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High-resolution abundance analysis of very metal-poor r-I stars

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Based on high-resolution spectra obtained with the VLT/UVES spectrograph, we derived abundances for a sample of metal-poor r-I stars, in order to understand the role of such stars for constraining the astrophysical nucleosynthesis event(s) responsible for the production of the r-process, and to investigate whether they differ, in any significant way, from the r-II stars. The results are compared with r-II and normal very and extremely metal-poor stars reported in the literature. Ages based on radioactive chronometry are explored using different models, and a number of conclusions about the r-process and the r-I stars are presented.

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1. Introduction

Neutron capture processes are responsible for building the most part of the elements beyond the iron-peak, hereafter the heavy elements, but up to date the full understanding of the nucleosynthesis due to the rapid component (r-process) and the related astrophysical sites remain unclear. The abundances of very and extremely metal-poor stars are the best sources of information to constrain the models.

According to their enhancement in r-process elements, Beers & Christlieb (2005) classified the metal-poor stars in moderately r-process-enhanced (r-I; +0.3 ≤ [Eu/Fe][1] ≤ +1.0) and highly r-process-enhanced (r-II; [Eu/Fe] > +1.0). Barklem et al. (2005), in the context of the Hamburg/ESO R-process Enhanced Star survey (HERES), analysed "snapshot" spectra of 253 metal-poor halo stars in the metallicity range −3.8 < [Fe/H] < −1.5 and identified 8 r-II and 35 r-I stars, showing that the r-I stars are, at least, four times as common as the r-II stars.

In this contribution we describe an abundance analysis of seven r-I stars selected from Barklem et al. (2005), based on high-resolution spectra. The major goal was performing a comparison of abundance ratios among r-process-enhanced stars in order to understand the role of these stars for constraining the astrophysical nucleosynthesis event(s) that is(are) responsible for the production of the r-process, and to investigate the differences, if they exist, between the r-I and r-II stars. The complete work is described in Siqueira-Mello et al. (2014).

2. Analysis and results

Our sample was selected to have [Fe/H] ≤ −2.3 and discarding the carbon-enhanced metal-poor (CEMP) stars, in order to avoid s-process contribution. The spectra were obtained with the VLT/UVES spectrograph in November 6 - 10, 2007, covering the spectral ranges 3400 - 4500 Å, 6800 - 8200 Å, and 8700 - 10000 Å, with resolving power of R∼40000 (blue) and R∼55000 (red). The radial velocity measurements do not present any indication of binarity.

The abundance derivation used the OSMARCS 1D LTE model atmosphere grid (Gustafsson et al. 2008), with the spectrum synthesis code Turbospectrum (Alvarez & Plez 1998). The effective temperatures were derived based on calibrations by Alonso et al. (1999), applied on $(B-V)$, $(V-I)$, $(V-R)$, $(J-H)$, $(J-K)$, and $(V-K)$ colors, using BVR_CI_C (Beers et al. 2007) and 2MASS JHK_S (Skrutskie et al. 2006) magnitudes. An iterative method was adopted to derive the surface gravity and microturbulence velocity, based on excitation and ionization equilibria of Ti and Fe lines. The equivalent widths were measured with a semi-automatic code, which uses a Gaussian profile to fit the absorption lines.

A line-by-line fitting was carried out to derive the abundances. Synthetic spectra were convolved with Gaussian profiles that take into account the effects of macroturbulence, rotational, and instrumental broadening. We have obtained abundances of the light elements Li, C and N, the α-elements Mg, Si, S, Ca and Ti, the odd-Z elements Al, K, and Sc, the iron-peak elements V, Cr, Mn, Fe, Co, and Ni, and the trans-iron elements from the first peak (Sr, Y, Zr, Mo, Ru, and Pd), the second peak (Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Yb), the third peak (Os and Ir, as upper limits), and the actinides (Th) regions. Table 1 presents the coordinates, the barycentric

[1] We adopt the notation [A/B] = $\log(n_A/n_B)_{star}$ - $\log(n_A/n_B)_{\odot}$, where n is the number density of atoms.

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Table 1: Coordinates, barycentric radial velocities, adopted atmospheric parameters, [C/Fe], [Eu/Fe], and [Ba/Eu] abundance ratios.

Star	α(J2000)	δ(J2000)	Mean RV_B	T_{eff}	log g	[Fe/H]	ξ	[C/Fe]	[Eu/Fe]	[Ba/Eu]
			(km s^{-1})	(K)	[cgs]		(km s^{-1})			
CS 30315-029	23:34:26.5	−26:42:19	−170.0	4570	0.99	−3.40	2.22	−0.06	+0.68	−0.51
HE 0057-4541	00:59:59.2	−45:24:54	13.7	5144	2.73	−2.40	1.79	+0.44	+0.58	−0.61
HE 0105-6141	01:07:38.0	−61:25:17	5.3	5234	2.91	−2.57	1.42	+0.17	+0.52	−0.67
HE 0240-0807	02:42:57.6	−07:54:35	−101.8	4740	1.50	−2.86	2.27	−0.43	+0.78	−0.58
HE 0516-3820	05:18:12.9	−38:17:33	154.4	5269	2.17	−2.51	1.48	+0.35	+0.64	−0.58
HE 0524-2055	05:27:04.4	−20:52:42	255.4	4749	1.53	−2.77	2.20	+0.10	+0.50	−0.54
HE 2229-4153	22:32:49.0	−41:38:25	−138.5	5156	2.67	−2.62	1.63	+0.53	+0.39	−0.58

radial velocities, the adopted atmospheric parameters, and the abundance ratios [C/Fe], [Eu/Fe], and [Ba/Eu].

