The link between symbiotic stars and chemically-peculiar red giants

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Abstract. Barium stars and technetium-poor, extrinsic S stars are binary systems with a white dwarf companion, and with orbital elements similar to those of symbiotic systems. One may thus wonder whether these various families of binary systems involving red giant stars are somehow related. This question is actually twofold:

(i) Do barium and binary S stars exhibit some symbiotic activity?
(ii) Do symbiotic systems exhibit overabundances of s-process elements like barium and S stars?

This paper reviews the current situation regarding these two questions.

1. The zoo of red giant stars

Symbiotic stars (SyS), barium stars and technetium-poor S stars are three families involving giant stars where binarity plays a key role. Thanks to the progress of UV astronomy, the binary nature of SyS now goes undisputed as their UV spectra bear the signature of a hot component, generally a white dwarf (WD), whereas the optical spectrum is dominated by the red giant (Mikołajewska, this conference).

Barium stars, first identified by Bidelman & Keenan (1951), are G and K giants where carbon and elements heavier than Fe, like Ba and Sr, have surface abundances in excess of the solar value (e.g. Wallerstein et al. 1997 and references therein), i.e., \[ \frac{X}{Fe} = \log \left( \frac{N(X)/N(Fe)}{N_{\odot}(X)/N_{\odot}(Fe)} \right) > 0, \]

where \( N(X) \) stands for the abundance of element X. Heavy elements like Sr and Ba are synthesized by the so-called s-process of nucleosynthesis, a sequence of neutron captures starting on abundant seed nuclei like iron-group elements (Burbidge et al. 1957; Wallerstein et al. 1997). The operation of the s-process is commonly associated with thermal pulses (TPs) occurring on the asymptotic giant branch (AGB; e.g. Goriely & Mowlavi 2000). AGB stars have a complex internal structure, consisting of a carbon-oxygen core, helium- and hydrogen-burning shells and a deep convective envelope (Olofsson & Habing 2003). TPs are a recurrent thermal instability affecting the He-burning shell. Right after a TP, the inner boundary of the convective envelope may penetrate the intershell region where the s-process operated. As a result of this mixing process (the so-called ‘third dredge-up’ – 3DUP), s-process-enriched material is brought to the stellar surface. Barium stars are, however, too warm and of too low a luminosity to be thermally-pulsing AGB (TP-AGB) stars (Scalo 1976). With the discovery
that the barium stars are all single-line spectroscopic binaries (McClure et al. 1980; McClure 1983; Jorissen et al. 1998), their chemical peculiarities have been ascribed to mass transfer across the binary system. The unseen companion is almost certainly a WD (McClure & Woodsworth 1990). In a former state of the binary system, that WD was a TP-AGB star where the s-process and the 3DUP were operating. If mass transfer processes (like wind accretion or Roche lobe overflow – RLOF) were able at that stage to dump s-process-rich and C-rich material from the AGB star onto its companion, that companion would be turned into a barium star (see Jorissen 2003 for a review). This is the so-called binary paradigm to account for the barium syndrome.

The stars of spectral type S (first identified by Merrill in 1922) exhibit chemical peculiarities very similar to those of barium stars. However, the S star family hosts two kinds of stars, the so-called extrinsic and intrinsic S stars, having very different evolutionary status (Van Eck & Jorissen 2000). They are best distinguished by the presence or absence of Tc lines, a heavy element with no stable isotopes (Van Eck & Jorissen 1999). Intrinsic S stars exhibit Tc lines, and are AGB stars where the s-process is operating, as indicated above. There is thus no need to invoke mass transfer across a binary system to account for their chemical peculiarities. On the contrary, extrinsic S stars have no Tc lines, and are all binary stars (Jorissen et al. 1998). They are the cool analogs of barium stars. For both barium and extrinsic S stars (collectively referred to as peculiar red giants – PRG – in the following), the companion mass inferred from the observed mass-function distribution is consistent with that companion being a WD (McClure & Woodsworth 1990; Jorissen et al. 1998; North et al. 2000).

Since both PRG and SyS are binary systems consisting of a red giant and a WD, the relation between these families ought to be elucidated; more precisely: (i) Do PRG exhibit symbiotic activity? (ii) Do SyS exhibit the barium syndrome?

