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Observing the Signatures of the r-Process in the Oldest Galactic Stars

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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, these stars allow us to study the formation and evolution of the elements and the involved nucleosynthesis processes. This knowledge is invaluable for our understanding of the cosmic chemical evolution and the onset of star- and galaxy formation. Metal-poor stars are the local equivalent of the high-redshift Universe, and thus offer crucial observational constraints on a variety of issues regarding the early Universe. This review presents an introduction to metal-poor stars and their role as "cosmic lab" for the study of neutron-capture nucleosynthesis processes, particularly that of the r-process. 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-chronomtery, i.e., the determination of stellar ages. HE 1523−0901 appears to be ~ 13 Gyr old. Age uncertaintites range from 2 to 5 Gyr for individual chronometers, and are largly due to theoretical uncertainties in the initial production ratio of the employed chronometers. 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.

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1. Introduction

The first stars that formed from the pristine gas left after the Big Bang were very massive, of the order of 100 $\mathrm{M}_\odot$ [1]. After a very short life time these co-called Population III stars exploded as supernovae, which then provided the first metals to the interstellar medium. All subsequent generations of stars formed from chemically enriched material. Metal-poor stars are early Population II objects and belong to the stellar generations that formed from the non-zero metallicity gas left behind by the first stars. Due to their low masses ($\sim 0.8\,\mathrm{M}_\odot$) they have extremely long lifetimes that exceed the current age of the Universe of $\sim$ 14 Gyr years. Hence, these stellar "fossils" of the early Universe are still observable today.

In their atmospheres these old objects preserve information about the chemical composition of their birth cloud. They thus provide archaeological evidence of the earliest times of the Universe. In particular, the chemical abundance patterns provide detailed information about the formation and evolution of the elements and the involved nucleosynthesis processes. This knowledge is invaluable for our understanding of the cosmic chemical evolution and the onset of star- and galaxy formation. Galactic metal-poor stars are the local equivalent of the high-redshift Universe. They allow us to derive observational constraints on the nature of the first stars and supernovae, and on various theoretical works on the early Universe in general [2].

Focusing on long-lived low-mass metal-poor main-sequence and giant stars, we are observing stellar chemical abundances that reflect the composition of the interstellar medium during their star formation processes [3]. Stars spend $\sim 90\%$ of their lifetime on the main sequence before they evolve to become red giants. Main-sequence stars only have a shallow convection zone that preserves the stars' birth composition over billions of years. Stars on the red giant branch have deeper convection zones that lead to a successive mixing of the surface layers with nuclear burning products from the stellar interior. In the lesser evolved giants the surface composition has not yet been significantly altered by any such mixing processes and are useful as tracers of the chemical evolution. Further evolved stars (e.g., asymptotic giant branch stars) usually have surface compositions that have been altered through repeated events that dredge up events of nucleosynthetic burning products.

The main indicator used to determine stellar metallicity is the iron abundance, [Fe/H], which is defined as [A/B]$= \log_{10}(N_\mathrm{A}/N_\mathrm{B})_\star - \log_{10}(N_\mathrm{A}/N_\mathrm{B})_\odot$ for the number N of atoms of elements A and B, and $\odot$ refers to the Sun. With few exceptions, [Fe/H] traces the overall metallicity of the objects fairly well. This review focuses on metal-poor stars that have around 1/1,000 of the solar Fe abundances, and are thus able to probe the earliest epochs of nucleosynthesis processes. A detailed summary of the history and the different "classes" of metal-poor stars and their role in the early Universe can be found in ref. [4].

