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### Constraints on the r-Process

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# HST/STIS abundances in the uranium rich metal poor star CS 31082-001: Constraints on the r-Process

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## Abstract.

As a brief revision, the origin of heavy elements and the role of abundances in extremely metal-poor (EMP) stars are presented. Heavy element abundances in the EMP uranium-rich star CS 31082-001 based mainly on near-UV spectra from STIS/HST are presented. 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, given that the new element abundances not available in previous works (Ge, Mo, Lu, Ta, W, Re, Pt, Au, and Bi) make CS 31082-001 the most completely well studied r-II object, with a total of 37 detections of n-capture elements.

## 1. Introduction

The origin of the elements is a fundamental field in modern astrophysics, and the production mechanisms of the neutron-capture elements are still not known with certainty. In their seminal paper B<sup>2</sup>FH [1] 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 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. Therefore very different sites are needed to support these mechanisms.

In the case of the r-process, the classical sites are high-entropy neutrino-driven winds of neutron-rich matter in core-collapse supernovae [2,3], but hydrodynamical simulations do not reach the extreme conditions necessary for the r-process and the proton or neutron richness of the wind remains to be investigated in more detail, though the weak r-process [4-6] and the  $\nu$ p-process [7-10] make this scenario an interesting possibility to explain the origin of lighter heavy elements [11], accounting for the light element primary process [12].

Alternative sites have been suggested to explain the so-called “main” r-process, as the merging of two neutron stars or the merging of a neutron star and a black hole [13-19]. Supernova-jet-like explosion is another exciting possibility, where the neutron-rich matter collimated in jets presents the right r-process conditions [20].

Detailed abundances of the elements produced by r-process nucleosynthesis in various circumstances are our best observational clues to the nature of this mechanism. A good picture can be obtained by considering the products of heavy-element production in the first generation(s) of stars, as recorded in the low-mass stars that survive until today, and the extremely metal-poor (EMP) Galactic halo stars have a special role in this problem. As discussed by many authors [21-23], 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. Consequently, the analysis of these objects provides an insight into the astrophysical site(s) for the r-process.

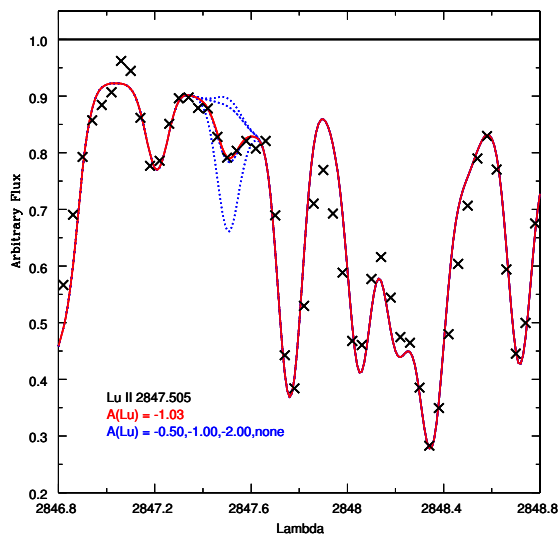
## 2. The uranium-rich star CS 31082-001

CS 31082-001 is among the 12 known EMP r-II (following the Beers & Christlieb classification [24]) giant stars. It was observed during the ESO large programme “First Stars” [25-27], showing for the first time a measurable uranium line U II 3859.57 Å, and opening up a new possibility for nucleochronology [28]. This is one of the most extreme r-element enhanced giants, and its abundance pattern was studied in detail in the optical domain [29], showing for the first time in an EMP star a boost of the actinides as compared with the general r-process abundance level. The lead abundance in this star is a puzzle, since in the purely r-process enriched photosphere of CS 31082-001, most of the lead results from the decay of  $^{232}\text{Th}$ ,  $^{235}\text{U}$ , and  $^{238}\text{U}$ , which leaves very little space for Pb production during the r-process [30]. Improved transition probabilities and other atomic data were important pieces obtained by several authors [31,32], from which accurate calculations of chemical abundances were possible.

