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The formation of barium stars as constrained by Gaia distances

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Abstract. Barium (Ba) stars are prototypical post-interaction binary systems, polluted with mass transferred from a former asymptotic-giant-branch companion. The companion is now a cool and dim white dwarf (WD) that, in most cases, we cannot detect directly. However, thanks to the combination of long-term binary monitoring, high-resolution spectra, MARCS model atmospheres and *Gaia* distances, we obtained information about the mass of 132 WD companions of Ba stars.

Key words. stars: late-type – stars: chemically peculiar – stars: binaries: spectroscopic – techniques: spectroscopic

1. Introduction

Stellar masses are crucial parameters in astrophysics, but are very difficult to measure directly. However, when a star belongs to a binary system, the orbital motion provides us with constraints on the mass. In this contribution, we use high-resolution spectra, *Gaia* DR2 distances, and other high-quality data to obtain information about the mass of otherwise undetectable faint and cool white dwarfs (WDs), taking advantage of the fact that they are member of spectroscopic binary systems.

We focused on a family of peculiar stars named barium (Ba) stars (Bidelman & Keenan 1951). Ba stars are main-sequence or red-giant stars that show surface enhancement of barium and other heavy elements produced by the slow-neutron-capture (s-) process. This nucleosynthesis process takes place in the interiors of asymptotic-giant-branch (AGB) stars (Käppeler et al. 1990; Käppeler 1999), hence Ba stars are not evolved enough to synthesise these elements themselves. It is known that they were polluted by a former AGB companion through mass transfer (McClure 1984). This former companion is now a cool WD, which, in most systems, is difficult to detect directly (Gray et al. 2011).

The initial stellar and orbital parameters and the details of the interaction processes needed to form barium stars are not yet completely understood (e.g. Pols et al. 2003, Bonačić Marinović et al. 2008, Izzard et al. 2010). Our goal is to collect observational information about these post-interaction binary systems in order to better understand their formation and evolution. In particular here, we aimed at deriving information about the initial mass of the two components of the binary system. These masses are a key ingredient to learn about the initial characteristics of Ba star systems.

In this paper, we summarise, combine, and compare results recently published by Escorza et al. (2019) and Jorissen et al. (2019) about Ba dwarfs and giants respectively. From their location in the Hertzsprung-Russell (HR) diagram, we derived the evolutionary mass of 132 Ba stars at different evolutionary stages. Additionally, we put constraints on the mass of the unseen WD companions by combining these Ba star masses with the orbital parameters of the systems, obtained thanks to long-term radial-velocity monitoring programmes. Section 2 describes the various data sets that were used and in Sect. 3, we summarise and compare the obtained WD mass distributions for the different subsamples of Ba stars. Finally, in Sect. 4, we describe the implications of our results.

2. Observational constraints

2.1. Orbital elements and mass function

The orbital periods of Ba stars range from a few hundreds to more than 10 000 days, which makes orbital coverage and orbital-parameter determination a challenge. Intensive long-term radial-velocity monitoring programmes of these objects and other wide binaries have been carried out with both the CORrelation RAdial VELocities (CORAVEL) spectrometers (Baranne et al. 1979) and the High-Efficiency and Resolution Mercator Echelle Spectrograph (HERMES, Raskin et al. 2011). Complementary radial-velocity data from ELODIE and the High Resolution Spectrograph (HRS; Bramall et al. 2010, 2012; Crause et al. 2014) mounted on the Southern African Large Telescope (SALT) was used in this work. See Escorza et al. (2019) and Jorissen et al. (2019) for a more detailed description of the data.

By combining all these radial-velocity datasets, we covered a time range of more than 40 years for some systems. We fit Keplerian orbits to the combined radial-velocity curves and obtained the period (P), the eccentricity (e), and the velocity semi-amplitude (K_1) of a sample of 132 Ba and related polluted stars at different evolutionary stages (find the individual orbital elements in table 1 of Escorza et al. 2019; table 4 of Jorissen et al. 2019; tables A.1 and A.2 of Van der Swaelmen et al. 2017; and North et al. 2019, *in prep.*).

