Probing the Neutron-Capture Nucleosynthesis History of Galactic Matter

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ABSTRACT

The heavy elements formed by neutron capture processes have an interesting history from which we can extract useful clues to and constraints upon both the characteristics of the processes themselves and the star formation and nucleosynthesis history of Galactic matter. Of particular interest in this regard are the heavy element compositions of extremely metal-deficient stars. At metallicities [Fe/H] $\leq$ –2.5, the elements in the mass region past barium (A $\gtrsim$ 130-140) have been found (in non carbon-rich stars) to be pure r-process products. The identification of an environment provided by massive stars and associated Type II supernovae as an r-process site seems compelling. Increasing levels of heavy s-process (e.g., barium) enrichment with increasing metallicity, evident in the abundances of more metal-rich halo stars and disk stars, reflect the delayed contributions from the low- and intermediate-mass (M $\sim$ 1-3 $M_{\odot}$) stars that provide the site for the main s-process nucleosynthesis component during the AGB phase of their evolution. New abundance data in the mass region 60 $\lesssim$ A $\lesssim$ 130 is providing insight into the identity of possible alternative r-process sites. We review recent observational studies of heavy element abundances both in low metallicity halo stars and in disk stars, discuss the observed trends in light of nucleosynthesis theory, and explore some implications of these results for Galactic chemical evolution, nucleosynthesis, and nucleocosmochronology.

Subject headings: Galaxy: evolution — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II

1. INTRODUCTION

Element abundance patterns in metal-poor halo field stars and globular cluster stars play a crucial role in guiding and constraining theoretical models of Galactic nucleosynthesis. These patterns can also provide significant clues to the natures of the nucleosynthesis mechanisms themselves. Nowhere is this more true than for the case of the neutron-capture (n-capture) processes that are understood to be responsible for the synthesis of the bulk of the heavy elements in the mass region A $\gtrsim$ 60: the s-process and the r-process. Nucleosynthesis theory identifies quite different physical conditions and astrophysical sites for these two distinct processes. r-Process nuclei are effectively *primary* nucleosynthesis products, formed under dynamic conditions in an environment associated with the evolution of massive stars (M $\gtrsim$ 10 $M_\odot$) to supernova explosions of Type II and the formation of neutron star remnants. s-Process nuclei are understood to be products of neutron captures on preexisting silicon-iron "seed" nuclei, occurring under hydrostatic burning conditions both in the helium burning cores of massive stars and particularly in the thermally pulsing helium shells of asymptotic giant branch (AGB) stars. In this picture, the first heavy (A $\gtrsim$ 60) elements introduced into the interstellar gas component of our Galaxy are expected to have been r-process nuclei formed in association with massive stars, on time scales τ_{star} $\lesssim 10^8$ years. Most of the s-process nuclei, on the other hand, are first introduced into the ISM on time scales ($\sim 10^9$ years) characteristic of the lifetimes of their stellar progenitors (M $\sim$ 1-3 $M_\odot$).

That the general features of this simple model are correct is confirmed by the finding that r-process contributions dominate the heavy element abundances in extremely metal-poor halo and globular cluster stars, while significant s-process contributions are first identifiable at metallicities of order [Fe/H] [5] ≈ -2. Observational constraints on r-process

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[5]We adopt the usual spectroscopic notations that $[A/B] \equiv \log_{10}(N_A/N_B)_{star} -$

nucleosynthesis sites are examined in §3. The implications of the observed scatter in the level of r-process nuclei relative to iron and trends in the heavy element abundances as a function of [Fe/H] over the early star formation history of the Galaxy are considered in §4. We also consider the use of the abundance data - particularly that involving the nuclear chronometers ^{232}Th and ^{238}U - for cosmochronology (§5). Finally, a brief examination of neutron-capture nucleosynthesis at low metallicities is presented in §6. We note there the importance of the carbon-rich stars. Although this review does not include a detailed examination of this class of metal-poor stars, the abundance patterns in these stars may provide insight into the earliest phases of Galactic nucleosynthesis. First, in order to provide a basis for our subsequent discussions of the heavy element abundance patterns in the stellar populations of our Galaxy, we briefly review in the next section the current status of theoretical models for s-process and r-process nucleosynthesis. Throughout this paper, our emphasis will be on (first) providing the best observational data currently available concerning heavy element abundances in stars in our Galaxy and (second) the use of this data to educate us concerning the physical characteristics, sites, and time scales of s-process and r-process nucleosynthesis.

2. S-PROCESS AND R-PROCESS SITES AND MECHANISMS

We are concerned in this review with the interpretation of the heavy element (A$\gtrsim$60) abundance patterns observed in diverse stellar populations in the context of nucleosynthesis theory. Following upon the early discussions of nucleosynthesis mechanisms by Cameron (1957) and Burbidge *et al.* (1957), we understand that most of the heavy elements are

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$\log_{10}(N_A/N_B)_\odot$, and that $\log \epsilon(A) \equiv \log_{10}(N_A/N_H) + 12.0$, for elements A and B. Also, metallicity will be assumed here to be equivalent to the stellar [Fe/H] value.

formed in two processes involving neutron captures: the s-process and the r-process. These two broad divisions are distinguished on the basis of relative lifetimes for neutron captures (τ_n) and electron decays (τ_β). The condition that $\tau_n > \tau_\beta$, where τ_β is a characteristic lifetime for beta-unstable nuclei near the valley of beta stability, ensures that as captures proceed the n-capture path will itself remain close to the valley of beta stability. This defines the s-process. In contrast, when $\tau_n < \tau_\beta$, it follows that successive neutron captures will proceed into the neutron-rich regions off the beta-stable valley. Following the exhaustion of the neutron flux, the capture products approach the position of the valley of beta stability by beta decay, forming the r-process nuclei. Using experimental determinations of the neutron-capture cross sections and the smooth behavior of the product of the abundance and cross section ($\sigma_{n,\gamma}N_s$) for nuclei lying along the s-process path, Käppeler *et al.*(1989) have identified and extracted (Figure 1) the s-process and r-process patterns characterizing solar system matter.

The significant point, for our purposes, is that these patterns are readily distinguishable. This immediately implies the following:

- If we can identify stellar environments in which either the s-process or the r-process contributions dominate, we can use this information to constrain the detailed characteristics of the corresponding nucleosynthesis mechanism.

- If we can distinguish s-process and r-process elemental contributions, we can use stellar abundance data to trace the chemical evolution of such processes over Galactic history.

In fact, we have been successful in both quests. Patterns of s-process elements are observed to be enriched in some red giant stars, reflecting *in situ* neutron capture nucleosynthesis. Indeed, it was the identification of technetium in the atmospheres of red giants by Merrill (1952) that provided a strong early clue to the fact that heavy element synthesis occurs in stars. Similarly, as we will see, the r-process distribution characteristic of solar system matter is unambiguously identifiable in the spectra of extremely metal-poor stars. The complicated chemical evolutionary histories of the two neutron capture processes can then be traced by examining, for example, the history of the barium (formed predominantly in the s-process) to europium (nearly an r-only element) ratio as a function of [Fe/H]. We will return to this issue in §4.

2.1. s-Process Nucleosynthesis

Theory has proposed the existence of several quite different astrophysical sites for the operation of the two neutron-capture nucleosynthesis mechanisms. In fact, as we shall see, it would now appear that there may be (at least?) two identifiable and distinct components (environments) for both s-process and r-process nucleosynthesis. For the case of the s-process, the two astrophysical environments are:

- The helium burning cores of massive stars (M $\gtrsim$ 10 $M_\odot$) provide an environment in which the ^{22}Ne(α,n)^{25}Mg reaction can operate to produce s-process nuclei through the mass region A $\approx$ 90 (the *"weak"* component). First studied by Peters (1968) and by Lamb *et al.* (1977), this process can in principle provide a source of the lightest s-process nuclei during the early stages of Galactic evolution (as soon as significant production of iron seed nuclei has occurred). Recent studies (Raiteri, Gallino, & Busso 1992; Baraffe, El Eid, & Prantzos 1992; Heger et al. 2002) reveal that the efficiency of production of s-process nuclei decreases at low metallicities (below [Fe/H] $\approx$ -2) due to the increased competition arising from the elevated levels of abundance of nuclei from Ne to Ca relative to iron. We will return to this issue when we discuss the evolution of s-process abundances in §4.

- The thermally pulsing helium shells of asymptotic giant branch stars provide an environment in which the ^{13}C(α,n)^{16}O reaction can operate to produce s-process nuclei in the heavy region through to lead and bismuth (the *"main"* component). First identified as a promising s-process site by Schwarzschild and Härm (1967), this site has since been investigated extensively by a number of authors (see, e.g., the recent review by Busso, Gallino, & Wasserburg (1999). This s-process site (the *"main"* s-process component), which is understood to be responsible for the synthesis of the s-process nuclei (A $\gtrsim$ 90), operates predominantly in low mass (M $\sim$ 1-3 $M_\odot$) stars. The lifetimes of stars in this mass range are typically ($\tau \gtrsim 10^9$ years), significantly greater than the lifetimes of the massive stars (M $\gtrsim$ 10 $M_\odot$) that are the site of formation of both the weak s-process component and the r-process heavy nuclei. These differential time scales for the return of the products of s-process and r-process nucleosynthesis to the interstellar medium (ISM) imply a rather complicated chemical evolutionary history for the elements in the mass range A $\gtrsim$ 60–70. We will explore this history in greater detail in section 4.

2.2. r-Process Nucleosynthesis

The site(s) of the astrophysical r-process(es) remains a challenge to theorists (see the earlier review by Cowan, Thielemann & Truran 1991). While the general nature of the r-process and of its contributions to the abundances of heavy elements in the mass range through uranium and thorium are generally understood, the details remain to be worked out. There are considerable uncertainties associated both with the basic nuclear physics of the r-process - which involves the n-capture, β-decay, and fission properties of unstable nuclear species far from the region of β-stability - and with the characteristics of the stellar or supernova environments in which r-process synthesis occurs. Until recently, it was at least reassuring that, in contrast to *s*-process, it appeared a single *r*-process site was involved. Observations reviewed in section 3 now suggest that this is not true - rather, there must be distinct classes of *r*-process events operating in the mass regimes above and below masses A $\approx$ 130-140.

Promising and studied sites of *r*-process nucleosynthesis include the following:

- The *r*-process model that has received the greatest study in recent years involves a high-entropy (neutrino-driven) wind from a Type II supernova (Woosley *et al.* 1994; Takahashi, Witti, & Janka 1994). The attractive features of this model include the facts that it may be a natural consequence of the neutrino emission that must accompany core collapse in Type II events, that it would appear to be quite robust, and that it is indeed associated with massive stars of short lifetime. Recent calculations have, however, called attention to a critical problem associated with this mechanism: the entropy values predicted by current Type II supernova models are too low to yield the correct levels of production of both the lighter and heavier *r*-process nuclei.