2. Observing the r-Process Signature in the Oldest Stars

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 [5] that is responsible for the production of the heaviest elements in the Universe. In those stars we can observe the

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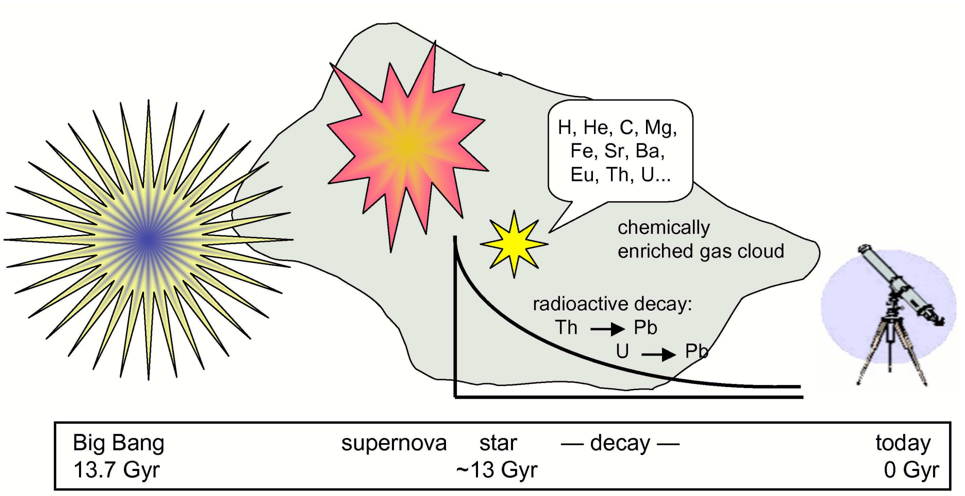

Figure 1: Schematic view of the formation process of r-process-enhanced metal-poor stars. They inherit the "chemical fingerprint" of a previous-generation supernova explosion.

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 $8-10\,\mathrm{M}_{\odot}$ are the most promising locations (see contribution of Qian in this volume).

The giant HE 1523$-$0901 ($V = 11.1$) was found in a sample of bright metal-poor stars [6] from the Hamburg/ESO Survey. It 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] $= -3.0$ [7]. 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. A full discussion of the complete abundance analysis will be given elsewhere (A. Frebel et al. 2008, in preparation). 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 [8] with [r/Fe] $= 1.6$ and in 2001, CS 31082-001 [9] 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. In Figure 3, the observed abundance patterns of HE 1523$-$0901 and other, similar, objects are presented. As can be seen, in the mass

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

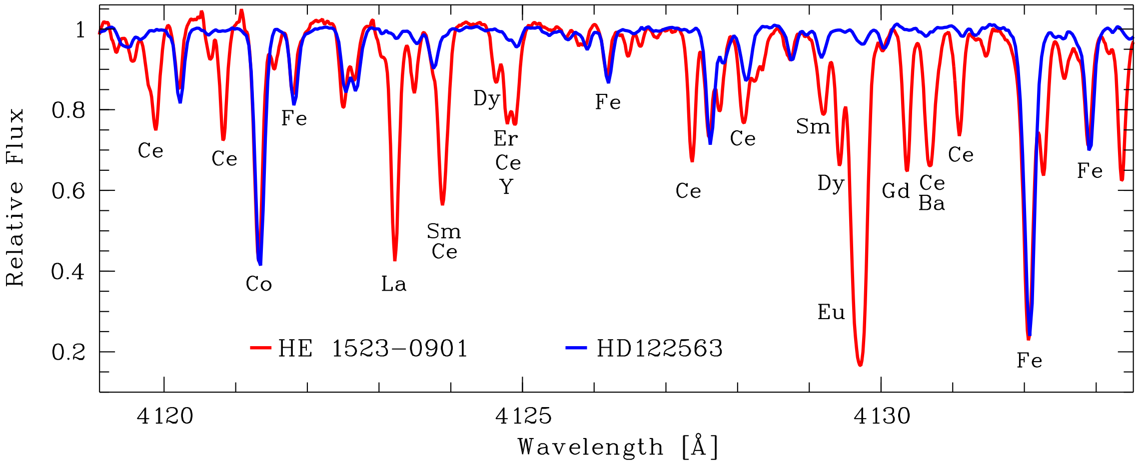

Figure 2: Spectral comparison around the Eu II line at 4129 Å of the r-process *deficient* star HD122563 and the most r-process enhanced star HE 1523−0901. Both stars have similar temperatures and metallicities.

range $56 < Z < 77$, the stellar abundances very closely follow the scaled solar r-process pattern [10]. This repeated 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.

