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Neutron-Capture Element Abundances and Cosmochronometry

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Abstract. Abundance ratios of radioactive to stable neutron-capture elements in very metal-poor stars may be used to estimate the age of our Galaxy. But extracting accurate ages from these data requires continuing work on many fronts: a) identification of more low metallicity stars with neutron-capture element excesses; b) acquisition of the best high resolution stellar spectra; c) improvement in neutron-capture element transition probabilities; d) calculation of more realistic nuclear models for, and interactions among the heaviest elements; and e) and more self-consistent production predictions for these elements in supernovae. This review discusses several of these areas and makes suggestions about how to improve the accuracy of Galactic cosmochronometry.

1. Introduction

The dominant isotopes of elements with atomic numbers (Z > 30) are synthesized in neutron bombardment reactions during late stellar evolution. Some of the heaviest of these so-called neutron-capture (*n*-capture) elements are radioactively unstable but long-lived on astrophysically interesting (many Gyr) time scales. In principle, abundance analyses of old, metal-poor stars that compare radioactive to stable n-capture elements can be used to determine the age of the Galactic halo. But there are practical difficulties in applying this idea to most halo stars. In this brief review we focus on studies of n-capture elements relevant to cosmochronometry, discussing in turn general n-capture abundance trends with metallicity, detailed distributions of these elements in a few very well-observed stars, and possible new initiatives to improve the use of n-capture elements in the description of early Galactic nucleosynthesis.

2. Overall n-Capture Abundance Trends with Metallicity

Abundances of n-capture elements vary respect to those of the Fe-peak by several orders of magnitude from star to star. This "scatter" is most apparent in the lowest metallicity regimes. The onset metallicity of the n-capture scatter is poorly established, but at least for stars with [Fe/H] < -2, the total range in [$<$ n-capture$>$/Fe] is $\sim \pm 1.5$ dex (e.g., Gilroy et al. 1988, McWilliam et al. 1995, Ryan et al. 1996, Burris et al. 2000). (Here, [$<$ n-capture$>$/Fe] stands for abundance ratios [Sr/Fe], [Ba/Fe], [La/Fe], etc.) The abundance scatter is far greater than that ascribable to uncertainties in the observed stellar spectra, atomic data, or model atmosphere parameters. The variation is clearly seen in published spectra of very metal-poor stars (e.g. Figure 16, McWilliam et al. 1995; Figure 3, Burris et al. 2000; Figure 1, Westin et al. 2000). This provides direct evidence that local nucleosynthesis events added to an early Galactic halo ISM that remained poorly mixed on time scales corresponding to the formation of stars with metallicities as high as [Fe/H] ~ -2.

Abundance ratios among the n-capture elements in very metal-poor stars are distinctly non-solar. Spite & Spite's (1979) high resolution spectroscopic investigation of a few bright metal-poor stars provided the first convincing observational evidence of this phenomenon. In the metallicity domain $0 >$ [Fe/H] $>$ -2, the surveys cited above have shown that the ratio [Ba/Eu] ~ 0, but by [Fe/H] $\sim$ -3 this ratio has declined to ~ -1. Barium is synthesized most efficiently via slow neutron captures (the s-process) while europium is predominantly created via rapid neutron captures (the r-process). Thus observed low [Ba/Eu] values in the most metal-poor stars suggest (e.g. Truran 1981) that r-process products comprise most of the n-capture abundances at lowest metallicities. This supports the notion that n-capture element production in the early Galaxy should have been from very short-lived, high mass stars that generate large neutron fluxes during their death throes. Products of the s-process come from longer-lived ($> \sim 10^8$ yr) low-to-intermediate mass stars. The evident lack of s-process contributions at [Fe/H] ~ -3[1] argues for a very rapid buildup of Galactic metallicity to this level from first onset of star formation.