Figure 1 shows the obtained orbits in an eccentricity-period (e-log$P$) diagram. Main-sequence Ba stars are represented with orange squares and Ba giants are shown as black circles. In the background, we included orbits (determined by Mermilliod et al. 2007) of K- and G-type giants, similar to our Ba giants, but in binary systems that have not interacted (Van der Swaelmen et al. 2017). We can clearly see how binary interaction shapes the e-log$P$ diagram and how for the same periods, the post-interaction giants have significantly lower eccentricities.

A product of orbital fitting for SB1 systems is the mass function. This expression relates the masses of the two components in a binary system and the inclination of the system (i), with the orbital parameters P, e, and K_1 as follows:

$$f(m_1, m_2) = \frac{m_2^3}{(m_1 + m_2)^2} \sin^3 i =$$

$$= 1.0361{\times}10^{-7}(1{-}e^2)^{3/2} K_1^3 P \quad [\mathrm{M}_\odot], \qquad (1)$$

where m_1 is the mass of the Ba star and m_2 the mass of the WD companion. The period is expressed in days and K_1 in km s^{-1}.

Since the orbital elements have been determined, we know $f(m_1, m_2)$. Information about the mass of the Ba star, m_1, and the orbital inclination, i, would help us to determine the mass of the WD companion, m_2.

2.2. Hertzsprung-Russell diagram and Ba star masses

In order to determine the masses of the Ba stars, we located them in the HR diagram. Their atmospheric parameters were derived from HERMES high-resolution spectra as described by Karinkuzhi et al. (2018). For the southern objects that are not observable with

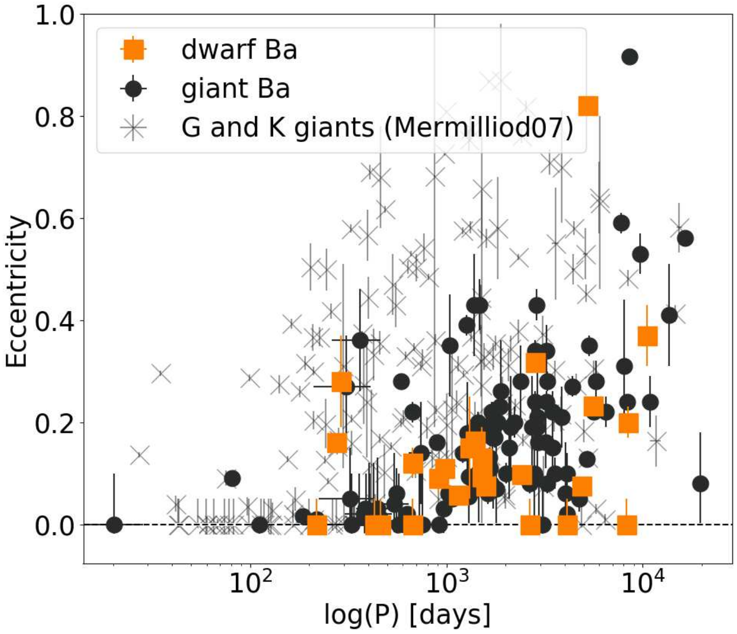

Fig. 1. Eccentricity-period diagram of main-sequence (orange squares) and giant (black circles) Ba stars. The orbits determined by Mermilliod et al. (2007) for their sample of K- and G-type giants in binary systems that have not interacted (see Van der Swaelmen et al. 2017) are included as gray crosses for comparison.

the Mercator telescope (having declinations, $\delta \lesssim 30$ deg), we used atmospheric parameters available in the literature. We then used the spectroscopic parameters (i.e. effective temperature T_{eff}, surface gravity $\log g$, and metallicity [Fe/H]) and broadband photometry available in the literature[1] to constrain the line-of-sight extinction and find the best-fitting MARCS model atmosphere (Gustafsson et al. 2008) in a parameter-grid search. The luminosity was then obtained from the integrated spectral energy distribution over all wavelengths and using *Gaia* DR2 Bayesian distances from Bailer-Jones et al. (2018). Finally, we derived the mass of the Ba stars by interpolating between STAREVOL (Siess et al. 2000; Siess & Arnould 2008) evolutionary tracks, which were computed with different metallicities in order to use the appropriate value for each object.

