BARIUM AND TC-POOR S STARS: BINARY MASQUERADERS AMONG CARBON STARS

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Abstract. Our current understanding of the origin of barium and S stars is briefly reviewed, based on new orbital elements and binary frequencies.

1. The relation of barium and S stars to carbon stars
Since the last conference (IAU Coll. 106, Evolution of Peculiar Red Giants, Johnson & Zuckermann eds., 1989) devoted to chemically-peculiar red giants (PRGs), much progress has been made in understanding how barium and S stars relate to the other PRGs. The discovery of the binary nature of barium stars (McClure et al. 1980; McClure 1983) suggested from the beginning that mass transfer was likely to play a key role in the formation of the barium syndrome. As far as S stars are concerned, it has become clear that Tc-rich and Tc-poor S stars form two separate families with similar chemical peculiarities albeit of very different origins (Iben & Renzini 1983; Little-Marenin et al. 1987; Jorissen & Mayor 1988; Smith & Lambert 1988; Brown et al. 1990; Johnson 1992; Jorissen & Mayor 1992; Groenewegen 1993; Johnson et al. 1993; Jorissen et al. 1993; Ake, this conference). Tc-rich (or ‘intrinsic’) S stars are genuine thermally-pulsing AGB stars where the s-process operates in relation with the thermal pulses, and where the third dredge-up brings the freshly synthesized s-elements (including Tc) to the surface (e.g. Iben & Renzini 1983; Sackmann & Boothroyd 1991). By contrast, Tc-poor (or ‘extrinsic’) S stars are believed to be the cool descendants of barium stars.

Figure 1 summarizes our current understanding of the relationship between the different families of PRG stars. This general picture raises several
Figure 1. Relationship between several families of PRG stars. Grey symbols represent heavy-element-rich stars, and dashed boundaries indicate Tc-rich stars. The left column depicts the normal (i.e. not requiring binarity) M–S–C evolution on the AGB, whereas the right column represents the evolution of a companion star. Note in particular the possibility that this companion itself evolves into a Tc-rich S star on the AGB, after having first shown up as an extrinsic S star.

questions, that will briefly be addressed in this paper:

1. Is binarity a necessary condition to produce a barium star?
2. What is the mass transfer mode (wind accretion or RLOF?) responsible for their formation?
3. Do barium stars form as dwarfs or as giants?
4. Do barium stars evolve into Tc-poor S stars?
5. What is the relative frequency of Tc-rich and Tc-poor S stars?
6. Are the abundances in the mass-loser star (i.e. the AGB progenitor of the present white dwarf companion) compatible with those presently observed in the barium or extrinsic S star?

We refer to Jorissen & Boffin (1992), Han et al. (1995) and Busso et al. (1995) for a detailed discussion of item 6.
2. Is binarity a necessary condition to form a barium star?

To answer that question, all 27 barium stars with strong anomalies (i.e. Ba3, Ba4 or Ba5 on the scale devised by Warner 1965) south of $\delta = -25^\circ$ from the list of L"{u} et al. (1983) have been monitored with the CORAVEL spectrovelocimeter (Baranne et al. 1979) since 1984. HD 19014 is the only star in that sample that does not show any sign of binary motion. No detailed abundance analysis to confirm the barium nature of that star is available, unfortunately. For a fictitious population of binaries observed with the same time sampling and the same internal errors as the real sample of barium stars, and having eccentricity and mass-function distributions matching the observed ones, a Monte-Carlo simulation yields a binary detection rate comprised between 96% (25.9/27) and 98% (26.5/27), depending on whether the observed period distribution is extrapolated or not towards periods as long as $2 \times 10^4$ d [see Jorissen et al. 1997 for more details]. Binarity is thus a necessary condition to produce strong barium stars.

In a comparison sample of 28 mild barium stars (i.e. with Ba1 and Ba2 indices) randomly selected from the list of L"{u} et al. (1983) and monitored in a similar way as the strong barium stars, 23 (82%) are definitely spectroscopic binaries, 2 (7%) are probably binaries, and 3 (11%; HD 50843, HD 95345, HD 119185) show no sign of radial velocity variations at the level 0.3 km s$^{-1}$ r.m.s. after more than 10 y of monitoring. Detailed spectroscopic abundance analyses performed on HD 95345 (Sneden et al. 1981) and HD 119185 (Za\'cs et al. 1996) confirm the existence of mild heavy-element overabundances ([s/Fe] = 0.2 to 0.3 dex) for these stars with constant radial velocity. This frequency of constant stars is again consistent with the binary detection rate predicted for that sample by a Monte-Carlo simulation, provided that the period distribution of mild barium stars extends up to $2 \times 10^4$ d. In these conditions, there is no need to invoke any formation mechanism other than mass transfer in a binary system to produce mild barium stars. On the contrary, an alternative formation scenario (like galactic fluctuations of the s/Fe ratio; Williams 1975, Sneden et al. 1981, Edvardsson et al. 1993) may be required to account for a population of non-binary stars found among dwarf mild barium stars (North et al., this conference).