[1]Here we do not consider the so-called CH stars, ones that exhibit extremely large overabundances of C and of n-capture elements evidently created via the s-process (Norris et al. 1997a,b; Hill et al. 2000). Most such stars are binaries, undoubtedly victims of mass transfer from higher-mass former AGB companions. These nucleosynthesis events eventually lead to the buildup of s-process levels in the Galaxy, but contribute little at lowest metallicities.

Less discussed is the lack of good correlation between abundances of heavier ($Z \geq 56$) and lighter (Z = 38–40; Sr-Y-Zr) n-capture elements. While the heavier elements appear to be r-process in origin, the lighter elements cannot be fit by the main s-process or r-process or their combination. Instead, it may require a complicated admixture of the *weak* s-process and the r-process to reproduce the Sr-Y-Zr abundance ratios in well-observed very metal-poor stars (e.g., Cowan et al. 1995). Moreover, Wasserburg et al. (1996) have argued that the solar-system r-process distribution results from two different sources or sites – one for the lighter and one for the heavier n-capture elements. It is also not yet fully understood why the abundances of the Sr-Y-Zr group correlate much more closely with Fe-peak abundances than do the heavier n-capture abundances, although it might suggest a role for the *weak* s-process operating in massive stars early in the history of the Galaxy. The lighter n-capture elements will be considered again in the next section.

3. n-Capture Element Distributions in Well-Observed Halo Stars

To thoroughly examine the details of n-capture abundances in metal-poor stars it is necessary to detect many elements over the entire Z = 31–92 element range. This in turn requires identification of stars with $[< n\text{-capture}>/\text{Fe}] \gg +0.5$, in order to maximize the spectroscopic contrast between the strengths of n-capture and Fe-peak absorption features. The few known extremely n-capture-rich metal-poor stars subjected to detailed abundance scrutiny have been serendipitous discoveries, e.g. HD 115444 (Griffin et al. 1982; Westin et al. 2000), CS 22892-052 (McWilliam et al. 1995; Sneden et al. 2000a, and references therein), and now CS 31082-001 (Cayrel et al. 2001). Much attention has been given to CS 22892-052, and in Figure **??** we summarize the results of Sneden et al. This figure also adds revised abundance determinations from the same observed spectra for elements with new transition probability and hyperfine structure data: La (Lawler et al. 2001a), Ce (Biémont et al. 2000), Tb (Lawler et al. 2001b), and Dy (Wickliffe et al. 2000). The CS 22892-052 abundances are compared with scaled solar-system r-process, s-process, and total abundance distributions.

Three features stand out in the plots of Figure **??**. First, the scaled solar r-process distribution almost perfectly fits the observed abundances of the 18 heavier ($Z > 56$) stable n-capture elements; the other two solar-system distributions fail by large margins. While the "solar total" curve appears to hold promise in comparison to the observed abundances, normalizing the curve to Eu or Dy yields a mismatch by 0.5–0.9 dex in the Ba–Ce group. Second, among the long-lived radioactive elements, the observed abundance of Th ($Z = 90$) falls below the "solar r-process" curve, as does the observed upper limit to the abundance of U ($Z = 92$). Thus if these elements were originally synthesized in the same proportions with respect to the lighter stable n-capture elements that occurred prior to solar system formation, then CS 22892-052 is substantially older than the solar system, and in fact its n-capture elements were synthesized $\sim$15 Gyr ago (e.g., Cowan et al 1999). Third, none of the solar system abundance distributions provide satisfactory matches to the lighter ($38 \leq Z \leq 48$) n-capture element abundances of this star.

