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The elusive nature of the R stars

I. Domínguez[1], L. Piersanti[2], R. Cabezón[3], O. Zamora[1], D. García–Senz[3], C. Abia[1], and O. Straniero[2]

[1] Departamento de Física Teórica y del Cosmos, Universidad de Granada, 18071 Granada, Spain
[2] INAF-Osservatorio Astronomico di Collurania, 64100 Teramo, Italy
[3] Departament de Física i Enginyeria Nuclear, Universitat Politécnica de Catalunya, Diagonal 647, 08028 Barcelona, Spain

Abstract. R stars are carbon stars, less luminous and hotter than the carbon stars evolving along the AGB phase. Thus, their carbon enrichment cannot be a consequence of the third dredge-up, a fact also in agreement with the lack of *s*-element enhancements in their envelopes. Since their discovery the absence of binaries has lead to the conclusion that a previous merger might play a fundamental role in the observed chemical composition, likely through non-standard mixing at the time of the He-flash. On the other hand numerical simulations, in which the He-flash is artificially located close to the edge of a degenerate He core, have successfully induced mixing of carbon into the envelope. In this context it has been suggested that the merger of a degenerate He core with that of a normal red giant star could lead to the formation of a rapidly rotating core undergoing off-centre He ignition in highly degenerate conditions. This scenario is also supported by statistical analysis of the potential mergers that could explain the number, and location in the Galaxy, of observed R stars. Basing on detailed stellar models we will show the evolution of these mergers, that are very common in nature, and do not seem to be the progenitors of (hot) R stars.

Key words. Stars: abundances – Stars: binaries – Stars: chemically peculiar – Stars: carbon – Stars: evolution – Stars: rotation

1. Introduction

R-type stars are carbon stars, chemically characterized by C/O $>$ 1 (by number) in their envelopes. This is a peculiar characteristic: in the Sun C/O $\approx$ 0.5. R-stars are further classified in to two groups (Shane 1928): R0-4 (hot, early R stars) equivalent to K-type giants and R5-8 (cool, late R stars) equivalent to M stars.

A sample of R-type stars have been recently analyzed (Zamora et al. 2009) using high-resolution optical spectra. They confirm that only early, hot R stars should be consider as R-type stars, as late, cool R stars are normal (N-type) AGB carbon stars. They also confirm, in agreement with the sole previous abundance analysis by Dominy (1984), that hot R stars are carbon stars with near solar metallicity showing enhanced nitrogen, low ^{12}C/^{13}C ratios and no *s*-element enhancements. In addition, derived Li abundances are larger than expected for post RGB tip giants. It was also found that a significant number ($\sim$ 40%) of the

Send offprint requests to: I. Domínguez

Table 1. Summary of (hot) R-stars observed properties (from Zamora et al. 2009).

T_{eff} (K)	3800 – 4600
L	$L_{C(N)}/10$
[M/H]	-0.77 – 0
C/O	0.8 – 3
$^{12}C/^{13}C$	5 – 20
[N/H]	0.1 – 1
ϵ(Li)	0.5 – 1
No s-element enhancements	
No evidence of O-depletion	
No binaries	

hot-R stars were wrongly classified, being classical CH stars and normal K giants.

An important observational constraint comes from their observed luminosities: they are above 10 times less luminous than normal AGB carbon stars (e.g. Scalo 1976), being located in the H-R diagram at the same place as the red clump stars (Knapp et al. 2001; Perryman & ESA 1997). Thus, they are He-core burning stars or post helium core stars, in agreement also with the lack of *s*-element enhancements in their envelopes. Note that "normal" intrinsic carbon stars are AGB stars: it is along this phase that their envelopes are enriched in C and *s*-elements through the action of the 3rd dredge-up.

Finally, a surprising figure is that no R star has been found so far in a binary system (McClure 1997) although a minimum of $\sim$ 30% binary systems is expected in any stellar population. McClure (1997) suggested that R stars were initially all binaries that coalesced into a single object during their evolution.

How a *single* giant star (coming or not from a merging) and not luminous enough to be on the AGB phase, shows C/O > 1 at the surface is still a mystery. The mentioned observed properties are summarized in Table 1.

2. Mixing at the He-flash

The first suggestion of mixing at the He-flash was proposed by Schwarzschild & Härm (1962) and, since then, a lively discussion about the properties and correct treatment of the He-flash (i.e. Härm & Schwarzschild 1966; Despain 1982) has been going on. Recently 3D hydrodynamical simulations (Dearborn et al. 2006; Lattanzio et al. 2006; Mocák et al. 2008; Mocák 2009) have shown that the properties of the He-flash do not differ significantly from the 1D hydrostatic calculations. These results are in agreement with observations: the majority of the low-mass stars pass through the He-flash without substantially altering their physical structure or surface chemical composition.

