A new r-process star with low abundances of r-process elements

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Abstract. Metal-poor stars with measurable r-process element abundances provide key clues to the production site(s) of the r-process and how its products are mixed with the surrounding medium. While the number of stars exhibiting strong enhancements of r-process elements has grown over the years, the lower “floor” of r-process enrichment in metal-poor stars has yet to be established, largely in part due to the difficulty in detecting weak neutron-capture element absorption lines in stellar spectra. Here we present detailed abundances of 16 neutron-capture elements for a star exhibiting the lowest level of r-process enrichment yet detected and still following the solar system r-process pattern. Taken into consideration with most of the r-process enriched stars currently in the literature, the range of r-process element enrichment spanned by this sample is at least $\sim$1.3 dex or a factor of more than 20. That the r-process abundance pattern is unchanged while the degree of enrichment varies may suggest that the r-process yields are constant while the gas mass into which they are mixed varies. Given that all stars have similar $[\text{Fe}/\text{H}]$ values then suggests that only one or few previous stellar generations provided the observed chemical abundances, meaning that perhaps only one r-process event occurred prior to their formation. This would be consistent with a (near) constant r-process yield per event. Obtaining detailed element abundances for stars with mild r-process element enhancements is necessary to better constrain the ubiquity of the r-process pattern, the yields of r-process elements, and the site of its production.

1. Introduction
Understanding r-process nucleosynthesis is a central topic of nuclear physics theory and experiments. Much has to still be learned about it, including its astrophysical site and whether it is universal across the full range of neutron-capture elements or just for the heaviest elements. Observations of old metal-poor stars displaying the chemical fingerprint of the r-process in their spectra help to constrain some of these questions. We refer the reader to [1] for a detailed discussion of how metal-poor stars serve to constrain the history of neutron-capture elements. Examining the range of r-process enhancements in metal-poor stars may thus prove to be useful in observationally constraining the levels of r-process yields, how those yields are mixed into star-forming gas, and at what metallicities r-process enhancement becomes dominant.

So far, only stars with large overabundances have been analyzed in detail since they have proved to be the most promising stars to study the details of the stellar r-process pattern [2]. This led to the remarkable discovery that the r-process element abundance pattern appears to be universal, as the scaled solar r-process pattern matches that of these metal-poor stars nearly perfectly (for $Z \geq 56$) [3, 4, 5]. However, discrepancies among lighter neutron-capture elements...
were also found, suggesting different contributions or production mechanisms for elements such as Sr, Y and Zr [6, 7]. While many stars with mild r-process enhancements have also been discovered [8], comparably few of those have been analyzed in detail. Accordingly, little is known about the range of the actual r-process yields (as opposed to the pattern, i.e., the abundance ratios). Moreover, it remains to be seen how “diluted” an r-process pattern can become, i.e. what the lowest absolute values for a confirmed r-process pattern in a metal-poor star could be.

In this study, we attempt to address some of these questions with a newly discovered metal-poor star that shows the signature of the r-process, but at an overall level of enrichment that is the lowest one yet studied in detail.

2. A new r-process star with low levels of r-process abundances

The red giant HE 0147−4606 was initially selected from the sample of bright metal-poor stars from the Hamburg/ESO survey [9]. The metallicity determined from its medium-resolution spectrum was [Fe/H] = −2.5, which warranted high-resolution spectroscopic follow-up. We obtained a high-resolution MIKE [10] spectrum with the Magellan-Clay Telescope at Las Campanas Observatory, Chile, in 2013 January 08 and 09, and 2013 May 29, 30 and 31, observing HE 0147−4606 for a total of about 2 h.

Using a 0."7 slit, the spectral resolution is $R \sim 35,000$ in the blue spectral range, and the signal-to-noise is above 300 at the Mg I b triplet. We show a portion of the spectrum around the Eu line at 4129 Å in Figure 1.

Using a standard 1D LTE plane parallel model atmosphere analysis, we derived stellar parameters of $T_{eff} = 4944$ K, $\log g = 1.15$, $v_{mic} = 2.15$ km s$^{-1}$ and [Fe/H] = −2.72. Furthermore, we found this star to show a mild enhancement of r-process elements, as evidenced by its [Eu/Fe] = 0.7. According to [8] it is thus an r-I star.