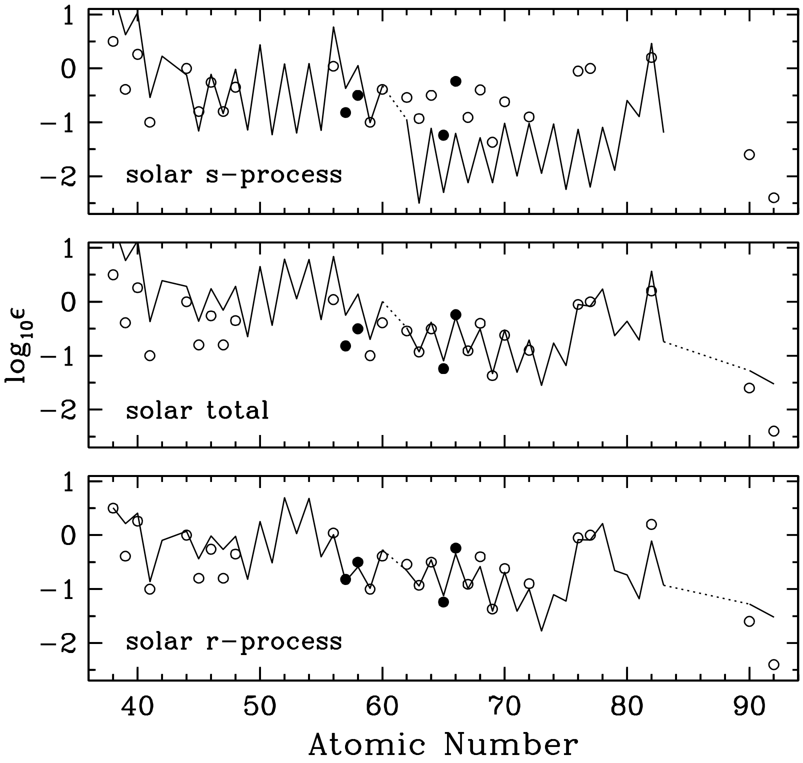

Figure 1. CS 22892-052 n-capture abundances (points) and scaled solar system abundance distributions (solid and dashed lines). Open circles are from Sneden et al. (2000a), and filled circles are abundances determined from the same observational data but with new atomic data (see text). The abundances units are $\log_{10}\epsilon(\mathrm{A}) \equiv \log_{10}(\mathrm{N_A}/\mathrm{N_H}) + 12.0$. The U (Z = 92) abundance is an upper limit. Uncertainties in individual abundances are $\sim \pm 0.05$–0.10 dex. The solar system distributions are from Burris et al. (2000). The scaling factors in the middle and bottom panels force agreement with the Eu abundance; the scaling factor in the top panel is approximate, for display purposes only.

The excellent agreement between observed abundances of the heavier stable elements and the "solar r-process" is not confined to CS 22892-052. It is repeated in each of the few ultra-metal-poor stars ([Fe/H] $<$ –2.5) studied in comparable detail (Westin et al. 2000; Johnson & Bolte 2001). Note in particular the halo giant BD+17 3248. This star has a nearly pure r-process signature among the n-capture elements, but with [Fe/H] $\sim$ –2.0, it is the highest metallicity example of very r-process enriched material. It will be of great interest to explore further the [Fe/H] $>$ –2 domain to discover at what metallicity the influence of individual r-process synthesis events are lost in the general Galactic n-capture element buildup.

Recently Cayrel et al. (2001; see also their contribution to this conference volume) have discovered that the UMP star CS 31082-001 ([Fe/H] $\sim$ –3) may have even larger n-capture element overabundances than does CS 22892-052.

Most interesting is their detection of *many* transitions of Th II and the strongest U II line; the combined abundances of two radioactive elements (with different half-lives) suggests to them that the "age" of the n-capture elements in this star is ∼13 Gyr. Their ongoing study of this star finds an *observed* [Th/Eu] ratio that is much larger than in CS 22892-052 (Sneden et al. 2000a), HD 115444 (Westin et al. 2000), several other halo stars (Johnson & Bolte 2001) and in globular cluster stars (Sneden et al. 2000b). This higher abundance ratio in CS 31082-001 would imply a young age comparable to the solar system, obviously inconsistent with this star's metallicity and halo membership. This may indicate something unusual about the abundances in CS 31082-001, or it may indicate that the production ratio of [Th/Eu] is not single-valued and may lead to inconsistencies in age determinations (e.g., Goriely & Clerbaux 1999). It is clear that many more Eu and Th abundances need to be determined for halo stars, in order to make some sense of this issue.

