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# Spectroscopic binaries among Hipparcos M giants*

## III. The eccentricity - period diagram and mass-transfer signatures

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**ABSTRACT**

*Context.* This paper is the third one in a series devoted to studying the properties of binaries involving M giants.
*Aims.* We use a new set of orbits to construct the first $(e - \log P)$ diagram of an extensive sample of M giant binaries, to obtain their mass-function distribution, and to derive evolutionary constraints for this class of binaries and related systems.
*Methods.* The orbital properties of binaries involving M giants were analysed and compared with those of related families of binaries (K giants, post-AGB stars, barium stars, Tc-poor S stars).
*Results.* The orbital elements of post-AGB stars and M giants are not very different, which may indicate that, for the considered sample of post-AGB binaries, the post-AGB star left the AGB at quite an early stage (M4 or so). Neither are the orbital elements of post-mass-transfer binaries like barium stars very different from those of M giants, suggesting that the mass transfer did not alter the orbital elements much, contrary to current belief. Finally, we show that binary systems with $e < 0.4 \log P - 1$ (with periods expressed in days) are predominantly post-mass-transfer systems, because (i) the vast majority of barium and S systems match this condition, and (ii) these systems have companion masses peaking around 0.6 $M_\odot$, as expected for white dwarfs. The latter property has been shown to hold as well for open-cluster binaries involving K giants, for which a lower bound on the companion mass may easily be set.

**Key words.** binaries: spectroscopic - stars: late-type - stars: AGB and post-AGB - stars: symbiotic

## 1. Introduction

This paper is the third in our series discussing the spectroscopic-binary content of a sample of M giants drawn from the Hipparcos Catalogue (ESA 1997), for which CORAVEL radial velocities have been obtained in a systematic way (Udry et al. 1997; Famaey et al. 2005). The availability of an extensive set of orbital elements for M giants, assembled in Paper I (Famaey et al. 2009), allows us to address here evolutionary issues through the study of the eccentricity – period diagram [denoted $(e - \log P)$ in the following].

The comparison in Sect. 2 of such $(e - \log P)$ diagrams for K and M giants will reveal the operation of tidal effects, whereas a comparison of the diagrams of pre-mass-transfer systems with post-mass-transfer systems (like post-AGB stars in Sect. 2.2 and barium stars in Sect. 2.3) will illustrate the impact of the mass-transfer process on the orbital elements.

Finally, we will show that the impact of mass transfer on orbital elements is also readily apparent when considering how mass functions distribute across the $(e - \log P)$ diagram (Sect. 3). This paper presents for the first time compelling evidence that the lower-right corner of the $(e - \log P)$ diagram contains mostly post-mass-transfer objects with presumably white-dwarf companions. This demonstration is based on the analysis of the mass functions from K giants in open clusters (Mermilliod et al. 2007).

## 2. The $(e - \log P)$ diagram of M giants: Insights into binary evolution

The $(e-\log P)$ diagram offers good diagnostics about physical processes at work in binary systems. The $(e - \log P)$ diagram of M giants, constructed from the new and literature orbital data collected in Table 8 of Paper I[1], is presented in Fig. 1.

* Based on observations carried out at the Swiss telescope installed at the *Observatoire de Haute Provence* (OHP, France), and at the 1.93-m OHP telescope

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[1] Note that the short-period orbit of HD 115521, whose keplerian nature is in fact questionable (see Sect. 3.3.2 of Paper I), has not been included in the figure.

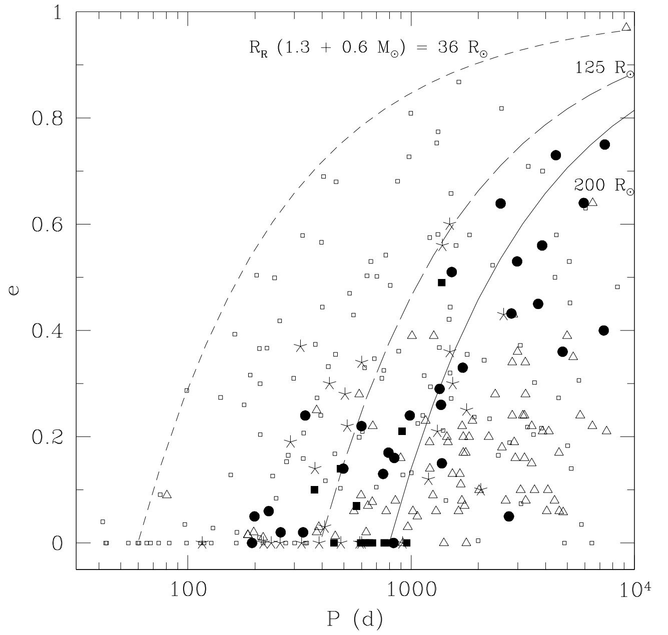


**Fig. 1.** The $(e - \log P)$ diagram for spectroscopic binaries involving M giants (black dots, from this work and collected from the literature), K giants in open clusters (small open squares), barium and S stars (open triangles), symbiotic stars *involving an M giant* (thus excluding yellow symbiotics; filled squares) and post-AGB stars (star symbols). The short- and long-dashed lines correspond to loci of constant periastron distance (78 and 280 $R_\odot$), translating into Roche radii of 35 and 125 $R_\odot$, respectively (assuming masses of 1.3 and 0.6 $M_\odot$ for the two components). They provide good fits to the upper envelopes of the regions where K or M giants with non-circular orbits are located. The solid line corresponds to a periastron-distance of 450 $R_\odot$ and a Roche radius of 200 $R_\odot$. In Fig. 6 of Paper II (Frankowski et al. 2009), a different periastron-distance limit was adopted for M giants (70 $R_\odot$, instead of 125 $R_\odot$ here), because the important issue in the context of Paper II was to find a limit enclosing *all* M stars, whereas here, a good fit to the envelope of the region occupied by non-circular M giants was seeked.

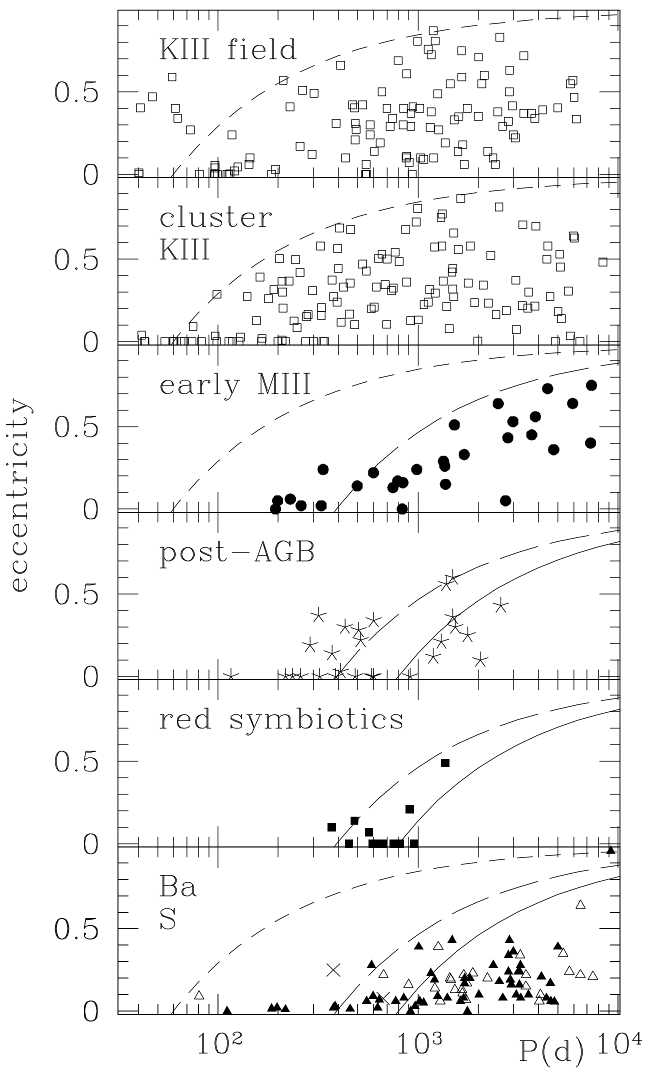


**Fig. 2.** Same as Fig. 1 in sequential order, with the addition of field K giants from the Ninth Catalogue of Spectroscopic Binary Orbits (Pourbaix et al. 2004), from which the systems with sdO/sdB or white dwarf companions (like barium stars) have been removed (since they are plotted in the bottom panel). For the sake of clarity, all panels start at a period of 30 d, although field K giants may be found in binary systems with periods as short as 4 d (see Fig. 6 of Paper II; Frankowski et al. 2009). The lines and symbols are as in Fig. 1 except for the the S and Ba star panel where the crosses denote S stars with an unexpectedly large mass function (HD 191589 and HDE 332077), open triangles denote mild Barium stars, and filled triangles strong barium stars and Tc-poor S stars. Mild and strong barium stars are separated according to the photometric DDO index $\Delta(38-41)$ (see text).