Looking for special conditions able to produce a non-standard He-flash, the location of He-ignition was moved *ad hoc* towards the outer part of the He-core (Paczynski & Tremaine 1977) and in this way a dredge-up leading to mixing was obtained. This is like the 3rd dredge-up mechanism. However, it is difficult to imagine a real physical situation that would lead to this effect without altering other properties of the He-core and happening only in some cases. For example, if the energy losses due to axions are included (Domínguez et al. 1999), the location of the He-ignition is shifted outwards by an amount that depends on the assumed axion mass. In a similar way, a successful mixing has been obtained increasing artificially the neutrino energy losses until He-ignition occurs close enough to the edge of the He-core to produce carbon dredge-up (Angelou & Lattanzio 2008). However, as in the case of axions, all stars undergoing the He-flash would be affected in a similar way. Moreover, a dredge-up would not lead to the observed enhanced nitrogen and low $^{12}C/^{13}C$ ratios.

The situation is completely different for Z=0 models (Fujimoto et al. 1990; Hollowell et al. 1990), in this case mixing occurs in the standard evolutionary calculations but it is a consequence of the lack of CNO elements in the H-shell and thus, it cannot be extrapolated to more metal-rich models. However, note that this type of mixing, in which protons are engulfed by the hot deeper layers, may produce the observed enhanced nitrogen and low $^{12}C/^{13}C$ ratio.

2.1. Including rotation at the He-flash

Mengel & Gross (1976) included rotation in their evolutionary calculations of low-mass stars and found that rotation led, in a natural way, to an off-centre He ignition. Faster rotators ignite He further from the centre, thus only in few cases would the standard evolution be significantly altered. However, their faster model, with a rotation period at the centre of 0.58 minutes, does not lead to mixing. In that model the mass of the He-core is increased by 0.14 $M_\odot$ while the mass coordinate at which He is ignited changes only by 0.09 $M_\odot$, being finally further from the edge of the He-core than in the standard case (as Luciano Piersanti likes to say, rotation is "democratic").

In spite of this, it is nowadays assumed that the C-enrichment of the envelope is related to rotation. In favour of this idea is the fact, previously quoted, that R stars are not found in binaries (McClure 1997), leading to the conclusion that they are the product of a merger and mergers are known to produce fast rotators. On the other hand, (a) observational evidence shows enhanced nitrogen and low $^{12}C/^{13}C$ ratios and this property could not be fulfilled by a 3rd dredge-up like mechanism and (b) a merger can significantly alter the physical structure of the He-core, as will be shown in this work.

3. Mergers and selected models

Based mainly on the idea that the absence of binarity implies a previous merger (McClure 1997), Izzard et al. (2007) explored statistically the different binary scenarios that might produce R stars. They discuss different channels, the most favourable being the merger of a He white dwarf (He-WD) with a red giant (RG) star. A fast rotating He-core is expected to be formed after the merger and it is then assumed that, as a consequence of rotation, a strong He-flash would be ignited off-centre, close to the H-shell and provoking somehow the mixing of carbon into the envelope. However this sequence of events has never been studied in detail before.

We select three systems among all the possible ones representing this channel in Izzard et al. (2007), see their Fig. 2. In Table 2 we show the mass of the RG (M_{RG}) and its core (M_{RGcore}), the He-WD mass (M_{WD}), the separation (A) and the residual mass (M_{fin}, core plus envelope) of the RG before the merging (see next Section).

4. Numerical simulations

In the merging scenario three different phases can be distinguished: 1) the coalescence, during which the two degenerate components spiral in during the common envelope phase, 2) the merging itself, corresponding to the formation of an accretion disk around one of the degenerate cores, and 3) the accretion, *i.e* the deposition of mass from the disk to the He-core.

4.1. Stellar evolution and the coalescence phase

We follow the evolution of the "future" RG from the main sequence phase up to the onset of the common envelope phase. These models are computed by means of the 1D hydrostatic code FRANEC (Chieffi & Straniero 1989), adopting as initial chemical composition Z=0.02 and Y=0.28 (solar composition); we use the metal distribution derived by Piersanti et al. (2007) for the Grevesse & Sauval (1998) mixture and, consistently, we adopt for the mixing length parameter the value $\alpha = 2.25$. All the input physics (namely, equation of state and radiative opacity coefficients) are the same as in Piersanti et al. (2007). The contribution of electron conduc-

Table 2. Properties of the selected models before the merging. Masses are in $M_{\odot}$.

M_{RG}	1.4	1.3	1.2	
M_{RGcore}	0.19	0.20	0.17	
M_{WD}	0.20	0.15	0.38	behav
A ($R_{\odot}$)	20	20	16	
M_{fin}	0.76	0.75	0.78	

tion to the opacity is evaluated according to Potekhin et al. (1999).

4.2. Dynamical merger

To simulate the dynamical stages of the merging of the RG star and the He-WD we have performed 3D hydrodynamical simulations using the smoothed particle hydrodynamics technique (SPH) for the second model shown in Table 2, M_{WD}=0.15 and M_{RGcore}=0.20 $M_{\odot}$. For details see Piersanti (2010).