Given the relative brightness of this object ($V \sim 10.7$ mag), its high $S/N$-spectrum allowed us to measure abundances for total of 16 neutron-capture elements to establish a detailed abundance pattern. Comparison with the scaled solar r-process pattern revealed this star to show signs of

![Figure 1](image.png)

Figure 1. Portion of the spectrum in HE 0147−4606 around the Eu line at 4129 Å. Several elements are labeled.
Figure 2. Neutron-capture abundances (circles) in our new r-process metal-poor star HE 0147−4606 compared with the scaled solar r-process pattern [11] denoted with the dashed line. Note the good agreement for elements heavier than Ba (Z ≥ 56).

r-process nucleosynthesis, i.e. HE 0147−4606 formed from a gas cloud that was enriched by an r-process event, although at a very modest level. We show our abundances compared to the scaled solar pattern [11] in Figure 2.

The r-process pattern in HE 0147−4606 is of the lowest level studied in detail. All other r-process stars with published abundance patterns have larger r-process abundances in terms of their log ϵ(X) values. This is mostly due to a bias, in that stars with stronger enhancements show stronger spectral features making them easier to analyze. However, this leaves the actual enrichment level of r-process elements in star forming gas clouds largely unexplored.

As stellar ages can be derived for many r-process stars exhibiting detectable features of unstable isotopes of elements such as Th and U, we attempted to obtain a thorium abundance for HE 0147−4606. Given than the r-process enhancement is not as strong, this has proven difficult. More detailed results will thus be reported in a forthcoming paper.

3. The range of r-process element abundances in metal-poor stars

Figure 3 shows the log ϵ(X) values of neutron-capture elements of 12 r-process enhanced stars [12, 13, 14, 15, 13, 16, 17, 4, 13, 5, 18] as well as HE 0147−4606. This is a near-complete sample of (r-II) stars for which detailed neutron-capture elements are available in the literature, with the addition of the r-I star studied here. Rather than scaling them all to a particular element, e.g., Eu, we plot the abundances on top of each other without any scaling. As a visual aid, we scaled the solar r-process pattern to the level of each star (normalized to its Eu abundance) and plotted it together with each star. What is immediately apparent in Figure 3 is the large scatter among patterns of nearly 1.5 dex in log ϵ. This corresponds to range of r-process material of more than
Figure 3. Same as Figure 2, but for 12 out of 14 r-process stars from the literature for which detailed abundance analysis results are available. Rather than scaling them all to a particular element, e.g., Eu, we plot them on top of each other without any scaling. This illustrates the variations in the level of r-process enrichment which are more than 1 dex. HE 0147−4606 is shown with black symbols and the star whose r-process pattern is at lowest levels.

20. For comparison, the metallicity spread of our sample is only $\sim 0.5$ dex. We have included HE 0147−4606 there, and it has the pattern at the lowest abundance level. Furthermore, there appears to be a continuum between the stars’ abundance levels (seen in the variations of the loge values of each element) over those $\sim 1.5$ dex.

Given that stars with lower amounts of r-process elements can often not be analyzed in detail due to their weak neutron-capture features, it is likely that many more r-I stars would contain little r-process material that would place them towards the bottom of what is shown in Figure 3, i.e. they would have abundances even lower than what HE 0147−4606 has. This implies that the scatter among the levels of r-process enrichment is likely even larger, perhaps more than a factor of 100, and that we are thus far only seeing the tip of the iceberg.

This could mean that there is either a smooth range of r-process yields, or that – if r-process yields were always of the same amount – the dilution into the star forming gas mass varies a great deal, thus providing the range of observed r-process levels. Either way, investigating the amounts of r-process material in large samples of r-process metal-poor stars should provide constraints on these questions.

4. When did the first r-process event happen?

The two most feasible proposed sites of the r-process are core collapse supernovae [19] and neutron-star mergers [20] (though both scenarios have their problems). A key clue to distinguish between these two scenarios is the frequency of stars exhibiting a clear r-process signature, and establishing when the first r-process events may have occurred e.g., at what [Fe/H] the r-process
first appears, and how many stellar generations contributed elements by that time. Observations have already suggested that there is a “main” r-process that appears to run to completion, and likely also a “failed” r-process that preferentially produces lighter neutron-capture elements.

