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r-PROCESS ABUNDANCES IN THE EMP STAR CS 31082-001 USING STIS/HST

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Abstract. We present a brief revision of the origin of heavy elements and the role of abundances in extremely metal-poor (EMP) stars, in providing improved constraints on the nature of the early nucleosynthesis mechanisms. Heavy element abundances in the EMP uranium-rich star CS 31082-001 based mainly on near-UV spectra from STIS/HST are presented. With new abundances for 9 n-elements not available in previous works (Ge, Mo, Lu, Ta, W, Re, Pt, Au, and Bi) this work makes CS 31082-001 the most completely well studied r-II object, with a total of 37 detections of n-capture elements. These results should be useful for a better characterisation of the neutron exposure(s) that produced the r-process elements in this star, as well as a guide for improving nuclear data and astrophysical site modelling.

Keywords: Galaxy: Halo, Stars: Abundances, Stars: individual: BPS CS 31082-001, Nucleosynthesis

1 Introduction

The origin of the elements is a fundamental field in modern astrophysics, and the problem of the heavy elements has been gaining attention in recent decades. In the seminal paper B^2FH (Burbidge et al. 1957) the authors propose two major mechanisms of neutron capture to explain the origin of the elements beyond iron: the s-process and the r-process. The (slow) s-process occurs with longer rates compared to the half-life of the beta decay of the newly formed nuclei, and consequently the chain of reactions must follow the valley of beta stability, while the (rapid) r-process occurs with shorter rates and it is able to produce neutron-rich nuclei far from the region of stability, which will decay after the action time of the mechanism. The n-capture elements can be composed of some isotopes built by pure r-process, other by pure s-process, and other built by the s- and r-process (Simmerer et al. 2004).

The time between the absorption of two neutrons is typically hundreds or thousands of years in the case of the s-process and 0.01 to 0.1 seconds in the case of the r-process. Completely different sites are needed to support these mechanisms.

The site of the r-process is not completely defined: the most likely sites are high-entropy neutrino-driven winds of neutron-rich matter in core-collapse supernova (Woosley et al. 1994; Wanajo 2007), but hydrodynamical simulations still encounter difficulties to reproduce the necessary neutron flux (Fischer et al. 2010; Hüdepohl et al. 2010; Martínez-Pinedo et al. 2012; Roberts 2012; Roberts & Reddy 2012), and alternative sites have been

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suggested, as the merging of two neutron stars or the merging of a neutron star and a black hole (Lattimer et al. 1977; Meyer 1989; Freiburghaus et al. 1999; Surman et al. 2008; Goriely et al. 2011; Wanajo & Janka 2012; Korobkin et al. 2012). The origin of the lightest trans-Fe elements gallium through cadmium adds another difficulty to this picture, since it has been attributed in varying degrees to several processes, e.g., the light element primary process (Travaglio et al. 2004); the weak r-process (Wanajo & Ishimaru 2006; Farouqi et al. 2010; Wanajo et al. 2011); and the νp-process (Fröhlich et al. 2006; Pruet et al. 2006; Wanajo 2006; Arcones & Montes 2011).

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. As discussed by many authors (e.g., François et al. 2007; Sneden et al. 2008; Siqueira-Mello et al. 2012a, and references therein), the neutron-capture element abundances in EMP stars should be predominantly due to the r-process, since the main s-process is significant only in later phases of the Galaxy. This assumption was first suggested by Truran (1981) based in particular in the observational studies of Spite & Spite (1978). Consequently, the analysis of these objects provides an insight into the astrophysical site(s) for the r-process.

2 The uranium-rich star CS 31082-001

CS 31082-001 was observed during the ESO large programme "First Stars" (see in particular Cayrel et al. 2004; Bonifacio et al. 2007, 2009), showing for the first time a measurable uranium abundance, using the line U II 3859.57 Å, opening up a new possibility for nucleochronology (Cayrel et al. 2001). CS 31082-001 is in the group of the 12 EMP r-II (following the classification from Beers & Christlieb 2005) giant stars known, it is one of the most extreme r-element enhanced giants, and its abundance pattern was studied in detail in the optical domain by Hill et al. (2002), showing for the first time in an EMP star the presence of an actinide boost compared with the general r-process level. The lead abundance in this star is also a puzzle, since in the purely r-process enriched photosphere of CS 31082-001, most of lead results from the decay of ^{232}Th , ^{235}U, and ^{238}U, which leaves very little space for Pb production during the r-process (Plez et al. 2004).

2.1 New abundances from STIS/HST

Observations with STIS/HST are crucial to obtain abundances of elements that have no measurable lines in the visible domain, leading us to observe CS 31082-001 with the Space Telescope Imaging Spectrograph (STIS) in the near UV. Requiring 45 orbits, the mean spectrum has good S/N $\sim$ 40 in the range 2600 - 3070 Å, with resolution of R = 30 000. We also use a new UVES spectrum centered at 3400 Å. The present abundance determinations are based on OSMARCS 1D LTE atmospheric model (Gustafsson et al. 2008) and the spectrum synthesis code Turbospectrum (Alvarez & Plez 1998). The stellar parameters are adopted from Hill et al. (2002): $T_{eff} = 4825 \pm 50$ K, log $g = 1.5 \pm 0.3$ [cgs], [Fe/H] = -2.9 ± 0.1 dex, and $v_t = 1.8 \pm 0.2$ km s^{-1}. We also adopted the abundances of the elements from C to Zn determined in previous works. The calculations used the atomic line lists from the VALD2 compilation (Kupka et al. 1999), except if updated oscillator strengths were available in the literature.