In order to find more r-process stars in a systematic fashion, the Hamburg/ESO R-process Enhance Star survey (HERES) project was carried out, drawing candidates from the fain Hamburg/ESO survey sample. Over the course of several years, the HERES project [11] has indeed led to the discoveries of more r-process-enhanced metal-poor stars. However, none of them is as strongly enhanced as CS 22892-052, CS 31082-001, or HE 1523−0901, and all of them are relatively faint ($14 < B < 16$) so that the acquisition of very high S/N data necessary for the U detection would be somewhat a challenge. HE 1523−0901 is thus the first "uranium star" discovered in the Hamburg/ESO Survey, although drawn from the bright sample (see ref. [6] for a discussion of these samples). Only a very few r-process enhanced stars are suitable for a detection of U because the objects need to be bright, sufficiently cool, strongly overabundant in heavy neutron-capture elements, and have low C abundances to facilitate the U detection. It is of great importance, however, to find further uranium stars. This group of objects (currently with three members) will provide crucial observational constraints to the study of the r-process and its possible production site(s).

From the large HERES sample ($\sim$ 350 stars) it became clear that the production of neutron-capture elements is decoupled from that of other, lighter elements with $Z \leq 30$. The abundance spread of, e.g, Eu, at low metallicities is extremely large, while for example, Mg, has a well-defined correlation ([Mg/Fe] ~ 0.4 for the vast majority of stars below [Fe/H] < -1.5). The different behavior can be explained with different production mechanisms and sites for these groups of elements. Although still within supernova explosions, the progenitor mass range and associated differences in nucleosynthesis events and timescales likely plays the most important role. The increas-

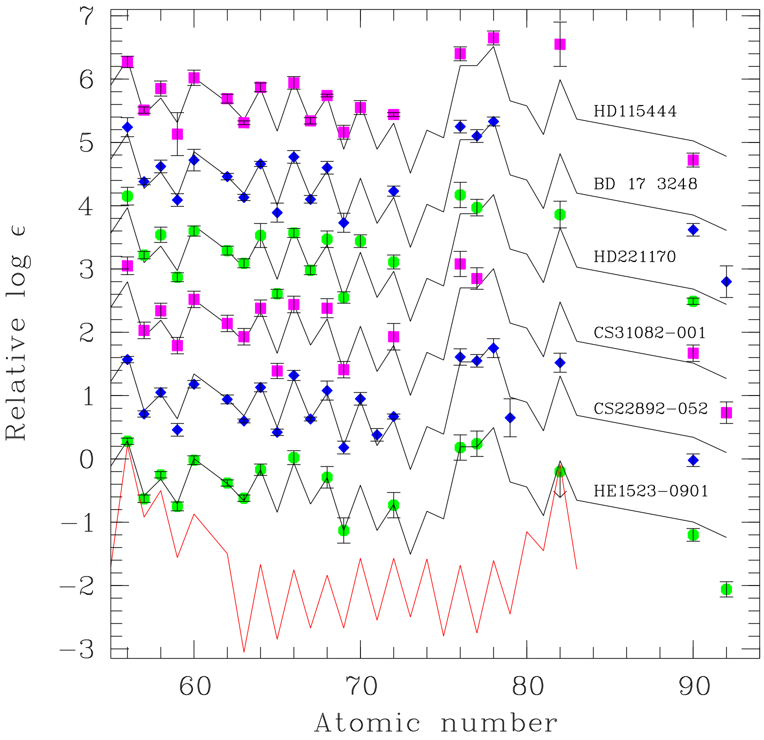

Figure 3: Neutron-capture element abundances ($Z \geq 56$) of HE 1523−0901 and the other most strongly-enhanced r-process stars in comparison with those of the scaled solar r-process [10]. There is excellent agreement between the stellar data and the solar r-process pattern. In red, the scaled solar s-process pattern is shown. It does not match the abundances. All patterns are arbitrarily offset to allow a visual comparison. References are given in Table 1.

ingly large scatter of Eu towards lower metallicities also suggests that the production of neutron-capture elements might have been rather sporadic and not was not nearly as well-established and significant as the production of the lighter elements.