- The conditions estimated to characterize the decompressed ejecta from neutron star mergers (Lattimer *et al.* 1977; Rosswog et al. 1999) may also be compatible with the production of an *r*-process abundance pattern generally consistent with solar system matter. The most recent numerical study of *r*-process nucleosynthesis in matter ejected in such mergers (Freiburghaus, Rosswog, & Thielemann 1999) show specifically that the *r*-process heavy nuclei in the mass range A $\gtrsim$ 130-140 and produced in solar proportions. Here again, the association with a massive star/Type II supernova environment is consistent with the early appearance of *r*-process nuclei in the Galaxy and the mechanism seems quite robust. A potential problem with this source, pointed out by Qian (2000), is that the observed frequency of such events in the Galaxy, lower by a factor $\approx$ 100 than the frequency of Type II supernovae, demands that a high mass of r-process matter ejected per event. He argues that this is inconsistent with the level of scatter of [r-process/Fe] observed in halo stars.

- LeBlanc & Wilson (1970) have considered possible ejection of neutronized material in magnetized jets from collapsing stellar cores. This mechanism, which has most recently been examined by Cameron (2001), is again tied to massive star/Type II SNe environments.

- The helium and carbon shells of massive stars undergoing supernova explosions can also give rise to significant neutron production, via such reactions as ^{13}C(α,n)^{16}O, ^{18}O(α,n)^{21}Ne, and ^{22}Ne(α,n)^{25}Mg, involving residues of hydrostatic burning phases (Truran, Cowan, & Cameron 1978; Thielemann, Arnould, & Hillebrandt 1979; Blake *et al.* 1981). Here again, the site is associated with a Type II supernova event. The weakness of this environment, as revealed by the calculations cited above, is the fact that the expected neutron exposure is not consistent with the production of the entire range of r-process nuclei through uranium and thorium. Recent calculations (Truran & Cowan 2000) suggest that these supernova conditions may be consistent with the production of the lighter r-process nuclei, through the mass range A $\approx$ 130-140. As we will discuss in the next two sections, this might explain the lighter n-capture element abundance patterns observed in certain low-metallicity stars. However, preliminary calculations by Heger *et al.* (2002) indicate, rather, that the available neutron flux for these environments may not be sufficient to synthesize even these lighter r-process elements. The question regarding the contributions of the helium and carbon shells of massive stars to solar system and galactic r-process abundances thus remains open.

In summary, the theoretical picture indicates the inherent complexity of the heavy element nucleosynthesis history. There is increasingly strong observational evidence that the

r-process isotopes identified in solar system matter are in fact the products of two distinct classes of r-process events - for the regions A $\gtrsim$ 130-140 and A $\lesssim$ 130-140. Supernovae of a certain mass range, or neutron star mergers, appear to be the most promising candidates for production of nuclei in the mass regime A $\gtrsim$ 130-140. Shock processing of the helium and/or carbon shells in Type II supernovae may produce the r-process nuclei in the mass range A $\lesssim$ 130-140. The (seemingly) lower level of the r-process abundances for A $\lesssim$ 130-140 in extremely metal deficient halo stars like CS 22892-052 (Sneden *et al.* 2000a) may simply be attributable to the operation of the helium/carbon shell mechanism at low metallicities. Alternatively, perhaps supernovae of different mass range or frequency than those that produced the heavier r-process elements might be responsible for the synthesis of nuclei with A $\lesssim$ 130-140. There have also been suggestions (Cameron 2001) that the entire abundance distribution could be synthesized in a certain type of core-collapse supernova. Note that in all cases the site is associated with massive stars and can therefore enrich the interstellar medium on a relatively rapid time scales.

3. EVIDENCE FOR R-PROCESS NUCLEOSYNTHESIS AT EARLY GALACTIC EPOCHS

Studies of element abundances in the oldest and most metal-deficient stars in our Galaxy are extremely important because they serve as tests of nucleosynthesis theories and of models of Galactic chemical evolution, and can provide critical inferences concerning the star formation histories of stellar populations. Reviews of overall abundance patterns as a function of metallicity [Fe/H] have been provided by Spite & Spite (1985), Wheeler, Sneden, and Truran (1989), and McWilliam (1997). In this review, we concentrate specifically on the heavy element products of s-process and r-process nucleosynthesis.

The fact that there exist real and systematic depletions in the s-process elements relative to iron in stars of low [Fe/H] was first emphasized by Pagel (1968). Observed trends in the abundances of the designated s-process nuclei were scrutinized by Tinsley (1979; see also Truran 1980) and found to be inconsistent with "conventional theories." The clue to what was happening here was provided by the observations of Spite & Spite (1978) of the europium abundances in metal poor stars. Europium is an element with two stable isotopes, the abundances of both of which are dominated by their r-process contributions. The Spite & Spite data revealed that the Eu/Fe ratio was essentially solar (or higher), even for stars of very low metallicity ($-3 \lesssim$ [Fe/H] $\lesssim -2$), leaving no doubt that r-process nucleosynthesis had occurred. Many of the "anomalous" trends in "s-process" abundances at low metallicities then became interpretable rather on the basis of their levels of production in the r-process (Truran 1981).

This r-process interpretation has since been unambiguously confirmed by observations, beginning with studies of n-capture elements in HD 122563 ([Fe/H] ≈ -2.7) and HD 110184 ([Fe/H] ≈ -2.5) by Sneden & Parthasarathy (1983), Sneden & Pilachowski (1985) and with the larger survey by Gilroy *et al.* (1988). These papers all demonstrated that the heavy element abundance patterns in very low-metallicity giants were consistent with solar system r-process, but not s-process, abundances.

Recent observational studies have served both to confirm and to make clearer the presence of such patterns in low metallicity stars and to emphasize the extraordinary agreement of the observed r-process patterns with that of solar system matter. Both ground based (Sneden *et al.* 1996; Sneden *et al.* 2000a; Burris *et al.* 2000; Westin 2000) and space based (Cowan *et al.* 1996; Sneden *et al.* 1998) observational studies have now confirmed that the abundances of the heavy n-capture products (A $\gtrsim$ 130-140) in the most metal deficient halo field stars and globular cluster stars ([Fe/H] $\lesssim$ -2.5) were formed in an r-process event. This is reflected in the abundance pattern for the ultra metal poor ([Fe/H]

= -3.1), but r-process enriched ([r-process/Fe] $\approx$ 30-50), halo star CS 22892-052 shown in Figure 2. Note the truly remarkable agreement of the elemental abundance pattern in the region from barium through at least iridium, and probably through lead with the solar system elemental pattern.

This comprehensive level of agreement of the metal-poor star heavy element abundance pattern with (solar system) r-process abundances is seen in most of the stars of [Fe/H] $\lesssim$ –2.5 with published detailed n-capture abundance patterns.[6] The heavy element abundance patterns for the three r-process rich stars CS 22892-052 (Sneden *et al.* 2000a), HD 115444 (Westin *et al.* 2000), and BD +17^{o}3248 (Cowan *et al.* 2002) are compared with the solar system r-process abundances in Figure 3. The robustness of the r-process mechanism operating in the early Galaxy is reflected in the spectacular agreement of these three stellar patterns (which represent the nucleosynthesis products of, at most, a relatively small number of earlier stars) with the solar system r-process pattern (which represents the accumulated production of r-process elements over billions of years of Galactic evolution). Note the extraordinary agreement with solar system r-process abundances over this range, for the eighteen elements for which abundance data is available. These data provide conclusive evidence for the operation of an r-process at the earliest Galactic epochs that synthesizes the heavy r-process nuclei (barium and beyond), including the long lived isotopes ^{232}Th and ^{238}U critical to dating. The identification with massive stars seems compelling, although it is possible that neutron star mergers rather than a supernova environment may be responsible.

A critical question arises here involving the abundances of r-process nuclei less massive

[6]We note, however, that the observed stars tend to be r-process "rich," and we do not have as much data for the r-process "poor" stars from [Fe/H] –2.5 to –3.0, nor for metal-poor stars with metallicities below –3.0 (see discussion below in §6).

than barium. The incompatibility of the abundances of the short lived radioactivities ^{107}Pd and ^{129}I in early solar system matter with a model of "uniform production" that works well for both the actinide chronometers and the short lived isotope ^{182}Hf led Wasserburg *et al.* (1996) to argue for a second r-process component for the mass region below A $\approx$ 130-140. Studies of abundances in the mass range from the iron region through barium in low metallicity stars can be utilized to provide significant input in this regard. Returning to Figure 2 we note that while there is remarkable agreement with solar r-process abundances for the the heavier nuclei, the abundance pattern in the mass regime below A $\approx$ 130-140 does not exhibit this consistency. This is evident as well for the halo star BD $+17^{o}3248$ (Cowan *et al.* 2002), as shown in Figure 4.

Recent observational studies of the heavy element abundance patterns in globular clusters provide further evidence of the early dominance of the r-process contributions in Galactic matter. Here, we are particularly interested in the question as to whether the abundance history of [r-process/Fe] in globular clusters parallels that of the field halo stars. To date, there have been only a few detailed abundance studies of the heavy neutron capture elements in globular clusters (see, e.g. Ivans *et al.* 1999; 2001). One such study by Sneden et al. (2000b) (see Figure 5) does indicate a pattern similar to that seen in the field halo stars, and again consistent with the scaled solar system r-process abundances. We also note the detection of the long-lived radioactive element thorium in several of the giants in M15. These detections hold implications for radioactive age determinations and cosmochronology, as discussed in section 5.

4. CHEMICAL EVOLUTION OF r-PROCESS and s-PROCESS ABUNDANCES

In this section we examine more closely the abundance histories of individual neutron capture elements as a function of metallicity. As we shall see, they serve to provide important information concerning the earliest stages of star formation and nucleosynthesis enrichment in the early Galaxy.

4.1. Scatter in the Early Galaxy

We first explore the abundance scatter in the Galaxy. Early work by Gilroy *et al.* (1988) first proposed that the stellar abundances of r-process elements with respect to iron, particularly Eu/Fe, showed a large scatter at low metallicities. Their work suggested that this scatter appeared to diminish with increasing metallicity. A more extensive study by Burris *et al.* (2000) confirmed the very large star-to-star scatter in the early Galaxy, while studies of stars at higher metallicities, involving mostly disk stars (Edvardsson *et al.* 1993; Woolf *et al.* 1995), show little scatter. In Figure 6, we plot the data from a number of these surveys (Burris *et al.* 2000; Edvardsson *et al.* 1993; Woolf *et al.* 1995; Jehin *et al.* 1999; McWilliam et al. 1995, McWilliam 1998). These studies, which cover a broad metallicity range of $-3.5 \leq$[Fe/H]$\leq +0.5$, include large numbers of stars and hyper fine splitting in the derivation of Ba abundances.

We have also plotted in Figure 6 abundance determinations from several individual stars with large overabundances of r-process elements, which we refer to as r-process "rich" stars. These include CS 22892-052 (Sneden et al. 2000a), HD 115444 (Westin et al. 2000), CS 31082-001 (Hill et al. 2002) and BD $+17^{o}3248$ (Cowan et al. 2002). Thus, in some of those stars we see the ratio of the r-process element Eu, to Fe, with values reaching as high as [Eu/Fe] $\approx$ 50. (Even though the total Eu abundance is still less, the ratio of this element to iron is much higher in some of these stars than in the Sun.) At a metallicity of [Fe/H]=–3 in Figure 6, the abundance ratio of [Eu/Fe] varies by more than two orders of magnitude. However, near [Fe/H] = –1 the variation in [Eu/Fe] is reduced to less than a factor of $\sim$ five. The star-to-star scatter illustrated in this figure can most easily be explained as due to local inhomogeneities resulting from contributions from individual nucleosynthetic events (e.g., supernovae), and strongly suggests an early, unmixed, chemically inhomogeneous Galaxy.

r-Process abundances in low metal stars also provide further clues to the natures of the r-process and s-process sites. For example, the increasing level of scatter of [Eu/Fe] with decreasing metallicity, most pronounced at values below [Fe/H] $\sim$ –2.0, makes clear that not all early stars are sites for the formation of both r-process nuclei and iron. In the absence of other sources for either iron peak nuclei or r-process nuclei in the early Galaxy, this scatter is consistent with the view that only a small fraction (2%–10%) of the massive stars that produce iron also yield r-process elements. Discussions of this issue may be found in the papers by Fields, Truran, & Cowan (2002) and Qian & Wasserburg (2001).

