Stellar Abundance Observations

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Abstract. Ground- and space-based observations of stellar heavy element abundances are providing a clearer picture of the chemical evolution of the Galaxy. A large number of (r)apid and (s)low neutron capture process elements, including the first Hubble Space Telescope observations of Pt, Os, Pb and Ge, have been identified in metal-poor, galactic halo stars. In the very low metallicity (i.e. [Fe/H] < -2.0) stars, the abundance pattern of the elements from Ba through the third neutron-capture peak (Os-Pt) is consistent with a scaled solar *r*-process distribution. These results support previous observations that demonstrate the operation of the *r*-process, including the synthesis of the heaviest such elements, early in the history of the Galaxy. New ground-based observations further confirm that the *s*-process element Ba and the *r*-process element Eu were both synthesized solely by the *r*-process at low metallicities, and indicate the onset of the *s*-process occurred near [Fe/H] $= -2$. Over a range of metallicity ($-2.90 <$ [Fe/H] < -0.86) the data indicate that there exist real star-to-star differences in the ratios of the [n-capture/Fe] abundances as well as in the actual spectra of the stars.

1. Introduction

Observations of elemental abundances in metal-poor halo stars provide important evidence regarding the early history, evolution and age of the Galaxy. Spectroscopic studies over a number of years have indicated the presence of neutron-capture, specifically rapid neutron-capture (*i.e.* *r*-process), elements in a number of these metal-poor halo stars (see *e.g.* Spite and Spite 1978, Sneden and Parthasarathy 1983, Sneden and Pilachowski 1985, Gilroy et al. 1988, Gratton and Sneden 1991, 1994, Sneden et al. 1994, McWilliam

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et al. 1995a, 1995b, Cowan et al. 1996, Sneden et al. 1996, Burris et al. 1998). In addition, abundance comparisons of the *r*-process and *s*-process (*i.e.* slow neutron-capture) elements between the oldest metal-poor halo stars and more metal-rich halo and disk stars provide direct evidence about the nature of the chemical evolution of the Galaxy.

2. Abundance Observations of Metal-Poor Halo Stars

The abundance patterns in the very old halo stars indicate the nature of the early galactic populations and nucleosynthetic processes. One of the most well-studied such stars is CS 22892–052. Although iron poor ([Fe/H]$\simeq -3.1^2$), it is neutron-capture element rich. Sneden *et al* (1996) have used high resolution, high signal-to-noise (S/N) spectra to examine the CS 22892-052 spectrum, determining abundances of 20 neutron-capture elements in this star. Some of these elements (such as terbium, holmium, thulium and hafnium) had never previously been detected in metal-poor halo stars. We show in Figure 1 a comparison between the abundances of the neutron-capture elements in CS 22892–052 and a scaled solar *r*-process elemental distribution (solid line).

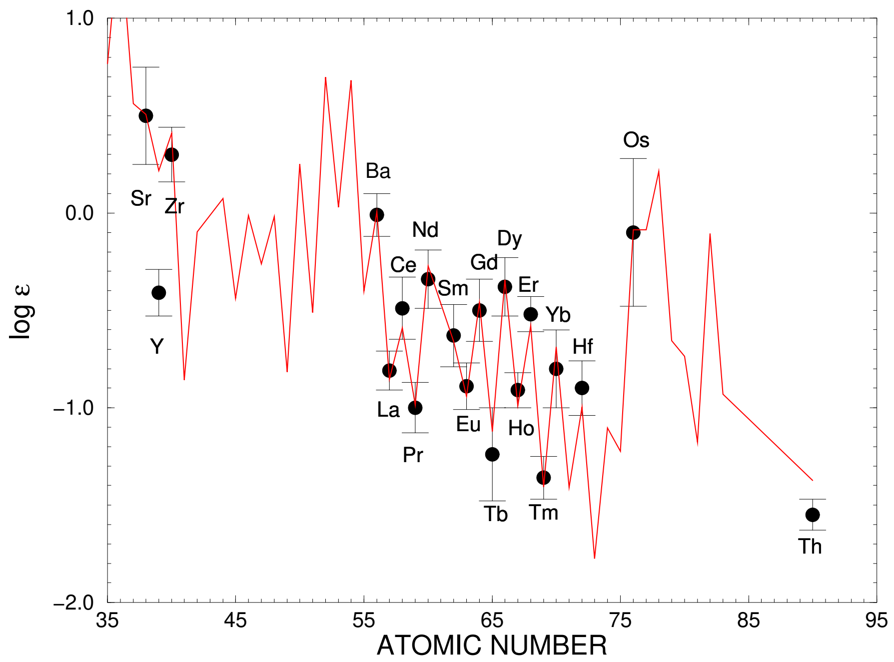

Figure 1. Comparison of neutron-capture element abundances in CS 22892–052 with the solar system *r*-process distribution.