3. 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.

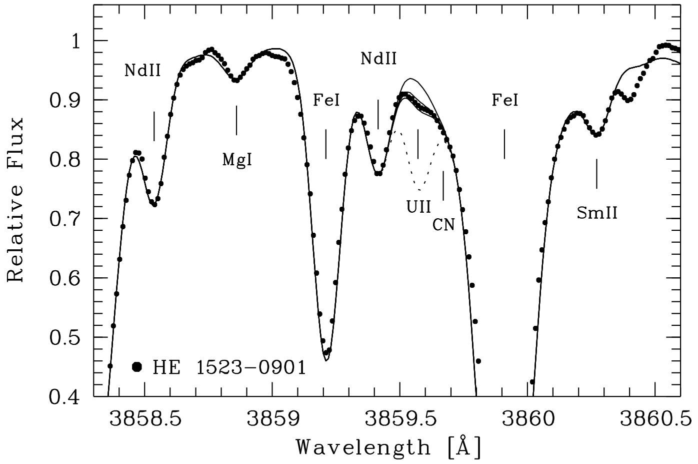

Figure 4: Spectral region around the U II line in HE 1523−0901 (*filled dots*) and CS 31082-001 (*crosses*; right panel only). Overplotted are synthetic spectra with different U abundances. The dotted line in the left panel corresponds to a scaled solar r-process U abundance present in the star if no U were decayed. Figure taken from ref. [7].

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 [12]. The U/Th chronometer was first measured in the giant CS 31082-001 [9] 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 is much more robust to uncertainties in the theoretically derived production ratio due to the similar atomic masses of Th and U [13]. Hence, stars displaying Th *and* U are the most valuable old stars.

In addition to the heaviest stable elements in HE 1523−0901, also the radioactive isotopes Th and U were measured. In fact, the U measurement in this star is the currently most reliable one of the only *three* stars with such detections. Figure 4 shows the spectral region around the only available optical U line from which the U abundance was deduced. For HE 1523−0901, the availability of both the Th and U opened up the possibility for the first time to use seven different chronometer pairs consisting of Eu, Os, Ir, Th, and U. It should be noted, that the other star with a reliable U abundance, CS 31082-001, suffers from what has been termed an “actinide boost” [14]. Compared with the scaled solar r-process (i.e., with other stable r-process elements), it contains too much Th and U. Hence, its Th/Eu ratio yields a negative age. The origin of this issue has yet to be understood. As a result, however, it has become clear that this star likely has a different origin.

There are three types of chronometers that involve the abundances of Th, U and naturally occurring r-process elements [9].

$$\Delta t = 46.7[\log(\mathrm{Th/r})_{\mathrm{initial}} - \log\varepsilon(\mathrm{Th/r})_{\mathrm{now}}]$$

$$\Delta t = 14.8[\log(\mathrm{U/r})_{\mathrm{initial}} - \log\varepsilon(\mathrm{U/r})_{\mathrm{now}}]$$

$$\Delta t = 21.8[\log(\mathrm{U/Th})_{\mathrm{initial}} - \log\varepsilon(\mathrm{U/Th})_{\mathrm{now}}]$$

Table 1: Stellar ages derived from different abundance ratios

Star	Age (Gyr)	Abundance ratio	Ref.
HD115444	15.6 ± 4	Th/Eu	[17]
CS 31082-001	14.0 ± 2	U/Th	[16]
BD $+17^\circ$ 3248	13.8 ± 4	average of several	[18]
CS 22892-052	14.2 ± 3	average of several	[12]
HD221170	11.7 ± 3	Th/Eu	[19]
HE 1523$-$0901	13.2 ± 2	average of several	[7]

Here, the subscript "initial" refers to the theoretically derived initial production ratio (PR), while the subscript "now" refers to the observed value of the abundance ratio.