Only about 5% of metal-poor stars show a strong enhancement in r-process elements (r-II stars), although up to 14% or more may show a mild enhancement (r-I stars) [8]. However, all the strongly-enhanced stars are found in a relatively narrow metallicity range of $[\text{Fe/H}] \sim -2.5$ to $\sim -3.0$, while r-I stars spread to higher metallicities of $[\text{Fe/H}] \sim -1.5$. With $[\text{Fe/H}] \sim -2.7$, HE 0147−4606 fits right into the r-II metallicity range, though. We show the r-II star metallicity range in Figure 4. For the following discussion we focus on r-II stars, but as Figure 3 demonstrates that at least one r-I star follows the r-process pattern, we will extend this discussion to r-I stars in a forthcoming paper.

Considering only the ∼dozen stars known so far with strong r-process enhancement (r-II stars) and their 5% occurrence rate among metal-poor stars immediately suggests that the r-process is a rare event [8]. The fact that they have a narrow metallicity range near $[\text{Fe/H}] \sim -3$ furthermore suggests that only few, perhaps just one, supernovae provided all the elements with $Z \leq 30$ observed in a given star (although each star likely formed in a different gas cloud). If the r-process operated in supernova then the r-process elements would have come from these events also.

This conclusion is independent of the neutron-capture element abundances: canonically, only one supernova iron yield of $0.1 \, M_\odot$ (instantaneously) mixed into a hydrogen gas mass of $10^5 \, M_\odot$ results in a gas, and hence, stellar metallicity of $[\text{Fe/H}] = -3.2$. It should be noted that in this example, the iron and gas mass can easily vary by more than a factor of 10. However it illustrates that only few supernovae are required – otherwise the metallicity of the resulting stars would become higher, as in the cases of many r-I stars. If the r-process occurred within supernovae, then the r-process must have operated already in the first few generations of massive stars. But given the rarity of r-II stars, the r-process perhaps only operated in a particular mass range (8 to $10 \, M_\odot$) [21].

Additionally, stars with metallicities down to $[\text{Fe/H}] \sim -5$ are also known by now [22, 23, 24, 25]. They have not been found to show clear signs of r-process nucleosynthesis, mostly because no neutron-capture elements could be detected Strontium was detected at the level $[\text{Sr}/\text{Fe}] = 1.2$ in HE 1327−2326, but its origin remains uncertain since Ba could not be detected in the star [26]. While an r-process origin cannot be excluded when taking the upper limit of Ba into account, the s-process operating in massive near-zero metallicity stars [27] could also provide large amounts of Sr. Overall, the current body of data at $[\text{Fe/H}] \sim -5$ suggests that the r-process did not occur in the very first stars or perhaps the second generation, depending on the mass functions of the respective earliest stellar generations.

Finally, we can also turn the argument around: given that the spread in amounts of r-process material in the r-II stars is extensive, we speculate that it could also be possible that the initial r-process yields are always of the same magnitude, and that it is just the star forming gas mass that is varying. Alternatively, after the r-process event, some inhomogeneous mixing and dilution could occur, especially if the supernova is not spherically symmetric. Both effects would result in variations in the observed abundance levels. Calculating backwards in the same simple way as above suggests that an average Eu r-process yield could be $\sim 10^{-7} \, M_\odot$ per event. Taking into account the pattern spread from Figure 3, the maximum yield would then $6 \times 10^{-6} \, M_\odot$ per event. Assuming a smaller gas mass of $10^5 \, M_\odot$, this would result in $6 \times 10^{-4} \, M_\odot$ per event. The numbers of $10^{-4}$ to $10^{-6}$ actually correspond to yields calculated for r-process element production in core-collapse supernovae [28].
Figure 4. Histogram of $[\text{Fe/H}]$ metallicities of the r-II stars shown in Figure 3.

5. Conclusion
Metal-poor stars showing any sign of r-process content are a “cosmic lab” for studying the r-process, its astrophysical site and the chemical evolution of r-process elements at the earliest times. By increasing the sample of stars exhibiting r-process enhancements and for which there are detailed element abundances, we can constrain the level or r-process yields as well as the robustness and universality of the r-process. This, in turn, may shed lights on the astrophysical site or at least the frequency of r-process events in the early universe.

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