Important clues can be obtained about the evolution of binaries when comparing the location of M giants in this diagram with that of other classes of binary stars, namely K giants in open clusters (Mermilliod et al. 2007) or in the field[2] (from the Ninth Catalogue of Spectroscopic Binary Orbits; Pourbaix et al. 2004), barium and (Tc-poor) S stars (Jorissen et al. 1998), symbiotic stars with M-giant primaries (Belczyński et al. 2000; Mikołajewska 2003; Fekel et al. 2007) and post-AGB stars (Van Winckel 2007). For the sake of clarity, these different stellar classes are presented again in separate panels in Fig. 2. In that figure, mild and strong barium stars are separated according to the DDO index (Lü 1991) $\Delta(38-41) = C(38-41) - 0.90\ C(42{-}45){+}1.33$ being respectively $\leq -0.11$ or $> -0.11$ (see Jorissen & Boffin 1992, and the Appendix of Jorissen et al. 1998). If the DDO indices $C(38-41)$ and $C(42-45)$ needed to construct the $\Delta(38-41)$ index are not available, the Warner Ba index has been used instead (respectively Ba $\leq 2$ or Ba $\geq 3$ for mild and strong barium stars).

The various classes of binary stars presented in Figs. 1 and 2 are very likely linked through what may be called the *mass transfer scenario* (McClure 1983): the evolution followed by a system consisting initially of two low- or intermediate-mass

[2] Systems with sdO/sdB or white dwarf companions (like barium stars) have been removed from that sample (in order not to duplicate systems between the bottom and the top panels of Fig. 2).

main-sequence stars will go through the various phases listed above, along the sequence illustrated in Fig. 3. At point 5 in this evolution, part of the mass lost by the asymptotic giant branch (AGB) component will be accreted by the companion, thus increasing the abundances of those elements produced by the AGB nucleosynthesis, most notably C, F and s-process elements. Note that red symbiotics apparently do not exhibit such enhancements and their exact status in this sequence is still debated (see Jorissen 2003a; Jorissen & Van Eck 2005; Frankowski & Jorissen 2007, for recent reviews).

In some systems (most probably the closest), the binary evolution may branch to an Algol configuration at phases 2, 3 or 4 on Fig. 3. This branching is not discussed here (see instead Fig. 10 of Jorissen & Mayor 1992, and Eggleton 2006). In yet other systems, phase 5 of Fig. 3 may give rise to a common envelope, and those systems then end their evolution as cataclysmic variables or even coalesce. This situation is thought to occur for systems where a component with a deep convective envelope fills its Roche lobe (Pastetter & Ritter 1989; Eggleton 2006). This is supposed to have occurred in some barium systems, and yet these systems did not end up as cataclysmic variables. Why barium and Tc-poor S stars did escape this dramatic fate has remained unclear so far (but see Frankowski & Jorissen 2007).

As binary stars evolve along the sequence displayed in Fig. 3, their orbital elements are expected to vary, be it due to tidal effects, to interaction with a circumbinary disc, or to mass loss or mass transfer (through wind accretion or Roche Lobe overflow – RLOF; see Eggleton 2006; Frankowski & Jorissen 2007, for recent discussions). Therefore, the comparison of orbital elements for binary stars located at different stages in the sequence is expected to shed light on the various physical processes that have occurred along their evolution. The availability of the extensive set of orbital elements for M giants obtained in the present study brings an important element to this comparison.

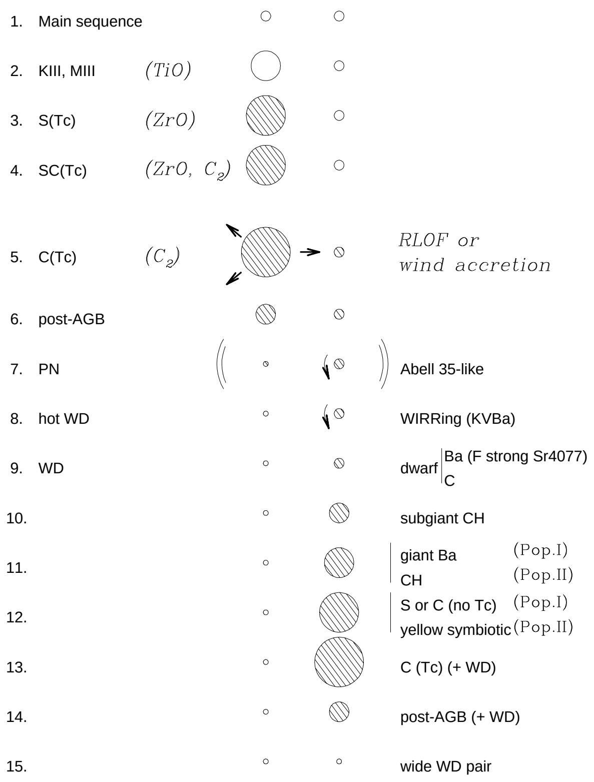


**Fig. 3.** One among the various possible evolution channels for a system consisting initially of two low- or intermediate-mass main-sequence stars. The left column corresponds to the normal evolutionary sequence of single stars, while the right column represents the various classes of stars with chemical peculiarities specifically produced by mass transfer across the binary system. Hatched circles denote stars with atmospheres enriched in carbon or heavy elements (see Jorissen 2003a, for a detailed description of the various stellar families involved). Other evolutionary channels would end with a cataclysmic variable or go through an Algol phase, and are not depicted here (see, e.g., Nelson & Eggleton 2001; Eggleton 2006, for details).

## 2.1. Smooth evolution KIII – MIII – Ba/S

Figures 1 and 2 reveal a smooth evolution along the sequence KIII – MIII – Ba/S, in the sense that the upper boundary of the populated region in the $(e - \log P)$ diagram moves towards longer periods (this is reflected by the three curved lines which roughly delineate the regions populated by these three classes, their exact definition being given below). This is clearly a consequence of the larger radii reached by stars evolving along this sequence. In the case of Ba and Tc-poor S giants, it is actually their white dwarf (WD) companions which reached very large radii while evolving on the AGB. For K giants, the situation is in principle somewhat more complex, since this class mixes stars on the first giant branch and stars in the core He-burning phase. *Low-mass* stars belonging to the latter category have gone through the RGB tip, where they reached a very large radius (similar to, or even larger than that of M giants). Therefore, if those low-mass, core-He burning stars were to dominate among K giants, their distribution in the $(e - \log P)$ diagram should be characterised by an envelope located at even longer periods than that for M giants. Fig. 2 shows that this is not the case, because the sample of open-cluster K giants plotted in Fig. 2 is in fact dominated by intermediate-mass stars, as may be judged from the turnoff masses of the corresponding clusters, most of them being larger than 2 $M_\odot$ (Mermilliod et al. 2007). The complication introduced by the mixture of evolutionary states among K giants is thus not a concern.

Equating the stellar radius to the Roche radius results in a threshold period (for given component masses) below which the primary star undergoes RLOF. Adopting Paczyński's usual expression for the Roche radius $R_{R,1}$ around star 1

$$R_{R,1}/A = 0.38 + 0.2 \log q \qquad (0.5 \leq q \leq 20), \qquad (1)$$

where $q = M_1/M_2$ and $A$ is the orbital separation, one finds that a star of radius 40 $\mathrm{R}_\odot$ fills its Roche lobe in a system of period $P = 70$ d, for masses $M_1 = 1.3\,\mathrm{M}_\odot$ and $M_2 = 0.6\,\mathrm{M}_\odot$. Although the Roche lobe concept is in principle only applicable to circular orbits, one may formally compute the orbital periods for which the primary star fills its Roche lobe *at periastron*, by replacing $A$ by $A(1-e)$ in the above expression. It is quite remarkable that the relationship between $P$ and $e$ so obtained (assuming $R_R = 36$ R$_\odot$) exactly matches the boundary of the region occupied by KIII giants in the $(e - \log P)$ diagram, both for cluster and field[3] giants (Fig. 2). This excellent match thus clearly suggests that mass transfer at periastron plays a crucial role in shaping the $(e - \log P)$ diagram (Soker 2000).

It may seem surprising that the 'periastron envelope' [$A(1-e)$ = constant, or $P^{2/3}(1-e)$ = constant] represents a better fit to the data than the 'circularisation envelope' [$A(1-e^2)$ = constant, or $P^{2/3}(1-e^2)$ = constant; see Fig. 6 of Paper II], resulting from the fact that circularisation keeps the angular momentum per unit reduced mass constant (Zahn 1977; Hut 1981; Duquennoy et al. 1992). Indeed, as the star gets closer to its Roche lobe, it should circularise first and then fill its Roche lobe, and possibly disappear from the sample due to cataclysmic mass transfer. The samples of K-giant binaries clearly favour the periastron envelope over the circularisation envelope. The reason for this may be the following. When a system is close to filling its Roche lobe at periastron, circularisation proceeds fast at this moment. But since the circularisation path in the $(e - \log P)$ diagram is steeper than the periastron line (see Fig. 6 of Paper II), circularisation drags the system away from Roche lobe filling at periastron and thus also slows down its own rate. Circularisation can accelerate only when other effects bring the star and its Roche lobe closer again. Therefore an ensemble of binaries traces on their $e - \log P$ diagram the current periastron envelope rather than any circularisation path (see also Paper II, Sect. 2.5).