While Os was observed in CS 22892–052, in general the 3^{rd} *r*-process peak elements (Os-Pt) have dominant transitions in the uv, and thus are not accessible to ground-based observations. Recently we have observed three metal-poor halo stars using the GHRS of the Hubble Space Telescope (HST) (Sneden et al. 1998). We show two of those stars,

[2] We adopt the usual spectroscopic notations that $[A/B] \equiv \log_{10}(N_A/N_B)_{star} - \log_{10}(N_A/N_B)_\odot$, and that $\log \epsilon(A) \equiv \log_{10}(N_A/N_H) + 12.0$, for elements A and B. Also, metallicity will be arbitrarily defined here to be equivalent to the stellar [Fe/H] value.

HD 115444 ([Fe/H] = –2.7) and HD 126238 ([Fe/H] = –1.7), respectively in Figures 2 and 3. The HST data are indicated by solid circles and ground-based data (an average of the observational values from Griffin et al. 1982 and Gilroy et al. 1988) are indicated by open circles. For comparison we show in these figures a scaled total solar system (dashed line) and a solar system r-process (solid line) abundance distribution.

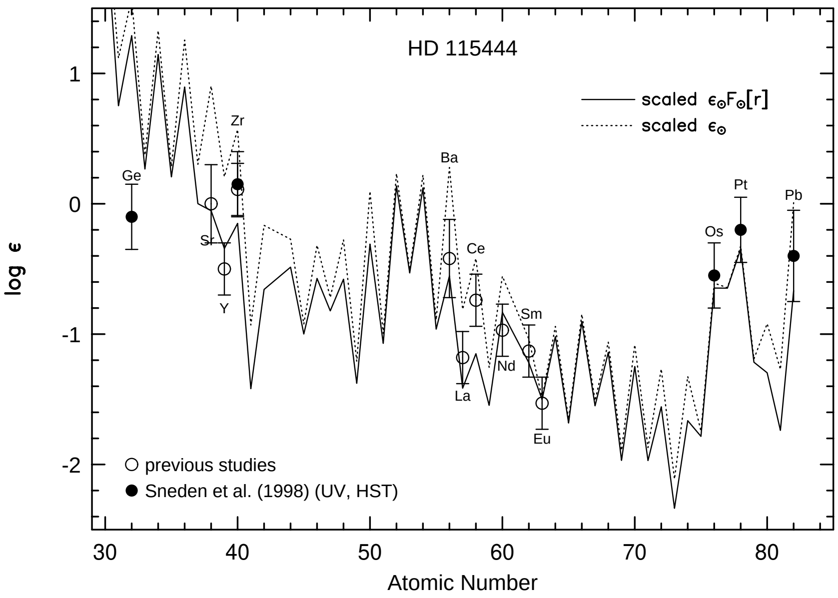

Figure 2. An abundance comparison between the neutron-capture elements in HD 115444 ([Fe/H] = –2.7) and a scaled total solar system (dashed line) and solar system r-process (solid line) abundance distribution. Ground-based data (from various sources, see text for discussion) is indicated by open circles, while HST data are indicated by solid circles.