2. Do PRG exhibit symbiotic activity?

2.1. Physical conditions required to trigger symbiotic activity

Before reviewing the symbiotic activity observed in the various classes of PRG (Sect. 2.2), it is useful to formally identify the physical conditions required to trigger symbiotic activity. The key to this activity lies in the luminosity of a hot \((T > 50000 \, \text{K})\) companion star, estimated to be at least 10 \(L_{\odot}\) (Mürrset et al. 1991; Yungelson et al. 1995), which emits UV radiation that ionizes the wind from the cool star, giving rise to the rich emission-line spectrum (Nussbaumer & Vogel 1987). Different physical processes, all related to the accretion of mass by the companion, may be at the origin of this high luminosity (Yungelson et al. 1995; Iben & Tutukov 1996): (i) steady hydrogen burning at the surface of a WD (ii) thermonuclear flashes at the surface of a WD [associated with symbiotic novae] (iii) release of gravitational energy associated with accretion, partially converted into radiative energy. Regimes (i) and (ii) correspond to accretion rates respectively above and below some critical value \(M_{\text{crit}}^{\text{acc}}\) (Eq. b of Table 1; about \(5 \times 10^{-8} \, M_{\odot} \, \text{y}^{-1}\) for a 0.6 \(M_{\odot}\) WD). Regime (iii) applies to main-sequence or neutron-star accretors, and to WD accretors in between
H-burning flashes (since the accretion luminosity is smaller than the H-burning luminosity at any given WD mass $M_h$; see Table I and Fig. 5 of Iben & Tutukov 1996). Formulae relating the luminosity $L_h$ of the compact companion to its mass $M_h$ for these three regimes are provided in Table I. A convenient analytical formula for the accretion rate $\dot{M}_{h_{\text{acc}}}$ is available in the framework of the Bondi-Hoyle regime of wind accretion (Bondi & Hoyle 1944), although detailed hydrodynamical simulations (Theuns, Boffin & Jorissen 1996; Mastrodemos & Morris 1998; Folini & Walder 2000) have shown that the Bondi-Hoyle accretion rates (Eq. c in Table I with $\eta \sim 1$) are generally an order of magnitude too large when the wind velocity is of the same order as the orbital velocity, as it is the case for SyS. The parameter $\eta$ appearing in Eq. (c) of Table I must therefore be taken of the order of 0.1 to reflect the results of numerical simulations when $v_{\text{wind}}/v_{\text{orb}} \lesssim 1$.

To summarize, Table I provides relationships that may in principle be used to propagate the condition $L_h > 10 L_\odot$ defining a SyS into constraints on the various physical parameters involved (the hot companion mass $M_h$, the cool star mass $M_c$, its luminosity $L_c$ and temperature $T_c$, the metallicity $Z$ and the orbital period $P$), namely:

\[
10 L_\odot < L_h = f [M_h, \dot{M}_{h_{\text{acc}}}] = f [M_h, \dot{M}_{h_{\text{acc}}}(M_{c_{\text{wind}}}, v_{\text{wind}}, M_c, P)] = f [M_h, \dot{M}_{h_{\text{acc}}}(M_{c_{\text{wind}}}[M_c, T_c, L_c(M_c, T_c, Z)], v_{\text{wind}}(L_c, Z), M_c, P)] = f [M_h, M_c, T_c, Z, P].
\]

The metallicity $Z$ enters the discussion through the mass-loss properties of the cool star, especially its wind velocity (Eq. e of Table I; Van Loon 2000). In the various empirical parametrizations reviewed by Zijlstra (1995), the wind mass loss rate $\dot{M}_{c_{\text{wind}}}$ depends explicitly upon $M_c$, $L_c$ and the stellar radius $R_c$, which transforms into a function of $M_c, T_c$ and $Z$ using the Stefan-Boltzmann formula to eliminate $R_c$ and the evolutionary track to express $L_c$ as a function of $M_c, T_c$ and $Z$. All the empirical formulae reviewed by Zijlstra (1995) predict that the mass loss rate increases with increasing $L_c$ and $R_c$. This will turn out to be a very important property to understand the occurrence of – or lack of – symbiotic activity in the various families of PRG.

The above discussion assumes that the system is detached, which sets yet another constraint, namely $P > P_{\text{RLOF}}(R_c, M_c, M_h)$ (Eq. d of Table I) where $P_{\text{RLOF}}(R_c, M_c, M_h)$ is the orbital period of the (semi-detached) system with a cool star of radius $R_c$ filling its Roche lobe.

### 2.2. Symbiotic activity among PRG

**Ba stars.** Symbiotic activity among barium stars is basically inexistent, except for the barium supergiant 56 Peg and for HD 46407, a barium star with one of the shortest orbital periods (456.6 d). 56 Peg is an X-ray source with a hot WD (Schindler et al. 1982; Dominy & Lambert 1983; Schwake et al. 2000). HD 46407 exhibits dust obscuration episodes (Jorissen 1994, 1997) reminiscent of those observed in symbiotic Miras (Munari & Whitelock 1989), although to a much lesser extent. This quasi-absence of symbiotic activity among barium stars
Table 1. A compendium of formulae to transform the condition $L_h > 10 L_\odot$ defining SyS into constraints on the various physical parameters involved. Luminosities, masses and radii are expressed in solar units, mass loss and accretion rates in $M_\odot y^{-1}$, velocities in km s$^{-1}$ and periods in y. Subscripts $h$ and $c$ refer to the hot and cool components, respectively.

- **Regime (i): steady H-burning on WD:** $\dot{M}_{\text{acc}}^h > \dot{M}_{\text{crit}}^{acc}$
  
  \[ L_{\text{He}}^h = 4 \times 10^5 M_h^{6.5} \quad (M_h < 0.5: \text{RGB - like, He core}) \]  
  \[ L_{\text{CO}}^h = 60 000 (M_h - 0.52) \quad (M_h > 0.5: \text{AGB - like, CO core}) \]  

- **Regime (ii): H-flash on WD:** $\dot{M}_{\text{acc}}^h < \dot{M}_{\text{crit}}^{acc}$
  
  \[ L_{\text{cold He}}^h = 46 000 (M_h - 0.26) \equiv L(\text{plateau after flash on a cold He core}) \]  

- **Regime (iii): accretion luminosity** (main sequence companion, or between H-flashes on a WD)
  
  \[
  L_{\text{acc}}^h = 3 \times 10^{7} \frac{\dot{M}_{\text{acc}}}{M_h} \frac{M_h}{R_h} \quad \frac{\dot{M}_{\text{crit}}}{1.06 - 1.16 M_h} \quad \text{(general expression)}
  
  \[
  = 3 \times 10^{9} \frac{\dot{M}_{\text{acc}}}{1.06} \quad \text{(WD)}
  \]

with $L_{\text{acc}}^h (\dot{M}_{\text{crit}}^{acc}) << L_{\text{He}}^h, L_{\text{CO}}^h < L_{\text{cold He}}^h$