Finally, consider the non-conformity of CS 22892-052 abundances in the $38 \leq Z \leq 48$ domain to any of the scaled solar system curves. Previous studies have indicated that the abundances of Sr–Zr did not fall on the same curve as the heavier elements, but this is the first case where elements between Z = 40–50 have been detected. The difference between the lighter and heavier n-capture element abundance distributions in CS 22892-052 (as shown in Figure **??**) has been explained as the superposition of two distinct r-process events (Wasserburg & Qian 2000), or perhaps resulting from different regions of the same neutron-rich jet of a core-collapse supernova (Cameron 2001) that are responsible for synthesizing the lighter and heavier n-capture elements. The breakpoint between the two r-process signatures is predicted to occur near Ba, as observed in CS 22892-052. However, there has been no success thus far in fitting the individual abundances in this star, although the entire set of n-capture abundances in just CS 22892-052 has been used to constrain nuclear mass models and theoretical r-process predictions (Cowan et al. 1999). Further, since knowledge of the $41 \leq Z \leq 48$ elements is confined so far to just CS 22892-052, what is most needed now are abundances of the lighter n-capture elements in more stars.

4. Some Future Prospects

The link between n-capture elemental abundances and Galactic time scales lies with the long-lived cosmochronometer elements. So far, ratios of Th and U to each other and to other elements do not yield a consistent answer for the age of the Galactic halo when the observed abundances of a (very) few stars are compared to zero-age predictions for them. The [Th/Eu] ratios in CS 22892-052 and HD 115444 suggest ages of ∼15 Gyr, while that of CS 31082-001 yields ∼4 Gyr. But the [Th/U] ratio of this star pushes the age back to ∼13 Gyr. Johnson & Bolte (2001) find that the ages of their five stars with detected Th II features can range from 11-15 Gyr, depending on assumptions about initial Th/Eu production ratios. Clearly both further theoretical (e.g. Cowan et al. 2001) and observational efforts are needed on this problem. Extensive n-capture abundance distributions should be derived in at least ∼30 very low metallicity stars, to discover what is the normal abundance level of the radioactive chronometer elements in the Galactic halo.

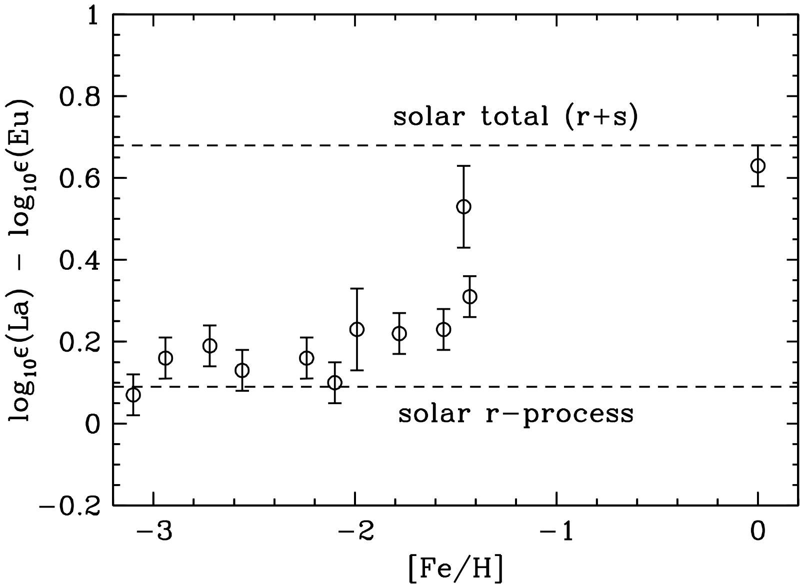

Figure 2. Ratios of La to Eu abundances in a few representative stars over most of the Galactic halo metallicity range. The La abundances have been derived using new La II laboratory data from Lawler et al. (2001a).

