Session VI

Heavy Elements

Stéfane Goriely taking questions at the end of his review on s-process elements, chaired by Francesca Primas.

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Cosmic Evolution of r-Process Elements

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Abstract. The rapid neutron capture process (*r*-process) is understood to be responsible for the synthesis of approximately half of all of the isotopes present in Solar System matter in the mass region from approximately zinc through the actinides. While the general features of this process were identified in the classic papers by B^2FH (1957) and Cameron (1957), our current understanding of the *r*-process remains woefully incomplete. We have yet to cleanly identify which of the studied astrophysical sites contribute significantly to the observed abundance pattern. We have yet to reconcile the apparent duplicity of *r*-process sites with extant models for the operation of the *r*-process in diverse astronomical environments. While we may still remain theoretically challenged in our attempts to understand the *r*-process mechanism and to identify its site, significant clues have come from the observational side. Triggered by the first detections of the element europium (formed predominantly by the *r*-process) in low metallicity stars (Spite & Spite 1978), observations of heavy element abundances in halo stars have since served to provide tremendously important clues to the nature of the *r*-process mechanism. Identified constraints include: the utter dominance of the *r*-process contributions (over those of the *s*-process in extremely metal deficient stars; an extraordinary robustness of the *r*-process pattern in the mass range A $\gtrsim$ 130–140; and the demand for a second *r*-process site for the production of the A $\lesssim$ 130 *r*-process nuclei. We will review these observational trends and theoretical models in the context of the Galactic (Cosmic) evolution of *r*-process abundances.

Keywords. nuclear reactions, nucleosynthesis, abundances, stars: abundances

1. Introduction

Progress in nucleosynthesis theory has been guided and constrained historically by our knowledge of the abundances of the elements in the matter of which our Solar System, our Galaxy, and the Cosmos itself is composed. Over the past several decades, element abundance patterns in metal-poor halo field stars and globular cluster stars have played an increasingly important role. Nowhere is this more true than for the case of the neutron-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. We will be concerned in this review primarily with the history of r-process nucleosynthesis in Galactic matter. The important early paper by Spite & Spite (1978) triggered activities by theorists and observers alike that have led to significant progress in our understanding of the r-process. In the next section, we first review r-process history and current theoretical models. Observations of halo stars and the significant clues they have provided to our understanding of the r-process are identified in section 3. Discussion of our current understanding of the character of the astrophysical r-process and its contributions to nucleosynthesis follows.

2. r-Process history and current theoretical models

The rapid (r-)process of neutron capture synthesis was first identified and defined in the now classic papers by Cameron (1957) and Burbidge *et al.* (1957). This process, responsible for the synthesis of approximately half of the heavy elements in the mass range A$\gtrsim$60-70, involves conditions of high neutron density such that the neutron capture timescales of individual species in the vicinity of the valley of beta stability are short with respect to characteristic β^--decay timescales. The r-process neutron capture path under such conditions can probe neutron-rich regions far from the beta-stable valley. The neutron closed shells at neutron numbers N= 82, and 126 are then encountered in neutron-rich regions such that, following beta decay, they give rise to the abundance peaks observed in Solar System abundances at mass numbers A$\sim$130 and 190. The r-process path continues well beyond the last stable isotopes at ^{208}Pb and ^{209}Bi through the actinide region, and is responsible for the synthesis of the interesting long-lived chronometers ^{232}Th ($\tau_{1/2}$= 1.40x10^{10} years), ^{235}U ($\tau_{1/2}$= 7.04x10^8 years), and ^{238}U ($\tau_{1/2}$= 4.47x10^9 years).

Critical to our understanding of the r-process has been the identification of the distinctly r-process contributions to the matter of which the Solar System is composed. This has been accomplished through the years with input from experimental nuclear physicists concerning the neutron-capture cross sections of critical nuclei along the s-process capture path. 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 along the s-process path, Käppeler, Beer, & Wisshak (1989) have identified and extracted (Figure 1) the s-process and r-process patterns characterizing Solar System matter. This serves two critical purposes: (1) it provides clues to the detailed nature of the r-process; and (2) we can use this knowledge of the specific s-process and r-process contributions, when compared with stellar abundance patterns, to trace the chemical evolution of these processes through Galactic history.