One other important trend is notable in Figure 6. At higher metallicities, particularly for [Fe/H] $\simeq$ –1, the values of [Eu/Fe] tend downward. This reflects the effect of increasing iron production, presumably from Type Ia supernovae, at higher Galactic metallicities. At very low metallicities high mass (and rapidly evolving) Type II supernovae contribute to Galactic iron production. The onset of the bulk of iron production from Type Ia supernovae (with longer evolutionary time scales due to lower mass progenitors) occurs only at higher [Fe/H] and later Galactic times.

4.2. Abundance Trends

Studies of the time history of the heavy (neutron capture) elements have historically been driven by observations. Early trends in the s-process element patterns as a function of [Fe/H] by Pagel (1968) motivated theoretical consideration of such trends in the context of models of Galactic chemical evolution (Truran and Cameron 1971; Tinsley 1980). The great increase in abundance data for metal-poor stars over the past decade has similarly motivated considerable theoretical activity. The ratio [Ba/Eu], which reflects the ratio of s-process to r-process elemental abundances, is displayed, in Figure 7, as a function of [Fe/H], for a large sample of halo and disk stars. Note that at the lowest metallicities the [Ba/Eu] ratio clusters around the pure r-process value. The question then is what is the Galactic metallicity at which major contributions from s-process nucleosynthesis began to generally appear in the halo ISM? Most s-process synthesis is associated with the AGB phases of low (M $\sim$ 1-3 $M_\odot$) and intermediate-mass (M $\sim$ 3.5-8 $M_\odot$) stars, 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. With earlier data, Gilroy et al. (1988) suggested that the onset of major Galactic s-process occurred at [Fe/H] ~ -2.3. Burris et al. (2000) found evidence for s-processing in some stars with metallicities as low as [Fe/H] ~ -2.8, with most stars with [Fe/H] $\sim > -2.3$ showing evidence for s-process contributions to the total n-capture abundances. This fairly wide range of metallicity might indicate the various contributions from both low-mass and intermediate-mass AGB stars with different evolutionary time scales for injecting s-process material into the ISM. These chemical evolution trends have also motivated extensive work on the problem of the early chemical evolution of the Galaxy (Mathews, Bazan, & Cowan 1992; Ishimaru & Wanajo 1999; Travaglio *et al.* 1999).

Another observed abundance trend is the large star-to-star scatter in [Ba/Eu] ratios. Whether this scatter is real or due to inadequate Ba abundance analyses, however, is not clear. Barium, with a number of isotopes and significant hyperfine and isotopic splitting, can be difficult to analyze. Thus, for example, estimates of the proportions of the relative isotopic abundances synthesized in the r- and s-processes are necessary for the abundance determination (e.g. Magain 1995, Sneden et al. 1996). In addition, abundances of Ba are also quite sensitive to the assumed values of the microturbulent velocity. These difficulties lead to typical uncertainties of at least $\sim \pm 0.2$ dex in the [Ba/Eu] ratios in most metal-poor stars, and thus make this ratio inadequate to map out the detailed Galactic chemical evolution of the r- and s-processes (see Sneden et al. 2001a, for further discussion).

As an alternative, La is also predominantly an s-process element in solar system material (Burris et al. 2000). Furthermore, with only one stable isotope, La has more favorable atomic properties than Ba does, making the abundance analysis more straightforward. Thus, La/Eu could be utilized for chemical evolution studies. For example, Johnson & Bolte (2001) argue that the [La/Eu] ratios indicate r-process dominance in Galactic stars as metal-rich as [Fe/H] ~ -1.5. A new large-sample study of La/Eu ratios in metal-poor stars as a function of metallicity is being conducted (Simmerer et al., in preparation). This survey employs higher resolution, higher S/N spectra and the new atomic data of Lawler *et al.* (2001). Preliminary analysis indicates an excellent line-by-line abundance agreement for La II in the Sun, CS 22892-052, and BD+17 3248 (Sneden *et al.* 2001b). In Figure 8 we show the behavior of [La/Eu] with [Fe/H] for a small sample of metal-poor but n-capture-rich stars. We note that, unlike the case for the [Ba/Eu] ratios illustrated in Figure 7, there is a very small star-to-star scatter in [La/Eu] at lowest metallicities. However, the sample is still small, but when the survey is completed it should be possible to ascertain with more certainty the metallicity at which the s-process begin to contribute significantly to most stars' n-capture abundances. Ultimately, such information should also help to determine how rapidly the Galaxy may have increased its Fe-peak metallicity before the initial onset of the *s*-process from the deaths of the first intermediate-mass stars.

5. NUCLEOCOSMOCHRONOLOGY WITH R-PROCESS CHRONOMETERS

The detections of thorium (^{232}Th) in several halo field stars and globular cluster stars make possible the use of its abundance, relative to stable *r*-process nuclei (e.g. Eu), to other long lived and spectroscopically observable radioactive species (e.g. ^{238}U), or to its progeny (^{208}Pb) as a chronometer. Until recently the main emphasis has been on the use of the ratio Th/Eu, taking advantage of the fact that Eu is almost entirely produced in *r*-process nucleosynthesis. A promising new development has been the very recent detection of both of the long-lived nuclear chronometers Th and U in one ultra-metal-poor (those with [Fe/H] $\lesssim -2.5$, hereafter UMP) halo star (see Cayrel et al. 2001). These stellar chronometric- (or radioactive-) age estimates are critically dependent upon accurate stellar abundance determinations and well-determined theoretical nucleosynthesis predictions of the initial abundances of the radioactive elements. Currently the uncertainties in the age estimates employing this technique are relatively large. It is expected, however, that these uncertainties will diminish with increasing numbers of stellar detections of Th and/or U and of the stable 3$^{\rm rd}$*r*-process peak elements - these latter measurements are needed to constrain theoretical abundance predictions of the radioactive chronometers. Ultimately, the availability of improved determinations of the abundance of Pb (and perhaps Bi) will make possible even tighter constraints on stellar ages. In the following, we briefly review the current status of these possible chronometers.

5.1. Ages from Th/Eu

The number of Th (produced solely in the r-process) detections in metal-poor and UMP halo stars has been increasing (Sneden et al. 1996; Cowan et al. 1997; Cowan et al. 1999; Sneden et al. 2000a; Westin et al. 2000; Johnson & Bolte 2001; Cayrel et al. 2001; Cowan et al. 2002). These detections have led to direct chronometric stellar age determinations. The typical technique has been to first determine the ratio of the abundance of radioactive thorium to the stable europium abundance value. Eu is a particularly good choice both because it is virtually a pure r-process nucleosynthesis product and because it is easily identified in the spectra of most metal-poor giant stars. These ratios are then directly compared with predictions of the initial (zero-decay) value of Th/Eu at the time of the formation of these elements. We illustrate this comparison in Figure 9, where the observed neutron-capture abundances in the UMP star CS 22892–052 (Sneden et al. 2000a) is compared with a scaled solar system r-process abundance distribution (solid line). It is clear from this comparison that the Th abundance has decayed (dropped) with respect to the stable heavy n-capture elements. Also shown in Figure 9 is a theoretical r-process abundance curve that reproduces the observed stable r-process elements and at the same time (i.e., in the same calculation) predicts the initial radioactive elemental abundances. Such predictions for initial abundance ratios of Th/Eu, or Th to other stable elements, have been necessary since the nuclei involved in the r-process are very far from stability, and there are little experimental nuclear data available. The difference in the initial (at time of formation) predicted ratio for Th/Eu and the observed stellar ratio directly reflects (properly) the age of the radioactive material that was produced in the r-process site, whatever that may be. However, since the time scale for formation of the current halo stars, after the ejection of this r-process material into the ISM, would have been relatively short (i.e., only millions of years, as compared to billions of years), this age can be thought of as the stellar age. Chronometric ages, based upon the Th/Eu ratios, have typically fallen in the range of 11–15 Gyr for the observed stars (Sneden et al. 1996; Cowan et al. 1997; Pfeiffer, Kratz, & Thielemann 1997; Cowan et al. 1999; Sneden et al. 2000a; Westin et al. 2000; Johnson & Bolte 2001; Cayrel et al. 2001; Cowan et al. 2002).

We also note that in one case Th/Eu ratios have been determined for several giants in the globular cluster M 15 (Sneden et al. 2000b), who estimated their average, and hence the cluster, age at 14 $\pm$ 4 Gyr.

Concern has been expressed, however, over the reliability of employing Th/Eu as an age indicator in all metal-poor stars (Goriely & Arnould 2001). In particular, Eu is widely separated in mass number from thorium and differences in the synthesis histories of these elements could lead to age uncertainties. Furthermore, the initial predicted values of this abundance ratio are very sensitively dependent upon the choice of nuclear mass formula – very different mass formulae lead to widely differing initial ratios and hence age estimates. Particularly troubling is the case of CS 31082–001. This UMP star shows very high values of Th and U with respect to the stable elements such as Eu (Cayrel et al. 2001; Hill et al. 2002). Schatz et al. (2002) in fact show that employing Th/Eu in this star leads to an unrealistically young age, while Th/U provides an answer (15.5 $\pm$ 3.2 Gyr) that is consistent with other age estimates for these metal-poor stars. It is not clear, at this point, whether CS 31082–001 is somehow unusual or whether is represents a different class of stars. The results for this star do suggest though caution in employing only Th/Eu for chronometric stellar age estimates. Clearly, obtaining abundances of stable elements nearer in mass number to thorium, or even better, obtaining two chronometers such as Th and U would be preferred for this radioactive dating technique.

5.2. Ages from Two Chronometers: Th/U

The recent, and first, detection of uranium in the UMP star CS 31082-001 ([Fe/H] = –2.9) by Cayrel et al. (2001) offers promise for these stellar age detections with the addition of a second chronometer. An added advantage is that uranium is nearby to thorium in nuclear mass, and thus might offer a more reliable comparison than lower mass (i.e., farther away) elements such as, for example, europium. Cayrel et al. (2001) (see also Schatz et al. 2002) employed the abundances of U and Th, in combination with each other and with some other stable elements, to find an average chronometric age of 12.5 $\pm$ 3 Gyr for CS 31082-001.