The operation of a given regime is dictated by the ratio $\dot{M}_{\text{acc}}^h / \dot{M}_{\text{crit}}^{acc}$:

where

\[
\dot{M}_{\text{crit}}^{acc} = 10^{-9.31 + 4.12 M_h - 1.42 M_h^2}
\]

\[
\dot{M}_{\text{acc}}^h = -\dot{M}_{\text{wind}}^c \eta \mu^2 \frac{k^4}{1 + k^2} \left( \frac{c}{v_{\text{wind}}} \right)^2
\]

where

\[
\mu = M_h / (M_h + M_c)
\]

\[
k = v_{\text{orb}} / v_{\text{wind}} = 30 \left( \frac{M_h + M_c}{p} \right)^{1/3} / v_{\text{wind}}
\]

\[
P > P_{\text{RLOF}}[R_c, M_c, M_h] = \frac{3 \times 10^{-4} R_c^{3/2}}{(M_c + M_h)^{1/2} (0.38 + 0.2 \log(M_c/M_h))^{3/2}}
\]

\[
\eta \sim 1 \quad \text{if } k^{-1} = v_{\text{wind}} / v_{\text{orb}} >> 1 \quad \text{(Bondi – Hoyle regime)}
\]

\[
\eta \sim 0.1 \quad \text{if } k^{-1} = v_{\text{wind}} / v_{\text{orb}} \leq 1
\]

\[
c = \text{sound velocity}
\]

\[
v_{\text{wind}} \propto L_c^{1/4} Z^{1/2}
\]

\[
\dot{M}_{\text{wind}}^c = \dot{M}_{\text{wind}}^c [M_c, T_c, L_c(M_c, T_c, Z)]
\]

References: (a) Iben & Tutukov (1996) (b) Yungelson et al. (1995) (c) Theuns et al. (1996) (d) Jorissen (2003) (e) Van Loon (2000) (f) Zijlstra (1995)
is not surprising given their rather low mass-loss rates $\dot{M}_\text{wind}^c$ (Drake, Simon, & Linsky 1987), consistent with their luminosities of RGB (rather than AGB) stars (Scalo 1976). Equation (c) of Table I then indicates that the accretion rate by the companion will be low as well ($< 10^{-10}$ $M_\odot$ yr$^{-1}$; Jorissen 1997). If anything, this situation leads to H-flashes on the WD companion (regime ii), although no such events have yet been reported for barium stars.

**S stars.** Van Eck & Jorissen (2002; their Table 2) have collected all S stars where signatures of symbiotic activity have been reported. All of these — with the exception of the Henize S stars (see below) — result from serendipitous discoveries, and thus rely on different diagnostics of symbiotic activity which are not equally sensitive to $\dot{M}_\text{acc}^h$. For instance, H$_\alpha$ emission is not observed in the long-period system HD 49368 (=$V613$ Mon; $P \sim 3000$ d) despite a strong UV excess (Ake 1996, priv. comm.). A similar situation is encountered for the SyS EG And (see in particular the discussion in Sect. 4.4 of Munari 1994).

Therefore, to find any systematics (like correlation with orbital period) requires a more systematic approach. The 66 binary S stars from the Henize sample (Van Eck & Jorissen 2000) offers such an opportunity. These stars were searched for H$_\alpha$ emission, resulting in the discovery of two new SyS (Hen4-18 and Hen4-121, following the SIMBAD terminology) and of two marginal cases (Hen4-134 and Hen4-137; Van Eck & Jorissen 2002). Their H$_\alpha$ profiles, displayed in Fig. I, are typical of SyS, since they closely resemble those labelled ‘S-3’ by Van Winckel, Duerbeck & Schwarz (1993; see Lee 2000 for a discussion of the formation mechanism of the H$_\alpha$ emission line in SyS). Figure I reveals that symbiotic S stars with H$_\alpha$ emission are found in the narrow period range 600 – 800 d (as noted above, S stars with longer periods may exhibit other signatures of symbiotic activity, though).

The absence of H$_\alpha$ emission among the shortest-period systems is an interesting result, which confirms that the orbital period is not the primary parameter controlling symbiotic activity, as inferred from Table I. The key parameter is rather the accretion rate $\dot{M}_h^\text{acc}$, which is a combination of several parameters, including $P$ and $\dot{M}_c^\text{wind}$ (Eq. c of Table I). The absence of symbiotic activity among short-period S stars is likely due to their low mass-loss rates $\dot{M}_c^\text{wind}$, which are in turn a consequence of the fact that S stars with short orbital periods cannot be located very far up the giant branch. They must thus have smaller radii, luminosities, and hence mass loss rates, than S stars with longer orbital periods. The orbital period indeed imposes a maximum admissible radius $R_c$ corresponding to the critical Roche radius (Eq. d of Table I). Put differently, this condition means that to any given spectral type corresponds a minimum admissible orbital period for unevolved (i.e., pre-mass-transfer) detached systems. Such a correlation is clearly apparent on Fig. II, which shows that the minimum orbital period among K giants is 40 d, increasing to 200 d for M giants, and even to 400 d for giants later than M0 III. A similar correlation has been found by M"urset & Schmid (1999) among SyS (see also Harries & Howarth 2000), despite the fact that SyS are not really unevolved systems.

