs (Davis et al. 2008) which suggests they are given a velocity kick at birth. Globular cluster models (Heyl 2008; Fregeau et al. 2009) support the idea that white dwarfs are kicked at their birth with a velocity of a few $\mathrm{km\,s^{-1}}$. It should be noted that this occurs in both single and binary stars, because NGC 6397 has a binary fraction of only 10%, so the phenomenon we are attempting to model is not unique to duplicitous stars.

If white dwarfs receive a kick in globular clusters, they should also in the field. A kick of a few $\mathrm{km\,s^{-1}}$ is too small to be seen in single stars because their Galactic velocities are much larger, but in binaries with orbital velocities of the same order of magnitude such kicks will impact the binary dynamics. The barium stars fall into just such a category and provide an interesting test case. Their orbital, wind and the kick velocities are all a few $\mathrm{km\,s^{-1}}$, providing an interesting test case for our understanding of binary stellar physics.

We have constructed some binary population synthesis models to investigate the effect of natal white dwarf kicks on the $e-P$ distribution of barium stars. Our first results are quite promising, at least for the eccentricity distribution. However, our models still make too many long period barium stars – we speculate on possible solutions to this problem.

2. Populations of Ba stars with white dwarf kicks

Our binary population synthesis model is based on that of Hurley et al. (2002) with nucleosynthesis as described by Izzard et al. (2004, 2006, 2009). Stars are chosen from the Kroupa et al. (1993) initial mass function, a flat distribution in $q = M_1/M_2$ and $\log a$, where a is the binary separation, with a thermal ($N(e) \propto e$) eccentricity distribution. Barium stars are selected from G or K type giants with [Ba/Fe] > 0.2. We assume that all stars start in binaries.

We choose a slightly sub-solar metallicity, $Z = 0.008$, with solar-scaled initial abundances from Anders & Grevesse (1989), and a ^{13}C efficiency of 1 i.e. the standard pocket of the Busso et al. (2001) models. This gives us a barium star fraction which approximately matches the observed 1% of G and K giants. Our TPAGB models are based on those of Karakas et al. (2002) with the Vassiliadis & Wood (1993) mass-loss prescription. Wind accretion by the companion follows the formalism laid out in Hurley et al. (2002) which is based on that of Bondi & Hoyle (1944). At the end of the TPAGB phase of the primary a kick is applied to the nascent white dwarf with a fixed velocity σ in a random direction.

2.1. The effect of white dwarf kicks

Fig. 1 shows the distribution of e versus $\log_{10} P$ from our population synthesis models compared to the observations of Jorissen et al. (1998). The left panel shows the canonical model, i.e. without kicks. Three main subpopulations can be seen. The first, with periods between 100 and 1000 days, is from wind accretion followed by Roche-lobe overflow

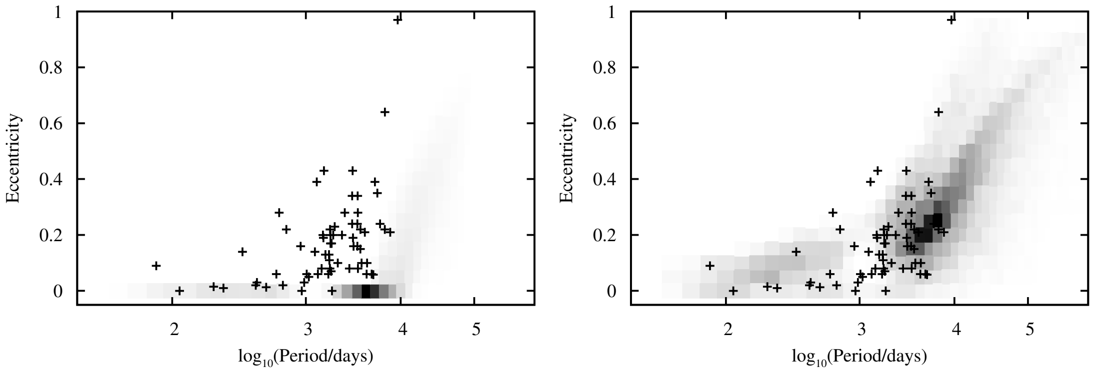

Fig. 1. The left panel shows the distribution of e versus $\log_{10} P$ of a canonical population synthesis of barium stars (coloured regions, darker means more populated) compared to observed barium stars (crosses, taken from Jorissen et al. 1998). The right panel shows the same model but with a $4\,\mathrm{km\,s^{-1}}$ kick given to nascent white dwarfs – the effect is to boost the eccentricity, particularly in the wider-period, less tightly bound systems.

