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Detailed abundance analysis of the very metal-poor, r-process enhanced star HE 2327-5642

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We present a detailed abundance analysis of the strongly $r-$process enhanced giant star newly discovered in the HERES project, HE 2327-5642, for which [Fe/H] = −2.78 and [r/Fe] = +0.99. The determination of the stellar parameters and element abundances was based on analysis of high-quality VLT/UVES spectra. The surface gravity was calculated from the non-local thermodynamic equilibrium (NLTE) ionization balance between Fe I and Fe II, and Ca I and Ca II. Accurate abundances were determined for a total of 40 elements and for 23 neutron-capture elements beyond Sr and up to Th. The heavy element abundance pattern of HE 2327-5642 is in excellent agreement with those previously derived for other strongly $r-$process enhanced stars. Elements in the range from Ba to Hf match the scaled Solar $r-$process pattern very well. No firm conclusion can be drawn with respect to a relationship between the first n-capture peak elements, Sr to Pd, in HE 2327-5642 and the Solar $r-$process, due to the uncertainty of the latter. A clear distinction in Sr/Eu abundance ratios was found between the halo stars with different europium enhancement. HE 2327-5642 is suspected to be radial-velocity variable based on our high-resolution spectra, covering $\sim$ 4.3 years.

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1. Introduction

In the early Galaxy, heavy elements beyond the iron group were primarily produced by the rapid (r) process of neutron captures. The astrophysical site(s) of the $r-$process has yet to be identified. Since 1994, a very few stars have been found that exhibit large enhancements of the n-capture elements, compared to Solar ratios, suggesting that their observed abundances are dominated by the influence of a single (or very few?) nucleosynthesis event(s). Following Beers and Christlieb [4], we refer to stars having [Eu/Fe] $> +1$ and [Ba/Eu] < 0 as r-II stars. For only six r-II stars, the abundance pattern for a broad range of nuclei were determined. Their analyses have placed important constraints on the origin of heavy elements, such as (i) a production ratio of the second $r-$process peak elements from Ba to Hf is universal during the Galaxy history, (ii) $r-$process yields in the actinide region ($Z \geq 90$) depend on some intrinsic and environmental factors, and (iii) the light trans-iron (Sr-Zr) and heavy elements beyond Ba were produced in the early Galaxy by a distinct mechanism. The detection of Th and U has allowed to derive the ages of the oldest stars and hence to determine a lower limit to the age of the Universe. To establish the astrophysical site(s) of the $r-$process, more numerous and accurate measurements of heavy elements are required.

HE 2327-5642 was identified as a candidate metal-poor star in the Hamburg/ESO Survey, and then it was included in the target list of the HERES project (see description of the project in [6]). Using "snapshot" spectra with $R \simeq 20\,000$ and $S/N \simeq 50$, Barklem et al. [3] showed that this star exhibits strong overabundances of the $r-$process elements, with $[\mathrm{Eu/Fe}] = +1.22$ and $[\mathrm{Ba/Eu}] = -0.56$. Using high-quality VLT/UVES spectra, Mashonkina et al. [9] performed a detailed abundance analysis of HE 2327-5642 and extended the knowledge of heavy element synthesis in the early Galaxy.

2. Stellar parameters and chemical abundances

High-quality spectra (R = 60 000, S/N = 60 – 120 in 3760-6795 Å, $\sim$ 10 at 3330 Å, and $>$ 100 in the red) of HE 2327-5642 were acquired during May–November 2005 with the VLT and UVES (ESO, Chile, Proposal numbers 170.D-0010 and 280.D-5011). The spectra cover the 3330–8508 Å range.

An effective temperature was derived from photometry and fitsof the Balmer line wings, and the obtained values were found to be consistent within the error bars. Surface gravity was determined from the NLTE ionization equilibrium between Ca I and Ca II, and Fe I and Fe II. The following stellar parameters were adopted for HE 2327-5642: $T_{\rm eff}$ = 5050$\pm$70 K, $\log g$ = 2.34$\pm$0.1, [Fe/H] = -2.78 ± 0.09, ξ_t = 1.8$\pm$0.1 km s^{-1}.