Recent observations of the spectrum of BD +17^{o}3248 also indicate the presence of uranium, albeit weakly, marking this as the second metal-poor halo star in which U has been detected (Cowan et al. 2002). These authors, employing Th, U, Eu and several 3rd$r$-process peak elements, estimate the age of BD +17^{o}3248 to be 13.8 $\pm$ 4 Gyr. All of these age calculations make use of the theoretically predicted initial (zero-decay) values for ratios such as Th/U, Th/Eu and Th/Pt. These in turn are based upon nuclear mass formulae and abundance fits to the heaviest stable neutron-capture elements, i.e., the 3rd$r$-process peak elements. Several nuclear mass formulae, such as the extended Thomas Fermi model with quenched shell effects far from stability, i.e., ETFSI-Q (see Pfeiffer et al. 1997 for discussion), have been employed in making the age determinations. (See also Schatz et al. 2002 for new age determinations of CS 31082-001 employing another nuclear mass model.) The number of abundance determinations of the 3rd$r$-process peak elements, including Pt, in metal-poor stars is also increasing, particularly as the result of the utilization of the Hubble Space Telescope (HST) – the dominant transitions of elements such as Pt are primarily in the ultraviolet requiring a space-based telescope. Such accurate stellar elemental abundances are important in ratio to the observed radioactive abundances and in constraining the predicted initial (time-zero) radioactive abundances employed in these chronometric-age determinations.

We caution, however, that even with these recent observational successes, uranium detections in metal-poor or UMP stars may turn out to be uncommon. Previous observations have failed to detect U in such stars as CS 22892–052 and HD 115444, although meaningful upper limits can also be employed to constrain the age estimates (see also Burles et al. 2002 for further discussion). Finally, the overlap among the various chronometric age estimates for the field halo stars and for the globular M15 with other globular cluster (e.g., 14 Gyr from Pont et al. 1998) and cosmological age determinations (e.g., 14.9 $\pm$ 1.5 Gyr from Perlmutter et al. 1999 and 14.2 $\pm$ 1.7 Gyr from Riess et al. 1998) is encouraging. While the chronometric age predictions have suffered from some uncertainties in the past, that situation has been slowly changing with the addition of more high resolution stellar data and more nuclear data leading to increasingly more reliable prescriptions for very neutron-rich nuclei (see Pfeiffer et al. 2001; Burles et al. 2002).

6. NEUTRON-CAPTURE NUCLEOSYNTHESIS AT VERY LOW METALLICITIES

In this section we examine the differences in abundances among r-process "rich" and "poor" stars as a further probe of the early history of Galactic nucleosynthesis. (We define r-process rich as [Eu/Fe] $>$ +0.7 and poor as [Ba/Fe] $<$ –0.7.) We compare abundances of these two groups for selected elements in Tables 1 and 2. A range in metallicity is seen in both groups with most of these stars having [Fe/H] between about –2.0 and –3.1, and that r-process "richness" does not correlate directly with metallicity – the r-process poor stars are not necessarily the most metal-poor.

The behavior of the Sr/Ba ratio, as a function of [Ba/Fe], is also illustrated in Figure 10 to compare and contrast these groups of stars. The r-process rich stars in Figure 10 generally have [Ba/Fe] > 0, or supersolar. The Sr/Ba ratios for these stars cluster around the pure r-process ratio. The situation is quite different for the r-process poor stars. They all have [Ba/Fe] ratios much below the solar value, typically $1/10^{\ th}$ or less. On the other hand, those same stars have very large values of [Sr/Ba] with ratios 10–100 times solar, in contrast to the subsolar values for the r-process rich stars. While the weak s-process in massive stars (discussed previously) can augment the synthesis of Sr, the key finding here is the extremely low values of the heavier neutron-capture elements, e.g., Ba, leading to the very large ratios of Sr/Ba observed in r-process poor stars.

This comparison of r-process-rich and r-process-poor stars suggests that the nucleosynthetic production (in an r-process environment) of the lighter elements, such as Sr, and probably Y and Zr, is favored over the the heavier elements such as Ba in the progenitors of some metal-poor stars. Production of the heavier r-process elements early in the history of the Galaxy may be delayed relative to the lighter ones. In this scenario the observed r-process poor stars may be showing the products of nucleosynthesis from progenitor stars that lived and died prior to the formation of the first "main" r-process stars. If lower mass (8–10 $M_\odot$) supernovae are a likely source for the main r-process (see e.g., Mathews et al. 1992; Wheeler, Cowan, & Hillebrandt 1998; Ishimaru & Wanajo 1999), then the high Sr/Ba ratios could be reflective of higher mass star ejecta. Both the lighter and heavier neutron-capture elements might have been synthesized in some type of incomplete or abbreviated r-process in early, extremely metal-poor massive stars, with a possible additional Sr synthesis from the weak s-process in these same stars. Such an incomplete r-process, with insufficient neutron flux to flow up to the heaviest neutron-capture elements can occur in some model calculations for certain astrophysical conditions (see Burles et al. 2002 for further discussion). It is also possible that some other element besides iron, for example silicon, could act as a seed for any initial r-processing (see Hannawald, Pfeiffer, & Kratz 2001). Thus, even in very metal-poor or UMP stars (with by definition low iron abundances) some r-processing could occur that might synthesize some levels of Sr and even Ba. Heavy element synthesis has even been predicted for certain types of inhomogeneous big bang models (see Rauscher et al. 1994). Some of these models, under certain very restrictive assumptions, can produce s-like, as opposed to r-like, abundance signatures for neutron-capture elements that would favor lighter neutron-capture element production.

Detailed abundance determinations for large numbers of neutron-capture elements in individual r-process poor stars have, in general, not been available. The low levels of the abundances and the weak lines have made such element detections difficult. One star that has been extensively studied is the bright giant HD 122563. In Figure 11 we show an abundance comparison between this star and four r-process rich stars (BD $+17^o3248$, CS 22892–052, CS 31082-001, and HD 115444). For each star we show the difference between the abundance value of the element and the corresponding solar system r-process prediction. A perfect agreement would result in a relatively flat-line curve. That is in general, what is observed for the four r-process rich stars, supporting earlier arguments that these neutron-capture elements in these stars are in scaled solar system r-process proportions. The abundance data, what there is of it, for HD 122563 does not follow the same pattern, however. Instead the abundances of the heavier neutron-capture elements seem to depend on, and decline with, atomic number, Z. This may, in fact, be another indication of an incomplete r-process synthesis from a massive star early in the history of the Galaxy. We caution, however, that our analysis is based so far only on HD 122562, and needs to be confirmed by additional stars.

While the most detailed abundance data is so far only available for HD 122563, there have been other recent papers noting somewhat similar abundance traits in some of the other very metal-poor stars. In particular, a few of these early Galactic stars show high concentrations of C, N or even O along with very low levels of heavier neutron capture elements (see e.g., Norris, Ryan & Beers 1997, 2001; Depagne et al. 2002).

In sum these brief comparisons suggest that the early phases of Galactic nucleosynthesis are likely to be complex. As evolutionary time scales become much shorter than Galactic mixing time scales, the yields from different (progenitor) mass-range stars may show up as different chemical mixes, so that the interpretation of abundances in stars that are more metal-poor than, for example, [Fe/H] = –3 may be problematic in the context of chemical evolution. Additional detailed abundance determinations, particularly for the more metal-poor and r-process poor stars, may help to clarify these issues in the future.

7. CONCLUSIONS

The detailed nature of the processes by which the heavy elements from iron to uranium are made in nature stands as one of the most fundamental and challenging unsolved problems in nuclear astrophysics. While the s-process is understood to occur primarily in the helium burning shells of AGB stars, the site of the r-process can only be constrained by theory to a rapidly evolving stellar/supernova environment, sufficiently short lived to explain the presence of r-process nuclei in the very oldest stars studied in our Galaxy. Furthermore, neither the nuclear physics of the r-process of neutron-capture synthesis nor the physical properties of the environment in which it might operate are known to sufficient reliability to allow us to understand the extraordinary robustness of the r-process abundance pattern in the mass region A $\gtrsim$ 130-140.

Enter the observational astronomers. Over the past two decades, high resolution spectroscopic studies have provided high quality data that has helped chemical evolution and nucleosynthesis theorists by imposing constraints upon both the nature of the nucleosynthesis sites and the abundance history of the early Galaxy. On the basis of the observed trends we have reviewed in this paper, we can summarize the following conclusions:

1. Observations leave absolutely no doubt but that the first contributions to the abundances of the heavy r-process elements in our Galaxy occurred at an early epoch, and well in advance of the first substantial s-process contributions. At metallicities [Fe/H] $\lesssim$ –2.5, the elements in the range Z $\geq$ 56 are virtually pure r-process products. r-Process synthesis of A $\gtrsim$ 130-140 isotopes happens early in Galactic history, prior to contribution of heavy s-process isotopes from AGB stars.

2. The r-process mechanism for the synthesis of the A $\gtrsim$ 130-140 isotopes (the "main" or "strong" component) is extremely robust. This is reflected in the fact that the abundance patterns in the most metal-deficient (oldest) stars, which may have received contributions from only one or at best a few r-process events, are nevertheless indistinguishable from the r-process abundance pattern that characterizes solar system matter. (The abundance patterns for the three stars CS 22892-052, HD 115444, and BD +173248 shown in Figure 2 reveal this remarkable agreement for stars of low metallicity but high [r-process/Fe].)

3. The Ba/Eu and particularly La/Eu ratios reveal that the first significant (or major) introduction of heavy s-process isotopes (the Ba peak nuclei and beyond: the main s-process component) occurred at a metallicity [Fe/H] $\sim$ -2. The time at which this occurred, presumably set by the lifetime of the low mass ($\sim$ 1-2 $M_{\odot}$) AGB star s-process nucleosynthesis site, is of order 10^9 years.

4. The increased scatter in [r-process/Fe] at low metallicities [Fe/H] presumably reflects a significant and increasing level of inhomogeneity present in the gas at that

epoch. It also provides evidence for the fact that only a fraction of the massive star ($M \gtrsim 10\ M_{\odot}$) and associated Type II supernova environments can have contributed to the synthesis of the heavy r-process isotopes. The data shown in Figure 4 reveal levels of r-process enrichment relative to iron of factors of approximately 50.

5. The observations, particularly in r-process rich-stars, indicate that the heavier (Ba and above, $Z \geq 56$, or $A \gtrsim$ 130-140) neutron-capture elements are consistent with a scaled solar system r-process curve. The data, although still incomplete, seem to indicate that the lighter neutron-capture elements (for example Ag) are not consistent with (i.e., fall below) that same scaled r-process curve. This behavior is shown in Figure 2 for CS 22892-052, and indicates that two distinct r-process environments may be required to synthesize both ends of the abundance distribution. These observations support earlier suggestions of two r-processes based upon solar system meteoritic (isotopic) data (Wasserburg et al. 1996). Analogously to the s-process, we can attribute the heavier neutron capture elements to a "strong" robust r-process, with a "weak" r-process responsible for the synthesis of the lighter elements below barium. Analyzing the lighter abundance data is complicated by the possibility of the production of s-process nuclei (in the weak s-process) from massive stars that might contribute to the production of Sr, Y and Zr only. Additional spectroscopic studies of the abundances of the lighter neutron-capture elements, in metal deficient stars, will be required to sort all of this out.

6. The identification of the r-process site with massive star environments implies that the critical nuclear chronometers for dating the Galaxy were formed early in Galactic history. This strongly supports the use of the r-process isotopes ^{232}Th, ^{235}U, and ^{238}U as reliable chronometers of the Galactic nucleosynthesis era. A more detailed discussion of this and related issues will be provided in a forthcoming paper (Burles

et al. 2002).