The role played by periastron RLOF in shaping the $(e - \log P)$ diagram is nicely illustrated by the M4III star HD 41511 (= SS Lep). With $P = 260.3$ d and $e = 0.02$ (Welty & Wade 1995), it is the fourth shortest orbital period among the spectroscopic systems involving an M giant. Verhoelst et al. (2007) provided convincing evidence that the M giant, having a radius of 110±30 $R_\odot$ derived from interferometric measurements and from the Hipparcos parallax (Table 1), fills its Roche lobe. This is consistent with the Roche limit set at 125 $R_\odot$ in Figs. 1 and 2. As a further evidence to this claim, these authors show that the A-type companion appears to be a main-sequence star, which has swollen as a result of accretion from the lobe-filling M giant. Indeed, its radius is ten times that of a typical A1V star, but its mass, derived from the surface gravity and radius, is not that of a massive supergiant. Finally, the system is surrounded by a circumbinary disc (Jura et al. 2001; Verhoelst et al. 2007), probably fed by the RLOF, which thus appears to be non conservative. The A star is rapidly rotating ($V \sin i = 117$ km s$^{-1}$; Royer et al. 2002), possibly as a result of spin accretion or, alternatively, as the primordial rotation speed of the main sequence star. All these features are very suggestive of a scenario outlined by Frankowski & Jorissen (2007) for an evolving M giant binary.

For M giants with radii somewhat smaller than that of SS Lep, but still representing a fair fraction of the Roche radius, tidal effects will take place, and the star will then be seen as an ellipsoidal variable. The M2.5III star HD 190658 (V1472 Aql) is such a case (Samus 1997). It has the second shortest orbital period among M giants ($P = 199$ d, $e = 0.05$; Lucke & Mayor 1982). A rotational velocity of $V \sin i = 15.1$ km s$^{-1}$ is found from the CORAVEL cross-correlation dip width calibrated by Benz & Mayor (1981). Assuming that the giant star rotates in synchronism with the orbital motion, a radius of 59 $R_\odot$/sin $i$ is derived, corresponding to $R/A_1 = 1.16$, where $A_1$ is the semi-major axis of the giant's orbit around the centre of mass of the system (Lucke & Mayor 1982). Adopting typical masses of 1.7 $M_\odot$ for the giant and 1.0 $M_\odot$ for the companion, one obtains $R/A = 0.43$ and $R/R_R = 1$ !

Interestingly, the Ba/S star HD 121447 (with an effective temperature equivalent to that of a M0III giant) is another example: with $P = 185.7$ d and $e = 0$, it falls just besides HD 190658 in the $(e - \log P)$ diagram and seems to be an ellipsoidal variable as well (Jorissen et al. 1995), although that interpretation has been challenged by Adelman (2007), based on the presence of chromatic variations.

HD 9053 (=$\gamma$ Phe), with $P = 193.8$ d and $e = 0$, has the shortest period among M-giant binaries. Jancart et al. (2005) used the spectroscopic elements and the Hipparcos data to derive a combined orbit yielding a precise inclination $i = 46 \pm 4°$. The system cannot therefore be eclipsing, so that the eclipsing-like light curve reported by Otero (2007) should in fact be re-interpreted in terms of ellipsoidal variations, a possibility mentioned by Otero (2007). The angular radius measured by Richichi & Percheron (2005) is $3.22 \pm 0.43$ mas, yielding 50 $R_\odot$ when combined with the Hipparcos parallax of $13.94 \pm 0.64$ mas, to be compared with a Roche radius of 78 $R_\odot$ (adopting masses of 1.3 and 0.6 $M_\odot$ for the giant and its companion, respectively). The giant should therefore be well within its Roche lobe. Nevertheless, HD 9053 is a 'hybrid star' (Ayres 2005): despite being located to the right of the 'dividing line' between hot coronae and massive winds (Hünsch & Schroeder 1996; Reimers et al. 1996), the star exhibits signatures of hot gas, like X-ray flux and C IV line. One may wonder whether these could be signatures of matter being accreted by the companion in this close binary system. Also note that arguments were presented in Sect. 2.5 of Paper II that the usual expressions for the Roche radius (e.g., Eggleton 1983) may actually overestimate it when an extra-force (like radiation pressure) is present in the system (see also Dermine et al. 2009).

We will come back to the relationship between ellipsoidal variables and the periastron envelope observed in the $(e - \log P)$ diagram when we will show in Sect. 2.4 that the so-called long secondary periods (also called sequence D) in the $K - \log P$ diagram of long-period variables (LPVs) in the Large Magellanic Cloud (Wood et al. 1999; Wood 2000) may

[3] In the sample of KIII binaries in the field, there are several systems with non-zero eccentricities falling to the left of the periastron envelope. Most of these systems are either pre-main sequence (PMS) binaries (mostly from Torres et al. 2002) or Algols (Nelson & Eggleton 2001; Eggleton 2006), i.e., (post-)mass-transfer systems (see also the discussion in relation with Fig. 6 of Paper II). The successive panels in Fig. 2 are meant to illustrate the evolution of the orbital elements as the system evolves from both components on the main sequence to one component being a white dwarf. Therefore, the Algols or PMS systems present in the sample of field KIII stars distort the picture, and should actually be disregarded.

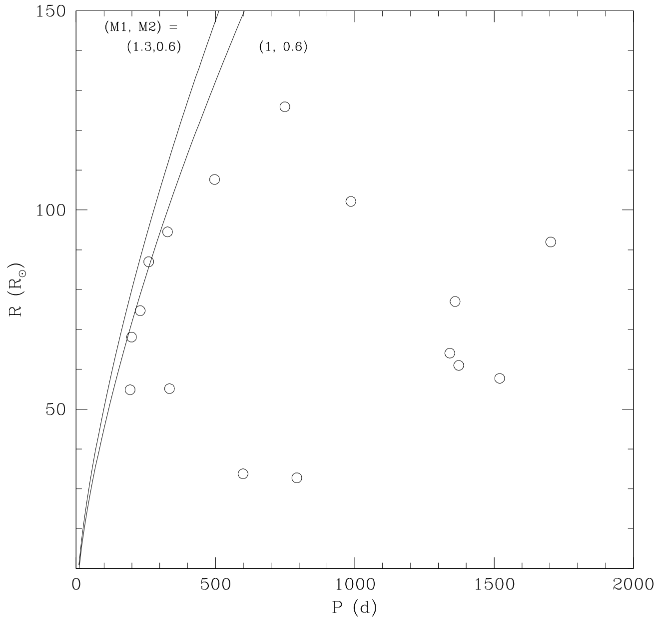


**Fig. 4.** The orbital-period – radius diagram for M giants in binary systems. The radii are derived from the Stefan-Boltzmann law applied on the effective temperatures and luminosities presented in Fig. 5. The solid lines display the Roche radii for the corresponding period, for two different choices of the component masses.

be identified with the periastron envelope in the $(e - \log P)$ diagram of galactic M giants (see also Soszyński 2007).

No similar evidence for RLOF or ellipsoidal variations has been found for the other two short-period M giants (HD 89758 and HD 147395).

The periastron-distance envelope seen in the $(e - \log P)$ diagram (Fig. 2) is also apparent in the radius – orbital-period diagram (Fig. 4). The radii plotted in Fig. 4 are derived from the Stefan-Boltzmann law and are in very good agreement with those derived by combining the uniform-disc diameters listed in the 'updated Catalogue of High Angular Resolution Measurements' (CHARM2; Richichi et al. 2005) and the Hipparcos parallaxes (Table 1). Fig. 4 shows that, for a given value of the radius, there is a lower bound on the orbital period[4], simply because stars with large radii cannot reside in too close systems, or they would undergo RLOF and would disappear from the sample by transforming into cataclysmic variables. The lines in Fig. 4 correspond to the limit imposed by equating the stellar radius to the Roche radius (Eq. 1, adopting $M_1 = 1.3\ M_\odot$ and $M_2 = 0.6\ M_\odot$, or $M_1 = 1.0\ M_\odot$ and $M_2 = 0.6\ M_\odot$), the stellar radius being computed using the Stefan-Boltzmann relation as explained before.

Finally, it is noteworthy that the solid line in Figs. 1 and 2 does not match well the upper boundary of the region occupied by barium and Tc-poor S stars, thus suggesting that for these classes of post-mass-transfer binaries, tidal processes and periastron mass-transfer were, as expected, not the only ones to operate. Mass transfer and interaction with a circumbinary disc must have played a role for these (Frankowski & Jorissen 2007). One mild barium star (HD 77247: $P = 80.5$ d; $e = 0.09$) deviates markedly from the rest of the sample of barium stars. One may wonder whether the location of HD 77247 in the $(e - \log P)$ diagram along the periastron envelope of K giants is just accidental, or whether it indicates instead that this system might not be a post-mass-transfer system after all, as are the other barium stars, but that its barium anomaly may rather be inherited from the gas out of which it formed, and be unrelated to its binary nature. HD 77247 would thus join the small number of (mostly dwarf) barium stars with no evidence for being binaries (see the review by Jorissen 2003a, and individual cases discussed by Tomkin et al. 1989, Edvardsson et al. 1993, North et al., 1992, 2000).

### 2.2. Relation with post-AGB stars

Binary post-AGB stars (Van Winckel 2003, 2007) are the immediate descendants of the binary M giants (Fig. 3), and indeed they share almost exactly the same location in the $(e - \log P)$ diagram.

The M4III + A system SS Lep already mentioned in Sect. 2.1 is very interesting in this respect, since it shares with post-AGB stars the presence of a circumbinary disc and its position in a group of binaries with the shortest orbital periods among both families. It may thus be considered as a system linking binary M giants and post-AGB systems in the sense that the M-giant component in SS Lep should shortly evolve into a post-AGB star.

