Mem. S.A.It. Vol. 77, 973

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The chemical composition of R-stars

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Abstract. The preliminary results of the chemical analysis of a sample of 22 galactic R-stars with measured parallaxes are presented. We have derived the C/O and $^{12}C/^{13}C$ ratios, the average metallicity ([M/H]) and the Li abundances. We find that most of the stars have $^{12}C/^{13}C$ below ~ 20 with no significant difference between cool and hot R-stars. The C/O ratio ranges between ~ 1 to 2. We obtain a clear separation in the Li abundance between hot and cool R stars, with a mean value of log ϵ(Li) = +0.90 and log ϵ(Li) = −0.50, respectively. Cool stars are of near solar metallicity whereas hot stars show a larger spread, $-0.5 \leq$ [Fe/H] $\leq +0.1$. Concerning the possibility of s-element enhancements, we obtain [Rb/M] > 0 in seven hot stars and in three of them (R-hot) the analysis of the 5924 Å TcI line might be compatible with Tc detection. However, the detection of other s-element enhancements is necessary to elucidate the evolutionary stage of these carbon stars of which origin is still unknown.

Key words. Stars: carbon stars – Stars: abundances – Stars: nucleosynthesis

1. Introduction

The R-stars are carbon stars (C/O > 1) belonging to the galactic disk (Stephenson 1973). Spectroscopically there are two different types of R stars (Gordon 1967): the early or hot (spectral types R0-R5) showing atomic-line spectra equivalent to the G9-K2 normal giant stars, and the late or cool (spectral types R6-R9) with spectra equivalent to M3 or later. In number, the hot R-stars represent $\sim 1\%$ of the disk G-K giants (Knapp et al. 2001) and are 10 times as numerous as normal (C(N)) thermally pulsating AGB carbon stars (Blanco 1965). The pioneer chemical analysis by Dominy (1984) of a few hot R-stars found no evidence of s-element enhancements, low carbon isotopic ratios $^{12}C/^{13}C \sim 7$, near solar metallicity, some carbon enhancement [C/H]$\sim +0.46$, and non detectable Li. However, up to now the chemical composition of cool R-stars is unknown, leaving unchecked the idea that they are the descendants of the hot R-stars.

Using Hipparcos parallaxes, Knapp et al. (2001) placed accurately the R stars in the H-R diagram. They found that the hot R-stars occupy the region of the red clump stars (i.e., core He burning stars) whereas the cool ones are on average redder [(H–K)> 0.3, $(V–K)_0 > 4$], some of them being in the region of C(N)-AGB stars. These authors also noted that the hot R-stars do not present significant dust emission and are non variable in general. However, some of the cool R-stars do show variability and dust emission (K–[12]> 0.7), probably indicating

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large mass loss rates and an advanced evolutionary stage.

The origin of the carbon enhancement in R-stars remains a mystery. Dominy (1984) argued that the carbon enhancement in the hot R-stars might be produced by a strong non-standard mixing process during the He-flash or, alternatively, to the coalescence of two stars in a binary system. From studies on the helium flash (see e.g. Deupree 1984) it is known that the canonical flash cannot produce a carbon star, although Paczynski & Tremaine (1977) obtained C/O > 1 in the surface modelling an anomalous off-centre He-flash. Concerning the coalescence scenario, McClure (1997) searched for radial velocity variations in a sample of 22 R-hot stars and found no evidence of binarity. However, because it is very difficult to understand the absence of binary systems among a given population of stars, he concluded that R-hot stars were all merged binaries. No similar study has been done yet for the cool ones.

A full chemical analysis of R-stars and the study of new evolutionary scenarios are needed to solve this mystery. We present here the preliminary result of the chemical analysis of a sample of 22 galactic R-stars.

2. Observations

The sample is composed by 22 bright ($V \leq 10$) R-stars selected from the Hipparcos catalogue with their parallaxes corrected according to Knapp et al. (2001). They were observed at optical wavelengths using the echelle spectrograph FOCES at the 2.2 m telescope CAHA (Calar Alto, Spain) during March and August 2003 and July 2004. The resolving power achieved in the spectra was $R \sim 35000$, with $S/N >> 100$ in the red orders and ~ 50 below ~ 5000 Å.

The data were reduced using the *echelle* package of the *Image Reduction Analysis Facility* (IRAF) following the standard procedure. The spectral continuum was set with the help of the carbon stars spectral catalogue by Barnbaum et al. (1996). We estimate a typical error of about $\sim 5\%$ in the continuum location.

