Nucleo-Chronometry of the Oldest Stars

A White Paper in Support of a High-Resolution Optical Spectrograph on Gemini

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Abstract

The abundance patterns of metal-poor stars provide us a wealth of chemical information about various stages of the chemical evolution of the Galaxy. In particular, r-process enhanced stars are a "cosmic lab" for the study of the production of heavy elements through neutron-capture. The metal-poor star HE 1523−0901 serves as an example for this group of objects. It displays in its spectrum the strongest overabundance of neutron-capture elements associated with the r-process. Heavy neutron-capture elements such as Eu, Os, and Ir were measured, as well as the radioactive elements Th and U. Abundance of Th and U, in conjunction with those of stable elements make possible nucleo-chronometry, i.e., the determination of stellar ages. HE 1523−0901 was found to be ~ 13 Gyr old. The decay product of the radioactive elements, lead, can be used to constrain r-process calculations. Only few such stars are currently known with detected U. These objects, however, are crucial for the study of this nucleosynthesis process. Once more objects are discovered, and assuming an old age for them (infered from their low metallicity), stars with measured Th *and* U abundances can become stellar age calibrators. This way, ages of stars in which only Th is measured (many more stars are available with a Th detection only), can be derived *indepedently* of model calculations. Over the next decade Skymapper is expected to uncover many new r-process stars. With an increased sample of these stars future r-process modelling, as well as understanding its astrophysical site, likely in core-collapse supernovae, and supernova nucleosynthesis can be constrained. Moreover, combining the chemical abundances with ages of old halo stars will reveal a detaild age-metallicity relation for fiel halo stars.

Introduction

All elements except H and He are created in stars during stellar evolution and supernova explosions. About 5% of metal-poor stars with [Fe/H] < -2.5 contain a strong enhancement of neutron-capture elements associated with the rapid (r-) nucleosynthesis process (Beers & Christlieb 2005) that is responsible for the production of the heaviest elements in the Universe. In those stars we can observe the majority (i.e., ~ 70 of 94) of elements in the periodic table: the light, α, iron-peak, and light and heavy neutron-capture elements. These elements were not produced in the observed metal-poor star itself, but in a previous-generation supernova explosions. The so-called r-process metal-poor stars then formed from the material that was chemically enriched by such a supernova. This is schematically illustrated in Figure 1. We are thus able to study the "chemical fingerprint" of individual supernova explosions that occurred just prior to the formation of the observed star. So far, however, the nucleosynthesis site of the r-process has not yet unambiguously been identified, but supernovae with progenitor stars of $8 - 10\,M_\odot$ are the most promising locations.

Opportunities in this Decade

The coming decade will be the "decade of surveys", Particularly SkyMapper (Keller et al. 2007) will yield many new metal-poor stars, including r-process stars, in need of spectroscopic follow-up for a full characterization of their nucleosynthetic origin. This can only be achieved with high-resolution spectroscopy since the neutron-capture lines are extremely weak, even in strongly r-process enhanced stars

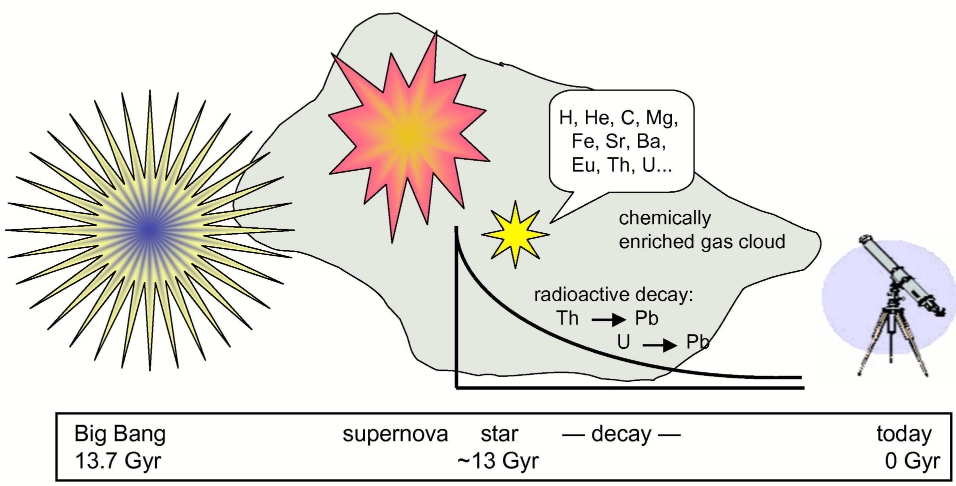

Figure 1: Schematic view of the formation process of r-process-enhanced metal-poor stars. They inherit the "chemical fingerprint" of a previous-generation supernova explosion.