Finally, it must be noted that the period range of red SyS (excluding symbiotic novae and symbiotic Miras) matches fairly well that of symbiotic S stars with H$_\alpha$ emission and, moreover, corresponds to the short-period tail of the M III
Figure 1. Residual H$_\alpha$ profiles obtained after subtracting a pure absorption H$_\alpha$ profile (from the S star Hen4-6), for S stars with known orbital periods (as indicated in the upper right corner), decreasing from top to bottom. It is clearly apparent that S stars with H$_\alpha$ emission are only found in the period range 600 – 800 d. The dashed vertical line is the rest H$_\alpha$ wavelength.
Figure 2. Comparison of the period distributions for samples of binary systems with different kinds of red giant primaries: S stars (Jorissen et al. 1998), red SyS (excluding symbiotic novae and symbiotic Miras; Mürset & Schmid 1999), M giants (Jorissen et al., in preparation) and K giants (Mermilliod 1996). The lower two panels present the orbital-period distribution for barium stars (Jorissen et al. 1998) and yellow SyS (Mürset & Schmid 1999). The shaded area marks stars with only a lower limit available on their orbital period. The numbers in the upper right corner of each panel correspond to the sample size.
binaries. The same holds true for the period distribution of yellow SyS, which corresponds to the short-period tail of barium stars (but not to the short-period tail of K III binaries!). The reason for this is clear: barium stars and yellow SyS are two families which involve WD companions, unlike K III binaries which may also involve main sequence companions. Therefore, barium and yellow SyS share the same evolutionary history, namely one component has gone through the AGB. The fact that these systems once contained a very extended star sets a lower limit on their orbital period, as discussed above in relation with Eq. d (for a more detailed discussion of these aspects, see Jorissen 2003). But this restriction does not apply to the sample of K III binaries, hence they may contain systems with much shorter orbital periods than barium stars and yellow SyS.

3. Do SyS exhibit the barium syndrome?

3.1. Physical conditions required to trigger the s-process

Here again, we start with a formal discussion of the conditions required to trigger the operation of the s-process in AGB stars, before considering the question whether SyS exhibit the barium syndrome. These conditions are:

| $M_h > 0.5 M_\odot$ | $Z < Z_\odot$ |

The first condition on the core mass of the AGB star (which is identical to the mass $M_h$ of the WD in the present SyS) expresses the fact that the AGB star must have gone through the TP phase (Sect. 4). Wagenhuber & Groenewegen (1998, their Fig. 7) provide the AGB core mass at the first TP, for AGB stars of various metallicities and initial masses, from which the first condition is derived.

The second condition, expressing that the efficiency of the s-process is higher in low-metallicity AGB stars, was first suggested by Clayton (1988). This efficiency may be expressed by a single quantity, $n_c$, the number of neutrons captured per (iron) seed nuclei. For example, $n_c \approx 138 - 56 = 82$ is required for $^{138}\text{Ba}$ to be synthesized from $^{56}\text{Fe}$. Assuming that there are no strong neutron poisons, all neutrons will be captured by Fe and its daughter nuclei, so that $n_c = N(\text{neutron supply})/N(\text{Fe})$. Neutrons are supplied by a ‘neutron source’, namely $^{13}\text{C}(\alpha,n)^{16}\text{O}$ as it is currently believed for AGB stars (see e.g., Wallerstein et al. 1997), with $^{13}\text{C}$ resulting from the so-called proton-mixing scenario (e.g., Goriely & Mowlavi 2000). In this scenario, protons from the convective envelope are mixed in layers enriched in $^{12}\text{C}$ by the former TP, resulting in the synthesis of $^{13}\text{C}$ through the chain $^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta)^{13}\text{C}$. In the framework of the proton-mixing scenario, $^{13}\text{C}$ may be considered as ‘primary’ (in the sense of galactic chemical evolution), since it is synthesized from primary species, namely hydrogen from the envelope and $^{12}\text{C}$ resulting from the $3\alpha$ reaction. Assuming that there is no leak in the neutron production by the $^{12}\text{C}$ source, all available $^{13}\text{C}$ nuclei will yield neutrons, so that $n_c = N(\text{neutron supply})/N(\text{Fe}) = N(^{13}\text{C})/N(\text{Fe}) \propto 1/Z$.

This expectation seems to be borne out by empirical evidence; see the discussion in Jorissen & Boffin (1992) and Jorissen et al. (1998; their Sect. 8)
The barium syndrome among yellow SyS. The spectral type of the cool component is taken from Mürset & Schmid (1999), or references therein. In column labelled ‘nebula’, ‘y’ means that an optical nebula has been detected, and ‘PN’ that, based on its emission line spectrum, the star has traditionally been included in planetary nebulae catalogues, even though no optical nebula may be visible.