On the contrary, one may wonder whether some among the post-AGB stars from panel 4 in Fig. 2 with circular orbits and $P \sim 200$ d like SS Lep (these are HD 101584, HD 213985 and IRAS 05208-2035, although in the case of HD 101584, the eccentricity is not well constrained) would not be genuine post-AGB stars, but rather be accreting main-sequence or white-dwarf stars which have swollen to giant dimensions in RLOF systems (as expected when the accreting main-sequence star has a radiative envelope: Kippenhahn & Meyer-Hofmeister 1977; Jorissen 2003a, or when the WD accretion rate is large enough to trigger shell H-burning: Paczyński & Rudak 1980, Iben & Tutukov 1996). The post-AGB stars in those systems would thus be the analogs of the A-type companion of SS Lep.

The spectrum of HD 101584 is very complex, combining emission lines with P-Cygni profiles indicative of ongoing mass loss and absorption lines. The remarkable characteristic of the optical spectrum of HD 101584 is the fact that different spectral regions resemble different spectral types. There is therefore no agreement about the effective temperature of the central star, with proposed values ranging from 8500 K (Sivarani et al. 1999) to 12 000 K (Bakker et al. 1996), or $8500 \pm 1000$ K for the post-AGB star and about 11 000 K for its companion (Kipper 2005). There is thus no clear evidence from recent works for the companion of the post-AGB star HD101584 to be an M giant, despite the early suggestion by Humphreys (1976).

[4] Pourbaix et al. (2004) have presented a spectacular figure (their Fig. 4) showing the minimum orbital period as a function of the $B-V$ index for the whole *Ninth Catalogue of Spectroscopic Binary Orbits* (SB9).

**Table 1.** Radii of M giants in binary systems derived from the Stefan-Boltzmann law ($R_{\rm SB}$) and from high-angular resolution measurements ($R_{\rm HR}$). The labels 'UD' and 'LD' refer to uniform discs or limb-darkened discs, respectively. Luminosities are derived from the Hipparcos parallaxes $\varpi$, from the 2MASS $K$ magnitudes and bolometric corrections $BC_K$ derived from the ($V-K$ , $BC_K$) analytical relation from Bessell & Wood (1984), which is in good agreement with the more recent calibration of Bessell et al. (1998). The Johnson $V_J$ magnitude from the Hipparcos catalogue has been used. Effective temperatures are derived from the $V_J - K$ indices using the 'bcd' calibration of Bessell et al. (1998).

| HD | $\theta/2$ (mas) | UD/LD | band | $\varpi$ (mas) | $R^a_{\rm HR}$ ($R_\odot$) | $R_{\rm SB}$ ($R_\odot$) | $K$ (2MASS) | $V_J-K$ | $BC_K$ | $\log L/L_\odot$ | $\log T_{\rm eff}$ (K) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9053 | $3.22 \pm 0.43$ | UD | 10 $\mu$m | $13.9 \pm 0.6$ | 50 | 55 | -0.50[b] | 3.9 | 2.65 | 2.75 | 3.58 |
| 41511 | $1.55 \pm 0.16$ | LD | K | $3.0 \pm 0.7$ | 110 | 109 | 1.67 | 3.3 | - | 3.08[c] | 3.51[c] |
| 42995 | $12.95 \pm 0.04$ | UD | K | $9.3 \pm 2.0$ | 145 | 153 | -1.72 | 5.0 | 2.85 | 3.50 | 3.55 |
| 89758 | $8.00 \pm 0.03$ | UD | V | $13.1 \pm 0.8$ | 66 | 75 | -1.01 | 4.1 | 2.69 | 2.99 | 3.57 |
| 132813 | $9.60 \pm 0.70$ | UD | K | $8.2 \pm 0.5$ | 126 | 126 | -0.96 | 5.6 | 2.91 | 3.29 | 3.54 |
| 137853 | $2.37 \pm 0.05$ | UD | K | $4.2 \pm 0.8$ | 62 | 61 | 1.93 | 4.1 | 2.69 | 2.81 | 3.57 |
| 220088 | $2.29 \pm 0.03$ | UD | K | $7.5 \pm 0.7$ | 33 | 35 | 1.81 | 3.8 | 2.61 | 2.38 | 3.59 |

[a] From Richichi et al. (2005; CHARM2) , Verhoelst et al. (2007) and Richichi & Percheron (2005)
[b] From Richichi & Percheron (2005)
[c] These values are taken from Verhoelst et al. (2007); the calibrations used for the other stars, and based on the $V-K$ colour index, cannot be used for HD 41511 because the $V$ band is contaminated by light from the A-type companion

In the spectral energy distributions presented by de Ruyter et al. (2006) for HD 213985 and IRAS 05208-2035, neither is there evidence for the presence of a cool giant companion, as it was the case for SS Lep (Verhoelst et al. 2007). Nevertheless, if the luminosity ratio between the post-AGB and the giant components is of the order 5 to 10[e], one may wonder whether the cool giant could at all be noticed (fitting the complex spectral energy distributions of post-AGB systems is a delicate operation involving many free parameters –like the reddening– with no unique solution; Van Winckel, priv. comm.). For the SS Lep system, the luminosity ratio is 1.6 in favour of the A component (Verhoelst et al. 2007). HD 172481 is another example of a F2Ia supergiant traditionally considered to be a post-AGB star, but which is more likely a white dwarf burning hydrogen accreted from its AGB companion (Whitelock & Marang 2001). For that system, the presence of an M giant companion is apparent from the detection of TiO bands, from the SB2 nature of the CORAVEL cross-correlation dip (Reyniers & Van Winckel 2001), and from Mira-type pulsations with a period of 312 d. From the SED, the luminosity ratio turns out to be similar to SS Lep: $L_{\rm F}/L_{\rm M} = 1.8$ (although that ratio is somewhat dependent upon the adopted reddening). No radial-velocity variations hinting at a period of a few hundred days have been detected for HD 172481 (Reyniers & Van Winckel 2001).

The papers mentioned above suggest different types of accreting components in SS Lep and HD 172481 but, in the absence of stringent constraints on the mass and luminosity of the accreting star, there is in fact no easy way to distinguish between WD and main-sequence accretors.

In summary, we conclude that some systems currently flagged as hosting a post-AGB star could in fact be better described as systems where an M giant dumps matter on its white-dwarf or main-sequence companion which then acquires supergiant dimensions, thus mimicking a post-AGB star. Such systems, currently plotted in panel 3 of Fig. 2 (post-AGB systems), do in fact belong to panel 2 (M giants), were it not for the light of the M giant being lost in the glow of its supergiant-like companion. In this scenario, one might however worry whether the accreting component could indeed become more luminous than the moss-losing giant.

[e] de Ruyter et al. (2006) suggest that $\log L/L_\odot = 3.6$ may be typical for post-AGB stars, and Fig. 5 reveals that M giants may be as dim as $\log L/L_\odot = 2.6$.

Another possible scenario to account for systems like HD 172481 could therefore be as follows, now stating instead that the post-AGB star is genuine, but its giant companion is fake. In a system with components of initial masses $(M_1, M_2) = (3, 1)\ M_\odot$, the star of mass $M_1 > M_2$ evolves faster, fills its Roche lobe on the AGB around the first thermal pulse and becomes a white dwarf (WD) with a mass of 0.55 $M_\odot$ (Blöcker 1995). It is not exactly clear what happens to the orbit, although Frankowski & Jorissen (2007) presented arguments for the orbital period remaining more or less unchanged (see also the discussion in Sect. 2.3). Then the star of mass $M_2$ (which could by now have reached 2–3 $M_\odot$ as a result of accretion) evolves in turn along the AGB, but having a lighter companion it can grow bigger and brighter without filling its Roche lobe, say up to a core mass of 0.6 $M_\odot$. Eventually star $M_2$ fills its Roche lobe and ejects most of its envelope, transferring part of it back to star $M_1$ (a few 0.01 $M_\odot$ is enough for $M_1$ to reignite its H shell and to swell again to giant dimensions; Frankowski 2003). There are now two cores with comparable envelope masses, both burning hydrogen in shells, the younger ($M_2$, i.e. the true-post AGB) burning it faster (as it has a more massive core). The younger core is brighter and evolves (contracts) faster. The difference in evolutionary speed becomes enormous as star $M_2$ gets to its post-AGB stage (3000 years off the AGB, the 0.6 $M_\odot$ core has already a temperature of $\log T_{eff} = 4.5$; Blöcker 1995) while star $M_1$ still sits on the AGB. Soon we are left with a giant configuration around $M_1$'s core and a hot, brighter post-AGB $M_2$. In this particular case the brightness difference is a factor of 3 to 5. The mass function would be high (0.16 $M_\odot$ for the sample case above, assuming

$e = 0, i = 90°$ – which makes it very similar to SS Lep, which has $f(M) = 0.26\ M_\odot$).

In any case, the suggestion that some stars flagged as post-AGB could in fact be components of binary systems caught in the act of mass transfer would have several interesting consequences. It could explain the unexpectedly large number of post-AGB systems (as compared to their short evolution time scale), the similarity between the orbital elements of post-AGB and M binaries (if post-AGB stars were *post*-mass-transfer systems rather than systems with *on-going* mass transfer as we suggest, the orbital elements should have been altered, at least to some extent). It would also explain why we could not find any other systems with characteristics similar to SS Lep [namely, early-type star with cool dust in a disc and spectral features typical of (super)giants], since they would all already have been flagged as post-AGB systems! The star 3 Pup (HD 62623) is sometimes presented as the twin of SS Lep (Jura et al. 2001), but the exact nature of this star is still much debated. At this point, it should be mentioned that the d' symbiotic systems could be related as well to post-AGB systems and SS Lep: they host a warm, fast-rotating giant (F to early K) with a hot compact companion which just left the AGB, as suggested by the presence of cool dust and, often, a planetary nebula. The fast rotation of the giant is very likely the signature of a recent mass-transfer episode (Jorissen et al. 2005; Zamanov et al. 2006).