Once the He-WD radius becomes equal to the Roche-lobe radius the mass transfer increases and the evolution becomes very dynamical. To follow that phase with SPH, the 1D structure coming from the previous phase was mapped to a 3D distribution of mass-particles. We have used $N = 50,000$ particles and $N = 36,833$ particles to describe the RG and the He-WD, respectively. With that choice we were able to resolve four orders of magnitude in density which is insufficient to include the H-envelope of the giant.

The less massive He-WD star is accreted by the RG-core, producing a positive feedback due to the increase of the gravitational potential of the RG-core and because, being a degenerated system, the mass lost by the He-WD produces an expansion of its radius favouring the mass transfer. When the He-WD has lost about 0.02 $M_{\odot}$ a fast decompression occurs leading to a rapid merger of the system, which happens within one orbit ($t \approx$ 3400-3600 s). Mass accretion rates are very high, above 10^{-5} $M_{\odot}$/s. In the moment of disruption the accreted mass achieves its maximum temperature and lowest density, 1.6×10^8 K and 5300 g/cm^3. These values are not high enough for efficient He-ignition.

Due to the strong restriction to the time-step imposed by the Courant time, simulations are limited to these dynamical stages, two hours of the real evolutionary time of the system. At this time the debris of the He-WD forms a Keplerian disk around a fast rotating core.

4.3. Accretion from the disk and subsequent evolution

We compute the accretion phase under the reliable assumption that no direct interaction of the envelope with the inner structure occurs at all. This is based on two facts: (a) the inner structure (He-core plus accretion disk) evolves on a very short timescale as compared to the evolutionary timescale of the extended envelope and (b) the accretion disk can be regarded as a sort of discontinuity in the system, insulating the accreting core from the H-rich envelope.

5. Results

Matter falling onto the He-core deposits angular momentum and delivers thermal energy by compression. Compression increases the local temperature while rotation lifts and cools the structure. To disentangle both effects, we compute models neglecting and including the transfer of angular momentum from the disk to the He-core. Moreover we also assume different values for the efficiency of the transport of angular momentum (for details see Piersanti 2010) that lead to differential and rigid rotation of the core. The results of these three numeri-

Table 3. Selected properties of rotating models at the He-flash under different assumptions for the transport of angular momentum. Masses are in $M_{\odot}$.

	No-rot	Rigid-rot	Diff-rot
$M_{He-core}$	0.40	0.41	0.47
M_{He-ig}	0.12	0.04	0.00
ΔM_{fl}	0.24	0.36	0.45

Table 4. C-rich RR Lyrae stars and (hot) R-stars (data for RR Lyrae stars from Wallerstein et al. 2009).

	[Fe/H]	C/O	[C/Fe]	[N/Fe]	[O/Fe]
KP-Cyg	+0.18	1.7	0.52	0.9	-0.07
UY CrB	-0.40	0.83	0.65	1.26	+0.59
(hot) R-stars	-0.28	1.6	0.53	0.60	?

cal experiments are summarized in Table 3, labeled “No-rot”, “Diff-rot” and “Rigid-rot”, respectively. In Table 3 we report $M_{He-core}$, the He-core mass at He-ignition, M_{He-ig}, the mass coordinate where the first He-flash is ignited and ΔM_{fl}, the maximum extension of the flash-driven convective shell.

As it is shown in Table 3, He-ignition occurs further from the edge of the He-core when rotation is included. Moreover, all the merging-models are hotter and thus, less degenerate, and experience weaker He-flashes, as compare to the standard evolution of low-mass stars. In all of them, the He-convective shell is well confined inside the core.

We realize that conditions favouring mixing are unlike to occur: in those models in which the He-WD is the less massive object (first two models in Table 2), He-ignition occurs after the accretion process has finished and the H-shell is active again, thus representing an entropy barrier that excludes the penetration downward of the convective envelope. At the other hand, in the model in which the RG is accreted by the more massive He-WD (third model in Table 2) the accretion disk insulates the core until the H-shell is reignited.

6. Conclusions

In this work we have explored the result of the merging of He-WDs with RGs. These systems are very common in nature (Izzard et al. 2007) and have not been studied in detail before (see Iben (1990) for He-WD mergers without rotation and Guerrero et al. (2004) for SPH simulations). We were able to perform 3D SPH simulations for the first two hours of the merging. These simulations show the fast rotation acquired by the He-core and the absence of nuclear burning during this dynamical phase of the merging.

The obtained 1D physical structures are very different (density, temperature and angular momentum) as compare to the standard RG evolution of low mass single stars. However, these differences do not favour mixing of carbon into the envelope in the way suggested by previous works: He-ignition is located further from the He/H interface, in fact it is located closer to the centre, and the He-flashes are weaker as compare to the standard evolution. Moreover the H-shell is active at He-ignition, insulating the core from the envelope and/or the He convective shell is well confined within the core.

We end without progenitors for (hot) R stars. However, Wallerstein et al. (2009) have found several carbon-rich (C/O > 1) RR Lyrae stars with similar N enhancements to those in (hot) R-stars (see Table 4 for a summary of observed properties) and suggest that their observed peculiarities are consistent with carbon mixed to the surface during the He-flash. This subject deserves a new insight and more investigation.

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