| Name            | Sp. Typ. | [Fe/H] | $V_r$ (km/s) | $b$ (°) | $[\text{Ba}/\text{Fe}]$ | $V \sin i$ nebula | Ref.   |
|-----------------|----------|--------|--------------|--------|---------------------|-------------------|--------|
| d'-type         |          |        |              |        |                     |                   |        |
| V417 Cen        | G8-K2    | ∼ 0.0  | −1           | 0.5    | 70                  | y                 | (5,11) |
| HDE 330036      | G5       | ∼ 0.0  | −14          | +4     | 0.6                 | 100               | PN     | (5,14) |
| =Cn 1-1         |          |        |              |        |                     |                   |        |
| AS 201           | G5       | ∼ 0.0  | +7           | 0.4    | 25                  | y                 | (5,12) |
| V471/V741 Per   | G5       | ?      | −12          | −9     | > 0                 | PN                | (5,14) |
| =M 1-2          |          |        |              |        |                     |                   |        |
| St Hα 190       | G5       | ∼ 0.0  | −10          | −35    | ∼ 0.5               | 100               | PN     | (5,12) |
| Wray 157        | G5       | ?      |              |        |                     |                   |        |
| Hen 1591        | < K4     | ?      |              |        |                     |                   |        |

| Name        | Sp. Typ. | [Fe/H] | $V_r$ (km/s) | $b$ (°) | $[\text{Ba}/\text{Fe}]$ | $V \sin i$ nebula | Ref.   |
|-------------|----------|--------|--------------|--------|---------------------|-------------------|--------|
| s-type      |          |        |              |        |                     |                   |        |
| UKS Ce-1    | C4.5Jch  | ?      | +20          | +20    | > 0                 |                  | (6)    |
| S 32        | C1.1CH  | ?      | +325         | −30    | > 0                 |                  | (6,14) |
| Hen 2-467   | K0       | -1.1   | −109         | −12    | +0.8               | n                 | (4,16) |
| BD-21:3873  | K2       | -1.1   | +204         | +37    | +0.5               | n                 | (3,15,16) |
|             |          | -1.3   |              | +0.3   |                     |                   | (9)    |
| AG Dra      | K2       | -1.3   | −148         | +41    | +0.5               | n                 | (8,16) |
| CD -43:14304| K7       | ?      | +27          | −41    | ?                   |                   | (7)    |

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-1.0 < 0.2

References: (1) Edvardsson et al., 1993, A&A, 275, 101 (2) Grauer & Bond, 1981, PASP, 93, 630 (3) Pereira et al., 1997, AJ, 114, 2128 (4) Pereira et al., 1998, AJ, 116, 1977 (5) Pereira et al., 2003, this conference (6) Schmid, 1994, A&A, 284, 156 (7) Schmid et al., 1998, A&A, 329, 986 (8) Smith et al., 1996, A&A, 315, 179 (9) Smith et al., 1997, A&A, 324, 97 (10) Smith et al., 2001, ApJ, 556, L55 (11) Van Winckel et al., 1994, A&A, 285, 241 (12) Schwarz, 1991, A&A, 243, 469 (13) Munari et al., 2001, A&A, 369, L1 (14) Schmid & Nussbaumer, 1993, A&A, 268, 159 (15) Munari & Patat, 1993, A&A, 277, 195 (16) Corradi et al., 1999, A&A, 343, 841
showing that binarity is not a sufficient condition to form a barium star, but that a subsolar metallicity seems to be required as well.

At this point, it should be remarked, however, that metallicity is also likely to have an impact on the wind accretion rate: at high $Z$, the wind velocity is larger (Eq. e of Table 1; also Zuckerman & Dyck 1989) and therefore the accretion rate is smaller, since $M_{\text{acc}} \propto v_{\text{wind}}^{-4}$ approximately. Therefore, barium stars may not form at high metallicities, not only because the s-process in the former companion AGB star is less efficient, but also because accretion of its wind is less efficient.

Because of this sensitivity upon metallicity, s-type yellow SyS, d'-type yellow SyS and red SyS have to be considered separately in the following, since they belong to different galactic populations.

### 3.2. s-Type yellow SyS are PRG

All known yellow SyS are listed in Table 2, which reveals that all the stars studied so far exhibit the barium syndrome. Yellow SyS with a stellar infrared continuum (s-type, as opposed to the dusty d'-type; see below) are clearly halo objects, as revealed by their low metallicities and high space velocities (CD $-43 : 14304$ may be an exception; however, it is of spectral type K7, and should perhaps not be included in the family of yellow SyS). The presence of the barium syndrome among a family of binary stars belonging to the halo fully supports the discussion of Sect. 3.1. about the conditions required for s-processing. It should be added at this point that s-type yellow SyS, with their metallicities lower than classical barium stars, may be expected to be, on average, more luminous than the latter (see Fig. 11 of Smith et al. 1996 comparing the luminosity function of Pop.I and Pop.II K giants). This is a direct consequence of the fact that evolutionary tracks shift towards the blue in the Hertzsprung-Russell (HR) diagram as metallicity decreases, as shown in Fig. 3b. Fig. 3a confirms that the yellow SyS AG Dra and BD $-21 : 3873$ are indeed more luminous than classical barium stars. This difference in the average luminosity – and hence mass-loss rate – of the two populations thus explains why yellow SyS, despite hosting a K giant, exhibit symbiotic activity whereas barium stars do not. The larger mass-loss rates for the cool components of s-type yellow SyS – as compared to Ba stars – may be inferred from the comparison of their IRAS $[12] - [25]$ color indices, which reflect the amount of dust present in the system: $(12) - (25)_{\text{Ba}} < 0.1$, as compared to 0.45 for AG Dra (Smith et al. 1996). Mürset et al. (1991) and Drake et al. (1987) provide direct measurements (or upper limits) for the mass loss rates of AG Dra and of Ba stars, respectively, which confirm the above conclusion.