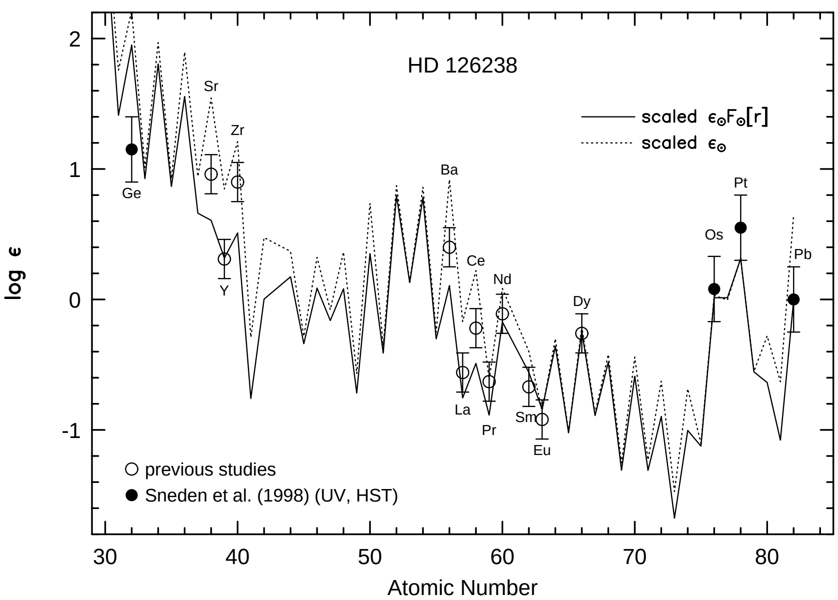

Figure 3. An abundance comparison for HD 122563 ([Fe/H] = –1.7) in the same style

as that of Figure 2.

3. Galactic Chemical Evolution Trends

A study of a number of galactic halo stars, spanning a metallicty range of -2.96 to -0.86, has recently been completed (Burris et al. 1998). Based upon data from Kitt Peak National Observatory neutron-capture element abundances have been obtained for approximately 40 stars. We show in Figure 4 the variation in [Ba/H] as a function of [α/H], where α is the average of the Ca and Ti abundances. Included in the figure are the new stellar abundance data from Burris et al. (1998), indicated by solid circles. Several other data sets for galactic halo stars are shown including those of Gratton and Sneden (1994) (open circles), McWilliam et al. (1995a, b) (crosses) and Ryan et al. (1991, 1996) (triangles). In addition, abundance studies of galactic disk stars by Edvardsson et al. (1993) and Woolf et al. (1995) (periods) are shown in this figure.

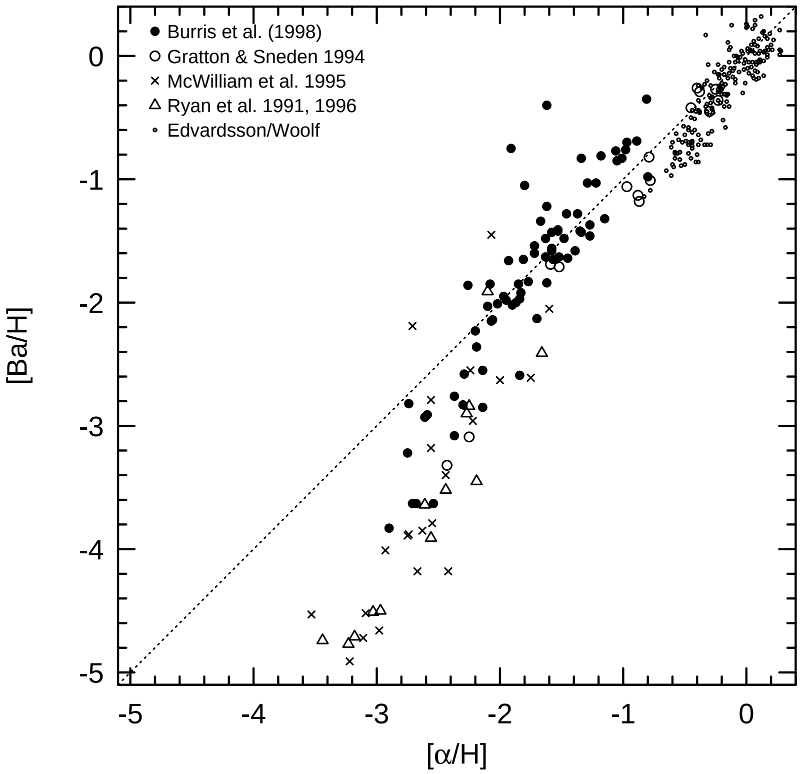

Figure 4. Comparison of [Ba/H] to [α/H], where α is the average of the Ca and Ti abundances, for a number of galactic stars.

As a comparison of the behavior of Ba, normally thought to be an s-process element, and Eu, normally thought to be an r-process element, we plot the variation of [Ba/Eu] versus metallicity in Figure 5 for the same abundance sets as shown in Figure 4.