Is binarity a sufficient condition to produce a barium star? Probably not, since binary systems consisting of a normal red giant and a WD companion with Ba-like orbital parameters do exist (Jorissen & Boffin 1992). DR Dra (= HD 160538) is probably the best example, with $P = 904$ d, $e = 0.07$ (compare with Fig. 3) and a hot WD companion detected by Fekel et al. (1993). Berdyugina (1994) finds a metallicity close to solar and normal Zr and La abundances in the giant. Za\'cs et al. (1996) basically confirm that result.
Metallicity may be the other key parameter, besides binarity, controlling the formation of barium stars. The s-process efficiency, expressed in terms of the neutron irradiation, seems to be larger in low-metallicity stars (Kovács 1985; Busso et al. 1995). Clayton (1988) provides a theoretical foundation for that empirical finding, provided that $^{13}\text{C}(\alpha, n)^{16}\text{O}$ is the neutron source for the s-process. Barium stars would therefore be easier to produce in a low-metallicity population.

3. Inferring the mass transfer mode from the orbital elements: Wind accretion and/or RLOF?

Synthetic binary evolution models (Han et al. 1995; de Kool & Green 1995) suggest that the bimodal period distribution exhibited by strong barium stars (Fig. 2) reflects the operation of two distinct mass-transfer modes, RLOF in the short-period mode (peaking around 500 d) and wind accretion in the long-period mode (around 3000 d).

This general picture actually faces three major difficulties: first, the threshold period (about 1000 d) between the RLOF and wind-accretion modes is much too short to accommodate the large radii reached by AGB stars. Second, the period – eccentricity diagram (Fig. 3) reveals that not all orbits in the short-period (i.e. post-RLOF) mode are circular, although tidal effects are expected to circularize the orbit in the phase of large radius just preceding RLOF (e.g. Zahn 1977). A similar problem exists for the orbits of dwarf barium stars (see North et al., this conference). Third, RLOF
from AGB stars with a deep convective envelope is dynamically unstable (‘unstable case C RLOF’; e.g. Tout & Hall 1991), with the ensuing common envelope stage generally accompanied by dramatic orbital shrinkage leading to the formation of a cataclysmic binary with a period much shorter than that of barium stars (e.g. Meyer & Meyer-Hofmeister 1979). To solve these problems, Han et al. (1995), Livio (1996) and Jorissen et al. (1997) propose avenues to explore. One of these involves Peter Eggleton’s CRAP (Companion-Reinforced Attrition Process; Eggleton 1986) speculating that larger mass-loss rates for AGB stars in binary systems may reverse the mass ratio of the system prior to RLOF, thus stabilizing the mass transfer process (Tout & Eggleton 1988; Han et al. 1995).

4. Do barium stars form as dwarfs or giants?

In Fig. 1, it is assumed that the mass transfer responsible for the barium syndrome occurred when the barium star was still on the main sequence. Because the stellar lifetime is longer on the main sequence than in the giant phase, that possibility indeed appears more probable than the formation of the barium star directly as a giant star. However, as pointed out by Iben & Tutukov (1985), the mismatch between the thermal time scale of the dwarf’s envelope and that of the mass-losing AGB star may prevent the
The formation of a barium star directly as a giant, though probably less frequent, is by no means excluded. The barium star HD 165141 may be such a case. HD 165141 is unique in sharing properties of barium and RS CVn systems (Fekel et al. 1993; Jorissen et al. 1996). Its rapid rotation (\( V \sin i = 14 \text{ km s}^{-1} \)) and X-ray flux (probably from a hot corona) are typical of RS CVn systems. However, the spin-up of that star (and the concomitant RS CVn properties) cannot be attributed to tidal effects synchronizing the stellar rotation with the orbit, as is the case for RS CVn systems, since the orbital period (about 5200 d) is much too long. That puzzle may be solved if the wind accretion episode responsible for the barium syndrome spun the star up, as suggested by detailed hydrodynamical simulations (Theuns & Jorissen 1993; Theuns et al. 1996). Since magnetic braking is generally faster than the stellar lifetime on the giant branch, wind accretion and concomitant spin-up must have occurred when HD 165141 was already a giant star. Strong support to that hypothesis comes from the fact that HD 165141 has a hot WD companion (Fekel et al. 1993) whose cooling time scale is shorter than the lifetime of HD 165141 on the red giant branch. Finally, note that Jeffries & Stevens (1996) have reported more cases of WIRRing (Wind-Induced Rapidly Rotating) stars among binary stars involving a hot WD.
5. Do barium stars evolve into Tc-poor S stars?