The left panel of Fig. 2 shows our sample of dwarf and giant Ba stars in the HR diagram and the right panel shows the derived primary-mass distributions. These figures show that our two subsamples are not fully evolutionary connected. The giant sample peaks at about 2 $M_{\odot}$ and has a high-mass tail while the dwarf distribution peaks at a significantly lower mass. We believe that this difference results from the observational bias against detecting hotter dwarf Ba stars. Indeed, the properties of A-type stars, such as rotation, pulsations or magnetic fields, could erase the signature of mass transfer in their spectra.

3. Results: companion-mass distributions

The orbital inclination is the only unknown preventing us from obtaining the masses of the

[1] This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

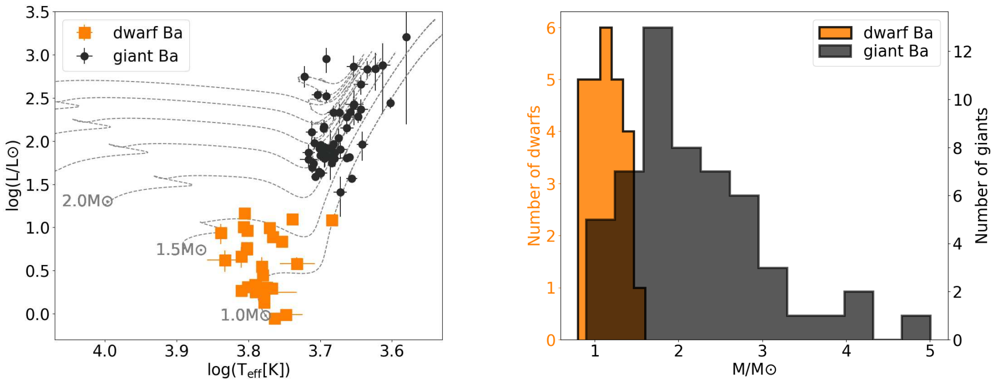

Fig. 2. Hertzsprung-Russell diagram (left) and mass distribution (right) of Ba stars. Dwarfs are plotted in orange and giants in black. STAREVOL evolutionary tracks with metallicity [Fe/H] = −0.25 are overplotted in the HR diagram as well.

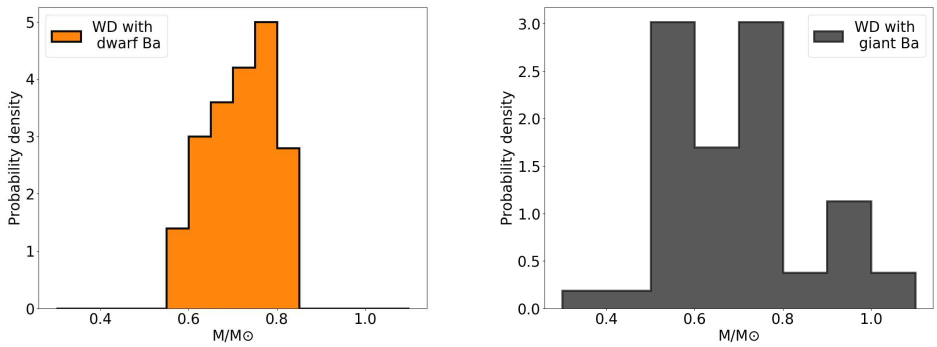

Fig. 3. Mass distributions of WD companions of Ba dwarfs (left) and giants (right).

WD companions (see Eq. 1). For a few targets, we could combine our orbital solutions with Hipparcos astrometric data and derive the astrometric orbit following the methodology used in Pourbaix & Jorissen (2000), Pourbaix & Boffin (2003), and Jancart et al. (2005), among others. From this reprocessing of the Hipparcos data, we obtained new parallaxes and orbital inclinations, and we could derive WD masses using Eq. 1 (see Escorza et al. 2019 and Jorissen et al. 2019 for the specific values). The obtained parallaxes were in agreement with *Gaia* DR2 parallaxes, even though the latter were obtained without taking the binary motion into account.