7. For the r-process poor stars at low metallicity the data seem to indicate that lighter elements such as Sr have high abundances with respect to heavier neutron-capture elements such as Ba. Also, for these stars (at least based upon the data available for the star HD 122563), the abundances of the heavier neutron-capture elements seems to depend more on atomic number (and to decline faster with atomic number) than the standard r-process production normally does. These results suggest that the early nucleosynthesis history of the Galaxy was quite complex with yields coming from various s- and r-process components and from synthesis sites with a variety of progenitor mass ranges.

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Table 1. Neutron-Capture Abundances in r-process Poor Stars

Star	[Fe/H]	[Sr/Fe]	[Ba/Fe]	[Sr/Ba]	[Eu/Fe]	[La/Fe]	[La/Eu]
HD 4306	–2.54	–0.20	–1.25	1.05	···	···	···
HD 88609	–2.93	0.30	–0.91	1.21	···	···	···
HD 122563	–2.71	0.17	–0.93	1.10	–0.30	–0.71	–0.41
BD -18 5550	–2.93	0.18	–1.02	1.20	–0.07	···	···
CS22897-008	–3.35	0.63	–1.23	1.86	···	···	···

Table 2. Neutron-Capture Abundances in r-Process Rich Stars

Star	[Fe/H]	[Sr/Fe]	[Ba/Fe]	[Sr/Ba]	[Eu/Fe]	[La/Fe]	[La/Eu]
HD 20	–1.39	0.05	0.58	–0.53	0.77	0.39	–0.38
HD 126587	–2.85	–0.45	–0.06	–0.39	0.75	0.30	–0.45
BD +17 3248	–2.1	0.09	0.40	–0.21	0.91	0.45	–0.46
CS22892-052	–3.1	0.70	0.41	–0.26	1.70	1.07	–0.63
HD 115444	–3.0	0.32	0.18	0.14	0.85	0.37	–0.48
CS31082-001	–2.9	0.65	1.17	–0.52	1.63	1.13	–0.50

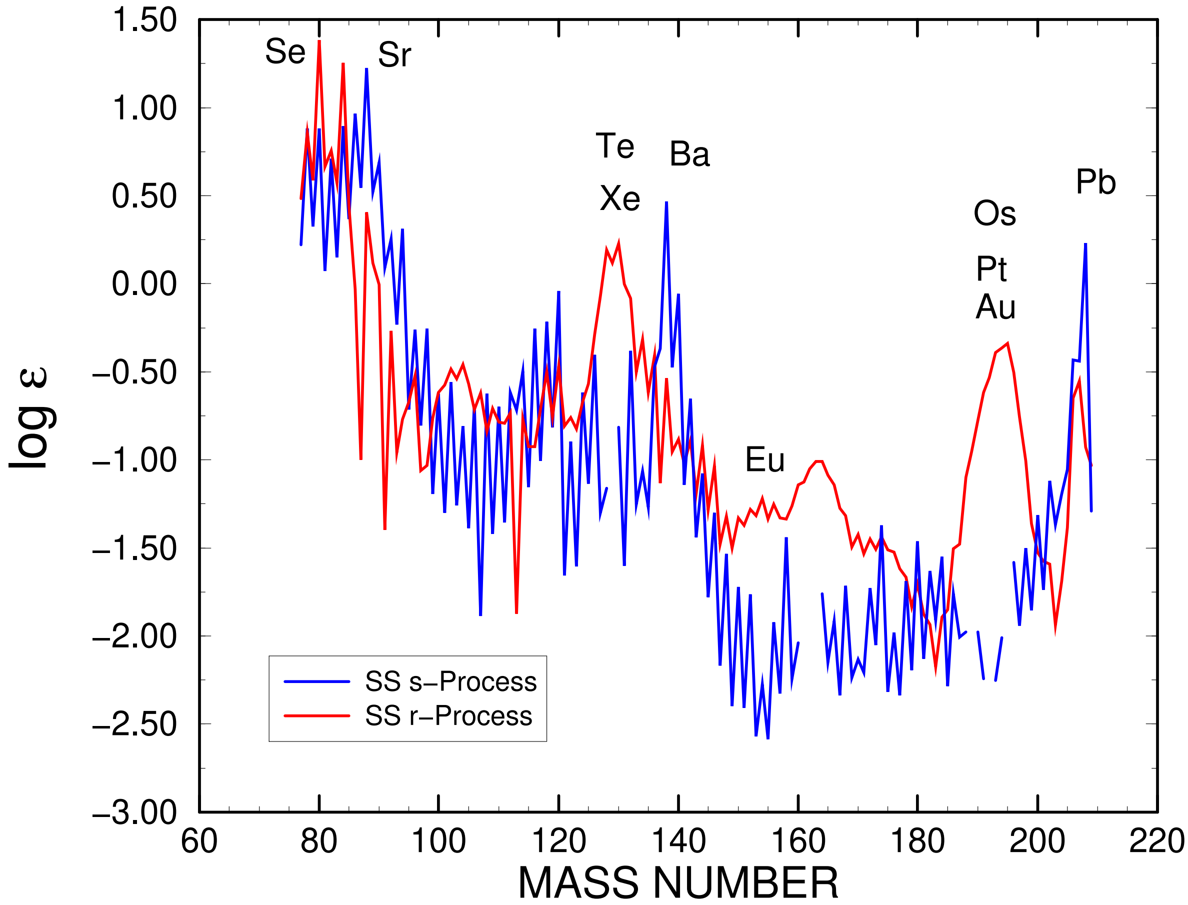

Fig. 1.— The *s*-process and *r*-process abundances in solar system matter, based upon the work by Käppeler *et al.* (1989). Note the distinctive *s*-process signatures at masses A ≈ 88, 138, and 208 and the corresponding *r*-process signatures at A ≈ 130 and 195, all attributable to closed shell effects on neutron capture cross sections. It is the *r*-process pattern thus extracted from solar system abundances that can be compared with the observed heavy element patterns in extremely metal-deficient stars. The total solar system abundances for the heavy elements are those compiled by Anders and Grevesse (1989).

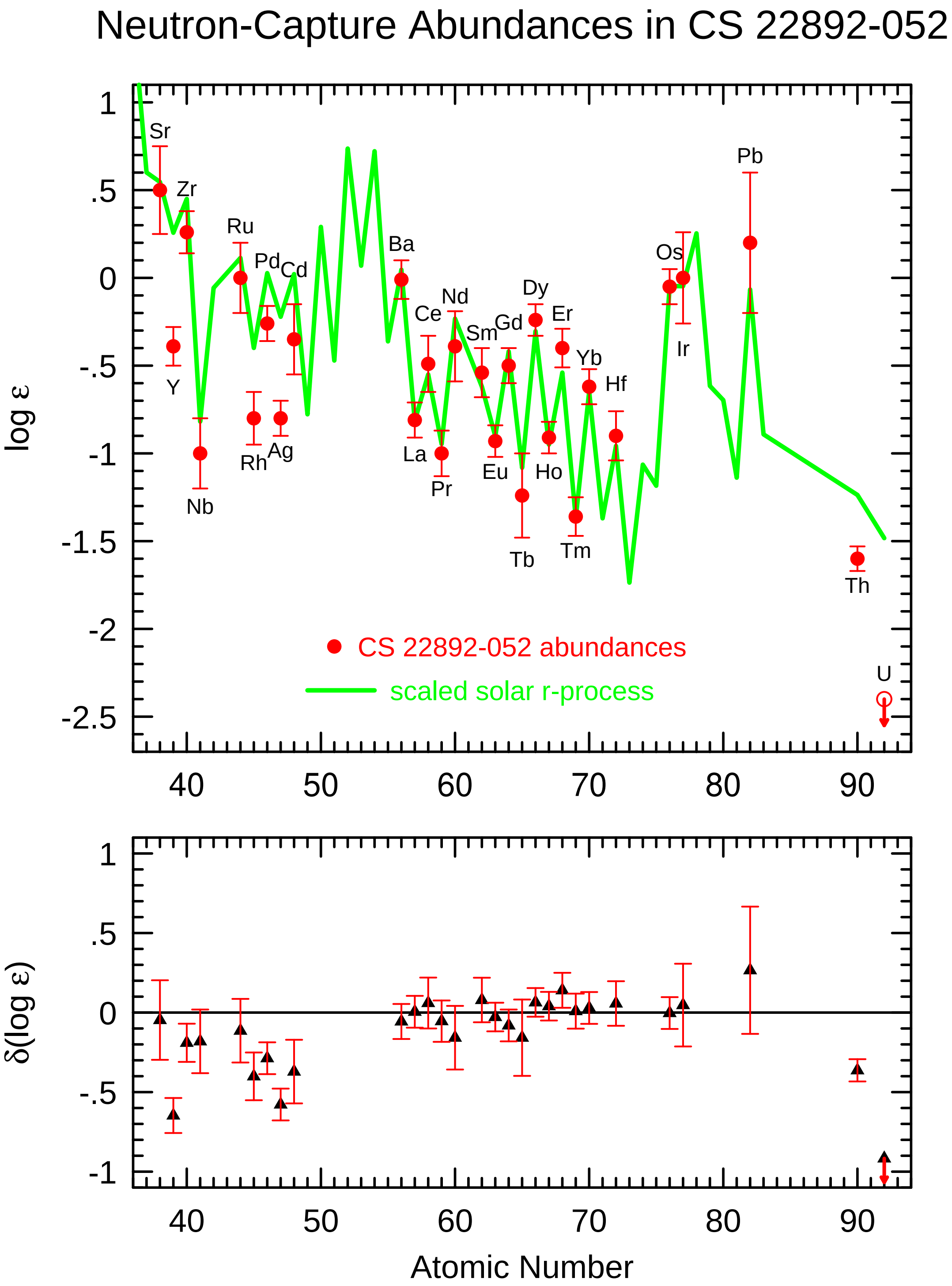

Fig. 2.— The total heavy element abundance patterns for CS 22892-052 is compared with the scaled solar system *r*-process abundance distribution (solid line). (Sneden *et al.* 2000a)

