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r-Process abundances in metal-poor Galactic halo stars

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Abstract. The site of the r-process is not completely defined, and several models try to explain the origin of the trans-Fe elements. Observed abundances are the best clues to bring some light to this multiplicity of possible mechanisms, and the extremely metal-poor (EMP) Galactic halo stars have a special role in this problem. In this contribution we present the solution of a long-standing problem about the origin of the heavy elements in the metal-poor halo subgiant star HD 140283, and its correlation with the Truran's theory. Next, we describe the results obtained with the EMP r-II star CS 31082-001 in the frame of the ESO Large Program "First Stars". Using STIS/HST observations we provide abundances for elements never presented before in this stars, making CS 31082-001 the most complete r-II object studied, with a total of 37 detections of neutron-capture elements. Finally, we present the results obtained from a sample of seven r-I stars, showing how those objects can help us solving the heavy elements problem. Conclusions are also described.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: halo – Galaxy: abundances

1. Introduction

In their seminal paper, Burbidge et al. (1957) outline the stellar nucleosynthesis, describing the origin of the elements beyond the iron peak in terms of the two major mechanisms of neutron capture, the s-process and the r-process. With different time scales due to the differences in the neutron fluxes, completely different astrophysical sites are needed for these mechanisms. To date, the site(s) of r-element production is/are still not known with any certainty (e.g. Wanajo & Ishimaru 2006; Kratz et al. 2007; Langanke & Thielemann 2013).

The most traditional models are those using high-entropy neutrino-driven winds of neutron-rich matter, which build up heavier nuclei near the neutrino sphere of a core-collapse supernova (e.g. Woosley et al. 1994; Wanajo 2007). However, the most recent hydrodynamic simulations find proton-rich winds, not neutron-rich (Arcones & Thielemann 2013), and the neutrino wind scenario became doubtful. Magneto-rotationally driven core-collapse supernovae with jet-like explosion are promising alternatives (Thielemann et al. 2012) and initial results for nucleosynthesis using these astrophysical site are available (Winteler et al. 2012).

Neutron-rich ejecta from neutron star-neutron star (NS-NS) or black hole-neutron star (BH-NS) binary mergers give the right conditions for a successful r-process (e.g. Wanajo, Janka, & Müller 2011; Korobkin et al. 2012). However, it is not clear if they occur early enough to explain the r-process enhancement in the abundance pattern of some extremely old and metal-poor stars.

The best way to bring some light to this problem is to compare the abundances produced by those models with observations, and a clear picture can be obtained with the low-mass extremely metal-poor (EMP) Galactic halo stars, which recorded the products of heavy-element in the first generations of stars. During the last decades few EMP stars extremely enhanced in r-process elements (r-II after Beers & Christlieb 2005) were discovered and analysed. The abundance pattern from Ba up to the actinides shows a very good agreement among those stars and with the r-process Solar values (see Sneden, Cowan & Gallino 2008, as example), claiming for an universal process to explain such agreement. On the other hand, the lightest trans-Fe elements present some differences and extra mechanisms are claimed to explain this behavior (Käppeler, Beer & Wisshak 1989; Travaglio et al. 2004; Wanajo, Janka, & Müller 2011; Arcones & Montes 2011; Arcones & Thielemann 2013).

2. The paradigm of Truran

Due to the evolutionary timescales of the proposed sites for the s-process, this mechanism is significant only in later phases of the Galactic chemical evolution, after the metallicity [Fe/H] reaches -2.6 dex (François et al. 2007), and the neutron-capture element abundances in EMP stars predominantly originate in the r-process. This assumption is used to interpret the abundances measured in EMP stars and was first suggested by Truran (1981).

Several authors confirmed the Truran's paradigm during the last years, but recently Gallagher et al. (2010) challenged this interpretation by analysing the isotopic fractions of barium in the well-studied metal-poor halo subgiant star HD 140283.

With metallicity [Fe/H] = -2.50 dex (Aoki et al. 2004), one can expect a strong r-process contribution to the atmospheric abundances in HD 140283, but Gallagher and colleagues found a barium isotopic fraction that indicates a 100% contribution by the s-process. In fact, this is a long-standing problem (see Magain 1995, as example) and the detection of an upper limit only for the Europium abundance by Gallagher et al. (2010) in HD 140283, a typical r-process element, puts the Truran's assumption in a bad situation.

To solve this problem in an independent way, we used a new spectrum with a very high resolution (R = 81000) and a very high signal-to-noise ratio (S/N = 800 - 3400 per pixel), obtained at Canada-France-Hawaii Telescope (ID: 11AB01; PI: B. Barbuy), from which it was measured the Eu abundance. We adopted the stellar parameters T_{eff} = 5750 K, [Fe/H] = -2.5 dex and v_t = 1.4 km.s^{-1} from Aoki et al. (2004) and log$g$ = 3.7 [cgs] from Collet, Asplund, & Nissen (2009), following Gallagher et al. (2010) to permit a consistent comparison. We also adopted the element abundances determined by Honda et al. (2004).