3. The two-colour diagram

Using the IR photometry JHK compiled by Knapp et al. (2001) and 2MASS data (Skrutskie et al. 2006), we constructed the IR two-colour diagram for the stars of the sample (see Figure 1). It is important to note that the spectral classification for some stars of the sample is ambiguous in the literature. This is probably due to the variability of some of the objects. To avoid this ambiguity, we consider in our study that a given object can be classified as a hot R star if the effective temperature derived (see next section) is $T_{\rm eff} > 3800$ K, or cool if $T_{\rm eff} \leq 3800$ K. In Figure 1 we see that most of the cool stars are located at the transition region between the hot R-stars and the C(N)-AGB stars, in fact, three of them occupy the same position as the C(N) stars. The cool R-star with the highest (H–K) value is a Mira variable.

4. Analysis

Synthetic spectra were computed using the Turbospectrum code by Alvarez & Plez (1998). The molecular line lists used are from Plez (private communication) whereas the atomic line lists are from VALD (Kupka et al. 1999). The gf-values of the strongest atomic lines were corrected according to the analysis in the solar spectrum by Thevenin (1989, 1990). The line lists were tested using a high quality spectrum of the solar metallicity carbon star WZ Cas which has well determined atmosphere parameters (Lambert at al. 1986).

The effective temperature was estimated from visual (V) and IR (JHK) photometry using the temperature calibration proposed by Bergeat et al. (2001) for carbon stars. The final $T_{\rm eff}$ adopted was the average value derived from the $(V\text{-}K)_0$, $(J\text{-}K)_0$ and $(H\text{-}K)_0$ colour index calibrations. We estimate an error of ± 300 K in the temperature determination. The gravity was computed assuming a stellar mass of 1 $M_\odot$ (Dominy adopted a mass in the range $0.7-1.3\,M_\odot$) and the classical relationship with the luminosity of the star. We compute bolometric magnitudes from the Hipparcos parallaxes considering the bolometric corrections in

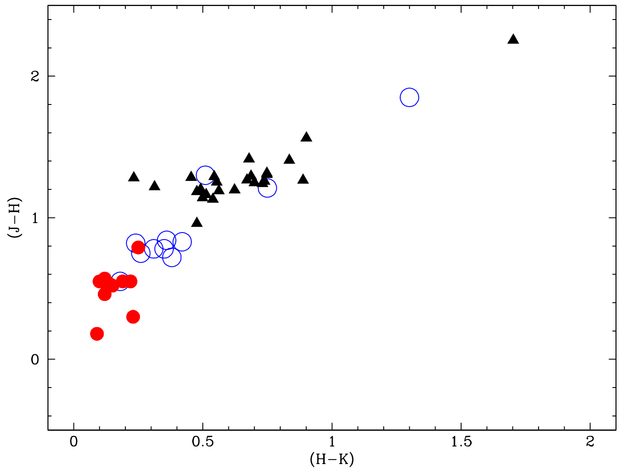

Fig. 1. The IR two-colour diagram of the R-stars in the sample compared with the C(N) stars in Abia et al. (2001). Filled circles represent hot R-stars, open circles are cool R-stars and triangles, C(N) stars.

K by Costa & Frogel (1996). The gravities derived are in the range log g = 2.0 – 2.5, with a typical error ±0.4 dex. Changes in the adopted stellar mass by ±0.5 $M_\odot$ introduce a variation of $\pm^{0.17}_{0.30}$ dex in the gravity. A microturbulence parameter was set at 2 ±1 km/s according to Dominy (1984).

We used the solar metallicity carbon-rich model atmospheres grid from Eriksson et al. (1984). When a carbon-rich atmosphere model was not available for a given star, which was the case for most of hot R-stars due to their higher effective temperature, we used O-rich MARCS or Kurucz model atmospheres, increasing the carbon abundance properly. This probably does not introduce a large error in the continuum opacity for stars with $T_{\rm eff} \geq 4000$ K. The final synthetic spectra were convolved with a Gaussian function according to the instrumental profile.

5. Results

Next, we present the preliminary results of our chemical analysis.