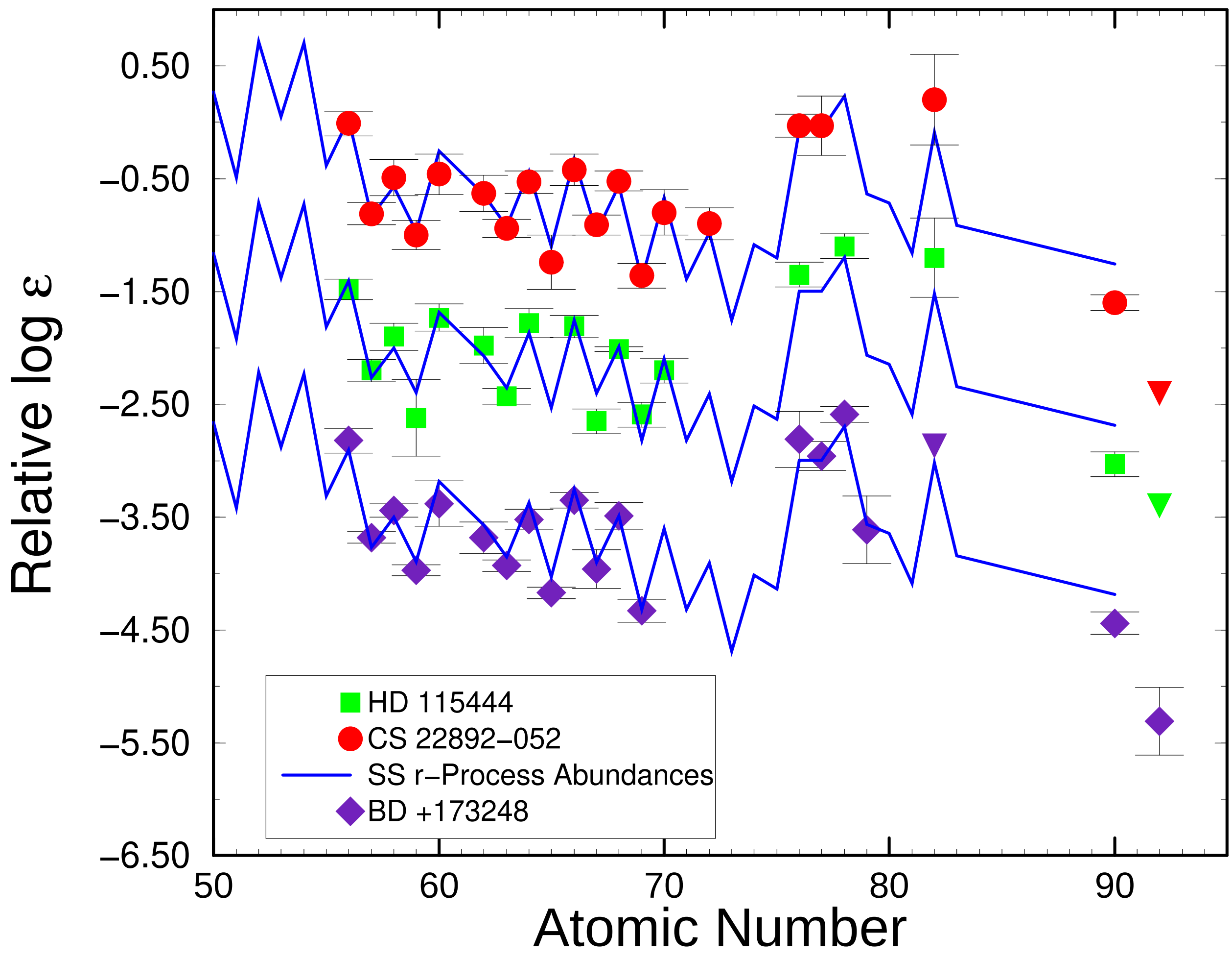

Fig. 3.— The heavy element abundance patterns for the three stars CS 22892-052, HD 155444 and BD +17^{o}3248 are compared with the scaled solar system r-process abundance distribution (solid line). (see Sneden *et al.* 2000; Westin *et al.* 2000; Cowan et al. 2002) Upper limits are indicated by inverted triangles.

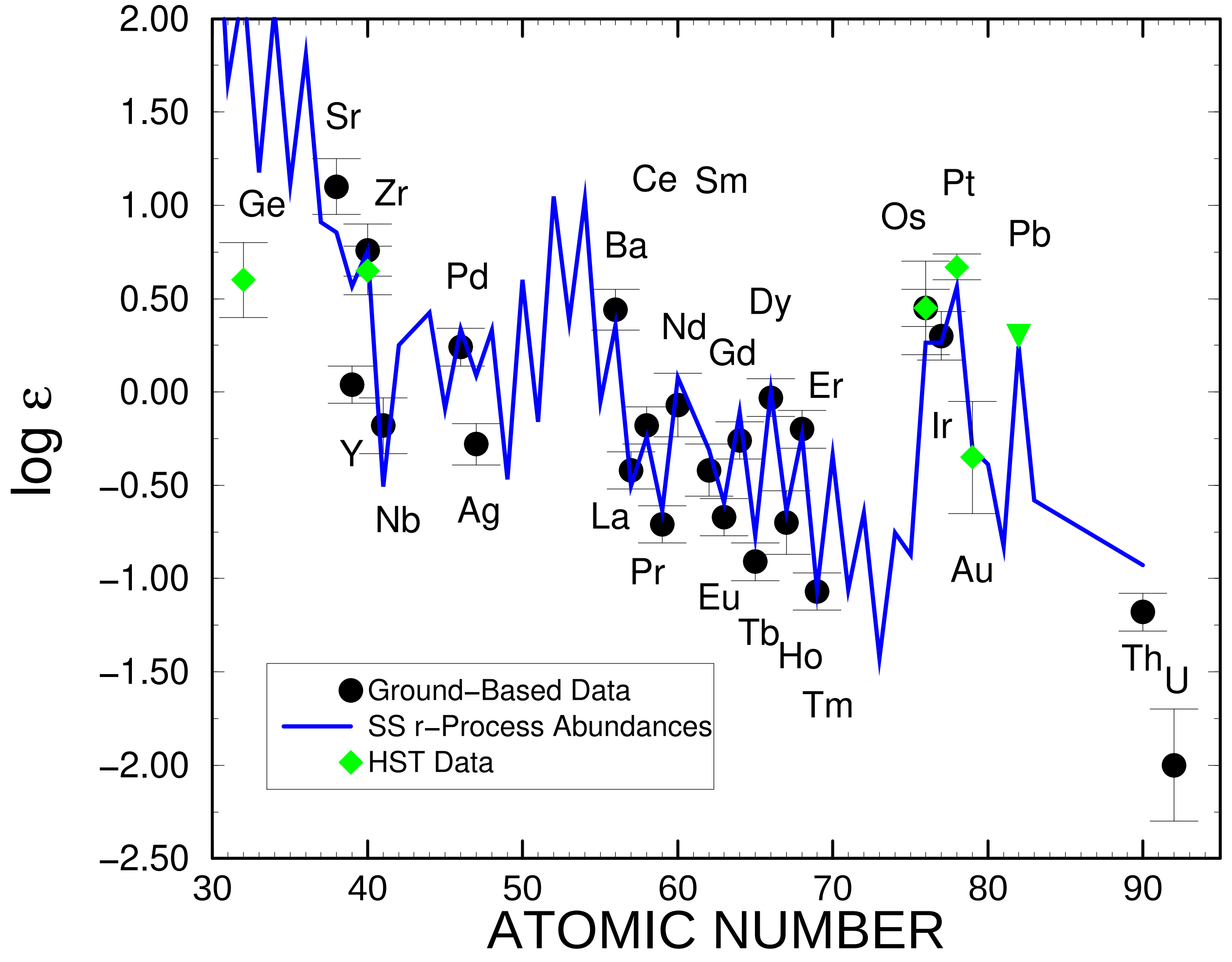

Fig. 4.— Neutron capture elements in the halo star BD +17°3248 (Cowan *et al.* 2002), obtained from ground based and HST observations, are compared to a scaled solar system *r*-process abundance curve. The upper limit on the lead abundance is denoted by an inverted triangle. Note also the thorium and uranium detections.

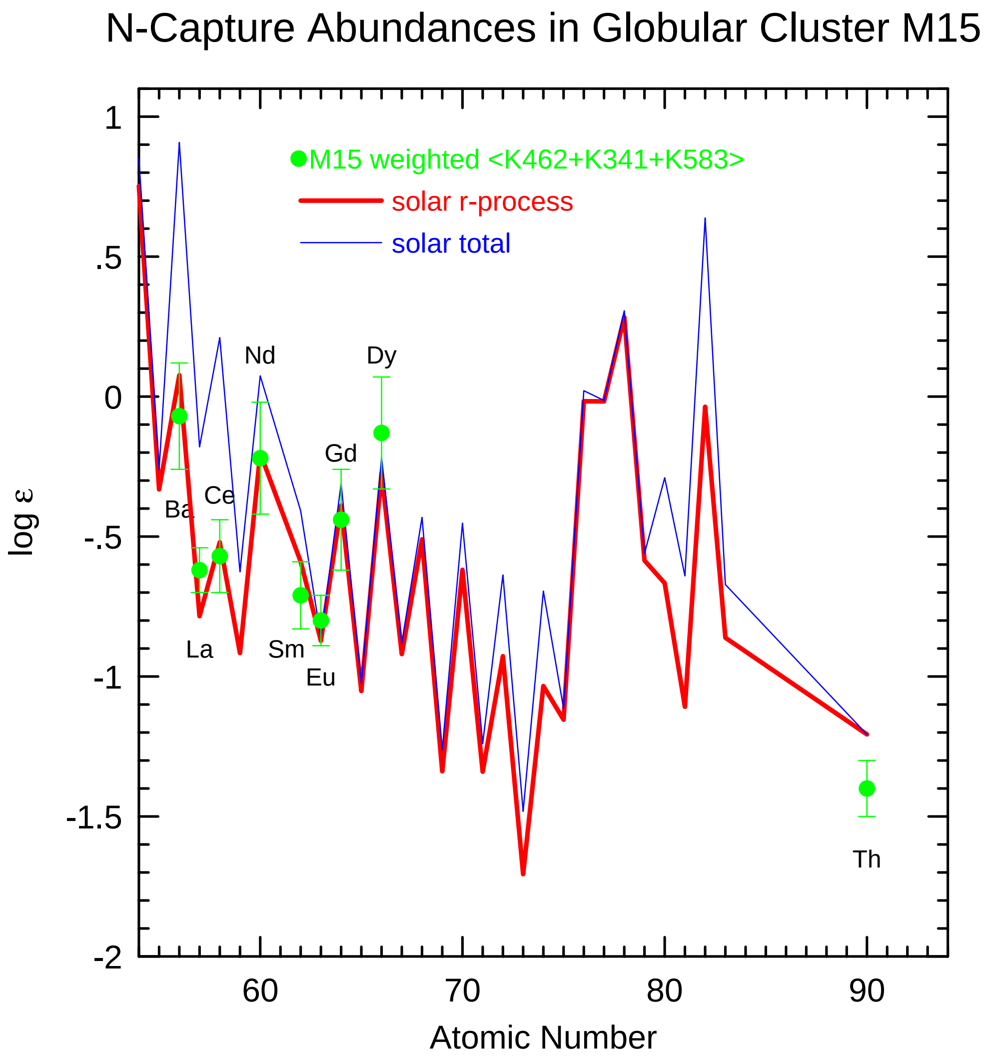

Fig. 5.— Weighted mean abundances of n-capture elements with Z $\geq$ 56 in M15 giants. In forming the means, the abundances of K462 are given triple weight, K341 double weight, and K583 single weight, to account for the relative [n-capture/Fe] abundance levels of these three stars. The solar-system r-process-only abundance distribution (Burris *et al.* 2000) has been shifted by its mean difference compared to the M15 points shown in this figure for elements Ba through Dy, and plotted as a solid curve. The solar-system total abundance distribution has been shifted by this same amount and plotted as a dotted line. (Sneden *et al.* 2000b)