We derived the abundances of 40 elements from Li to Th in HE 2327-5642 (Fig. 1), and for four elements among them (Ca, Ti, Mn, and Fe), from two ionization stages. The abundances of Na, Mg, Al, Ca, and Fe, were based on NLTE analysis. For every element with more than one line detected, the dispersion in the single line measurements around the mean does not exceed 0.11 dex. We found that a Li abundance of $\log \varepsilon = 0.99$ is typical of cool giants, and the C to Zn abundances are consistent with those of the cool very metal-poor giant sample of Cayrel et al. [5].

We detected 23 elements in the nuclear charge range between $Z = 38$ and 90 (Fig. 2). The abundance pattern of HE 2327-5642 in the Sr to Os range is similar to that of the r-II stars, such

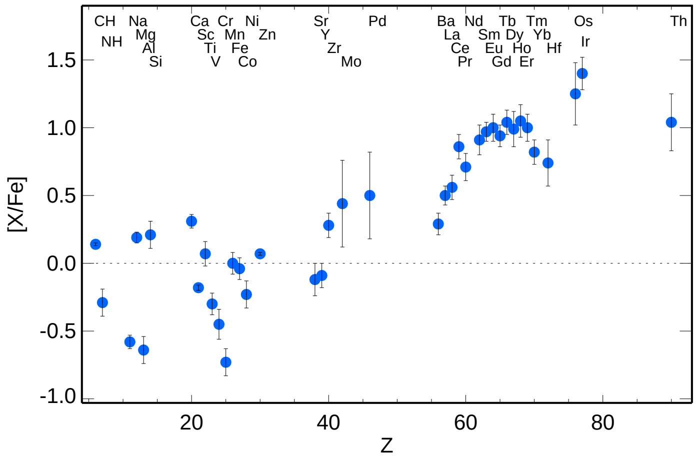

Figure 1: The abundance pattern of HE 2327-5642.

as CS 22892-052 [12], CS 31082-001 [11], and HE 1219-0312 [7]. In Fig. 2, we also plot the Solar System $r-$process residuals calculated with various Solar total abundances and $s-$process abundances. In the Sr-Ag range, $r-$residuals vary strongly depending on the used Solar total and $s-$process abundances. The elements in the range from Ba to Hf in HE 2327-5642 match the scaled Solar $r-$process pattern very well, with σ(HE 2327-5642 – SSr) = 0.07 dex. Here, SSr denotes the $r-$residuals based on the meteoritic abundances of Lodders et al. [8] and s-process abundances of Arlandini et al. [1]. For the seven nearly pure $r-$process elements from Eu to Tm, [r/Fe] = 0.99 ± 0.03. No solid conclusion can be drawn about any departures of Sr to Pd in HE 2327-5642 from the scaled Solar $r-$process pattern due to the uncertainty of the latter. One of the two detected elements of the 3rd $r-$process peak, iridium, seems to be overabundant with respect to the Solar $r-$process.

The detection of Th permitted an estimate of the radioactive decay age of HE 2327-5642, although the age uncertainty of 9.3 Gyr introduced by the uncertainty of the thorium abundance is rather large. Employing multiple thorium and rare-earth element abundance pairs (Th/X) and initial production ratios based on the Solar $r-$residuals, an age of 5.9 ± 2.8 Gyr was obtained from nine Th/X chronometers, involving elements in the Sm–Os range. Using the predictions of the high-entropy wind $r-$process model, as given by Hayek et al. [7], we obtained $\tau = 13.3 \pm 6.2$ Gyr from 12 Th/X pairs.

Is HE 2327-5642 a binary star? No signature of a double-lined spectroscopic binary star was found for HE 2327-5642, however, our analysis of the barycentric radial velocities taken during $\sim$ 4.3 years infers that $V_{rad,bary}$ varies on timescales of $\sim$ 10 days, and that the radial velocity curve underwent a minimum at the Modified Julian Date (MJD) 53620. The measurement at MJD 54407.019 deviates by ~ 20 km s^{-1} from the average of the radial velocities measured at the other epochs, and by a similar amount from the data taken only about three months later. We suspect that the orbit of the system is highly elliptical. The knowledge of the orbital period would help to obtain a lower limit to the mass of the secondary in this system and, thus, to constrain a scenario for the site of the $r-$process. Radial velocity monitoring of HE 2327-5642 is being continued.