Metal-deficient barium stars (with metallicities in the range $-1.1$ to $-1.8$ comparable to that of yellow SyS) were identified by Luck & Bond (1991) and Mennessier et al. (1997), and occupy the same region of the HR diagram as yellow SyS (Fig. 3b). The question thus arises why metal-deficient barium stars are not SyS. Different answers must be sought, depending upon their absolute visual magnitudes $M_V$. The most luminous systems, with $M_V < -2$, are likely
located on the TP-AGB\(^1\) so that their Ba syndrome may be explained by internal nucleosynthesis. They ought thus not be binaries, and therefore cannot be SyS! HD 104340 (open circle in Fig. 3b), a metal-deficient Ba star studied by Junqueira & Pereira (2001), provides a good illustration of this situation, since it lies above the TP-AGB threshold and 15 unpublished CORAVEL radial-velocity measurements spanning 7 y do not reveal any clear orbital motion.

The less luminous and warmest among metal-deficient Ba stars, clumping around \(M_V \sim +1\) in the HR diagram, are also sometimes classified as CH stars (crosses in Fig. 3b). They are not losing mass at a large enough rate to trigger any symbiotic activity, as revealed by their small \([12]-[25]\) color indices (< 0.3; Smith et al. 1996).

Finally, at intermediate luminosities \((-2 \lesssim M_V \lesssim +1\)), metal-deficient Ba stars are not luminous enough to be TP-AGB (hence they should be binaries), but yet their mass loss rates must be large enough to trigger symbiotic activity, since the yellow SyS belong to the same luminosity range. It would thus be of great interest to check (i) the binary nature of those metal-deficient Ba stars\(^2\) with intermediate luminosities, and (ii) their suspected symbiotic activity.

### 3.3. \(d'\)-type yellow SyS: young post-PN systems?

Yellow SyS of type \(d'\) (Allen 1982; Schmid & Nussbaumer 1993) differ from their s-type counterparts in several respects (Table 3): they host a complex circumstellar environment (including cool dust, bipolar outflows, extended optical nebulae or emission-line spectra closely resembling those of planetary nebulae), the cool components have early spectral types (F to early K), they are often fast rotators (with the possible exception of M 1-2 =V471 Per; Grauer & Bond 1981) and, finally, they belong to the galactic disk unlike s-type yellow SyS which belong to the halo.

All these arguments suggest that the hot component in \(d'\)-type SyS just evolved from the AGB to the WD stage. The rather cool dust (Schmid & Nussbaumer 1993) is a relic from the mass lost by the AGB star. The optical nebulae observed in \(d'\)-type SyS are most likely genuine planetary nebulae rather than the nebulae associated with the ionized wind of the cool component (Corradi et al. 1999). This is especially clear for AS 201 which actually hosts two nebulae (Schwarz 1991): a large fossil planetary nebula detected by direct imaging, and a small nebula formed in the wind of the current cool component. Finally, the rapid rotation of the cool component has likely been caused by spin accretion from the former AGB wind like in WIRRING systems (Jeffries & Stevens 1996; see also Jorissen 2003). The fact that the cool star has not yet been slowed down by magnetic braking is another indication that the mass transfer occurred fairly recently (Theuns et al. 1996). Finally, one may wonder whether the much

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\(^1\)According to Lattanzio (1991), the first TP in a 1 M\(_\odot\) AGB star of metallicity \([\text{Fe/H}]=-1.8\) occurs at \(M_{\text{bol}}=-3\), corresponding to \(M_V \sim -2\)

\(^2\)Primary targets with independent confirmation of their halo nature are HD 5424 (binary with \(P = 1881\) d; Jorissen et al. 1998), HD 55496, HD 104340, HD 148897 and HD 206983. Secondary targets, with their halo classification relying only on the Mennessier et al. (1997) analysis, are HD 15589, HD 43389 (binary with \(P = 1689\) d; Jorissen et al. 1998), HD 123396, HD 139409, HD 187762 and CD – 27:2233
Figure 3.  Left panel (a): Evolutionary tracks of Schaller et al. (1992) compared with the locations of classical barium stars (stars labelled ‘G’ in Mennessier et al. 1997; open dots) and the yellow SyS AG Dra (filled circle), BD −21 : 3873 (filled triangle) and Hen 2-467 (filled square). The bolometric magnitudes were taken from the references listed in Table 2. These bolometric magnitudes were combined with bolometric corrections from Bessel et al. (1998) and $B - V$ indices from Munari et al. (1992) and Munari & Buson (1992) to yield the absolute visual magnitudes.

Right panel (b): Same as the (a) but for yellow SyS (filled symbols as in the left panel) and metal-deficient barium stars (open triangles: stars flagged as ‘H’ by Mennessier et al. 1997; crosses: CH stars also flagged as ‘H’ by Mennessier et al. 1997; open circle: HD 104340, open square: HD 206983 from Junqueira & Pereira 2001). The dashed horizontal line represents the luminosity at the first TP in a 1 $M_\odot$ AGB star of metallicity [Fe/H] = −1.8 according to Lattanzio (1991)

earlier spectral types encountered among yellow d’-type SyS as compared to s-type SyS bear some relationship to their fast rotation (departure from thermal equilibrium?).