5.1. The C/O and $^{12}C/^{13}C$ ratios

Figure 2 shows a fit in the ~ 8000 Å spectral region of a cool (HIP 36623) and hot R-star (HIP 84266). The ratios obtained for the sample stars are shown in Figure 3. We can see that the carbon isotopic ratio is below ~ 20 in most of the objects, similar to the figure found in many K-M galactic RGB stars (e.g. Gilroy 1989, Gilroy & Brown 1991). It is well known that in low mass stellar models (M ≤ $2M_\odot$), mixing from the first dredge-up cannot account for these low isotopic ratios: an extra-mixing mechanism is commonly invoked (see e.g. Iben & Renzini 1983, Charbonnel 1994, Busso et al. 1999). Since the He-flash seems unable to modify the surface value of the $^{12}C/^{13}C$ ratio (Gilroy & Brown 1991), and that during the subsequent evolution in the AGB phase the ^{12}C added into the envelope by the third dredge-up episodes would raise further the $^{12}C/^{13}C$ ratio. Whatever the evolutionary status of the R-stars is, the operation of an extra-mixing process to explain the low carbon isotopic ratio, seems also necessary in these objects.

On the other hand, we find that there is no a significant difference in the $^{12}C/^{13}C$ ratio between cool and hot stars. The C/O ratio ranges from ~ 1 to 2, although two R-hot are not carbon stars (C/O < 1). The two cool stars which have the higher values of $^{12}C/^{13}C$ are located in the two-colour diagram at the position of C(N)-AGB stars (see Figure 1). The hot star with $^{12}C/^{13}C \sim 200$ in Figure 3 has been classified as a CH star by Bartkevicius (1996). This

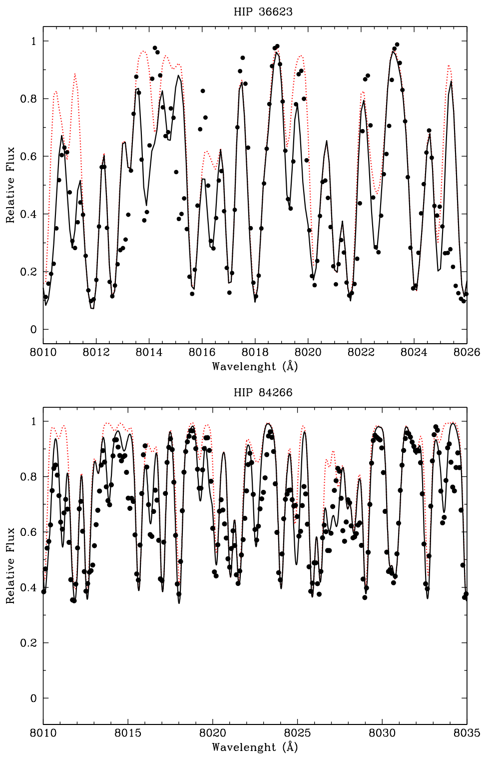

Fig. 2. Observed and theoretical spectra in the 8000 Å region of the cool R-star HIP 36623 (R9, T_{eff} = 3300 K) and the hot R-star HIP 84266 (R3, T_{eff} = 4371 K). Points: observed spectrum; dashed line: synthetic spectrum with no ^{13}C; solid line: best fit C/O= 1.04, $^{12}C/^{13}C$= 24 and C/O= 1.23, $^{12}C/^{13}C$= 12 for HIP 36623 and HIP 84266, respectively.

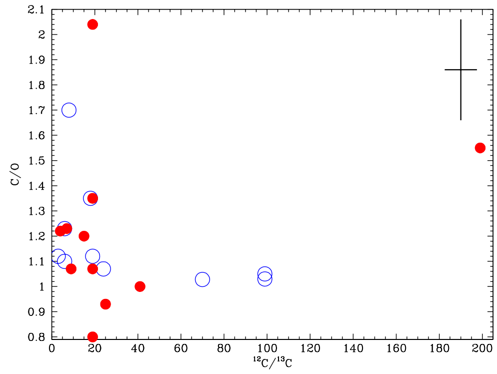

Fig. 3. C/O vs. $^{12}C/^{13}C$ in the sample stars. Filled circles: hot R-stars; open circles: cool R-stars. The error bar is an average value. Note that most of the $^{12}C/^{13}C$ ratios derived are below ∼ 20.