Figure 3 shows that strong barium stars and Tc-poor S stars occupy the same region of the \((e, \log P)\) diagram. The distributions of the mass function \(f(M)\) presented in Fig. 4 [where \(f(M) = M_2^3 \sin^3 i / (M_1 + M_2)^2 \equiv Q \sin^3 i\), \(M_1\) and \(M_2\) being the masses of the giant and of the WD, respectively] for the two families are compatible with the hypothesis that they are extracted from the same parent population. Following the usual analysis (Webbink 1986; McClure & Woodsworth 1990) of the mass function distribution in terms of a peaked distribution of mass ratios \(Q\) convolved with randomly inclined orbits, an average ratio \(Q = 0.045 \, M_\odot\) is found for the two classes, translating into a giant mass of 1.6 \(M_\odot\) when adopting \(M_2 = 0.6 \, M_\odot\) for the WD companion. These two results thus provide strong support to the hypothesis that barium and Tc-poor S stars represent successive stages in the evolutionary path sketched in Fig. 1.

Note, however, that the above comparison of the mass functions does not include two Tc-poor S stars (HD 191589 and HDE 332077) with main sequence companions detected with the International Ultraviolet Explorer satellite (Ake & Johnson 1992; Ake et al. 1992). The evolutionary status of these stars is currently unknown.

6. The relative frequency of intrinsic/extrinsic S stars

The evaluation of the relative frequency of intrinsic/extrinsic S stars faces two difficulties: (i) one needs an efficient criterion for distinguishing extrinsic from intrinsic S stars, and (ii) the frequency evaluation must be corrected from the selection bias, since extrinsic and intrinsic S stars follow different galactic distributions (Jorissen et al. 1993). As far as (i) is concerned, the defining criterion of intrinsic/extrinsic S stars based on the presence/absence of Tc, respectively, may be difficult to apply to a complete sample of S stars like Henize’s (see below), since it involves many faint stars for which high-resolution spectroscopy is difficult to secure. Binarity may be an alternative, since the binary paradigm for S stars states that all Tc-poor S stars should be binaries (Brown et al. 1990; Johnson 1992). However, some binaries must be expected among Tc-rich S stars as well, like in any class of stars. Binary intrinsic S stars with main sequence companions (case 3 in Fig. 1) include the close visual binary \(\pi^1\) Gru (Feast 1953) and stars with composite spectrum like T Sgr, W Aql, WY Cas (Herbig 1966; Culver & Ianna 1975), and possibly S Lyr (Merrill 1956). The situation is further confused by extrinsic S stars reaching the AGB phase and eventually becoming Tc-rich (case 8 in Fig. 1). \(o^1\) Ori, a Tc-rich binary S star with a WD companion (Ake & Johnson 1988), may be such a case.

The CORAVEL \(Sb\) parameter, measuring the average line width (see
Figure 5. The jitter \((\sigma^2 - \bar{\epsilon}^2)^{1/2}\) (where \(\bar{\epsilon}_1\) is the average error on one measurement, and \(\sigma\) is the standard deviation of the radial velocity for single stars, and of the \(O-C\) residuals around the computed orbit for binary stars) vs the CORAVEL line-width parameter \(S_b\) (see text).

Jorissen & Mayor 1988 for a more detailed definition), offers an interesting and efficient alternative to identify extrinsic/intrinsic S stars.

In cool red giants where macroturbulence is the main line-broadening factor, the \(S_b\) parameter may be expected to be a sensitive function of the luminosity, as is macroturbulence (e.g. Gray 1988). But at the same time, bright giants exhibit large velocity jitters probably caused by envelope pulsations (e.g. Mayor et al. 1984). A correlation between \(S_b\) and the radial velocity jitter must thus be expected, as observed in Fig. 5 for barium, intrinsic and extrinsic S stars (Jorissen & Mayor 1992; Jorissen et al. 1997).

All Tc-poor S stars are binary stars, as expected, but moreover, they are restricted to \(S_b < 5\) km s\(^{-1}\). That criterion has been used to identify extrinsic S stars among the Henize sample (Henize 1960). That sample covers the sky south of declination \(-25^\circ\) uniformly to red magnitude 10.5, and 205 S stars were found from their ZrO \(\lambda 6345\) band on red-yellow spectra with a dispersion of 450 Å mm\(^{-1}\) at H\(\alpha\). The galactic distribution of the Henize sample is presented in Fig. 6. Intrinsic S stars are clearly more concentrated towards the galactic plane than extrinsic S stars. Correcting for the uneven sampling of galactic latitudes, the frequency of intrinsic S
stars (based on the $S_b > 5$ km s$^{-1}$ criterion) then amounts to at least 62 ± 5% (in a magnitude-limited sample).

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