3.4. No extrinsic PRG among red SyS! Why?

A small number of galactic red SyS (UV Aur, SS 38, AS 210, HD 59643 = NQ Gem and V335 Vul) contain a cool carbon star as cool component, corresponding to a frequency of 5/176 = 0.03 in the catalogue of Belczyński et al. (2000). This small frequency contrasts with that prevailing in the Magellanic Clouds, where 6 out of 11 SyS contain cool carbon stars (Müset, Schild & Vogel 1996). The frequency of carbon-rich SyS actually reflects the number ratio of C to M stars in the parent galaxy, and this number ratio in turn reflects the metallicity of the population (Richer 1989). Therefore, these carbon SyS are likely intrinsic carbon stars (Müset et al. 1996), i.e., TP-AGB stars where the carbon observed in the atmosphere results from the 3DUP (see Sect. [4]).
The question then arises why there are no extrinsic C or S stars among SyS (Müerset & Schmid 1999), namely cool components polluted by carbon-rich matter from the former TP-AGB companion. Or in other words, why do red SyS not comply with the binary paradigm (Sect. 1.)? There are at least three possible explanations for the fact that red SyS contain M rather than S giants:

- the hot companion is a main sequence star rather than a WD;
- the former AGB star did not go through the TP-AGB, i.e., $M_h < 0.5 \ M_\odot$ (see Sect. 3.1);
- the former AGB star did go through the TP-AGB, but its high metallicity hindered the efficiency of the s-process and of the mass transfer (see Sect. 3.1).

The first question is difficult to address on observational grounds. Let us just mention here that the eccentricity – period diagram may, in some cases, be used to distinguish systems with WD companions from systems with main-sequence companions. As discussed by Jorissen et al. (1998, their Sect. 6 and Fig. 4), binary systems with $e < 0.1$ and $P > 300$ d most likely host a WD companion, whereas systems with $e > 0.23$ ($\log P(d) - 1$) are likely to host main sequence companions. Since most SyS have nearly circular orbits (Mikołajewska...
and Hinkle et al., this conference), they are likely to host WD companions indeed.

The second possibility \((M_h < 0.5 \, M_\odot)\) applies to a number of red SyS with companion masses fairly accurately determined (see also Mikołajewska, this conference), like AX Per (0.4 \, M_\odot), EG And (0.4 ± 0.1 \, M_\odot), SY Mus (0.43 ± 0.05 \, M_\odot), RW Hya (0.48 ± 0.06 \, M_\odot; Mürset et al. 2000 and references therein). There are, however, several other red SyS which do not fulfill this condition, either marginally (BX Mon: 0.55 ± 0.26 \, M_\odot) or more significantly (FG Ser: 0.60 ± 0.15 \, M_\odot; AR Pav: 0.75 ± 0.15 \, M_\odot; Mürset et al. 2000; Schild et al. 2001). For comparison, the mass of the WD companion in barium systems peaks at 0.67 \,(±0.09) \, M_\odot (North et al. 2000), in agreement with the requirement that the AGB progenitor went through the TP-AGB phase.

Therefore, the third possibility (high \(Z\)) must be invoked to account for the lack of barium syndrome in systems like FG Ser or AR Pav for example, which have \(M_h > 0.5 \, M_\odot\). Do red SyS indeed belong to a high-metallicity population? There are contradictory arguments in that respect. The distribution of carbon abundances in the cool components of SyS derived by Schmidt and Mikołajewska (this conference) is representative of red giants having slightly subsolar metallicities ([Fe/H] ∼ −0.3 to −0.5). On the contrary, Whitelock & Munari (1992) showed that the \(JHK\) colors of red SyS resemble more the colors of bulge-like M giants than those of normal M giants in the solar neighborhood. They argue that this color difference may be related to the higher metallicity of bulge-like giants, and, hence, of red SyS. A subsequent kinematical analysis (Munari 1994) confirmed that red SyS belong to the bulge/thick-disk population. A direct high-resolution spectroscopic determination of the metallicities of red SyS is needed to definitely settle that question. It must be hoped that such a study does indeed confirm the expectation of high metallicities for red SyS, otherwise answers to the lack of barium syndrome different from those discussed here would have to be found.

To conclude, a synopsis of the different families of PRG and SyS stars, and their relationship in terms of presence or absence of symbiotic activity and barium syndrome, is presented in Fig. 4.