The results for the heaviest r-elements were presented in Barbuy et al. (2011), the first determination of all measurable third-peak elements for an EMP r-process enhanced star, including Pt and Au. We were also able to present the first determination of Bi in a r-II star, besides confirming the deficiency in Pb obtained from the UVES/VLT spectrum. Siqueira-Mello et al. (2012b) concluded the study of the near-UV spectrum, presenting the analysis of the first and second peak of the r-elements, with new abundances for 23 n-elements, 6 of them - Ge, Mo, Lu, Ta, W, and Re - not available in previous works. Fig. 1 (left) shows the line Mo II 2660.576 Å as an example of a typical fit. When available (Andrievsky et al. 2009, 2011; Mashonkina et al. 2012), the NLTE corrections to these abundances have been applied.

Combined with theoretical calculations of the production ratios of the third-peak neutron capture elements and actinides, the result allows us to assess the consistency of the ages obtained from different radioactive chronometer pairs. The comparison of the abundance pattern observed in this star with those from different models of r-process permits to check these models. Fig. 1 (right) compares the new complete observed abundances in CS 31082-001 with the predicted abundance patterns from the hot (upper) and cold (lower) models by Wanajo (2007), as well as with the available NLTE abundances for some elements (red dots and respective error bars), and in the case of lead we also present the new NLTE+3D corrected abundance as the green symbol.

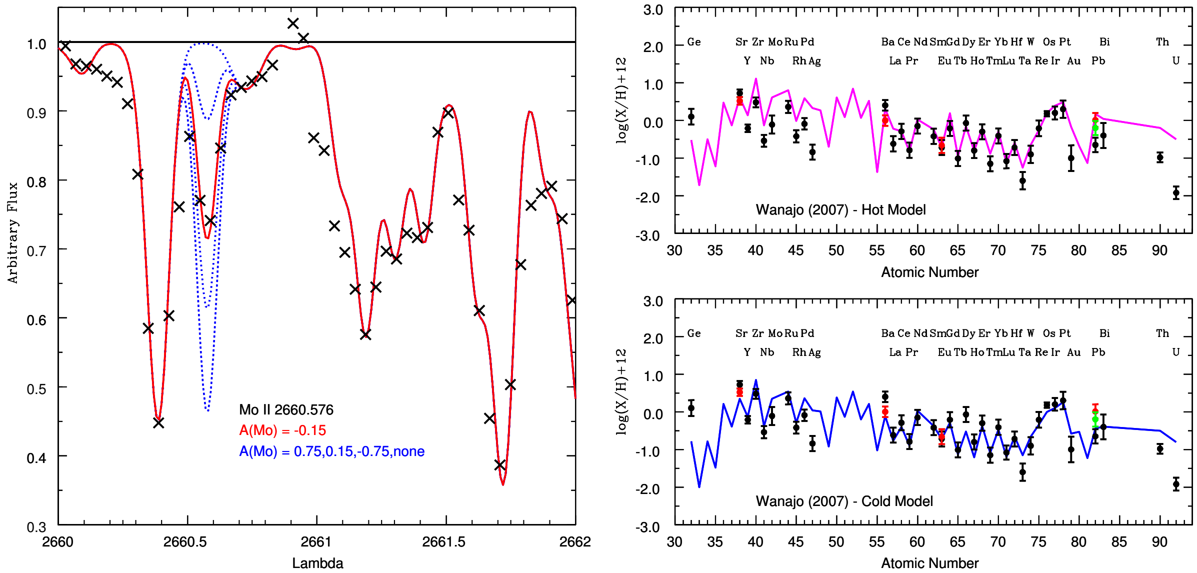

Fig. 1. Left: Fit of the observed Mo II 2660.576 Å line in CS 31082-001. Crosses: observations. Dotted lines: synthetic spectra computed for the abundances indicated in the figure. Solid line: synthetic spectrum computed with the best abundance, also indicated in the figure. **Right:** Predicted abundance patterns from the hot (upper) and cold (lower) models by Wanajo (2007) (solid lines), compared with the new complete observed abundances in CS 31082-001 (black dots and respective error bars). NLTE abundances for some elements (red dots and respective error bars) are compared with the LTE results. For Pb, the green symbol represents the NLTE+3D corrected value.

3 Conclusions

Together with the previous abundances, the new results make CS 31082-001 the most complete r-II object studied, with a total of 37 detections of n-capture elements, and a major template for studies of r-process models in this star, as well as a guide for improving nuclear data and modelling astrophysical site of elements production. The elements of the second and third peaks in this star are reasonably well represented by the abundance pattern from the cold model of Wanajo (2007), however this model overproduces the first peak elements (Sr through Ag) and is not able to explain the high abundance of Ge.

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