This "nuclear astrophysics" work provides a major complement to existing and future initiatives to better understand the nature of supernova nucleosynthsis and in particular the r-process. The NSF Physics Frontiers Center "Joint Institute for Nuclear Astrophysics" has this as a major goal, and so will the DOE-funded "Facility for rare isotop beams". Finally, the US decadal survey has listed the study of low-metallicity objects and how they can be employed to study the early Universe among their primary science goals.

r-Process Enhanced Metal-Poor Stars

The giant HE 1523$-$0901 ($V = 11.1$) has the so far strongest enhancement in neutron-capture elements associated with the r-process[1], [r/Fe] $= 1.8$. Its metallicity is [Fe/H] $= -3.0$ (Frebel et al. 2007). The spectrum of HE 1523$-$0901 shows numerous strong lines of ~ 25 neutron-capture elements, such as those of Sr, Ba, Eu, Os, and Ir. This makes possible a detailed study of the nucleosynthesis products of the r-process. This fortuitously also provides the opportunity of bringing together astrophysics and nuclear physics because these objects act as a "cosmic lab" for both fields of study.

Although a rarity, HE 1523$-$0901 is not the only star that displays [r/Fe] > 1.5. In 1995, the first r-process star was discovered, CS 22892-052 (Sneden et al. 1996) with [r/Fe] $= 1.6$ and in 2001, CS 31082-001 (Cayrel et al. 2001) with the same overabundance in these elements. Their heavy neutron-capture elements follow the scaled *solar* r-process pattern, and offered the first vital clues to the universality of the r-process and the detailed study of the r-process by means of stars. As can be seen, in the mass range $56 < Z < 77$, the stellar abundances very closely follow the scaled solar r-process pattern (Burris et al. 2000). This behavior suggests that the r-process is universal – an important empirical finding that could not be obtained from any laboratory on earth. However, there are deviations among the lighter neutron-capture elements. It is not clear if the neutron-capture abundance patterns are produced by a single r-process only, or if an additional new process might need to be invoked in order to explain all neutron-capture abundances.

[1]Stars with [r/Fe] > 1.0; r represents the average abundance of elements associated with the r-process.

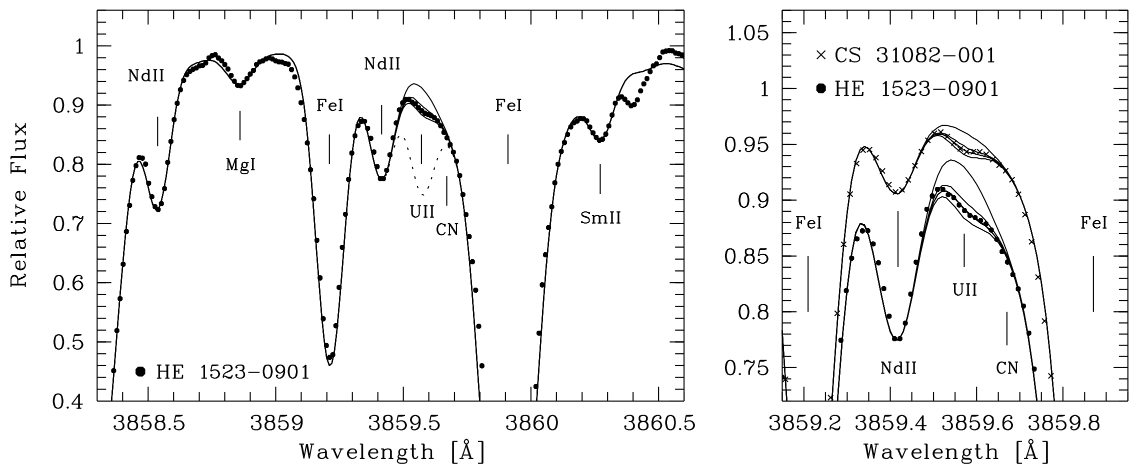

Figure 2: Spectral region around the U II line in HE 1523−0901 (*filled dots*) and CS 31082-001 (*crosses*; right panel only). Overplotted are synthetic spectra with different U abundances. The dotted line in the left panel corresponds to a scaled solar r-process U abundance present in the star if no U were decayed. Figure taken from Frebel et al. (2007).