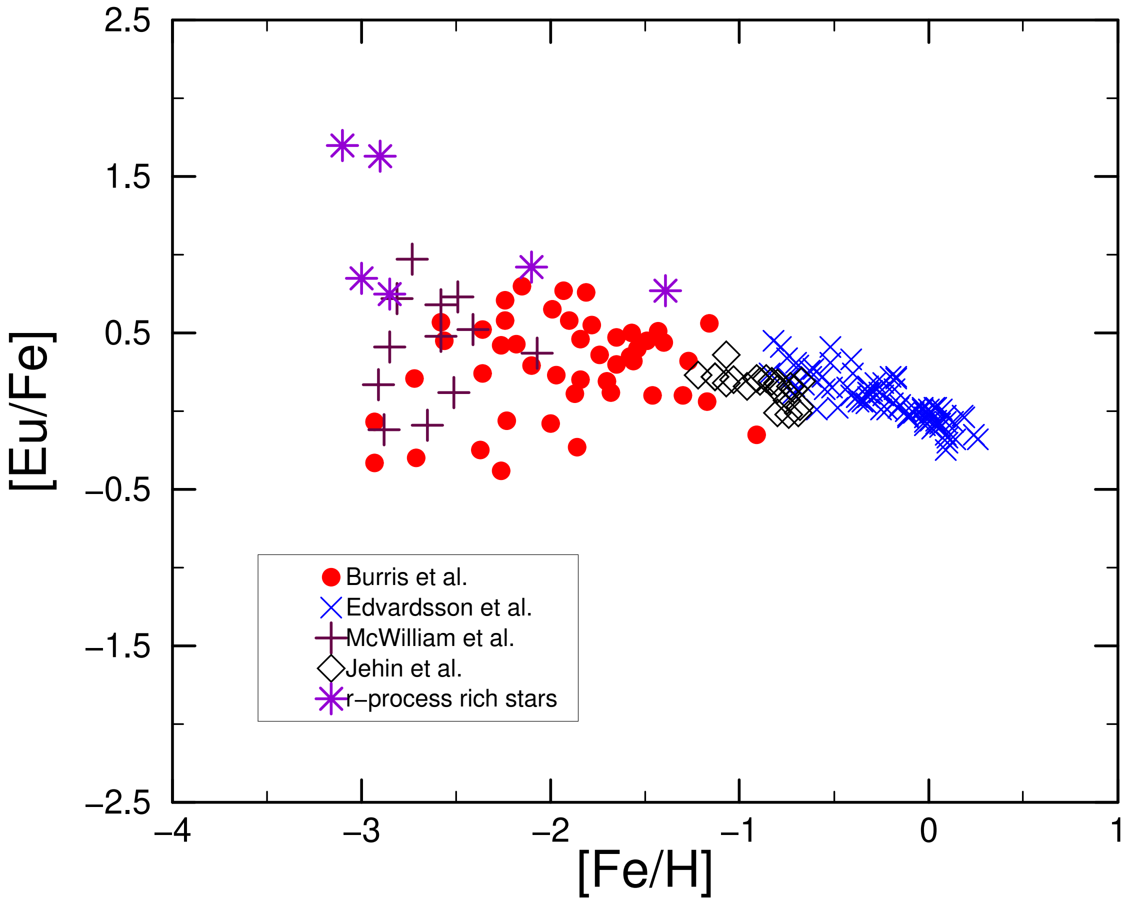

Fig. 6.— The ratio [Eu/Fe] is displayed as a function of [Fe/H] for a large sample of halo and disk stars (Burris *et al.* 2000; Jehin et al. 1999; Edvardsson et al. 1993; McWilliam et al. 1995, McWilliam 1998). r-process rich stars from Westin et al. (2000); Sneden et al. (2000a), Hill et al. 2002 and Cowan et al. (2002).

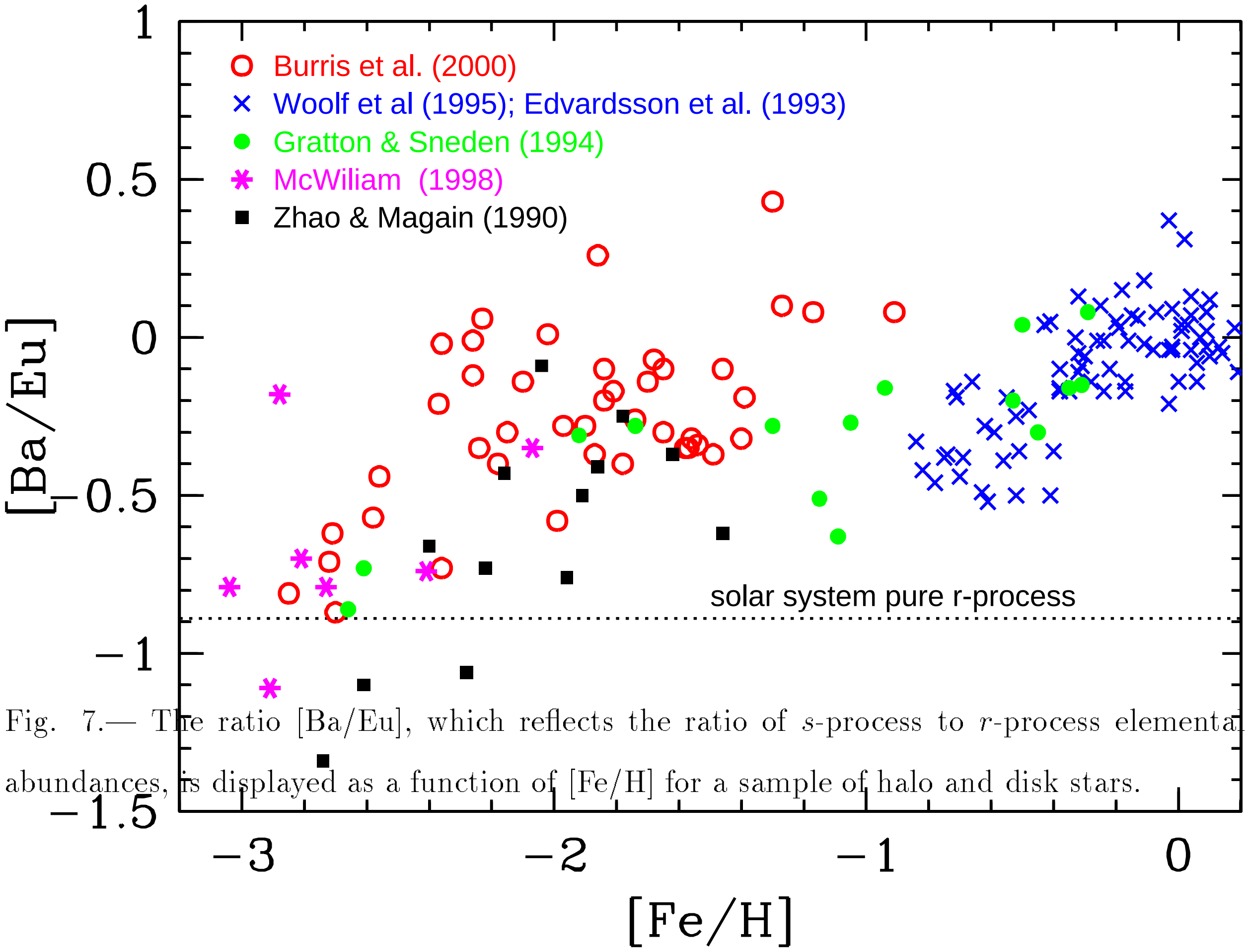

Fig. 7.— The ratio [Ba/Eu], which reflects the ratio of s-process to r-process elemental abundances, is displayed as a function of [Fe/H] for a sample of halo and disk stars.

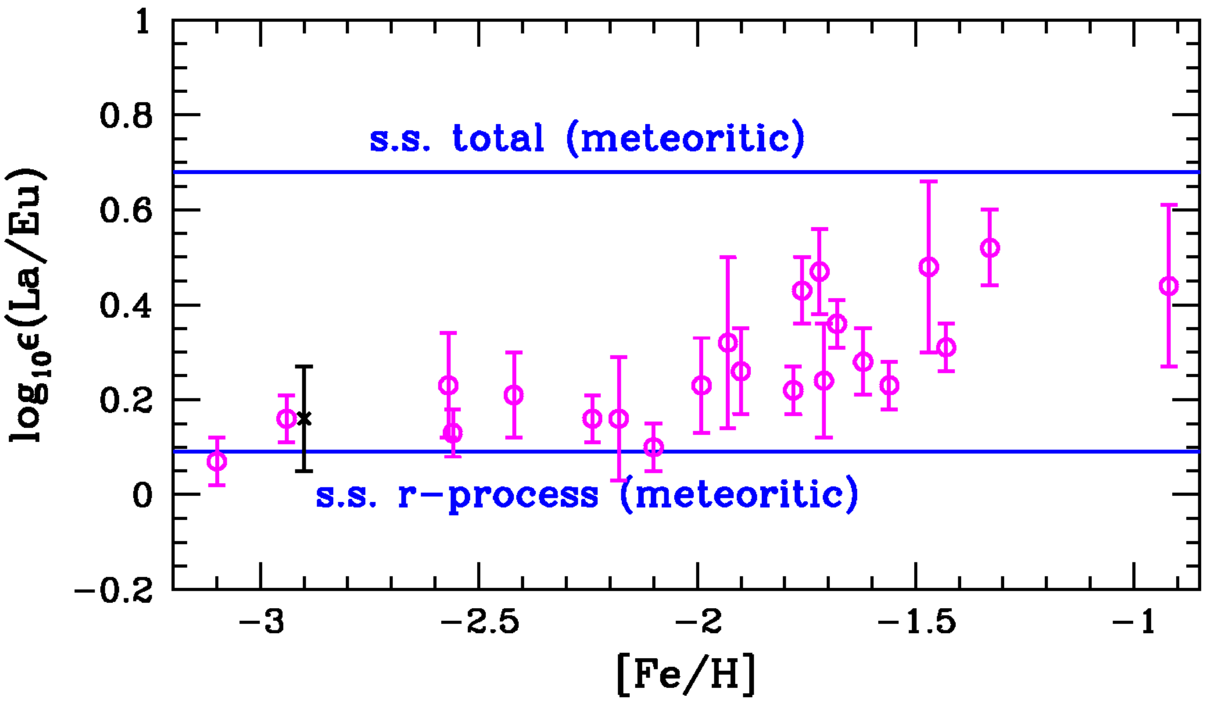

Fig. 8.— Ratio of La to Eu abundances in a few representative stars (open circles) over most of the Galactic halo metallicity range from Simmerer et al. (2002). The La abundances have been derived using new La II laboratory values from (Lawler *et al.* 2001). The data point indicated by an x is from Cayrel et al. (2001).

