Efficient Searches for $r$-Process-Enhanced, Metal-Poor Stars

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Neutron-capture-enhanced, metal-poor stars are of central importance to developing an understanding of the operation of the $r$-process in the early Galaxy, thought to be responsible for the formation of roughly half of all elements beyond the iron peak. A handful of neutron-capture-rich, metal-poor stars with $[\text{Fe/H}] < -2.0$ have already been identified, including the well known $r$-process-enhanced stars CS 22892-052 and CS 31082-001. However, many questions of fundamental interest can only be addressed with the assemblage of a much larger sample of such stars, so that general properties can be distinguished.

We describe a new effort, HERES: The Hamburg/ESO R-Process-Enhanced Star survey, nearing completion, which will identify on the order of 5–10 additional highly $r$-process-enhanced, metal-poor stars, and in all likelihood, a similar or greater number of mildly $r$-process-enhanced, metal-poor stars in the halo of the Galaxy. HERES is based on rapid “snapshot” spectra of over 350 candidate halo giants with $[\text{Fe/H}] < -2.0$, obtained at moderately high resolution, and with moderate signal-to-noise ratios, using the UVES spectrograph on the European VLT 8m telescope.

1. Introduction

Over the course of the past decade, a very rare sub-class of metal-poor stars in the halo of the Galaxy has been identified that is of great interest for developing detailed understanding of the astrophysical rapid neutron-capture process. These stars exhibit enhancements in their observed ratios of $r$-process elements, relative to iron, of from 2 to over 50 times the solar values, i.e., $+0.3 < [r\text{-process/Fe}] < +1.7$. The first star discovered in this class, CS 22892-052, a giant with $[\text{Fe/H}] = -3.1$, has been intensely studied in the optical with the world’s largest telescopes, as well as in the near ultraviolet with the Hubble Space Telescope. This star allowed the first application of the Th/Eu cosmo-chronometer to an extremely metal-poor star, and has been used to place direct age limits on the star, and in turn on the Galaxy and the Universe. The second example discovered, CS 31082-001, permitted the detection of U, and application of a new, and
in principle better understood chronometer, $\text{U/Th}$ $[3,4]$. Both of these stars, and other mildly $r$-process-enhanced stars discovered since, share the remarkable property that their “heavy” $r$-process elements, i.e., in the range $56 < Z < 76$, exhibit a pattern of $r$-process abundances that is identical to the solar $r$-process pattern, with clear implications for the nature of the $r$-process, and perhaps on its astrophysical site.

Many questions arise, however, as to the nature of mildly- to highly- $r$-process-enhanced, metal-poor stars, such as (a) What is the frequency of the enhancement phenomenon as a function of $[\text{Fe/H}]$? (b) What is the distribution of the level of enhancement – e.g., is it bimodal or continuous? (c) With what precision is the solar $r$-process pattern reproduced from star to star? and (d) How common is the so-called “actinide boost” problem (where the measured abundance of Th appears up to 0.4 dex higher than expected) noted by $[4]$ and $[5]$? The answers to these, and many other questions, requires a much larger sample of $r$-process-enhanced, metal-poor stars to be assembled.

2. The HERES Approach

The central difficulty in obtaining large samples of $r$-process-enhanced MP stars is their extreme rarity. Based on high-resolution spectroscopy that has been performed on the most metal-deficient giants, it appears that $r$-II stars (for convenience, a class defined by $+1.0 < [r-\text{process/Fe}]$) occur no more frequently than about 1 in 30 for giants with $[\text{Fe/H}] < -2.5$, i.e., roughly 3–4%. Due to the steep decrease of the metallicity distribution function of the Galactic halo at low metallicities, the candidates to be examined are rare themselves, although modern spectroscopic wide-angle efforts, such as the HK survey of Beers and collaborators, and the Hamburg/ESO survey (HES) of Christlieb and collaborators, have succeeded in identifying such stars with success rates as high as 10–20%. So, we are faced with the daunting prospect of searching for a rare phenomenon amongst rare objects. The $r$-I stars (a class defined by $+0.3 < [r-\text{process/Fe}] \leq +1.0$) appear to be found with a frequency that is at least a factor of two greater than this, and fortunately extend into the higher metallicity stars (e.g., BD+17:3248 with $[\text{Fe/H}] = -2.1$), where a greater number of candidates exist.

Detection of uranium presents an even bigger challenge, due to the weakness of the absorption lines involved, and blending with features of other species. It was not possible to measure even the strongest uranium line in the optical, $\text{U II 3859.57 Å}$, in the carbon-enhanced star CS 22892–052, due to blending with a CN line. Other lines (such as from Fe) can cause potential problems as well. The ideal star for detecting uranium would therefore be a cool giant with low carbon abundance, very low overall metallicity, but strong enhancement of the $r$-process elements. It would ideally be a bright star, because high signal-to-noise ($S/N$) ratios as well as high spectral resolving power ($R = \lambda/\delta\lambda > 60,000$) are required to measure the strength of the $\text{U II 3859.57 Å}$ line accurately. Note that in CS 31082–001, this line has an equivalent width of only a few mÅ.

Details of the techniques used to assemble the HERES sample are described by Christlieb et al. $[6]$; here we provide a brief overview.