and common-envelope evolution (see e.g. Han et al. 1995) hence these stars all have $e = 0$ (the period gap arises from orbital shrinkage during the common-envelope phase, see Section 2.2). The second group, formed by pure wind accretion, are close enough for tidal circularization to be effective. These represent the bulk of the modelled barium stars with periods between 10^3 and 10^4 days and again zero eccentricity, in stark contrast to the observed stars in this period range which have $0 \leq e \lesssim 0.5$. The third group has $P \gtrsim 5000$ days and significant eccentricity because the binary separation is large enough that circularization is inefficient. These are not seen in reality although some mild barium stars may have unmeasured long periods.

The right panel of Fig. 1 shows the effect of adding a $4\,\mathrm{km\,s^{-1}}$ kick to nascent white dwarfs at the end of the TPAGB. In most cases the eccentricity of the systems is increased. At short periods the effect is smaller because the binaries are more tightly bound, however over the whole period range from 100 to 10^4 days the effect of the kick is to generate the eccentricity required to match the observations. The period gap at 1000 days and the long period tail are still evident and at odds with the observations. A few systems are unbound by the kick but the number is small compared to the number of barium star systems produced.

2.2. Common envelope evolution

Our prescription for common-envelope evolution follows closely that of Hurley et al. (2002). There are two free parameters in this formalism: α_{CE}, the fraction of the orbital energy used to unbind the envelope, and λ which describes the structure of the giant envelope and is fitted to detailed stellar evolutionary models (Dewi & Tauris 2000). Our λ prescription includes a fraction λ_{ion} of the recombination energy of the envelope which contributes to its ejection: λ_{ion} is zero by default (as in Fig. 1). Because the TPAGB envelope is poorly bound and rather cool, even a small value of λ_{ion} greatly increases the energy available for unbinding the common envelope and can close the period gap. Fig. 2 shows how large the effect is even for $\lambda_{\mathrm{ion}} = 0.01$. For $\lambda_{\mathrm{ion}} \sim 0.1$ the period gap is completely removed. The effect of a large λ_{ion} is qualitatively similar to using the common-envelope prescription based on angular momentum of Nelemans & Tout (2005) which also fails to shrink orbits efficiently.

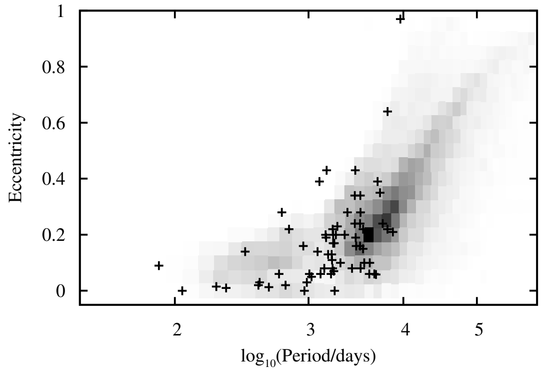

Fig. 2. As Fig. 1 but with a $4\,\mathrm{km\,s^{-1}}$ kick and enhanced common-envelope ejection efficiency ($\lambda_{\rm ion} = 0.01$). The effect is to move the short-period barium stars to longer periods and hence to reduce the period gap, which can be effectively removed if $\lambda_{\rm ion} \sim 0.1$.