Nucleo-chronometry

Among the heaviest elements are the long-lived radioactive isotopes ^{232}Th (half-life 14 Gyr) and ^{238}U (4.5 Gyr). While Th is often detectable in r-process stars, U poses a real challenge because *only one*, extremely weak, line is available in the optical spectrum. By comparing the abundances of the radioactive Th and/or U with those of stable r-process nuclei, such as Eu, stellar ages can be derived. Through individual age measurements, r-process objects become vital probes for observational "near-field" cosmology. Importantly, it also confirms that metal-poor stars with similarly low Fe abundances and no excess in neutron-capture elements are similarly old, and that the commonly made assumption about the low mass (0.6 to 0.8 $M_{\odot}$) of these survivors is well justified.

Most suitable for such age measurements are cool metal-poor giants that exhibit such strong overabundances of r-process elements. Since CS 22892-052 is very C-rich, however, the U line is blended and not detectable. Only the Th/Eu ratio could be employed, and an age of 14 Gyr was derived (Sneden et al. 2003). The U/Th chronometer was first measured in the giant CS 31082-001 (Cayrel et al. 2001) yielding an age of 14 Gyr. Since Eu and Th are much easier to detect than U, the Th/Eu chronometer is then used to derive stellar ages of r-process metal-poor stars. Compared to Th/Eu, the Th/U ratio, however, is much more robust to uncertainties in the theoretically derived production ratio due to the similar atomic masses of Th and U (Wanajo et al. 2002). Hence, stars displaying Th *and* U are the most valuable old stars.

Currently, only three stars have a detection of U (one of them a tentative detection). In the case of HE 1523−0901 and CS 31082-001, high-resolution spectra with $R \sim 80$K with a $S/N \sim 350 - 500$ at 4000 Å were required to the successful measurement of the only available optical U line from which the abundance was deduced. Figure 2 shows the spectral region around the U line. Clearly, more such objects are needed to arrive at statistically meaningful average abundances.

The averaged stellar age of HE 1523−0901 derived from seven chronometers involving combinations of Eu, Os, Ir, Th and U is ~ 13 Gyr. Table 1 lists the ages derived from the various abundance ratios, "chronometers". The employed initial production ratios can be found in the references given in the table. Such ages provide a lower limit to the age of the Galaxy and hence, the Universe which is currently assumed to be 13.7 Gyr (Spergel et al.

Table 1: Stellar ages derived from different abundance ratios

Star	Age (Gyr)	Abundance ratio
HD115444	15.6 ± 4	Th/Eu only
CS 31082-001	14.0 ± 2	U/Th only
BD $+17^{\circ}$ 3248	13.8 ± 4	average of several
CS 22892-052	14.2 ± 3	average of several
HD221170	11.7 ± 3	Th/Eu only
HE 1523$-$0901	13.2 ± 2	average of several (incl. U/Th)

2007). Realistic age uncertainties range from ~ 2 to ~ 5 Gyr.

Reverse Engineering: Using Stars to Calibrate Stellar Ages

Given the large systematic uncertainties in the initial production ratios which arise from uncertainties in r-process model calculations, it is not clear at this point, as to how and when these predictions would be significantly improved. In the absence of such values, one can resort to "eliminate" the problem by having available a large sample of strongly r-process enhanced metal-poor stars. In principal, one can use the old age of those stars to *predict* the initial production ratio by assuming that the stars are, for example, 13 Gyr old. Their low metallicity warrants such an assumption, and 13 Gyr is a plausible age for an early Population II star. Such predicted production ratios would then not only provide an empirical calibration for age determinations of other stars, but also offer strong observational constraints on any r-process model. Suitable for this procedure would be stars in which as many as possible chronometer ratios, including ratios involving U, can be measured to provide a good "internal" statistic. Then, at least a handful of stars would be required to obtain some meaningful statistic on the individual chronometer ratios as measured in several stars. This way, stars in which only Th is measured (because they are not r-rich enough or too C-rich, or too faint to allow acquisition of the required very high S/N data) can be age-dated, independent of any model calculations. This is important, because the often employed Th/Eu ratio is subject to large systematic uncertainties in the theoretically derived production ratio due to the large separation in atomic masses of Eu and Th.