Actually, the shape of the $(e - \log P)$ diagram of post-AGB stars, when compared to that of binary M and K giants, may be interpreted in two different ways. The first interpretation assumes that the location of post-AGB stars in the $(e - \log P)$ diagram is controlled by the periastron envelope corresponding to 200 $R_\odot$ (solid line in Fig. 2), with some circular systems at shorter periods *plus* some among these which had their eccentricities pumped upwards as a result of the interaction with the circumbinary disc (Artymowicz et al. 1991; de Ruyter et al. 2006; Frankowski 2008). In this scenario, the AGB precursors were thus allowed to evolve far up the AGB, up to at least 200 $R_\odot$. The similarity between the $(e - \log P)$ diagrams of M giants and post-AGB systems would thus be purely accidental.

The second interpretation assumes that this similarity is not accidental, and states that mass transfer or disc interaction has not dramatically altered the location of post-AGB binaries in the $(e - \log P)$ diagram (or as suggested above, some might even be *in the course* of the mass-transfer process). This case then differs from the first interpretation by implying that the AGB precursors must have left the AGB at a rather early stage in their evolution, given their location in the $(e - \log P)$ diagram between the tidal envelopes corresponding to 85 and 200 $R_\odot$ (Fig. 1). Like the M giants, *binary* post-AGB stars do not show evidence for s-process enrichment (despite the confusion introduced by the depletion pattern; Van Winckel 2007). We believe that the absence of s-process enrichments in both classes of stars is not a coincidence. In fact, it may be inferred that neither M giants nor post-AGB binaries reached a point on the AGB where s-process and dredge-ups were operating[6].

[6] Among the 4 MIII stars checked for the presence/absence of Tc (HD 2411 = TV Psc; HD 132813 = RR UMi; HD 187076 = $\delta$ Sge;

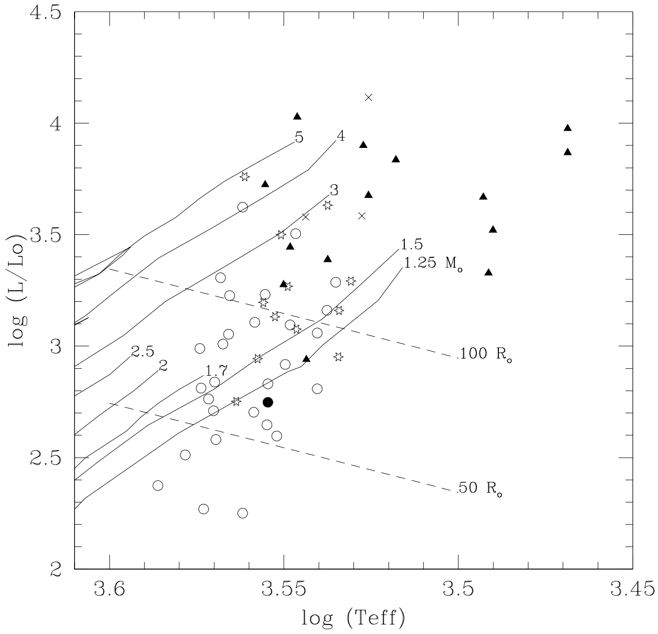


**Fig. 5.** Comparison of the location of M giants in binary systems (open circles) and Tc-rich S stars (filled triangles) in the HR diagram. The filled circle corresponds to the M giant HD 165374 which possibly hosts a WD companion. Star symbols correspond to Tc-poor S stars and crosses to S stars with Tc doubtful. The data for S stars are from Van Eck et al. (1998). For M stars, they are derived as explained in the caption of Table 1. The evolutionary tracks are from Charbonnel et al. (1996) for $Z = 0.02$ stars with masses 1.25 and 1.5 $M_\odot$, and from Schaller et al. (1992) for the more massive stars. In all cases, the tracks span the early AGB and stop at the first thermal pulse.

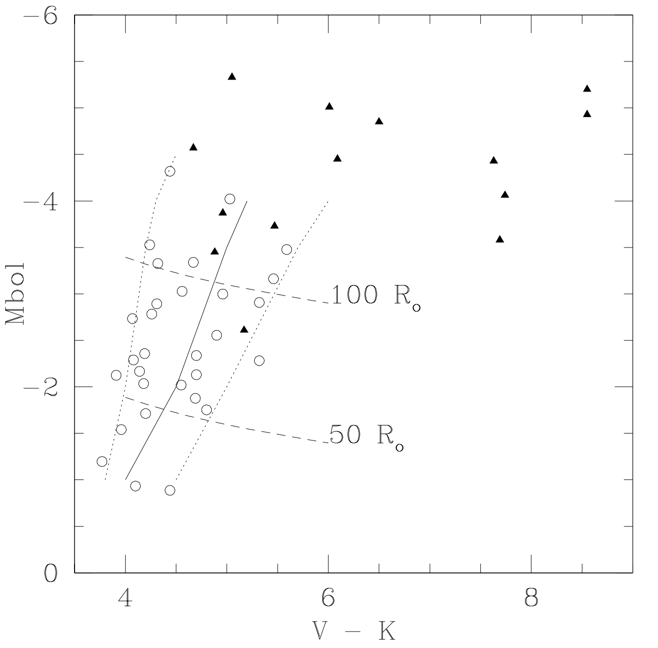


**Fig. 6.** Same as Fig. 5 but in terms of $V - K$ and $M_{\rm bol}$. The dotted lines delineate the region occupied by M giants. They define the range of possible stellar radii for a given $M_{\rm bol}$, used to construct the lower period bound from the Roche limit in Fig. 7.

This argument may actually be checked by locating M giants and post-AGB stars in the Hertzsprung-Russell (HR) diagram (Figs. 5 and 6) and comparing their location with that of Tc-rich S stars (from Van Eck et al. 1998), which are thermally-pulsing AGB (TP-AGB) stars enriched in s-process elements. Luminosities of post-AGB stars are extremely scarce. When available (e.g., from LMC objects and from a luminosity-period relationship for RV Tau stars calibrated on LMC stars; Alcock et al. 1998; de Ruyter et al. 2006) however, they are of the order of 4000 $L_\odot$ ($\log L/L_\odot = 3.6$). This luminosity lies in the middle of the range covered by Tc-rich S stars (Fig. 5), so that this argument does not really support a non-TP-AGB origin for post-AGB stars. However, the argument strongly relies on the adopted (uncertain) value for the typical luminosity of post-AGB stars.

### 2.3. Relation with S and barium stars

We now compare M giants in binaries with Tc-rich S stars. As expected, M giants are always less evolved than Tc-rich S stars. As already discussed by Van Eck et al. (1998), Tc-rich S stars are indeed found beyond the onset of the TP-AGB (i.e., to the right of the early AGB evolutionary tracks in Fig. 5). There is one exception, though [HIP 38502 = NQ Pup, a Tc-rich S star with $\log(L/L_\odot) = 2.9$], which illustrates the possible impact of biases when considering the individual locations of stars with non-negligible relative errors on their parallaxes (see Van Eck et al. 1998, and references therein). Nevertheless, overall, the segregation between Tc-rich S stars and M giants is very clear.

When M giants evolve further on the AGB, they will indeed turn into Tc-rich S stars, but at the same time are likely to become long-period variables (LPVs; Little et al. 1987). As discussed in Papers I and II, binary systems among LPVs are very difficult to detect for two reasons. First, given their large radii, only long-period systems may host them (see Fig. 4), but these systems necessarily have small values for the radial-velocity semi-amplitude $K$ (smaller than about 10 km s$^{-1}$; see Fig. 5 in Paper II and the discussion about Fig. 9.4 in Jorissen 2003a). Secondly, since they are LPVs, shock waves move across their atmospheres, and induce radial-velocity variations with amplitudes of 10 to 20 km s$^{-1}$ (Hinkle et al. 1997; Alvarez et al. 2001). Hence they are very difficult to detect. Spectroscopic binaries involving LPVs are not included in the present discussion since very few cases are known, and usually their orbital elements are not known (the supposed post-AGB + Mira system HD 172481 discussed in Sect. 2.2 is no exception). The list of AGB stars with composite spectra compiled by Jorissen (2003a) includes for instance the Tc-rich S stars W Aql, WY Cas and T Sgr, and the carbon stars SZ Sgr, TU Tau and BD -26°2983, but orbital periods are not known for them yet. Symbiotic stars hosting a Mira variable (the so-called d-type symbiotics; Allen 1982; Whitelock 1987) are perfect examples of binaries involving a very evolved AGB star. Schmid & Schild (2002) have succeeded in detecting the orbital motion of these systems using Raman polarimetry, and concluded that the orbital periods in these systems are of the order of 150 yr or 55 000 d. Intringuingly, Goldin & Makarov (2007) find a very short period of 141 d (from a fit to the Hipparcos Intermediate Astrometric Data) for the M5III semiregular variable star HIP 34922 (=HD 56096 = $L^2$ Pup), possibly a TP-AGB star since Little et al. (1987) find Tc to be possibly present. The period – eccentricity pair obtained by Goldin & Makarov (2007) ($P = 141 \pm 2$ d, $e = 0.52 \pm {}^{0.30}_{0.21}$) is, however, totally inconsistent with the values found for the other M giants in Fig. 2, so that its validity must be questioned, as discussed in the Appendix.