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References

Allen, D.A. 1982, in IAU Coll. 70, The Nature of Symbiotic Stars, ed. M. Friedjung & R. Viotti (Dordrecht: Reidel), 27
Belczyński, K., Mikołajewska, J., Munari, U., Ivison, R.J., & Friedjung, M. 2000, A&AS, 146, 407
Bessell, M.S., Castelli, F., & Plez, B. 1998, A&A, 333, 231
Bidelman, W. P., & Keenan, P. C. 1951, ApJ, 114, 473
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 4
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Clayton, D. D. 1988, MNRAS, 234, 1
Corradi, R. L. M., Brandi, E., Ferrer, O. E., & Schwarz, H. E. 1999, A&A, 343, 841
Dominy, J. F., & Lambert, D. L. 1983, ApJ, 270, 180
Drake, S. A., Simon, T., & Linsky, J. L. 1987, AJ, 93, 163
Folini, D., & Walder, R. 2000, Ap&SS, 274, 189
Grauer, A. D., & Bond, H. E. 1981, PASP, 93, 630
Goriely, S., & Mowlavi, N. 2000, A&A, 362, 599
Harries, T. J., & Howarth, I.D. 2000, A&A, 361, 139
Iben, I. Jr., & Tutukov, A. 1996, ApJS, 105, 145
Jeffries, R. D., & Stevens, I. R. 1996, MNRAS, 279, 180
Jorissen, A. 1994, in The Impact of Long-Term Monitoring on Variable Star Research, ed. C. Sterken & M. de Groot (Dordrecht: Kluwer), 143
Jorissen, A. 1997, in Physical Processes in Symbiotic Stars and Related Systems, ed. J. Mikolajewska (Warsaw: Copernicus Foundation for Polish Astronomy), 135
Jorissen, A. 2003 in Asymptotic Giant Branch Stars, ed. H. Olofsson & H. Habing (New York: Springer Verlag)
Jorissen, A., & Boffin, H. M. J. 1992, in Binaries as Tracers of Stellar Evolution, ed. A. Duquennoy & M. Mayor (Cambridge: Cambridge Univ. Press), 110
Jorissen, A., Van Eck, S., Mayor, M., & Udry, S. 1998, A&A, 332, 877
Junqueira, S., & Pereira, C. B., 2001, AJ, 122, 360
Lattanzio, J. 1991, ApJS, 76, 215
Lee, H.-W. 2000, ApJ, 541, L25
Luck, R. E., & Bond, H. E. 1992, ApJS 77, 515
Mastrodemos, M., & Morris, M. 1998, ApJ, 497, 303
McClure, R. D. 1983, ApJ, 268, 264
McClure, R. D., Fletcher, J. M., & Nemec, J. M. 1980, ApJ, 238, L35
McClure, R. D., & Woodsworth, A. W. 1990, ApJ, 352, 709
Mennessier, M. O., Luri, X., Figueras, F., Gomez, A. E., Grenier, S., Torra, J., & North, P. 1997, A&A, 326, 722
Mermilliod, J.-C. 1996 in ASP Conf. Ser. Vol. 90, The Origins, Evolution, and Destinies of Binary Stars in Clusters, ed. Milone, E.F. & Mermilliod, J.-C. (San Francisco: ASP), 95
Merrill, P.W. 1922, ApJ, 56, 457
Munari, U. 1994, Mem. Astron. Soc. Ital., 65, 157
Munari, U., & Whitelock, P. A. 1989, MNRAS, 237, 45P
Munari, U., Buson, L. M. 1992, A&A, 255, 158
Munari, U., Yudin, B. F., Taranova, O. G., Massone, G., Marang, F., Roberts, G., Winkler, H., & Whitelock, P. A. 1992, A&AS, 93, 383
Müri, U., Nussbaumer, H., Schmid, H. M., & Vogel, M. 1991, A&A, 248, 458
Müri, U., Schild, H., & Vogel, M. 1996, A&A, 307, 516
Mürset, U., & Schmid, H. M. 1999, A&AS, 137, 473
Mürset, U., Dumm, T., Isenegger, S., Nussbaumer, H., Schild, H., Schmid, H. M., & Schmutz, W. 2000, A&A, 353, 952
North, P., Jorissen, A., & Mayor, M. 2000, in IAU Symp. 177, The Carbon Star Phenomenon, ed. R. F. Wing (Dordrecth: Kluwer), 269
Nussbaumer, H., & Vogel, M. 1987, A&A, 182, 51
Olofsson, H., & Habing, H. 2003, Asymptotic Giant Branch Stars (New York: Springer Verlag)
Richer, H. B. 1989, in IAU Coll. 106, Evolution of Peculiar Red Giant Stars, ed. H.R. Johnson & B. Zuckerman (Cambridge: Cambridge Univ. Press), 35
Scalo, J. M. 1976, ApJ, 206, 474
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A.. 1992, A&AS, 96, 269
Schild, H., Dumm, T., Mürset, U., Nussbaumer, H., Schmid, H. M., & Schmutz, W. 2001, A&A, 366, 972
Schindler, M., Stencel, R. E., Linsky, J. L., Basri, G. S., & Helfand, D. J. 1982, ApJ, 263, 269
Schmid, H. M., & Nussbaumer, H. 1993, A&A, 268, 159
Schwarz, H. E. 1991, A&A, 243, 469
Schwope, A. D., Hasinger, G., Lehmann, I., Scharz, R., Brunner, H., Neizvestny, S., Uglyumov, A., Balega, Y., Trümper, J., & Voges, W. 2000, Astron. Nachr., 321, 1
Smith, V. V., Cunha, K., Jorissen, A., & Boffin, H. M. J. 1996, A&A, 315, 179
Theuns, T., Boffin, H. M. J., & Jorissen, A. 1996, MNRAS, 280, 1264
Van Eck, S., & Jorissen, A. 1999, A&A, 345, 127
Van Eck, S., & Jorissen, A. 2000, A&A, 360, 196
Van Eck, S., & Jorissen, A. 2002, A&A, in press
Van Loon, J.T. 2000, A&A, 354, 125
Van Winckel, H., Duerbeck, H. W., & Schwarz, H. E. 1993, A&AS, 102, 401
Wagenhuber, J., & Groenewegen, M. 1998, A&A, 340, 183
Wallerstein, G., Iben, I. Jr., Parker, P., Boesgaard, A. M., Hale, G. M., Champagne, A. E., Barnes, C. A., Käppeler, F., Smith, V. V., Hoffman, R. D., Timmes, F. X., Sneden, C., Boyd, R. N., Meyer, B. S., & Lambert, D. L. 1997, Rev. Mod. Phys., 69, 995
Whitelock, P. A., & Munari, U. 1992, A&A, 255, 171
Yungelson, L., Livio, M., Tutukov, A., & Kenyon, S. J. 1995, ApJ, 447, 656
Zijlstra, A. A. 1995, Astrophys. Sp. Sc., 224, 309
Zuckerman, B., & Dyck, H. M. 1989, A&A, 209, 119