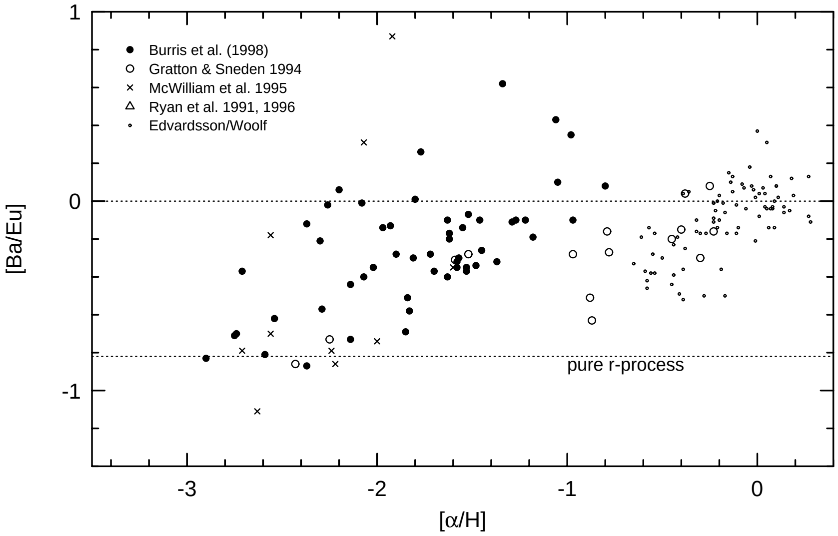

Figure 5. Comparison of [Ba/Eu] to [α/H] for a number of galactic stars.

Earlier work by Gilroy et al. (1988) presented evidence of a scatter in the abundances of the n-capture elements (with respect to iron) in the most metal-poor stars. Using additional and more accurate data, this suggestion has now been reexamined. In Figure 6 we show the average neutron-capture element abundances, with respect to iron, as a function of metallicity. For the data of Burris et al. (1998), the abundances of Ba, Eu, Nd, La and Dy were used. For all other data sets including McWilliam (1998), the abundances of Ba, Nd and Eu were used to determine the averages.

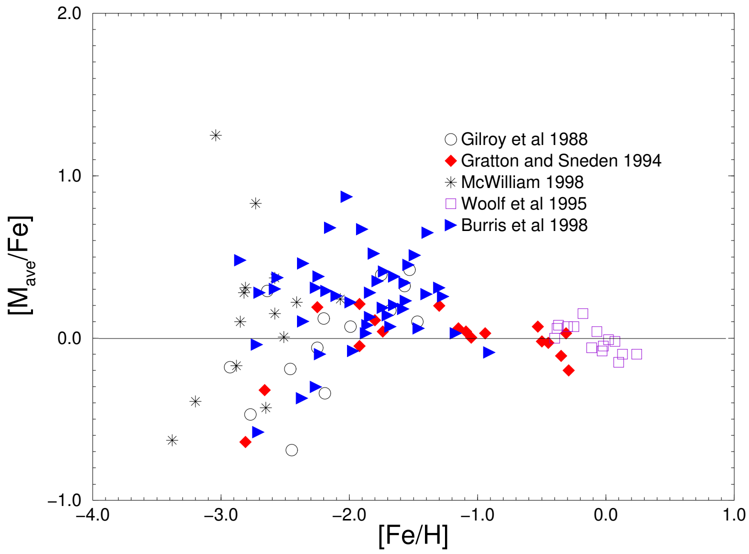

Figure 6. Average abundances of n-capture elements/Fe as a function of metallicity.

It is clear from Figure 6 that the newer data support the earlier conclusions of Gilroy et al. (1988). At the lowest metallicities, there is significant scatter in the total level of n-capture element/Fe abundances. (The relative element-to-element abundances are the *same* as shown above.) The spectra of the stars clearly indicate large differences in the strength of the individual lines (Burris et al. 1998). It is seen in this figure that for increasing metallicity the absolute scatter decreases and the average abundances for the most metal-rich halo stars and the disk stars are uniform. The newer data also support the suggestion of Gilroy et al. that at the earliest times (*i.e.* lowest metallicities) the Galaxy was not well mixed. Differences in the total n-capture element abundances from star-to-star could then be explained by the proximity of nucleosynthesis events (i.e. supernovae) prior to the formation of individual halo stars.