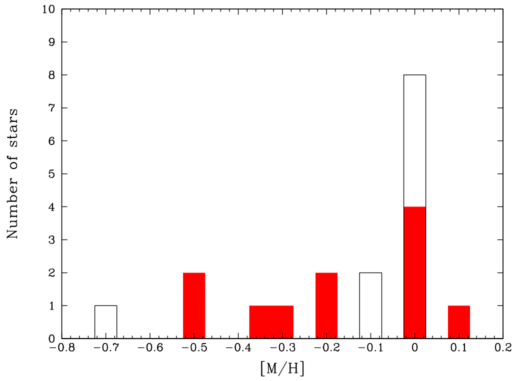

Fig. 4. Histogram of [M/H]. Empty boxes represent cool R-stars and filled boxes hot R-stars.

is compatible with the slight metal deficiency derived here.

5.2. Metallicity

The average metallicity ([M/H]) was computed by fitting a few *clean* FeI and NiI lines in the λ 6700 Å and λ 7800 Å spectral regions, respectively. The histogram (in Figure 4) indicates that most cool R-stars have solar metallicity whereas hot R-stars show a larger spread. Typical error in [M/H] is ±0.25 dex for the hot stars and ±0.30 for the cool ones. The cool star HIP 98223 with [M/H] = −0.7 has a high radial velocity (Wilson 1953); we suspect therefore that it is probably a CH star. Whether this spread in metallicity in the hot R-stars is an indication of a different stellar population to that of R cool or artificial, has to be confirmed with a more detailed chemical analysis using a larger number of metallic lines. Note that the spectrum of the R-cool stars are crowded with molecular lines and that in these stars we just computed the metallicity from one or two Fe-Ni lines, which can introduce systematic errors in the derivation of the metallicity.

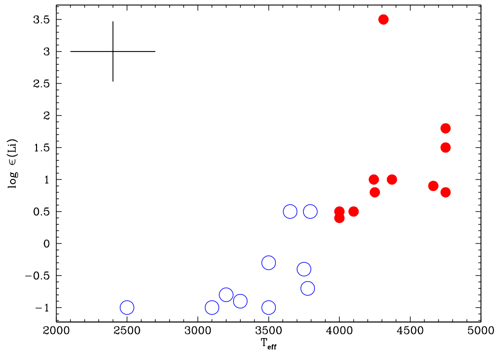

Fig. 5. Li abundances versus effective temperature. Symbols as in Figure 3. A clear separation in the Li abundance between the cool and hot stars exits.

5.3. Lithium

Figure 5 shows a clear separation between cool and hot R-stars in the Li abundance. The mean value obtained for the hot R-stars is log ϵ(Li) = +0.9 ± 0.6, which is similar to the value found in galactic K giants (Brown et al. 1989). In the cool ones, the average value is log ϵ(Li) = −0.5 ± 0.4, similar to the Li abundance in M giants and galactic C(N)-AGB stars (Luck & Lambert 1982, Boffin et al. 1993, respectively). Note that we find one Li-rich hot star (HIP 62944, log ϵ(Li) = 3.5) although it is not a carbon star (C/O = 0.93). The Li-rich nature of this star was already noted by Schild (1973) who classified it as a Li-rich K giant.

5.4. Rubidium and other s-elements

The Rb abundance is a tracer of the neutron density at which the s-process operates in AGB stars. We found Rb enhancements ([Rb/M] > 0) in several hot R-stars whereas the cool ones have typically solar ratios. The Rb enhancements found here are compatible with s-process model predictions by Gallino et al. (1998) in low mass AGB stars with the reaction ^{13}C(α, n)^{16}O being the main neutron source. However, since the s-process nucleosyntheis is not expected to work during the HB evolution (the most probable evolutionary stage of the R-hot stars), we cannot discern whether the Rb enhancements found are a consequence of the operation of the s-process nucleosynthesis or, on the contrary, the result of the chemical evolution of the Rb abundance with metallicity (see Tomkin & Lambert 1999; Yong et al. 2006). Obviously, the detection of other s-element enhancements could elucidate this.

On the other hand, the presence of Tc in the atmosphere of AGB stars is commonly interpreted as evidence of the operation of the s-process within stars. We have studied the TcI line at 5924.47 Å, obtaining a fit compatible with a non-zero Tc abundance in three R-hot stars: HIP 39118 (R2, $T_{\rm eff}$ = 4000 K), HIP 82184 (R2, $T_{\rm eff}$ = 4750 K) and HIP 86927 (R0, $T_{\rm eff}$ = 4650 K). However, due to the poor fitting of this spectral region, the possible Tc detection must be confirmed with the study of the TcI lines at ~ 4200 Å, which are stronger and more reliable abundance indicators.