It must be emphasised at this point that *Tc-poor* S stars[7] (star symbols in Fig. 5) are *post-mass-transfer* systems, and as such, may not be directly compared to M giants and Tc-rich S stars. Nevertheless, the above discussion, stating that binaries involving Tc-rich S stars and LPVs should have long orbital periods, leads to a very surprising conclusion: extrinsic, Tc-poor S stars occupy the region of the $(e - \log P)$ diagram where binary *Tc-rich* S stars are expected (Fig. 1). This implies that *the mass-transfer episode must have had little impact on the orbital elements.* This is quite surprising at first sight, since either the orbital period must have shorten dramatically (for the so-called 'case C' RLOF) or it must have increased considerably (for wind accretion), according to standard evolutionary prescriptions (e.g., Boffin & Jorissen 1988). This conclusion is clearly not compatible with the present data, and calls for alternative mass-transfer prescriptions, as it was already known for quite some time. Jorissen (2003a), Frankowski & Jorissen (2007) and Podsiadlowski & Mohamed (2007) have proposed new avenues to explore. For instance, in the context of the 'transient torus' scenario proposed by Frankowski & Jorissen (2007), a near constancy of the orbital period is not unexpected.

If it is correct that the mass transfer process does not alter much the orbital period, then the existence of mild barium stars with rather short orbital periods (i.e., the open triangles to the left of the solid line in Fig. 2) may be explained by the fact that their polluting companion did not evolve far up the TP-AGB, hence the AGB envelope was not much enriched in s-process elements. This hypothesis is especially appealing since the other possibility, suggested by Jorissen & Boffin (1992) and Jorissen et al. (1998) – namely, that mild barium stars belong to a more metal-rich population than strong barium stars, because the s-process is more efficient in low-metallicity stars (Goriely & Mowlavi 2000) – has been dismissed by the detailed abundance analysis of mild barium stars by Smiljanic et al. (2007), who conclude that there is no obvious metallicity difference between mild and strong barium stars.

The intriguing absence of s-process enrichment in red symbiotics (e.g., Jorissen 2003b; Frankowski & Jorissen 2007), despite the fact that they are likely post-mass-transfer systems like barium stars, may perhaps be understood by invoking the

HD 42995 = $\eta$ Gem; Little et al. 1987), none has been flagged as exhibiting Tc lines (only in HD 2411 is the presence of Tc qualified as doubtful; note that this M3III star falls beyond the 200 $R_\odot$ tidal envelope in Figs. 1 and 2, i.e., in the region occupied by barium stars).

[7] Tc-poor S stars owe their chemical peculiarities to mass transfer in a binary system; they are thus called *extrinsic* S stars in what follows (Van Eck & Jorissen 1999).

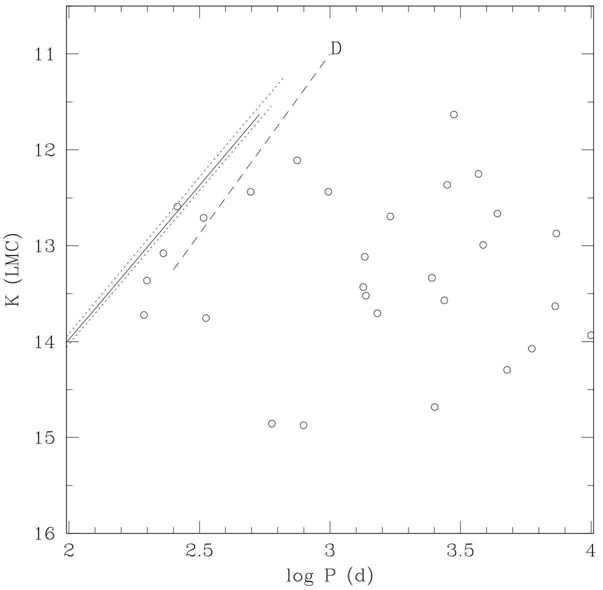


**Fig. 7.** The orbital-period as a function of (absolute) $K$ magnitude for galactic M giants in binary systems. The ordinate axis corresponds to the $K$ magnitude that the M giants would have if they were put at the distance of the LMC (see text). The dashed line labelled 'D' corresponds to Wood's sequence of long secondary periods. The solid and dotted lines correspond to the limit on the orbital period imposed by the Roche radius (for $M_1 = 1.3\ M_\odot$ and $M_2 = 0.6\ M_\odot$), for the stellar radii obtained from the Stefan-Boltzmann law applied on the $(V - K, M_{\rm bol})$ pairs defined by the same lines in Fig. 6.

same argument: as they fall in the same region as the (non-s-process-enriched) post-AGB stars in the $(e - \log P)$ diagram (Fig. 2), it is possible that their companion did not evolve far up enough on the AGB to activate dredge-ups and s-process.

### 2.4. Radius, period and Wood's sequence D in the period – luminosity diagram

Interestingly enough, our data may be used to shed light on the much debated nature of the so-called 'sequence D' found by Wood et al. (1999) and Wood (2000) in the period – luminosity diagram of LPVs in the Large Magellanic Cloud (LMC). This sequence (also called 'long secondary periods') is located to the *right* of the period – luminosity relationship for Miras pulsating in the fundamental mode ('sequence C'). Sequence D can thus not be associated with higher harmonics, which have *shorter* periods ('sequences A' and 'B'). A possible relation between Wood's sequence D and the Roche limit in binary systems (via ellipsoidal variations or dust obscuration events) was originally proposed by Wood et al. (1999) and Wood (2000), and more recently again by Soszyński et al. (2004), Derekas et al. (2006) and Soszyński (2007).

Fig. 7 is a variant of Fig. 4 that makes it easy to compare our data with the period – luminosity diagram of LPVs in the LMC (Wood et al. 1999; Wood 2000). The ordinate axis of Fig. 7 corresponds to the $K$ magnitude that our M giants would have if they were at the distance of the LMC, i.e., $K(\mathrm{LMC}) = M_K + 18.50$, where the McNamara et al. (2007) LMC distance modulus has been adopted. It is quite interesting to notice that Wood's sequence D does match the upper envelope of the region occupied by the galactic binary M giants. Our finding of a clear relationship between Wood's D sequence and the Roche limit in binary systems involving M giants supports the similar suggestion made by Soszyński et al. (2004) and Soszyński (2007).

### 2.5. Near absence of circular orbits among M III binaries

A striking difference between K and M giants apparent on Fig. 1 is the *lack, among binaries involving M giants, of the many circular systems at the short end of the period range that are observed among the K giants*. The short-period circular systems observed among K giants result from tidal effects which circularise the orbit when the giant star is close to filling its Roche lobe (e.g., North & Duquennoy 1992). The difference between K and M giants is surprising, since both stellar families involve stars with deep convective envelopes which should react similarly to tidal effects. M giants, however, have shorter lifetimes than K giants, because the former suffer from a much more severe wind mass loss, and this difference offers perhaps a clue to account for the differences observed at short periods in their $(e - \log P)$ diagrams. Tidal forces may not have enough time to efficiently operate in the case of M giants. Indeed, the many circular systems observed among post-AGB stars seem to be the circular population missing among the M giants. This hints at mass loss and tidal effects operating on similar time scales: shortly after the system has been circularised, the envelope is lost and the primary star no longer looks as an M giant but rather as a post-AGB star. The very existence of a system like SS Lep does lend support to the above suggestion. In Fig. 8 investigating a possible correlation between dust excess and position of the binary M giants in the $(e - \log P)$ diagram, SS Lep, having a large $K - [12]$ excess, appears as the big circle along the tidal boundary.

Similarly, it is interesting to note that circular orbits are common among red symbiotics as well, albeit with somewhat longer periods. The implications of this result actually depend on whether the red symbiotics are pre-mass-transfer systems (i.e., with a main-sequence companion) or post-mass-transfer systems (i.e., with a WD companion). This issue has not been solved yet (Frankowski & Jorissen 2007). In the former case, the longer periods are simply a consequence of the fact that the M giants in red symbiotics are on average of later types (i.e., later than M3) than those in our binary sample (Belczyński et al. 2000). Hence, they cannot be hosted by systems as close as those hosting earlier giants (Fig. 7). The absence of s-process enrichments in those red symbiotics – another puzzling issue (Jorissen 2003b; Frankowski & Jorissen 2007) – would then be explained naturally as previously for the post-AGB stars: the M giant has simply not yet reached the TP-AGB phase. In the latter case (the companion is a WD), the orbital periods fall in the short-period tail of the distribution of periods for post-mass-

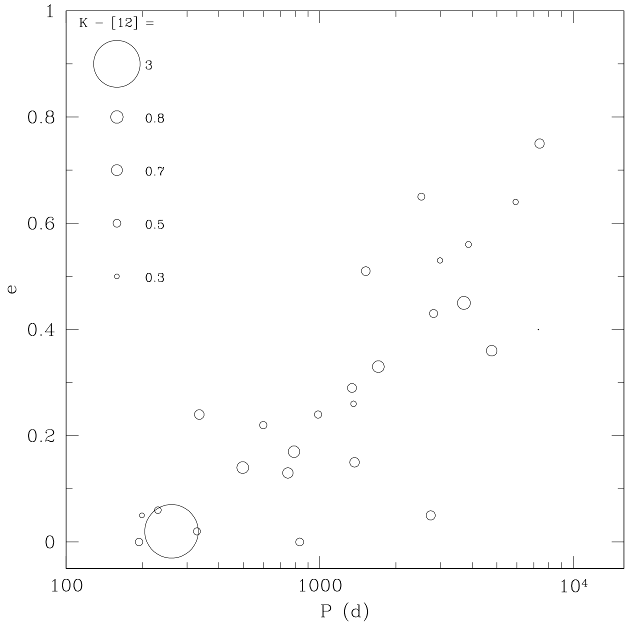


**Fig. 8.** The $(e - \log P)$ diagram for M giants, where the symbol size is proportional to the infrared $K - [12]$ index, indicative of the presence of dust in the system. The $K$ magnitude is from 2MASS, and $[12] = -2.5 \log(F12/28.3)$ is the magnitude associated with the IRAS 12 $\mu$m flux. $K - [12]$ of the order 0.3 – 0.5 is expected for non-dusty stars.

transfer systems like Tc-poor S stars, as expected, but then, the absence of s-process enrichment is puzzling unless these systems had not very evolved AGB progenitors.