4. Discussion and Conclusions

Ground-based observations of the halo stars have indicated the presence of a number of neutron-capture elements. The availability of the HST has allowed for other spectral regions to be studied, and as a result more elements have been detected in these stars. For example, Figures 2 and 3 illustrate (see also Sneden et al. 1998) that we have now detected the element Ge in (three) halo stars. In addition, the 3^{rd} *r*-process peak elements, Os-Pt, as well as Pb have also now been detected in two stars using the HST (Cowan et al. 1996, Sneden et al. 1998). Including the ground-based detections of Th in CS 22892–052 (see Figure 1) and in HD 115444 (see Cowan et al. 1998), *r*-process elements from proton numbers of Z = 32 to 90 have now been observed in metal-poor stars. This is a much wider range in proton (and mass) number than ever seen before and now includes the important 3^{rd} *r*-process peak. These detections further demonstrate that the *r*-process, ranging up to the formation of the element Th, was in operation early in the history of the Galaxy.

The observations also provide important information about the nature of the progenitors of the halo stars. The *r*-process elements cannot be internally synthesized in the halo stars. Instead they must be produced in a previous generation (or generations) in an *r*-process site. Since the metal-poor halo stars were formed early in the history of the Galaxy, presumably shortly after formation, the presence of *r*-process elements in the halo stars requires very short evolutionary timescales for their progenitors. This further implies massive stars. While there is some uncertainty about the exact nature of the astrophysical site for the *r*-process, it has long been suspected to be in supernovae, particularly core collapse supernovae from massive stars (see Cowan et al. 1991a). The abundance observations of the metal-poor halo stars appear to support that suspicion.

It has also become clear with the accumulating data that the neutron-capture elements in the metal-poor stars have an abundance pattern that appears to be the same as the solar *r*-process distribution. This is illustrated vividly in Figure 1, where all of the elements from Ba to Os in CS 22892–052 have relative solar abundances. While this correlation has been noted in the past (see *e.g.* Gilroy et al. 1988), the high-resolution data in this star, covering a wide range of elements including Os in the 3^{rd} *r*-process peak, makes the argument much stronger. This same solar *r*-process pattern also appears in other stars, as shown in Figure 2. Both ground-based and HST observations of HD 115444 ([Fe/H] = −2.7) show that the elemental abundance from

Ba to Pt are consistent with a scaled solar *r*-process curve. Further evidence of this is seen in the metal-poor halo star HD 122563 (Sneden et al. 1998). Elements such as Ba and La, which today are made predominantly in the *s*-process, appear to have been made exclusively in the *r*-process early in the history of the Galaxy. While this has been suggested previously (see *e.g.* Truran 1981), the new observational data strongly support the contention that most (or all) of the elements were made in the *r*-process at the earliest times in the Galaxy. The observations indicate the same relative *r*-process abundance pattern in the oldest galactic stars and in the solar material, at least for elements with Z $\geq$ 56. Therefore, the data indicate that the *solar system r-process abundances are not the result of global averages over different types of stars and epochs.* Instead, the stellar data suggest that the conditions that produced the *r*-process elements are narrowly confined, perhaps both in terms of temperature and density of the nucleosynthesis and in terms of the mass range of the astrophysical sites (see Wheeler et al. 1998, Freiburghaus et al. 1998). The apparent lack of mixing early in the history of the Galaxy, when the relative abundance pattern is already apparent, demonstrated by Figure 6 also makes it less likely that the solar system *r*-process distribution is the result of averages.

We note in Figure 1, however, that while the elements in CS 22892–052 from Ba and above (Z $\geq$ 56) are well-fit by the solar *r*-process distribution, the extrapolation to the lower mass elements does not entirely fit the abundance data. In particular, while Sr and Zr do appear to be solar, the Y abundance is far below the solar curve. It is difficult to explain why two but not three of these neighboring elements in this star are solar. We note, further, that the abundance data for HD 115444, shown in Figure 2, show a similar separation between the lighter and heavier n-capture elemental abundances. In this star, again the abundances from Ba and above appear solar, but Sr-Zr do not. There may be several possible explanations. The weak *s*-process, expected to occur during helium core burning in massive stars, is expected to contribute to the abundances of the elements from Sr-Zr. The data may be showing such a contribution and Cowan et al. (1995) even suggested some combination of the weak *s*-process and the *r*-process might be needed to explain the abundances of Sr-Zr in CS 22892–052. We note, however, one problem in this scenario is the apparent difficulty of producing *s*-process elements in stars of extremely low metallicity. An alternative explanation may be that the more massive *r*-process elements are synthesized in one site and the lower mass elements in another. Based upon meteorite data, Wasserburg et al. (1996) have suggested the existence of two *r*-process sites with the separation in production occurring near mass number 140, *i.e.* near Ba. Possible alternative *r*-process sites have been discussed by Wheeler et al. (1998) and Baron et al. (1998). Further observations and analyses will be needed to understand the formation history of the lower mass *r*-process elements.