So far, only HE 1523$-$0901 offers the possibility to serve as calibrator. Making use of this technique, the results are presented in Table 2 to illustrate the point. It should be kept in mind, however, that in a sample of one star, the observational errors have a rather large impact on the resulting ages of the other stars. Nevertheless, the ages generally are in a range that appears reasonable for this "trial" with only one calibration star. Having a better calibration sample at hand should greatly improve on the age uncertainties. For obvious reasons, it is crucial to discover more (preferably bright) r-process stars in which we can measure these abundances with the required high-precision so that they can be employed as nucleo-chronometric age-calibration stars. Only then will this technique be successful and provide self-consistent stellar ages as well as crucial observational tests for current r-process models. At the same time a field halo star age-metallicity relation can be established.

At the End of Everything: Lead

In addition to Th and U, the Pb line at 4057 Å, the decay product of Th and U, provides the ultimate constrain on any r-process model. A good model can correctly predict the (i.e. stellar) Pb abundance in an old metal-poor star, since the entire r-process determines the Pb production as well as the portions that arise from the direct decay of Th and U. The only Pb line in the optical at 4050 Å was now also detected in HE 1523$-$0901 (Frebel et al. in prep) in a new UVES spectrum ($R \sim 80$K, S/N of $\sim$ 500 at 4050 Å). Comparisons with various model

Table 2: Reverse engineering: Using HE 1523−0901 to calibrate ages of other metal-poor stars.

Ratio	Observed ratios	Initial prod. ratio derived from HE 1523−0901	Derived ages (in Gyr)	Stars
Th/Eu	−0.62, −0.51	−0.222	18.6, 13.5	CS 22892-052, BD +17° 3248
Th/Eu	−0.60, −0.60	−0.222	17.7, 17.7	HD221170, HD115444
Th/Os	−1.59, −1.63	−1.022	26.6, 28.5	CS 22892-052, BD +17° 3248
Th/Ir	−1.47, −1.48	−1.082	18.2, 18.6	CS 22892-052, BD +17° 3248
U/Eu	−1.33	−0.562	11.4	BD +17° 3248
U/Os	−2.45	−1.362	16.1	BD +17° 3248
U/Ir	−2.30	−1.422	13.0	BD +17° 3248
U/Th	−0.82	−0.344	10.4	CS 31082-001

calculations will be able to rule out certain classes of models based on the stellar abundances.

Summary of Technical Requirements

We propose the following technical requirements for a single-object, high-resolution spectrograph. High S/N observations with full wavelength coverage of bright stars are hereby the main target. Most neutron-capture absorption lines are located blueward of 4000 Å. The red end is limited by the Li line at 6707 Å.

Wavelength coverage: 3300 to 8700 Å; good blue efficiency important since targets are mostly giants
Resolution: > 60 K (image slicer capabilities for higher R capabilities desired for U and Pb measurement)
Existing similar facilities: VLT/UVES, Magellan/MIKE, Keck/HIRES

Bibliography

Beers, T. C. & Christlieb, N. 2005, ARA&A, 43, 531

Burris, D. L., Pilachowski, C. A., Armandroff, T. E., Sneden, C., Cowan, J. J., & Roe, H. 2000, ApJ, 544, 302

Cayrel, R., et al. 2001, Nature, 409, 691

Frebel, A., Christlieb, N., Norris, J. E., Thom, C., Beers, T. C., & Rhee, J. 2007, ApJ, 660, L117

Keller, S. C., et al. 2007, Publications of the Astronomical Society of Australia, 24, 1

Sneden, C., et al. 2003, ApJ, 591, 936

Sneden, C., McWilliam, A., Preston, G. W., Cowan, J. J., Burris, D. L., & Amorsky, B. J. 1996, ApJ, 467, 819

Spergel, D. N., et al. 2007, ApJS, 170, 377

Wanajo, S., Itoh, N., Ishimaru, Y., Nozawa, S., & Beers, T. C. 2002, ApJ, 577, 853