### 2.6. The long-period, small-eccentricity gap in the $(e - \log P)$ diagram

To conclude this discussion of the $(e - \log P)$ diagram, it must be pointed out that, for *pre*-mass-transfer binaries hosting main sequence stars, there is a void in this diagram at $P > 400$ d, $e < 0.1$. This gap is especially apparent in the $(e - \log P)$ diagram of G and K dwarfs of the solar neighbourhood (Duquennoy & Mayor 1991). The situation is quite different for *post-mass-transfer* systems like barium and Tc-poor S stars. Figure 1 of North et al. (2000) clearly shows that barium dwarfs fall almost exclusively within this gap. Similarly, Barium and Tc-poor S stars fill this gap almost completely (Fig. 2). Red symbiotics fill the gap till 1000 d with circular systems, but as discussed in Sect. 2.5, this may result as well from tidal effects.

There are in fact a few binaries involving K and M giants (most notably HD 165374, with $P = 2741$ d, $e = 0.05$ and a M2III primary) which fall in the long-period tail of this gap, as can be seen on Fig. 2. It is very likely that these systems are in fact *post*-mass-transfer binaries, a possibility that would be worth testing by looking for Ba-like abundance anomalies in these giants.

An indirect way to confirm the *post*-mass-transfer nature of the binaries with long periods and small eccentricities is to look for the presence of WD companions. McClure & Woodsworth (1990) have convincingly shown that the cumulative distribution of the mass functions may be used for that purpose: since WDs have masses spanning a rather narrow range (0.5 – 1.4 $M_\odot$, with a peak around 0.6 $M_\odot$, at least for *single* WDs), the mass functions of binaries involving a giant primary and a WD secondary may be expected to be much more peaked than in the case of main-sequence companions, which do not obey a similar constraint on their masses (except for being less massive than the primary, giant component). This is illustrated on Fig. 9, which compares the cumulative mass-function distributions for M giants, K giants in open clusters (Mermilliod et al. 2007) and S stars with WD companions (Jorissen et al. 1998). The sample of M giants may clearly be split in two subsamples, one with small mass functions matching those of Tc-poor S stars with WD companions, and the other with larger mass functions typical of main-sequence companions, like the remarkable system SS Lep discussed in this paper ($f(M) = 0.26\ M_\odot$).

Conversely, with a mass function of 0.078 $M_\odot$, HD 165374 could certainly host a WD companion of (minimum) mass 0.73 $M_\odot$ (respectively 0.78 $M_\odot$), adopting a mass of 1.5 $M_\odot$ (respectively 1.7 $M_\odot$) for the M2 giant, according to its location in the HR diagram of Fig. 5.

HD 108907 (4 Dra) is probably a post-mass transfer system as well, since it hosts a blue, hot companion, either a cataclysmic variable (Reimers et al. 1988) or more likely a single WD accreting from the wind of its red giant companion, as in normal symbiotic systems (Wheatley et al. 2003; Skopal 2005a,b). Its position in the $(e - \log P)$ diagram ($e = 0.33, P = 1703$ d) does not by itself hints at its post-mass-transfer nature, although it lies just at the border of the region occupied by barium and Tc-poor S stars, and close to that of the mild barium stars discussed above. It does not seem, however, to bear chemical anomalies typical of barium stars. It may therefore be yet another example of a system containing all the necessary ingredients for being a barium star, but which is not. Again, one may invoke the possibility that the AGB progenitor did not evolve far enough on the TP-AGB.

Sect. 3 furthers the considerations of the present subsection by showing that the long-period, low-eccentricity region of the $(e - \log P)$ diagram mostly contains systems with small mass functions hinting at WD companions.

## 3. A clear signature of mass transfer in the $(e - \log P)$ diagram of binaries involving K giants in open clusters

Mermilliod et al. (2007) provided an extensive set of orbital elements for 135 spectroscopic binaries with K giant primaries belonging to open clusters. The major asset of this sample, over one involving field K giants as available from the Ninth Catalogue of Spectroscopic Binary Orbits (Pourbaix 2004), is that the mass of the K giant is known: with a good accuracy, it may be identified with the cluster main-sequence turnoff mass (it is therefore essential to keep only cluster members in our study). A lower bound on the mass of the companion may then be easily obtained from the mass function $f(M)$ by setting $\sin i = 1$. The distribution of the companion masses in different

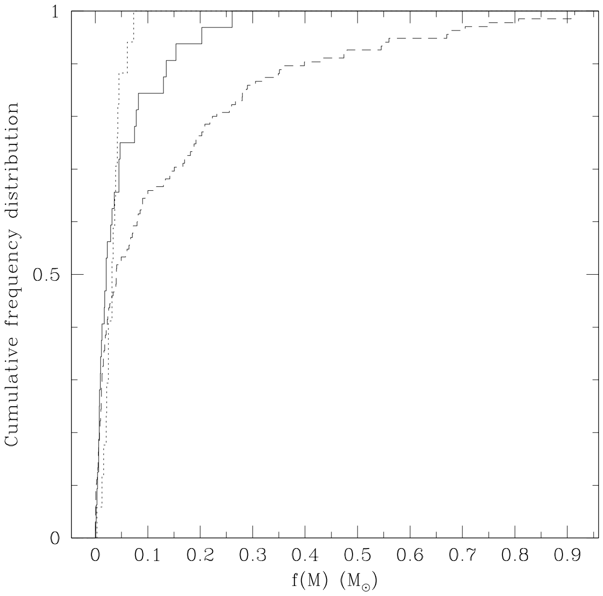


**Fig. 9.** The cumulative distribution of the mass function for M giants (solid line), K giants from open clusters (dashed line; Mermilliod et al. 2007) and S stars with WD companions (thus excluding the peculiar systems HD 191589 and HD 332077; Jorissen et al. 1998, dotted line).

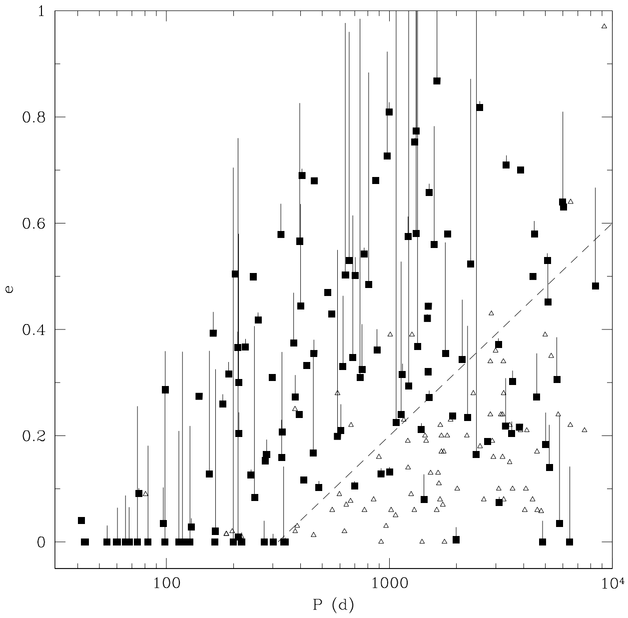


**Fig. 10.** The eccentricity–period diagram for spectroscopic binaries involving K giants in open clusters (filled squares; Mermilliod et al. 2007), and Ba and S stars (open triangles, from Jorissen et al. 1998). The vertical segments have lengths corresponding to mass functions expressed in solar masses. The diagonal dashed line delineates the region where most of the Ba/S stars are found.

regions of the $(e - \log P)$ diagram may then be compared. An obvious way to divide the $(e - \log P)$ diagram is through the line of equation $e = 0.4 \log P - 1$ [connecting the $(e, \log P)$ pairs (0, 2.5) and (0.6, 4)] under which lie most of the barium and Tc-poor S stars (Fig. 10). The results of this procedure is shown in Figs. 11 and 12.