The most metal-rich of the halo stars studied here is HD 126238, with a metallicity of [Fe/H] = –1.7. We see the same basic trends for this star in Figure 3 that are seen in the more metal-poor stars CS 22892–052 and HD 115444. We note, however, that the abundance of Ba seems to lie above the solar *r*-process curve. It was suggested by Cowan et al. (1996) that this might indicate some *s*-process contribution to the Ba abundance. In other words, by the time that HD 126238 formed at a metallicity of –1.7, presumably more recently than the other two previously mentioned stars, some galactic *s*-processing had occurred. It is seen in Figure 3 that the stellar Ba abundance is still below the total solar Ba abundance leading Cowan et al. to suggest that only the most massive stellar contributors to the *s*-process had evolved at that point in time. Some support for their contention is given by Figure 4, which indicates the galactic chemical evolutionary trends for Ba as a function of metallicity. In this case metallicity is indicated by α, which may be a more reliable metallicity indicator than Fe, which is formed in both Type II and Type I supernovae. These data spanning a wide range in metallicty might be explained by an evolutionary delay in the production of s-process material. As demonstrated earlier in this paper, at early times in the Galaxy Ba apparently is produced from the r-process. We note the clear change in slope in Figure 4 at a metallicity $[\alpha/\mathrm{H}] \simeq -2$ that appears to indicate the onset of the main s-process nucleosynthesis production for Ba (and presumably other n-capture elements) in the Galaxy. Further evidence of this change in production mechanism, as a function of metallicity (and presumably time), for Ba is given in Figure 5. At very low metallicities (and early times) the s-process element Ba and the r-process element Eu appear to be synthesized solely in the r-process. While there is scatter in the available data, we see that at the lowest values of $[\alpha/\mathrm{H}]$ the [Ba/Eu] value in most of the stars is consistent with a pure r-process origin.

The long-lived radioactive nuclei (known as chronometers) in the uranium-thorium region are formed exclusively by the r-process and can be used to determine the ages of stars and the Galaxy. One such chronometer, Th, has been detected in CS 22892–052 (Sneden et al. 1996, Cowan et al. 1997) (see Figure 1). Comparison between the initial abundance value produced in an r-process site (often known as the production value) and the observed abundance value leads to a direct estimate of stellar ages. The abundances of the stable elements in the 3^{rd} r-process peak, a nuclear region nearby to the U-Th region, can be used to help constrain the predictions of the initial values of the long-lived radioactive chronometers, independent of knowing the site for the r-process.

Comparing the solar and the observed Th/Eu ratio in CS 22892–052, Cowan et al. (1997) found an age estimate of 15 ± 4 Gyr for this star. They noted that consideration of galactic chemical evolution could lead to an older age of 17 ± 4 Gyr. Pfeiffer et al. (1997) employed newer and more accurate nuclear data in the context of a waiting point approximation r-process model. Using the stable stellar and solar data to constrain the predicted abundances of the radioactive r-process nuclei, they compared the initial (as opposed to solar) value of Th/Eu with the stellar value and found a best estimate for this star of 13.5 Gyr. Their result for CS 22892–052 was not only consistent with Cowan et al. (1997), but is also consistent with recent globular cluster age determinations based upon Hipparcos data (see Pont et al. 1998). (See also Cowan et al. 1991a,b for a discussion of galactic and cosmological age determinations.)

This technique, based upon predicted and observed radioactive chronometers, has been extended to an additional star with an age result approximately the same as that for CS 22892–052 (Cowan et al. 1998). We caution, however, that there are still many uncertainties, and to improve the accuracy of the chronometric estimates will require more observational and theoretical studies. It is encouraging to note, though, that the detection of thorium in CS 22892–052, and other halo stars, offers promise as an independent technique for determining stellar ages, and thus putting limits on galactic and cosmological age estimates.

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