The final abundances in our sample are compared with results for r-II and normal metal-poor stars reported in the literature (Cayrel et al. 2004, Bonifacio et al. 2009, François et al. 2007, Hill et al. 2002, Barbuy et al. 2011, Siqueira-Mello et al. 2013, Sneden et al. 2009). For α, odd-Z, and iron-peak elements there are no differences in the chemical content between r-I and normal stars. In Fig. 1 we show the Sc II 4246.82 Å line for HE 2229-4153 (upper left panel) as an example, as well as a comparison of the abundance ratio [Sc/Fe] obtained in this work with the LTE results from the literature (lower left panel).

A remarkable agreement among the neutron-capture elements from Ba to Yb is obtained in the r-process-enhanced stars sample, showing that the process responsible for this region (main r-process) must operate in the same way to build the chemical content observed in the atmospheres of r-I and r-II stars. In Fig. 1 we show the Eu II 4129.72 Å line for CS 30351-029 (lower right panel) as an example. On the other hand, it was obtained an enhancement of the lightest heavy elements Sr, Y, and Zr (others as upper limits) in r-I stars with respect to r-II objects, and an extra mechanism (traditionally called weak r-process in the literature) must be claimed to explain the origin of this pattern. The Zr II 3836.76 Å line for HE 2229-4153 is shown in Fig. 1 (upper right panel) as an example.

It was possible to measure the Th abundance in CS 30315-029, and the result is in the same level relative to the second r-process peak elements as the one observed for CS 31082-001 (Hill et al. 2002, Barbuy et al. 2011), a r-II star well known by the presence of an actinide boost. Several r-process models were applied to calculate the age of CS 30315-029 based on radioactive chronometry, and the result obtained is 13.5 ± 3.4 Gyr, and the error bar is the standard deviation of the values from different adopted models. Hydrodynamical models were also used for some elements and general behaviors for the 3D corrections were presented in Siqueira-Mello et al. (2014).

3. Some conclusions

Although the abundance ratios of the second r-process peak elements appear nearly identical for r-I and r-II stars, pointing out the same r-process component to explain the pattern, the first r-

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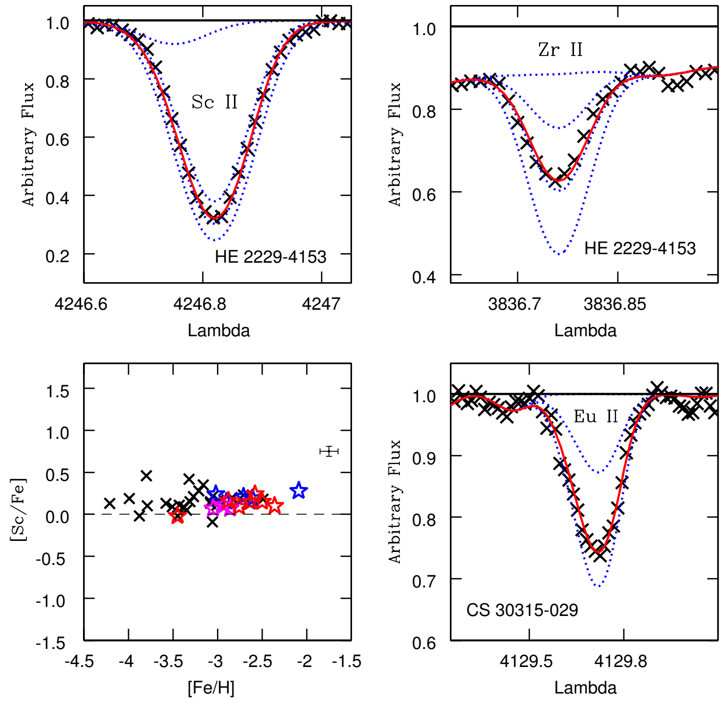

Figure 1: Upper left panel: Sc abundances from the Sc II 4246.82 Å line for HE 2229-4153. Observations (crosses) are compared with synthetic spectra computed with abundances A(Sc) = 1.2, 0.7, 0.2, none (blue dotted lines), as well as with the adopted abundances A(Sc) = 0.62 (red solid lines). **Lower left panel:** comparison of the abundance ratio [Sc/Fe] obtained in this work (red stars) with the LTE results from the literature: black crosses for normal stars; magenta for r-II stars; and blue for r-I stars. The average of the error bars is indicated in the figure. **Upper right panel:** Zr abundance from the Zr II 3836.76 Å line for HE 2229-4153. Synthetic spectra computed with abundances A(Zr) = 0.7, 0.2, -0.3, none, and adopted abundance A(Zr) = 0.15. **Lower right panel:** Eu abundance from the Eu II 4129.72 Å line for CS 30351-029. Synthetic spectra computed with abundances A(Eu) = -2.1, -2.6, none, and adopted abundance A(Eu) = -2.2.

process peak abundance ratios appear enhanced in r-I stars compared with r-II stars. This behavior was already observed among normal metal-poor stars (see François et al. 2007 as an example), and at least an extra mechanism is needed to explain it. In the present work it was observed the same effect among the r-process-enhanced stars, suggesting that different nucleosynthesis pathways were followed by stars belonging to r-I and r-II classifications, and to understand the nucleosynthesis of the r-elements, it is important to study r-I and r-II stars together.

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