HERES adopts a two-step approach to the identification of neutron-capture-rich metal-poor stars. The first step consists of the identification of a large sample of metal poor giants with $[\text{Fe/H}] < -2.5$ in the HES, by means of moderate-resolution (2 Å) follow-up
spectroscopy of several thousand cool (0.5 < B − V < 1.2) metal-poor candidates selected in that survey. In the second step, “snapshot” spectra (S/N > 20 per pixel at 4100 Å; $R \sim 20,000$) of confirmed metal-poor stars are obtained. Such spectra can be secured for a $B = 15.0$ star with a 8m-class telescope in exposure times of only 15 minutes, and under less than optimal observing conditions. The weak constraints on the observing conditions makes it feasible to observe large samples of stars.

The snapshot high-resolution spectra allow one to easily identify stars with enhancements of $r$-process elements, using the Eu II 4129.73 Å line, since this line is very strong in these stars. For example, in CS 22892–052, it has an equivalent width of more than 100 mÅ. HERES also identifies stars that are enhanced in $s$-process elements; these are generally distinguishable from the $r$-process-enhanced stars by the ratio [Ba/Eu], which is high for the $s$—process, but low in the case of the $r$—process.

We are executing the snapshot approach in a Large Programme (P.I. Christlieb) approved by ESO. A total of 376 stars (including 4 comparison stars) are scheduled to be observed; most of them are from the HES. These observations are expected to yield 5–10 new $r$-II stars, and about twice as many $r$-I stars. As a byproduct, our program will provide the opportunity to measure abundances of alpha-elements such as Mg, Ca, and Ti, and of iron-peak elements such as Cr, Mn, Fe, Co, Ni, and Zn, as well as others, depending on the S/N of each spectrum, for the entire set of stars that we plan to observe in snapshot mode.

Given the large number of spectra to be processed, it is mandatory that we employ automated techniques for abundance analysis. These techniques are described in detail in Barklem et al. [7]. The completion of HERES will result in, by far, the largest sample of very metal-poor stars with homogeneously-measured abundances of a significant number of individual elements. Figures 1 and 2 show examples of trends for Mg and Eu.

Figure 1. The [Mg/Fe] vs. [Fe/H] trend exhibited for stars in the HERES Pilot Program. When the complete HERES project is finished, the sample will contain ten times as many stars.

Figure 2. The [Eu/Fe] vs. [Fe/H] trend exhibited for stars in the HERES Pilot Program. Two of the stars with the highest values of [Eu/Fe] were previously known.
3. HERES Results To Date

Not all of the HERES spectra obtained thus far have been subjected to detailed analysis, but this is progressing rapidly. A pilot sample study of the first 35 stars obtained in the HERES program are described in detail in [7]. In this sample one new $r$-I star, and two new $r$-II stars have been discovered. This rate of detection of $r$-process-enhanced stars is in line with expectation, as noted above. In one of the newly discovered $r$-II stars, data in hand suggest that $U$ is detectable, and new, much higher-quality spectra of this star have already been obtained; Hill et al. (in preparation) will provide a detailed analysis. Further inspection of the HERES sample stars, including data obtained quite recently, has identified many (possibly 7) additional $r$-II stars, a similar number of $r$-I stars, some $15 s$-processed enhanced stars, and other interesting targets for detailed inspection at higher signal-to-noise ratios.

4. Future Survey Efforts

Our hope and expectation is that, in the near future, application of a similar approach to even larger numbers of targets will expand these classes further, and/or lead to the identification of new classes of $r$-process-enhanced MP stars. Discussion are now underway, for example, to couple medium-resolution spectroscopic surveys (such as the proposed extension to the Sloan Digital Sky Survey, SEGUE: Sloan Extension for Galactic Understanding and Evolution) to high-resolution follow-up with the Hobby-Eberly Telescope (HET). It is expected that SEGUE will discover some 10,000 giants with $[\text{Fe/H}] < -2.5$, at least a subset of which will be bright enough for the required high-resolution follow-up to commence. While waiting for SEGUE, we are hoping to conduct an exploratory HET program, using brighter (northern-hemisphere) HK-survey candidates.

REFERENCES

1. C. Sneden, G.W. Preston, A. McWilliam, and L. Searle, Astrophys. J. 431 (1994) L27
2. C. Sneden, J.J. Cowan, J.E. Lawler, I.I. Ivans, S. Burles, T.C. Beers et al., Astrophys. J. 591 (2003) 936
3. R. Cayrel, V. Hill, T.C. Beers, B. Barbuy, M. Spite, F. Spite et al. 409 (2001) 691
4. V. Hill, B. Plez, R. Cayrel, T.C. Beers, B. Nordstrom, J. Andersen et al., Astron. Astrophys. 387 (2002) 560
5. S. Honda, W. Aoki, T. Kajino, H. Ando, T.C. Beers, H. Izumiura et al., Astrophys. J. 607 (2004) 474
6. N. Christlieb, T.C. Beers, P. Barklem, M. Bessell, V. Hill, J. Holmberg et al., Astron. Astrophys. (2004) submitted
7. P.S. Barklem, N. Christlieb, T.C. Beers, V. Hill, J. Holmberg, B. Marsteller et al., Astron. Astrophys. (2004) submitted