Only after the third *Gaia* data release, which will include binary astrometric solutions, will we be able to obtain model-free masses for the WD companions of more Ba stars. In the meantime, we must work with distributions. First, we imposed that the mass-function distribution of Ba stars $f(m_{\rm Ba}, m_{\rm WD})$ can be fitted by a sample of orbits with a very narrow distribution of Q, where $f(m) = Q \sin^3 i$. This was first proposed by Webbink (1986) and suggests that $m_{\rm Ba}$ and $m_{\rm WD}$ are strongly correlated (see Boffin 2012; Van der Swaelmen et al. 2017 and references therein for more details). Additionally, we assumed that our binary systems are randomly oriented

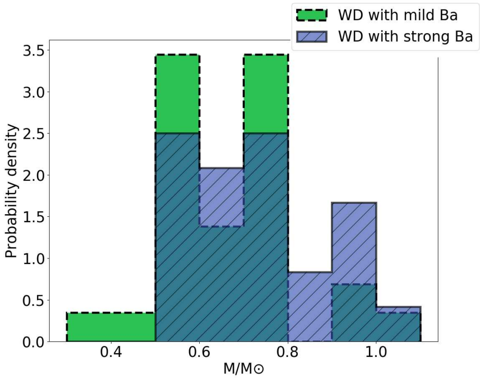

Fig. 4. Mass distributions of WD companions of strong (blue dashed histogram) and mild (green histogram) Ba giants.

in space. By combining the resulting distribution of inclinations with the mass-function distribution obtained from the orbital fitting described in Sect. 2.1, we obtained the best-fitting Q distributions for three different subsamples of Ba stars: Ba dwarfs, and strong and mild Ba giants. The distinction between strongly and mildly polluted Ba stars is based on the *Ba index* (Warner 1965). The *Ba index* reflects the strength of barium spectral lines on a scale from Ba1 to Ba5, where Ba5 corresponds to the strongest lines. Historically, Ba1 - Ba2 indices have been associated with a mild pollution and Ba3 - Ba5 indices with a strong pollution. Jorissen et al. (2019) showed that the threshold between mild and strong Ba giants lies close to [Ce/Fe] and [La/Fe] = +1.0 dex. Table 1 shows the mean and the sigma of the best-fitting Gaussian distributions of Q for the three subsamples.

Table 1. Best-fitting values of Q, with $Q = m_{\rm WD}^3/(m_{\rm Ba} + m_{\rm WD})^2$, used to obtain the mass distributions of WD companions of the different subsamples of Ba stars.

	Q [M$_\odot$]
Ba dwarfs	0.077 ± 0.010
Strong Ba giants	0.057 ± 0.009
Mild Ba giants	0.036 ± 0.027

Finally, the mass distribution of the WD companions can be derived assuming Q constant, from the definition of Q:

$$Q = \frac{m_{\rm WD}^3}{(m_{\rm Ba} + m_{\rm WD})^2} \tag{2}$$

Figure 3 shows the mass distribution of the WD companions of Ba dwarfs on the left and the mass distribution of the WD companions of Ba giants on the right. Additionally, Fig. 4 shows again the mass distribution of the WD companions of Ba giants, but divided in the two mentioned subsamples. The blue dashed histogram corresponds to WD companions of strongly polluted Ba giants and the green histogram to WD companions of mildly polluted Ba giants.

4. Discussion and conclusions

Although the mass distributions of WD companions of Ba stars presented in Fig. 3 and 4 are the main results of this contribution, several side products are obtained:

- Binary interaction shapes the eccentricity-period diagram of binary stars. If we compare the eccentricities of binary systems with primary stars of the same spectral type and class (K- and G-type giants in our case), post-interaction systems have significantly lower eccentricities than systems that have not interacted.
- There is an observational bias against hot dwarf Ba stars and we have not found yet the real progenitors of the classical Ba giants.

Additionally, we can conclude the following from Fig. 3 and 4:

- The mass distribution of WD companions of Ba dwarfs spans a much narrower range of masses. This is an effect of the narrow mass distribution of Ba dwarfs themselves.

- There is a hint that the WD companions of strongly enhanced Ba stars might be slightly more massive than those of mildly enhanced Ba stars (see Fig. 4). If this is confirmed when we derive model-free masses for these WD companions after *Gaia* DR3, this implies that the pollution with *s*-process elements is more efficient when mass is accreted from more massive AGB stars. Including this information in binary evolutionary models will improve our understanding of the initial conditions and interaction processes involved in the formation of Ba star systems.

Finally, this work is just a demonstration of how powerful the combination of long-term radial-velocity monitoring and *Gaia* astrometry will be in the near future to put constraints on the formation of post-mass-transfer chemically-peculiar binaries.

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