The measurement of Europium in HD 140283 is a challenge, since the available lines are very weak. The line Eu II 4129.70 Å does not present identified blends but is close to the wing of the Hδ hydrogen line at 4101.71 Å. Using OSMARCS LTE atmospheric model (Gustafsson et al. 2008) and the spectrum synthesis code Turbospectrum (Alvarez & Plez 1998), it was obtained A(Eu) = -2.35 ± 0.07 dex from this abundance indicator.

Adopting the solar abundance of europium $A(Eu)_\odot$ = +0.52 ± 0.03 dex (Caffau et al. 2011), we obtained [Eu/Fe] = -0.27 ± 0.12 dex, in excellent agreement with the trend observed for metal-poor stars, and with the Eu abundance expected from a pure r-process origin, according to Simmerer et al. (2004). Details of the analysis can be found in Siqueira-Mello et al. (2012).

3. r-II versus r-I stars

Up to now, 12 EMP r-II giant stars ([Eu/Fe] > 1.0 dex) are known (Hayek et al. 2009), and CS 31082-001 is an outstanding example of well-studied object (Hill et al. 2002; Plez et al. 2004; Sneden et al. 2009). However, despite all the efforts using ground-based facilities, most of the heavy elements are observable in the ultraviolet (UV), and for some of them only this spectral region shows measurable lines.

To complete the analysis of CS 31082-001, we report the measurements obtained with a STIS/HST spectrum (ID: 9359; PI: R. Cayrel), which required 45 orbits to give a resolution of R = 30000 and a signal-to-noise ratio S/N ~ 40. The analysis also used a new UVES/VLT spectrum obtained in the course of the large program "First Stars".

Adopting the atmospheric parameters T_{eff} = 4825 K, log$g$ = 1.5 [cgs], [Fe/H] = -2.9 dex, and v_t = 1.8 km.s^{-1} from Hill et al. (2002), we used OSMARCS LTE atmospheric models and the spectrum synthesis code Turbospectrum to derive abundances for 28 elements, 9 of them (Ge, Mo, Lu, Ta, W, Re, Pt, Au, and Bi) never reported before, making CS 31082-001 the most completely studied r-II star, with abundances for a total of 37 neutron-capture elements. The complete description of the results and comparisons with r-process models can be found in Barbuy et al. (2011) and Siqueira-Mello et al. (2013).

At least twice as common as their extreme counterparts (the r-II stars), the r-I stars present a lower r-enrichment (0.3 ≤ [Eu/Fe] ≤ 1.0) and they are found across a wide metallicity range. As discussed by Beers & Christlieb (2005), those stars provide valuable information on the consistency of the pattern of heavy r-process elements from star-to-star, as seen for r-II stars, but the lightest trans-Fe elements are higher than expected from the solar pattern. In addition, it was not very clear if the classification in r-II and r-I is connected with differences in the nature of those stars.

In order to explore these "moderate" stars, we selected 7 r-I objects from the HERES survey (Barklem et al. 2005) to perform a high resolution analysis using spectra obtained with UVES/VLT (ID: 080.D-0194(A); PI: V. Hill). Again, we used OSMARCS LTE atmospheric models and the spectrum synthesis code Turbospectrum to determine abundances from Carbon up to Thorium. Details of the analysis are presented in Siqueira Mello et al. (2014).

For a comparison of the abundance level of the lightest trans-Fe elements (first peak) with the abundance level of the main r-process (second peak), we can use the abundances ratio [(Sr,Y,Zr)/Eu], as a function of the enhancement in r-process ([Eu/Fe]); the "normal" metal-poor stars present a [first/second peak] ratio progressively higher for lower [Eu/Fe] values. On the other hand, this correlation seems to be weaker (maybe constant) for higher [Eu/Fe] values, the r-II stars (see Fig. 1 of Montes et al. 2007, for the same behavior). The results for the r-I stars are between the two different regions.

If we claim for an extra r-process mechanism (sometimes called "weak" component) to explain such differences in the abundances of the first peak elements, the r-I stars therefore appear to be tracers of this weak r-process, and the classification established originally by Beers & Christlieb (2005) should reflect different chemical enrichment histories.

4. Conclusions

The isotopic analysis is the next step to improve the information about abundance in stellar atmospheres, but the controversy around the isotopic fraction of barium in HD 140283 shows that it is necessary to be careful with results obtained from this technique. At the same time, the Europium abundance obtained for HD 140283 shows that it is possible to extract valuable informations even from well-studied stars.

About CS 31082-001, the new results make this stars the most completely studied r-II star, and an outstanding object to be used in comparisons with r-process models. In fact, it should be very useful to obtain such level of details for the chemical abundances in other r-II stars.

On the other hand, the r-I stars seem to be good candidates to bring new information about the "weak" r-process, as well as to help their extreme counterparts (r-II stars) to solve the "main" r-process problem.

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