It is quite clear already from Fig. 10 that the systems involving K giants and located in the same region of the $(e-\log P)$ diagram as the barium and Tc-poor S stars have a mass-function distribution which is significantly different from the distribution of the full sample. This is confirmed by Fig. 11. Moreover, these systems lying in the post-mass-transfer region have companions masses below 1.5 $M_{\odot}$ (with one exception discussed below), and peaking at 0.5 $M_{\odot}$, as expected for WD companions (Figs. 11 and 12). Since most of the clusters making up this supposedly post-mass-transfer sample have turn-off masses well *above* 1.5 $M_{\odot}$, the 1.5 $M_{\odot}$ threshold observed for the companion masses cannot be due to a selection effect. Star 170 (with $P = 2457 \pm 5$ d, $e = 0.16 \pm 0.01$ and $f(M) = 0.91 \pm 0.04\ M_{\odot}$) in NGC 129 (a young cluster with a turnoff mass of 5.5 $M_{\odot}$; Mermilliod et al. 1987) is the only outlier, with a $> 4.5\ M_{\odot}$ companion in a KII + BV pair.

With a maximum vertical distance of 0.25 between the cumulative frequency distributions of the two samples displayed in Fig. 11 (containing 29 and 106 stars), the Kolmogorov-Smirnov statistics leads to reject the null hypothesis that the two samples are extracted from the same parent population with a significance level of 10% (Performing the same comparison without star 170 in NGC 129 yields a maximum difference of 0.29 and a significance level of about 4%).

## 4. Conclusions

The main results of this paper are the following:

1. The $(e - \log P)$ diagram of pre-mass transfer binaries like most of the K binaries in open clusters and the binary M giants is bounded by an upper left envelope corresponding to a constant periastron distance. This distance corresponds to the maximum radius reached at a given spectral type, as shown from the similar boundary observed in the radius – orbital period diagram. Systems lying along that boundary often host a giant (nearly) filling its Roche lobe, and exhibiting either ellipsoidal variations (HD 9053, HD 190658) or mass-transfer signatures (like an inflated companion; SS Lep). The mass-transfer binary SS Lep (MIII + A), with its circumbinary disc most probably fed by non-conservative RLOF, represents a transition case between binary M giants and genuine post-AGB stars.
2. Systems similar to SS Lep and HD 172481, hosting an accreting star mimicking a (super)giant star, should be searched for among post-AGB systems lying along the upper envelope of the $(e - \log P)$ diagram. We suggest that the family of binary post-AGB stars might include systems in an active phase of mass transfer, where the accreting component has swollen to giant dimensions, thus mimicking a genuine post-AGB star.
3. The so-called Wood's sequence D in the period – luminosity diagram of LMC LPVs is closely linked to the upper envelope of the $(e - \log P)$ diagram for M giants.
4. The post-mass transfer systems like barium and Tc-poor S stars have orbital elements very similar to the pre-mass-transfer systems (binary M giants), suggesting that the mass transfer does not alter them much, in line with the new transient-torus

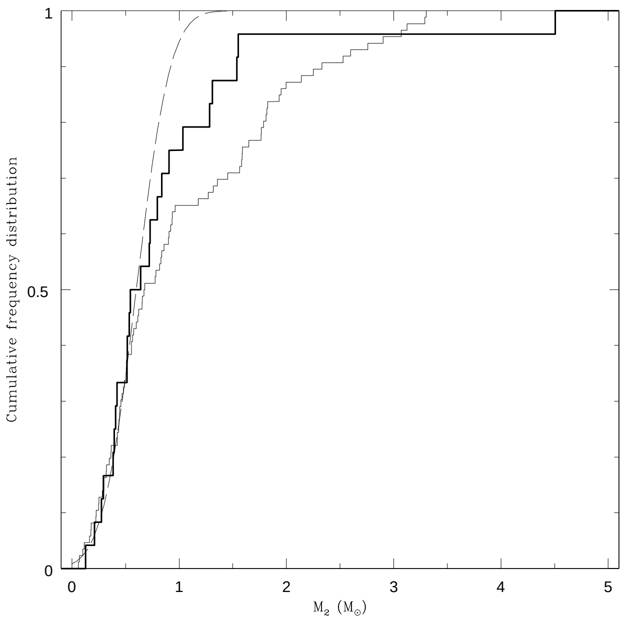


**Fig. 11.** The cumulative distribution of the companion masses for open-cluster K binaries, assuming an inclination of 90° for all systems (the plotted masses thus represent a lower bound to the true values): thick solid line: systems located in the post-mass-transfer region of the $(e - \log P)$ diagram, i.e., in the lower-right region below the dashed line plotted on Fig. 10; thin solid line: supposedly non-post-mass-transfer systems (i.e., located above the dashed line of Fig. 10); dashed line: for a gaussian distribution centered on 0.6 $M_\odot$ with a standard deviation of 0.25 $M_\odot$.

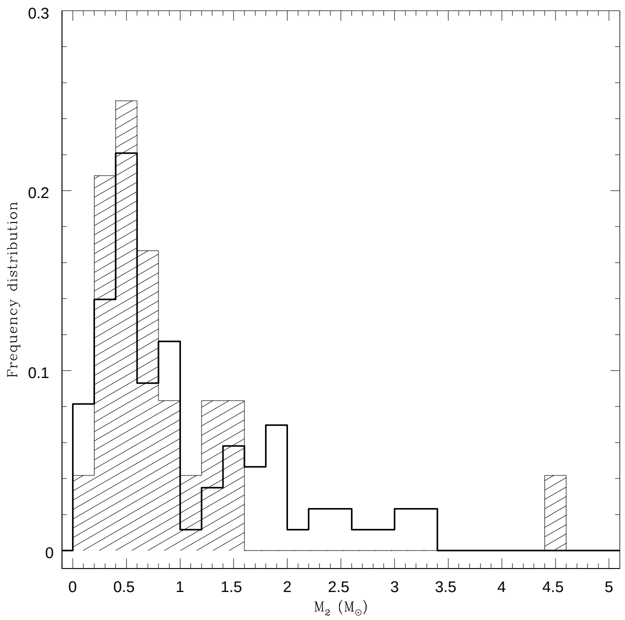


**Fig. 12.** Same as Fig. 11, but in the form of histograms (thick solid line: systems in the non-post-mass-transfer zone; thin solid line and shaded histogram: post-mass-transfer systems). In the post-mass-transfer region, all companions are less massive than 1.5 $M_\odot$, in accordance with the expectation for WDs, except for the companion to star 170 in NGC 129, which is a young cluster with a turnoff mass of 5.5 $M_\odot$.

scenario for mass transfer proposed by Frankowski & Jorissen (2007).

5. The lower right region of the $(e - \log P)$ diagram, as defined by the location of the barium and Tc-poor S stars, host mainly post-mass-transfer systems, also among K binaries in open clusters. This is very clearly seen from the fact that these systems have low mass functions consistent with WD companions. Whether these giants bear chemical signatures of mass transfer as do barium stars remains to be checked.

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## Appendix. Dismissing the binary nature of L2 Pup

The intringuing finding by Goldin & Makarov (2007) of a very short period of 141 d in the Hipparcos Intermediate Astrometric Data for the M5III semiregular variable star HIP 34922 (=HD 56096 = $L^2$ Pup) deserves a specific discussion. This 141 d period is clearly related to pulsation, since that periodicity is found in both the light and radial-velocity curves (Cummings et al. 1999; Lebzelter et al. 2005). The light curve has a large amplitude (about 2.5 mag in the visual), which cannot therefore be attributed to ellipsoidal variations. According to Lebzelter et al. (2005), the 141 d period moreover falls on sequence C of the period-luminosity diagram of Wood (2000), which corresponds to the fundamental pulsation mode of long-period variables (see Sect. 2.4). Assuming that the 141 d period corresponds as well to an orbital motion (in the case of a tidal lock between orbital motion and pulsations) leads, however, to major inconsistencies. The absolute semi-major axis for the photocentre of the system, inferred from Goldin & Makarov's angular value $a_0 = 9.5$ mas and from the parallax of $\varpi = 16.5$ mas, is 0.58 AU, which may be considered as the absolute semi-major axis of the orbit of the giant if one assumes that the companion contributes no light to the system. According to Dumm & Schild (1998), the minimum radius of an M5 giant is 60 $R_\odot$ (but the radius predicted by Dumm & Schild from the Barnes-Evans relationship for $L^2$ Pup is more like 125 $R_\odot$; Barnes & Evans 1976). The giant could just fit in the binary system, filling its Roche lobe at periastron, assuming a reasonable mass ratio of 1.5 and implying a semi-major axis $A = 1.45$ AU for the relative orbit. But then, according to Kepler's third law, the total mass of the system would be 20.4 $M_\odot$, or 12.2 $M_\odot$ for the giant and 8.2 $M_\odot$ for its companion, which is inconsistent with the M5III classification of the former. We thus conclude that, although the Hipparcos data are clearly inconsistent with a single point source (with residuals from the single-star solution amounting up to 10 mas), Goldin & Makarov's astrometric orbit is impossible to reconcile with current knowledge about this system. It could well be that the Hipparcos data have been confused by the asymmetric surface brightness typical of late-type stars (Ragland et al. 2006), especially so for a star as extended as $L^2$ Pup having a (predicted) apparent angular radius of 9.6 mas (Dumm & Schild 1998). A further argument *against* the binary nature of $L^2$ Pup is the detection of all three masers SiO, $H_2O$ and OH (Jura et al. 2002), since a binary companion, when orbiting in the layers where the maser activity should originate, prevents its operation (Herman & Habing 1985; Lewis et al. 1987; Schwarz et al. 1995).