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 \citep{McClureWoodsworth1990} 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 as predicted by tidal circularization theory \citep[e.g.][]{Zahn1977}. Most of the rest have periods between 500 and 10\(^4\) days and eccentricities \(0 \leq e \leq 0.5\) \citep{Jorissenetal1998}. Binary population synthesis models predict that these systems should have circularized and that the only eccentric barium stars should have periods in excess of about 5000 days \citep{Polsetal2003}. 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

\textsuperscript{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 (Bonacci Marinovic 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 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 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 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 $[\text{Ba}/\text{Fe}] > 0.2$. 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 in a random direction.

2.1. The effect of white dwarf kicks

Fig. 1 shows the distribution of $e$ versus log $P$ 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 sub-populations can be seen. The first, with periods between 100 and 1000 days, is from wind accretion followed by Roche-lobe overflow
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 $0 < e < 0.5$. 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 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: $\alpha_{\text{CE}}$, the fraction of the orbital energy used to unbind the envelope, and $\lambda$ which describes the structure of the giant envelope and is fitted to detailed stellar evolutionary models (Dewi & Tauris 2000). Our prescription includes a fraction $\alpha_{\text{ion}}$ of the recombination energy of the envelope which contributes to its ejection: $\alpha_{\text{ion}}$ is zero by default (as in Fig. 1). Because the TPAGB envelope is poorly bound and rather cool, even a small value of $\alpha_{\text{ion}}$ 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 $\alpha_{\text{ion}} = 0.01$. For $\alpha_{\text{ion}} \sim 0.1$ the period gap is completely removed. The effect of a large $\alpha_{\text{ion}}$ is qualitatively similar to using the common-envelope prescription based on angular momentum of Nelemans & Tout (2005) which also fails to shrink orbits efficiently.
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 $\dot{J}_{\text{orb}}$ in response to mass loss and accretion is given by

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

where $\dot{M}_w$ is the rate of mass loss by the primary of mass $M_1$, $\dot{M}_a$ is the rate of mass gain by the secondary of mass $M_2$, $a$ is the orbital semi-major axis and $\Omega_{\text{orb}}$ 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 $\dot{M}_a$ is large, around $0.8 \dot{M}_w$ (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 & Podsialowski (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 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 \citep{Fellhauer2003} and interaction with magnetic fields \citep{Spruit1998}. 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 momentum from the system and perhaps pumping the eccentricities of barium-star progenitor systems. We are working diligently to test this possibility.

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