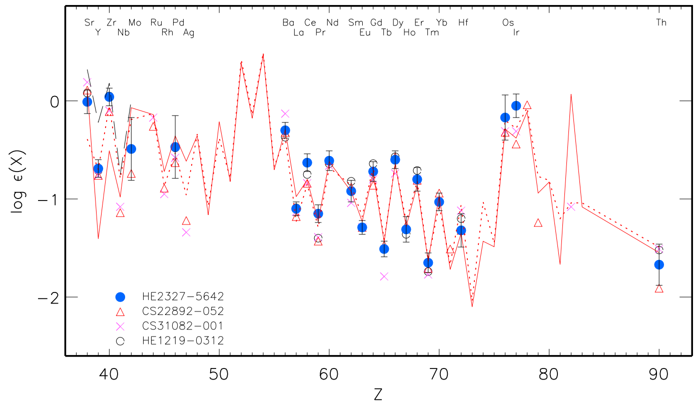

Figure 2: The heavy-element abundance pattern of HE 2327-5642 (filled circles), CS 22892-052 (open triangles), CS 31082-001 (crosses), and HE 1219-0312 (open circles) compared to the $r-$residuals calculated with various Solar total abundances and *s*-process abundances. Continuous and dotted curves correspond to the predicted *s*-process abundances from [1] and the Solar total abundances from [8] and [2], respectively. The dashed curve (only Sr–Mo) corresponds to the *s*-process abundances from [10] and the Solar total abundances from [8]. Each *r*-process abundance pattern was scaled to match the Ba–Hf in HE 2327-5642.

3. The 1st and 2nd neutron-capture element peaks in the Galaxy halo stars

We have chosen strontium and europium as representative elements of the first and second n-capture element peaks and inspected the Sr/Eu abundance ratios in a pre-selected sample of halo stars with a dominant contribution of the $r-$process to the production of heavy elements beyond Ba, i.e. with $[\mathrm{Ba/Eu}] \leq -0.4$ (see [9] for the sources of data). The stars are separable into three groups, depending on the observed europium enhancement: nine r-II stars with $[\mathrm{Eu/Fe}] > 1.0$, 32 stars with $0.2 \geq [\mathrm{Eu/Fe}] < 1.0$ (r-I), and 12 stars with $[\mathrm{Eu/Fe}] \leq 0.06$ (Eu-poor stars). The strongly $r-$process enhanced stars reveal a low Sr/Eu abundance ratio at [Sr/Eu] = -0.92 ± 0.13, while the r-I and Eu-poor stars have 0.36 dex and 0.93 dex larger Sr/Eu values, respectively, suggesting the existence in the early Galaxy a production mechanism(s) for the light trans-iron elements, which is different from the $r-$process. The Zr/Eu ratios exhibit a very similar behavior. We suggest using the [Sr/Eu] ratio in addition to [Eu/Fe] to separate the r-II stars from the other halo stars with dominant contribution of the $r-$process to heavy element production.

4. Conclusions

1. HE 2327-5642, with its [Fe/H] = -2.78 and [r/Fe] = 0.99 ± 0.03, is a member of the small sample of currently known r-II stars. Ba to Hf in this star match the scaled Solar $r-$process pattern very well and give evidence for an universal production ratio of the second $r-$process peak elements during the Galaxy history.

2. The ten known r-II stars have similar Sr-Hf abundance pattern, with [Sr/Eu] = -0.92 ± 0.13 and [Ba/Eu] = -0.60 ± 0.10. Sr to Pd in these stars originate from the classic r-process.

3. The other halo stars that have experienced a dominant $r-$process contribution to heavy element production beyond Ba, i.e., with [Ba/Eu] < -0.5, but of [Eu/Fe] < 1 reveal distinct pro-

duction mechanisms for the light trans-iron elements depending on stellar Eu enhancement.

4. HE 2327-5642 is suspected to be a radial-velocity variable, with a highly elliptical orbit of the system.

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