The averaged stellar age of HE 1523$-$0901 derived from seven chronometers involving combinations of Eu, Os, Ir, Th and U is $\sim$ 13 Gyr. Table 1 lists the ages derived from the various abundance ratios, "chronometers", measured in a number of stars, of which some are also shown in Figure 3. 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 [15]. Realistic age uncertainties range from $\sim$ 2 to $\sim$ 5 Gyr.

From a re-determination of the U/Th ratio in CS 31082-001 [16], a relative age of this star and HE 1523$-$0901 can be derived. HE 1523$-$0901 is found to be 1.5 Gyr younger than CS 31082-001, which is *independent* of the employed production ratio. This age difference is based on only a 0.07 dex difference in the observed U/Th ratios. Given that the observational uncertainties exceed that ratio difference, the derived ages of the two stars suggest that they formed at roughly the same time. This is also reflected in their almost identical metallicity of [Fe/H] ~ -3.0.

4. 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 maybe 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

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

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. 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 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.

5. At the End of Everything: Lead

We also attempted to measure the Pb line at 4057 Å, the decay product of Th and U. However, it could not be detected in the current spectrum of HE 1523−0901 because the S/N is not high enough. The upper limit of $\log\epsilon(\mathrm{Pb}) < -0.2$ can be compared with values calculated based on the decay of Th and U and all other nuclei with $A \geq 210$ into Pb. Following ref. [20], we determine Pb values based on the decay of ^{238}U into ^{206}Pb, ^{232}U into ^{208}Pb, and ^{235}U into ^{207}Pb, whereby the last one is based on a theoretically derived ratio of $^{235}\mathrm{U}/^{238}\mathrm{U}$. The total abundance of these three decay channels amounts to $\log\epsilon(\mathrm{Pb}) = -0.72$. This is in agreement with our upper limit of $\log\epsilon(\mathrm{Pb}) < -0.2$. There are, however, also other decay channels through which Pb is built up. Based on r-process model calculations predictions can be derived for the total Pb to be measured in HE 1523−0901. Preliminary calculations indicate that this value may be high enough so that with new, higher S/N data (S/N of 500 or more at 4050 Å) a detection of this very weak line should become feasible, or at least provide a much tighter and more constraining upper limit.

6. Outlook

Old metal-poor stars in our Galaxy have been shown to provide crucial observational clues to the nature of neutron-capture processes, in particular the r-process. However, even after dedicated searches, only about two dozens of these stars are known, and only three with any detection of U. Clearly, more such objects are needed to arrive at statistically meaningful abundances constraints for various r-process calculations. At the University of Texas, we have recently started a new observing project to identify the chemical nature of candidate metal-poor stars. The "Chemical Abundances of Stars in the Halo" (CASH) project is carried out with the Hobby-Eberly Telescope at the McDonald Observatory in West Texas [21]. With this new program, we aim to observe up to 1000 metal-poor halo stars over several years to build up the largest high-resolution spectroscopic database of these precious objects. It is expected that many "chemically peculiar" metal-poor stars (i.e., stars with deviations from the solar ratios) will be found, including new r-process stars. With an increasing sample size of these stars, the nucleosynthesis processes of the early Galaxy can be understood in more and more detail. This is an important step towards unraveling the chemical nature of the Milky Way. Combining the chemical abundances with ages of old halo stars, as well as their kinematic information and the theoretical understanding of nucleosynthesis & star formation processes in the early Universe will finally provide us with new, exciting insight into the entire formation history of our Galaxy.

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