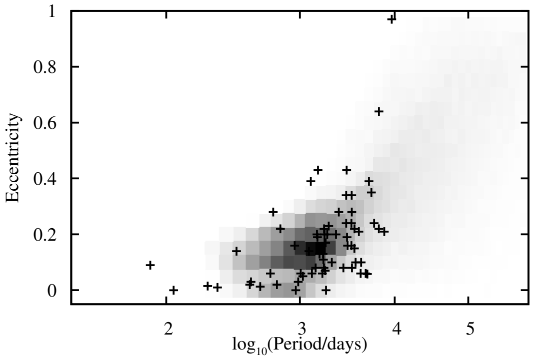

Fig. 3. As Fig. 2 but with 80%-efficient wind accretion. This causes the barium star systems to lose so much orbital angular momentum that their periods shorten enough to bring them into line with observed periods. They do not circularize because they are kicked at the end of the TPAGB when the stellar envelope is already lost and tides are no longer efficient.

2.3. Orbital angular momentum

The long-period tail is seen in all our models. The most obvious idea for removing it is to reduce the wind accretion efficiency because this should affect the long-period systems most. However, this has the effect of reducing the number of barium stars such that it is much less than the observed 1% of G/K giants. Introducing a white-dwarf kick makes the problem worse by further widening weakly-bound binaries.

We stumbled across a potential solution to the wide barium stars by accident. In the Hurley et al. (2002) wind-accretion model, the rate of change of orbital angular momentum $J_{\rm orb}$ in response to mass loss and accretion is given by

$$\dot{J}_{\rm orb} = -\left(\left|\dot{M}_w\right| + \frac{M_1}{M_2}\left|\dot{M}_a\right|\right)\left(\frac{aM_2}{M_1+M_2}\right)^2 \Omega_{\rm orb},$$

where $\dot{M}_w$ is the rate of mass loss by the primary of mass M_1, $\left|\dot{M}_a\right|$ is the rate of mass gain by the secondary of mass M_2, a is the orbital semi-major axis and $\Omega_{\rm orb}$ is the orbital angular velocity. While we have some doubts regarding the origin of this formula and its applicability to barium stars, it does have the general property that when $\left|\dot{M}_a\right|$ is large, around $0.8\left|\dot{M}_w\right|$ (the maximum possible in the Hurley, Tout, & Pols 2002 prescription), the rate of orbital angular momentum loss is almost doubled. Fig. 3 shows how this shrinks the systems which make barium stars enough that even after the kick they mostly have periods less than 10^4 days. Such efficient wind accretion onto the secondary is not predicted by the Bondi-Hoyle theory, but could be possible according to the "wind-RLOF" models of Mohamed & Podsiadlowski (2007), even at periods as long as those of the barium stars. We are working on an improved wind-accretion prescription.

3. Conclusions

With a combination of white dwarf kicks, efficient common envelope ejection and efficient angular momentum loss our simulated barium star population matches the observed distribution of periods and eccentricities much better than canonical models. A kick velocity of a few $\mathrm{km\,s^{-1}}$ is sufficient to make barium stars with eccentricities similar to those observed. Such a kick velocity is supported by independent observations of globular clusters and is thought to occur in both single and binary stars. We have deliberately not discussed the origin of the kick but likely candidate mechanisms include asymmetric mass loss (Fellhauer et al. 2003) and interaction with magnetic fields (Spruit 1998). The imposition of highly efficient angular momentum loss is perhaps more controversial. Our prescription possibly gives the right answer for the wrong reason. Not only is a wind accretion efficiency of 80% rather high, but the formalism which describes the angular momentum loss rate is probably invalid in the barium-star regime when the wind velocity and orbital velocity are of the same order of magnitude. Interaction with a circumbinary disk may be responsible for efficiently removing angular from the system and perhaps pumping the eccentricities of barium-star progenitor systems. We are working diligently to test this possibility.

Acknowledgements. We would like to thank Melvyn Davies and Alain Jorissen for many fruitful discussions on the subject and John Fregeau for introducing RGI to the white-dwarf kick problem at the Lorentz Centre workshop on Stellar Mergers. RGI is the recipient of a Marie Curie-Intra European Fellowship at ULB and thanks Lund Observatory for the hospitality. RPC would like to thank the Wenner-Gren foundation for a stipend.

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