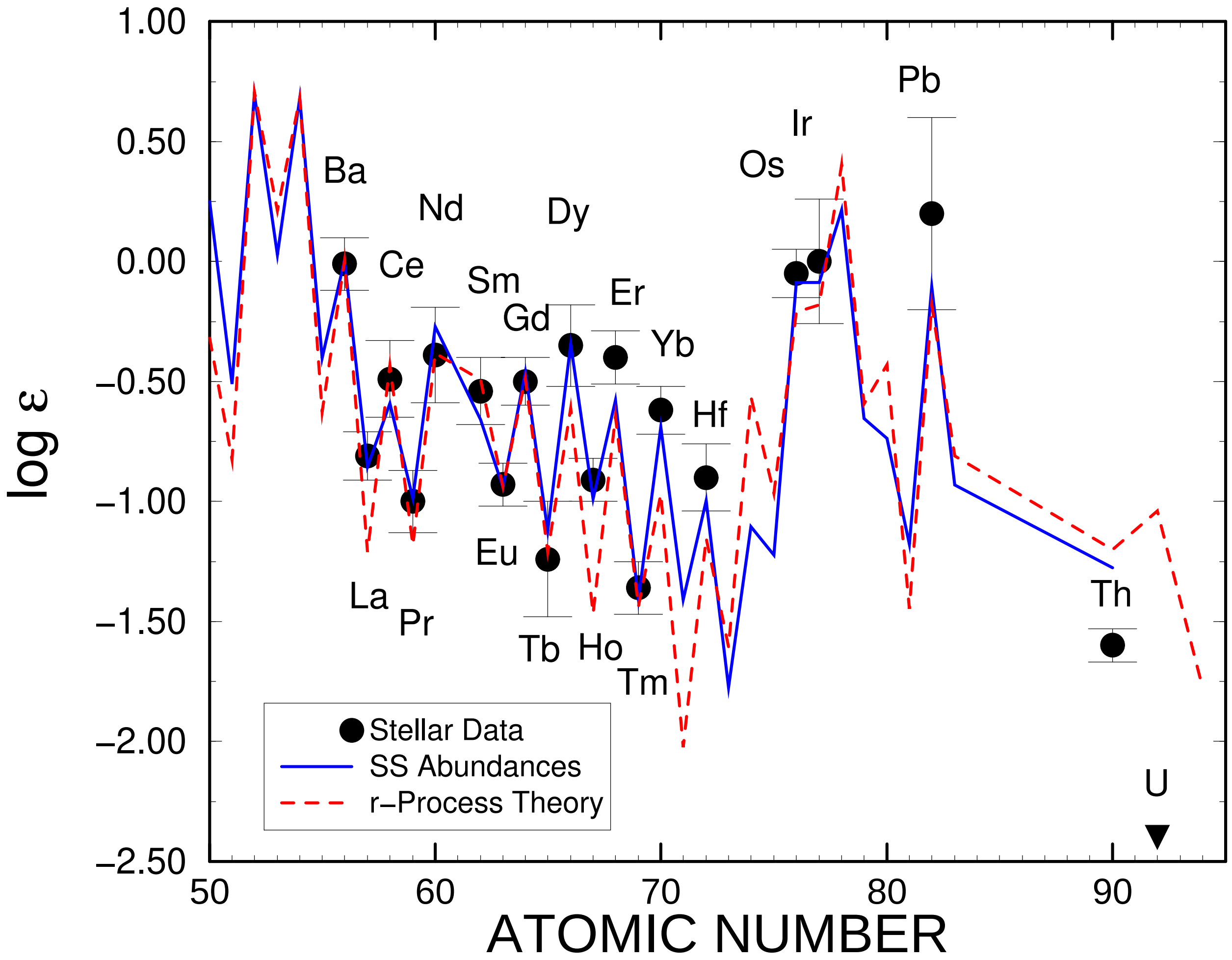

Fig. 9.— The heavy element abundance patterns for CS 22892-052 is compared with the scaled solar system r-process abundance distribution (solid line). (Sneden *et al.* 2000). Also shown is a theoretical r-process abundance curve (dashed line) from Cowan et al. (1999).

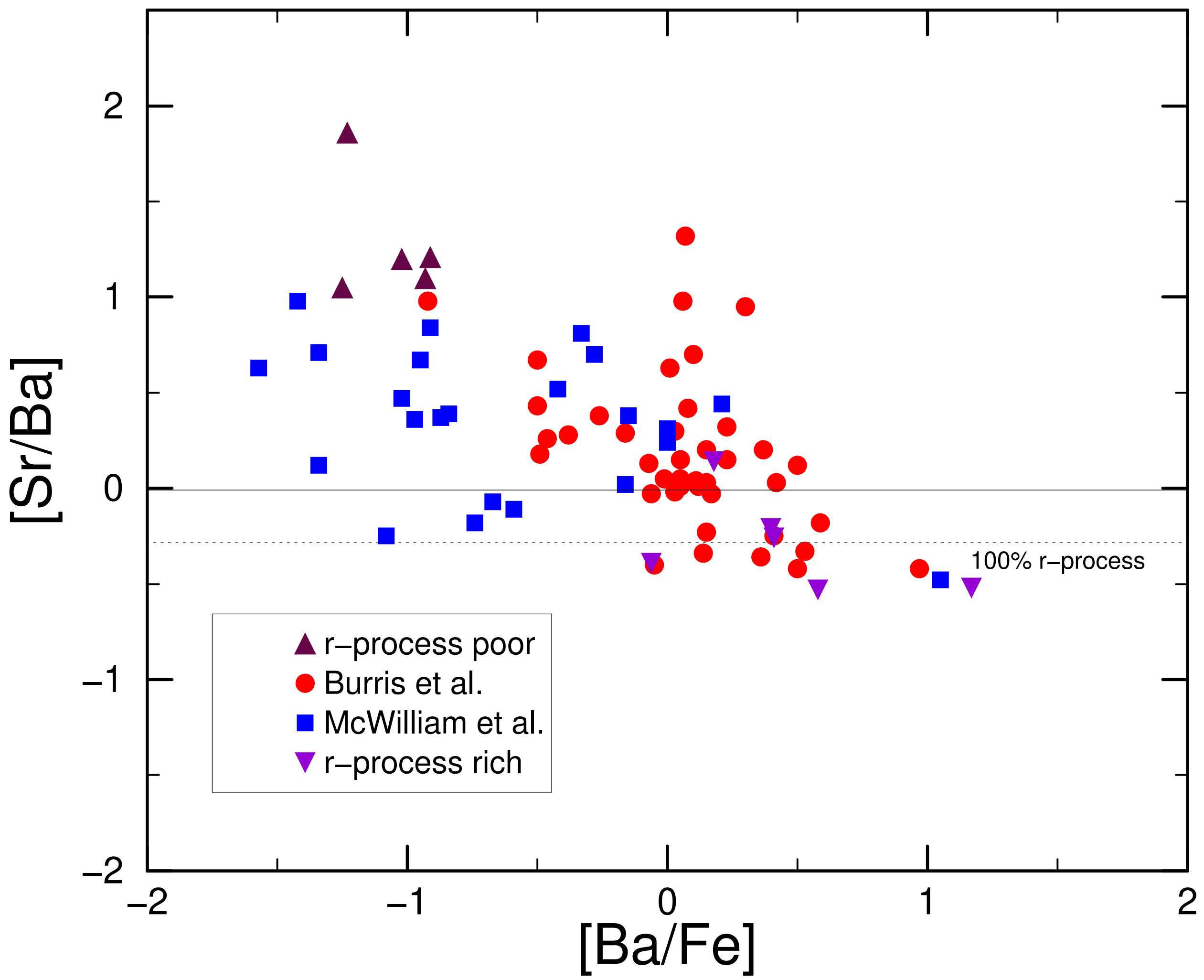

Fig. 10.— The ratio [Sr/Ba] is displayed as a function of [Fe/H] for a sample of halo and disk stars (Burris *et al.* 2000; Jehin et al. 1999; Edvardsson et al. 1993; McWilliam et al. 1995, McWilliam 1998). Note in particular the r-process poor and r-process rich stars.

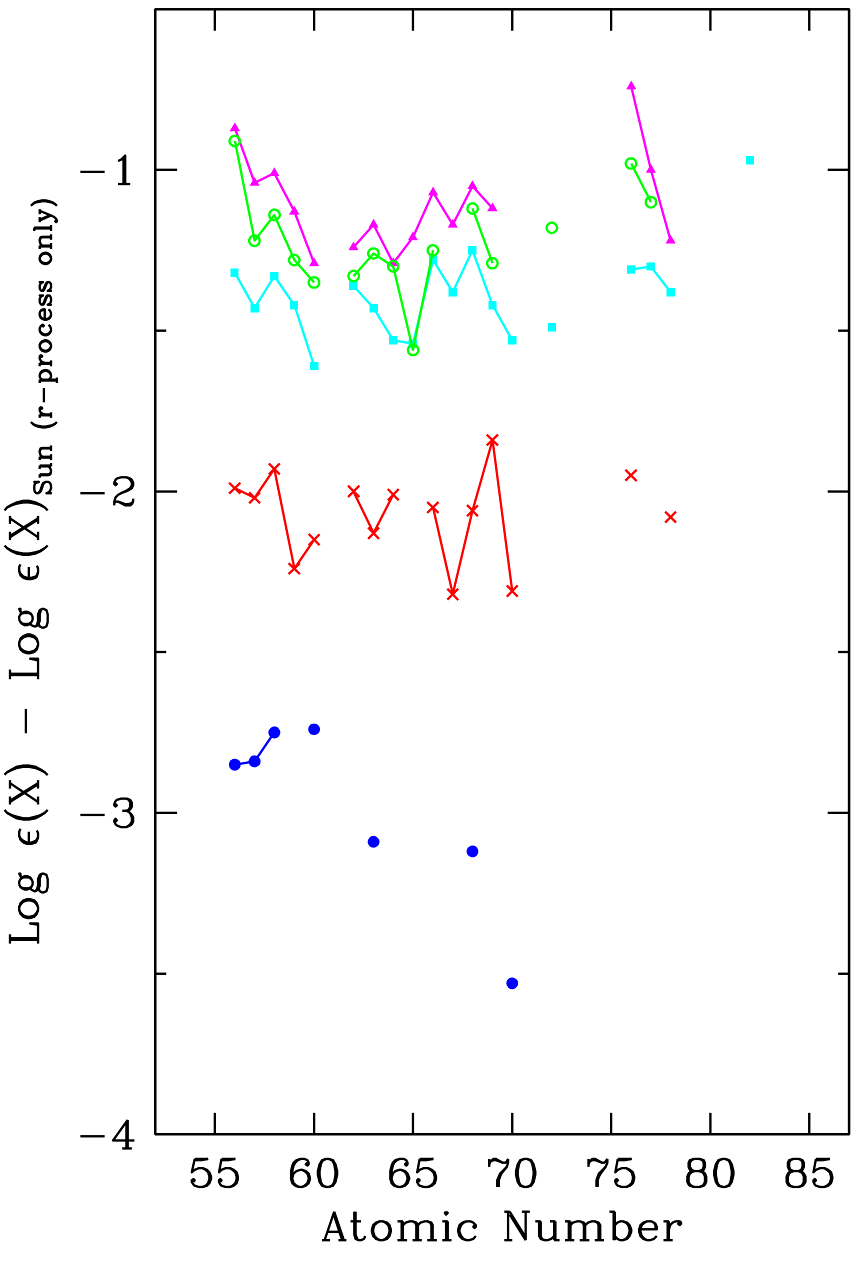

Fig. 11.— Comparisons of the abundance patterns between four r-process rich (bd+17 3248, triangles, CS 22892-052, squares, HD 115444, crosses, CS 31082-001, open circles) and the r-process poor star HD 122563 (filled circles).