Probably no other *absolute* Galactic time scale information can be deduced from n-capture elements in metal-poor stars. But recent improvements in stellar spectroscopic and laboratory atomic data permit renewed attack on an unsolved *relative* time scale question: what is Galactic metallicity at which major contributions from s-process nucleosynthesis began to generally influence the halo ISM? Most s-process synthesis is associated with the AGB phases of intermediate-to-low mass stars, $\mathcal{M} < 8\mathcal{M}_\odot$, whose evolutionary time scales are $\geq \sim 10^8$ yr. Metallicity regimes with little or no detectable s-process contributions are those resulting from the first waves of Galactic nucleosynthesis that happened on faster time scales. The approximate [Fe/H] indicating a general rise in the s-process should tell us how much the first nucleosynthesis burst contributed to overall Galactic metallicity.

This question has usually been empirically addressed by trying to find the metallicity domain for substantial movement in [Ba/Eu] ratios from the r-process-dominated value of ∼–0.9 at [Fe/H] ∼ –3 toward the solar-system $r + s$ value of ∼0.0 that appears to be complete by [Fe/H] ∼ –1.5. With such data, Gilroy et al. (1988) suggested that the onset of major Galactic s-process occurred at [Fe/H] ∼ –2.3, while Burris et al. (2000) argue that this may happen at [Fe/H] ∼ –2.8. At present it is impossible to narrow this metallicity down to better than somewhere in the range –3 ≤ [Fe/H] ≤ –2.

This situation may never change, because large observed star-to-star scatter exists in [Ba/Eu] ratios at all Galactic halo metallicities. The scatter may be intrinsic to the stars, or it may simply be an artifact of abundance analyses. The problem lies in basic atomic structure. Unlike the first ions of neighboring rare earth elements, Ba II has a structure that in cool stellar atmospheres gives rise to only five very strong transitions from lower energy levels in the visible spectral range. All other Ba II transitions are very weak ones from higher excitation levels. Significant hyperfine and isotopic splitting exists for the strong low excitation lines, and Ba has 5 stable isotopes whose relative abundances are synthesized in different proportions under the r- and s-processes; estimates of these proportions becomes part of the abundance derivation process (e.g. Magain 1995, Sneden et al. 1996). Abundances of Ba also are very sensitive to values of microturbulent velocity assumed in the analyses. All in all, it is difficult to believe [Ba/Eu] ratios in most metal-poor stars to better than an uncertainty of $\sim \pm 0.2$ dex, and this is inadequate to map out the metallicity evolution of the s- and r-processes.

Fortunately other ($Z \geq 56$) elements have very different abundances resulting from the two n-capture events, and in particular [La/Eu] and [Ce/Eu] have r-/s-process sensitivities nearly equal to that of [Ba/Eu] (e.g., see Figure 1 of Sneden et al. 2001). Both La II and Ce II have much more favorable atomic structures than does Ba II, and these elements have one very dominant isotope each. McWilliam (1997) advocated abandoning the use of [La/Eu] in favor of [Ba/Eu] (see his Figure 10). But the data depicted in that diagram still has significant scatter. Johnson & Bolte (2001) argue from better data that observed [La/Eu] ratios indicate r-process dominance in stars as metal-rich as [Fe/H] $\sim$ –1.5. Now, armed with higher resolution, higher S/N spectra and employing the new atomic data of Lawler et al. (2001a), we are beginning a large-sample survey of [La/Eu] in metal-poor stars. Excellent line-by-line abundance agreement is seen for La II in the Sun, CS 22892-052, and BD+17 3248 (Sneden et al. 2001) and in Figure **??** we show the run of [La/Eu] with [Fe/H] for a few very metal-poor but n-capture-rich stars. The small star-to-star scatter in [La/Eu] at lowest metallicities is so far very encouraging, but the sample is very small. When this survey is completed we hope to be able to tell with far greater certainty the metallicity at which the s-process makes substantial contributions to most stars' n-capture abundances, and hence be able to tell how fast the Galaxy may have increased its Fe-peak metallicity before the deaths of the first intermediate-mass stars.

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