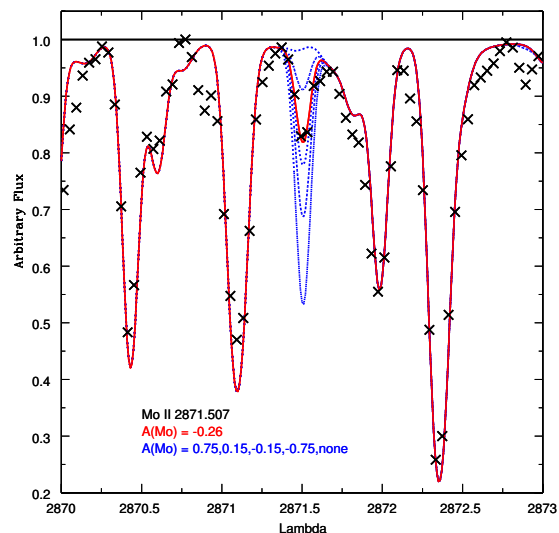
Even if many of the key neutron-capture elements in these star are observable from the ground, observations in space ultraviolet are crucial to obtain abundances of elements that have no measurable lines in the near-UV and visible domain, leading us to observe CS 31082-001 with the Space Telescope Imaging Spectrograph (STIS) in the space near UV. These observations are also important to check the abundances calculated from other lines from the ground spectra. Requiring 45 orbits, the mean spectrum has good S/N  $\sim 40$  in the range 2600 - 3070 Å, with resolution of  $R = 30\,000$ . In this analysis we also used a new ground UVES spectrum centered at 3400 Å. The abundance determinations are based on OSMARCS 1D LTE atmospheric model [33] and the spectrum synthesis code Turbospectrum [34]. The stellar parameters are adopted from [29]:  $T_{eff} = 4825 \pm 50$  K,  $\log g = 1.5 \pm 0.3$  [cgs],  $[\text{Fe}/\text{H}] = -2.9 \pm 0.1$  dex, and  $v_t = 1.8 \pm 0.2$

km s<sup>-1</sup>. 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 [35], except if updated oscillator strengths were available in the literature.

The results for the heaviest r-elements were presented in [36], 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 of Pb obtained only from the UVES/VLT spectrum. The study of the near-UV spectrum was concluded in [36,37], presenting the analysis of the r-elements, with new abundances for n-elements, 9 of them - Ge, Mo, Lu, Ta, W, Re, Pt, Au, and Bi - not available in previous works. Fig. 1 and fig. 2 show the lines Lu II 2847.505 Å and Mo II 2871.507 Å, as examples of typical fits. When available, the NLTE corrections to these abundances [38-40] have been applied, and in the case of lead we also present a new NLTE+3D corrected abundance.



**Figure 1.** Fit of the observed Lu II 2847.505 Å line in CS 31082-001. Crosses: observations. Dotted lines: synthetic spectra computed for the abundances indicated. Solid line: synthetic spectrum computed with the best abundance, also indicated.

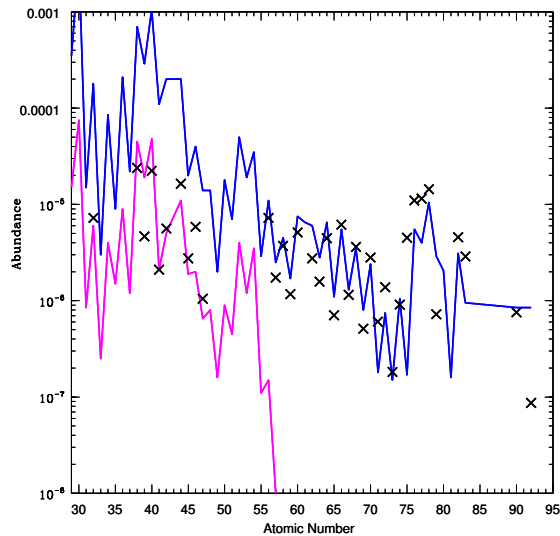


**Figure 2.** Fit of the observed Mo II 2871.507 Å line in CS 31082-001. Symbols as in Fig. 1.

The result obtained allows us to assess the consistency of the ages obtained from different radioactive chronometer pairs, when combined with theoretical calculations of the production ratios of the third-peak neutron capture elements and actinides. The comparison of the abundance pattern observed in this star with those from different models of r-process production permits to check these calculations. Fig. 3 compares the new complete observed abundances in CS 31082-001 with the predicted abundance patterns in the framework of neutrino-driven winds [41] using different electron abundance ( $Y_e$ ), showing that the whole mass region can be fitted by using different parameters, in agreement with the need of more than one site for the r-process and/or different conditions into the same environment.

### 3. Conclusions and perspectives

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



**Figure 3.** Comparison of the new complete observed abundances in CS 31082-001 (crosses) with theoretical yields [41], using  $Y_e$  of 0.498 (magenta solid line) and 0.482 (blue solid line). For each  $Y_e$  the superposition of the entropies spans from  $S = 5 k_B/\text{nucleon}$  to the maximum entropy  $S_{final}(Y_e) \sim 300 k_B/\text{nucleon}$ .

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. In general, the comparisons between calculations and observations do in fact argue for a combination of processes to reproduce the full range of observed stellar abundances, but it is necessary to increase the number of stars with abundance patterns determined to obtain strong conclusions in this field. Forthcoming projects involving the new spectrographs SOAR/STELLES and VLT/CUBES are planned.

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