With respect to the possibility of other s-element enhancements, our preliminary search indicates the presence of prominent BaII lines in one hot and one cool star. Obviously, a detailed spectral analysis is needed before concluding anything about the s-element enhancement in R-stars.

6. Conclusions

We have shown that there is no a significant difference between hot R-stars and cool R-stars in the ^{12}C/^{13}C ratio. Most of the stars have ^{12}C/^{13}C below ~ 20 and C/O ratios in the range 1 – 2, although two stars in our sample (R-hot) are not strictly carbon stars. The Li abundances obtained are in agreement with the values measured in the galactic K giants (R-hot), and M giants and/or C(N)-AGB stars (R-cool). Most of R-cool have near solar metallicity whereas the hot ones show some spread −0.5 ≤ [M/H] ≤ +0.1. Concerning the presence of s-element enhancements, we found Rb overabundances in seven hot stars and Tc might be present in three of them. On the contrary, Tc has not been detected in the cool R-stars. The presence or not of s-element enhancements would be crucial to disentangle the origin of these stars.

Comparison with the analysis by Dominy (1984) for the hot stars show a good agreement within the error bars in the average metallicity ([M/H] = −0.25), and carbon enhancement ([C/H] = +0.23). Our carbon isotopic ratios are, nevertheless, slightly higher than the average value (7) derived by Dominy. Contrary to this author, we detect Li in all our R-hot with a mean value of log ϵ (Li) = +0.90.

With the present abundance data, we cannot answer the question about the intrinsic or extrinsic nature of the R-stars. Several scenarios are still possible. For instance, M. Feast (private communication) even suggests that R-stars are the consequence of the evolution in a triple stellar system! Apart from the possible s-element enhancement that calls for deeper studies, the present abundance results suggest that R-hot stars are similar to K and M giants of similar metallicities, except for their higher carbon abundance. At contrary R-cool stars look like normal C(N) stars except for the lack of s-element enhancements in the former, however, this figure has still to be confirmed.

Acknowledgements. OZ is grateful to T. Masseron and P. de Laverny for their support and suggestions on the synthetic spectral technique. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This work has been partially supported by the Spanish grant AYA2005-08013-C03-03.

References

Abia, C. et al. 2001, ApJ, 559, 1117
Alvarez, R., & Plez, B. 1998, A&A, 330, 1109
Arenou, F. et al. 1992, A&A, 258, 104
Barnbaum, C. et al. 1996, ApJS, 105, 419
Bartkevicius, A. 1996, Baltic Astronomy, 5, 217
Bergeat et al. 2001, A&A, 369, 178
Blanco, V. M. 1965, Galactic Structure, 241
Boffin, H. et al. 1993, A&AS, 102, 361
Brown, J. A. et al. 1989, ApJS, 71, 293
Busso, M., Gallino, R., & Wasserburg, G. J. 1999, ARA&A, 37, 239
Charbonnel, C. 1994, A&A, 282, 811
Costa, E., & Frogel, J. A. 1996, AJ, 112, 2607
Deupree, R. G. 1984, ApJ, 287, 268
Dominy, J. F. 1984, ApJS, 55, 27
Eriksson, K. et al. 1984, A&A, 132, 37
Gallino, R. et al. 1998, ApJ, 497, 388
Gilroy, K. K. 1989, ApJ, 347, 835
Gilroy, K. K., & Brown, J. A. 1991, ApJ, 371, 578
Gordon, R. C. P. 1967, Ph.D. Thesis
Iben, I., & Renzini, A. 1983, ARA&A, 21, 271
Knapp, G. et al. 2001, A&A, 371, 222
Kupka, F. et al. 1999, A&AS, 138, 119
Lambert, D. L. et al. 1986, ApJS, 62, 373
Luck, R.E., & Lambert, D.L. 1982, 256, 189
McClure, R. D. 1997, PASP, 109, 256
Paczynski, B., & Tremaine, S. D. 1977, ApJ, 216, 57
Schild, R. E. 1973, AJ, 78, 37
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Stephenson, C. B. 1973, Publications of the Warner & Swasey Observatory, 1
Thevenin, F. 1990, A&AS, 82, 179
Thevenin, F. 1989, A&AS, 77, 137
Tomkin, J., & Lambert, D. L. 1999, ApJ, 523, 234
Wilson, R. E. 1953, Carnegie Institute Washington D.C. Publication, 0
Yong, D., Aoki, W., Lambert, D. L., & Paulson, D. B. 2006, ApJ, 639, 918