2.1. *r-Process models*

Identification of the site or sites in which the r-process occurs remains a challenge to theorists (see, e.g., the review by Cowan, Thielemann, & Truran 1991). The situation is complicated by the considerable uncertainties associated with both the basic nuclear physics of the r-process and the characteristics of the stellar or supernova environments in which r-process nucleosynthesis occurs. Observations discussed in the next section also now suggest there to be two distinct classes of r-process event - 1 "weak" r-process and a "main" r-process – which contribute, respectively, in the regimes below and above masses A $\approx$ 130-140. Possible sites include: (1) a high entropy (neutrino-driven) wind from a Type II supernova (Woosley *et al.* 1994; Takahashi *et al.* 1994); (2) conditions estimated to characterize the decompressed ejecta from neutron star mergers (Lattimer *et al.* 1977; Rosswog *et al.* 1999; Freiburghaus *et al.* 1999); (3) the ejection of neutronized matter in magnetized jets from collapsing stellar cores (LeBlanc & Wilson 1970; Cameron 2001); (4) prompt explosion of supernovae from lower mass stars (Wanajo *et al.* 2003); and (5) the helium and carbon shells of massive stars undergoing supernova explosions (Truran *et al.* 1978; Thielemann *et al.* 1979; Heger *et al.*2005). It is noteworthy that all of these environments are tied to massive stars and associated Type II supernovae and remnants. This is compatible with the early entry of their nucleosynthesis products into Galactic matter. Finally, we should note increasing interest in the possibility of an r-process associated with gamma-ray burst environments.

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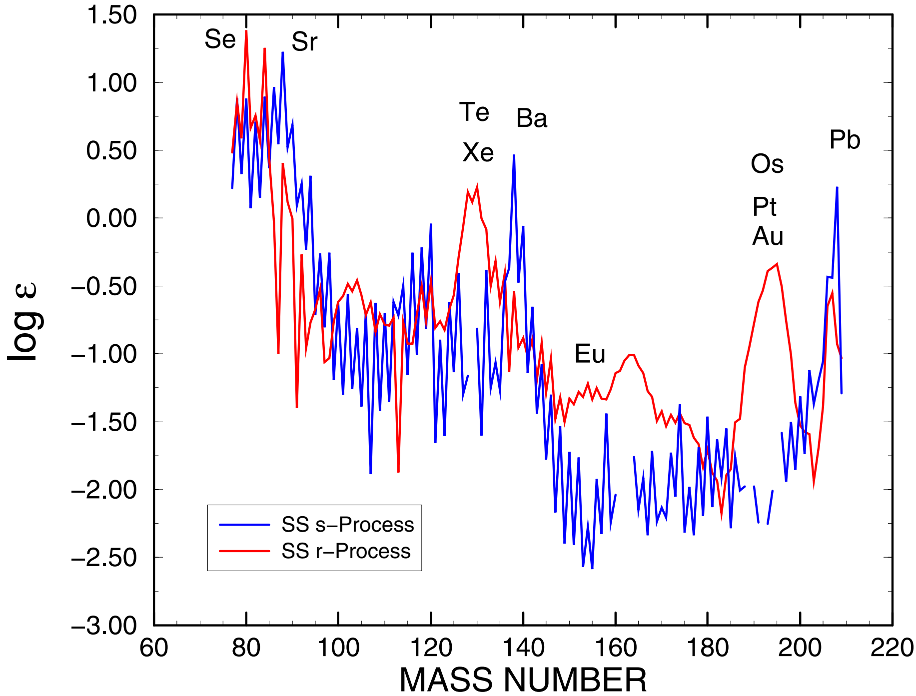

Figure 1. s-process and r-process abundances in Solar System matter, based upon the work by Käppeler *et al.* (1989). It is the r-process pattern thus extracted from Solar System abundances that can be compared with the observed heavy element patterns in extremely metal deficient stars. (Figure reference: Truran *et al.* 2002).

3. Halo star abundance clues to r-process mechanism

Recognition of interesting abundance trends in the heavy element region (past iron) first occurred some forty years ago. Utilizing data for only a handful of stars, Pagel (1967) called attention to the fact that the Sr/Fe and Ba/Fe ratios exhibited different dependences on Fe/H. It was unclear at that time how this might be related to possible distinct contributions from r-process and s-process nucleosynthesis sites.

The first systematic study providing critical observational clues concerning r-process history was that of Spite & Spite (1978). This work: (1) confirmed the presence of the element europium – produced almost entirely by the r-process – in halo stars of extremely low metallicity, at levels $(\mathrm{Eu/Fe}) \gtrsim (\mathrm{Eu/Fe})_{\odot}$; and (2)indicated that r-process synthesis occurred in the earliest phases of Galactic evolution, presumably in an environment associated with massive stars and Type II supernovae. It was then noted (Truran 1981) that the Eu/Ba ratios in the Spite & Spite sample stars were compatible with the Eu/Ba abundance in the Solar System r-process abundance pattern, suggesting that the heavy element patterns in the most extremely metal-deficient halo stars (on a timescale short with respect to that of the likely red-giant progenitors of the heavy s-process elements) were dominated by the r-process.

This interpretation has since been unambiguously confirmed by a large number of observational studies (Sneden & Pilachowski 1985; Sneden *et al.* 2000; Westin *et al.* 2000; Cowan *et al.* 2002; Sneden *et al.* 2004; Hill *et al.* 2002; Truran *et al.* 2002). The heavy element abundance patterns for the three r-process-rich stars CS 22892-052, HD 155444, and BD +17°3248 are compared with the Solar System r-process abundance pattern in Figure 2. (The star CS 311098-001, studied by Hill *et al.* (2002), exhibits a Solar System

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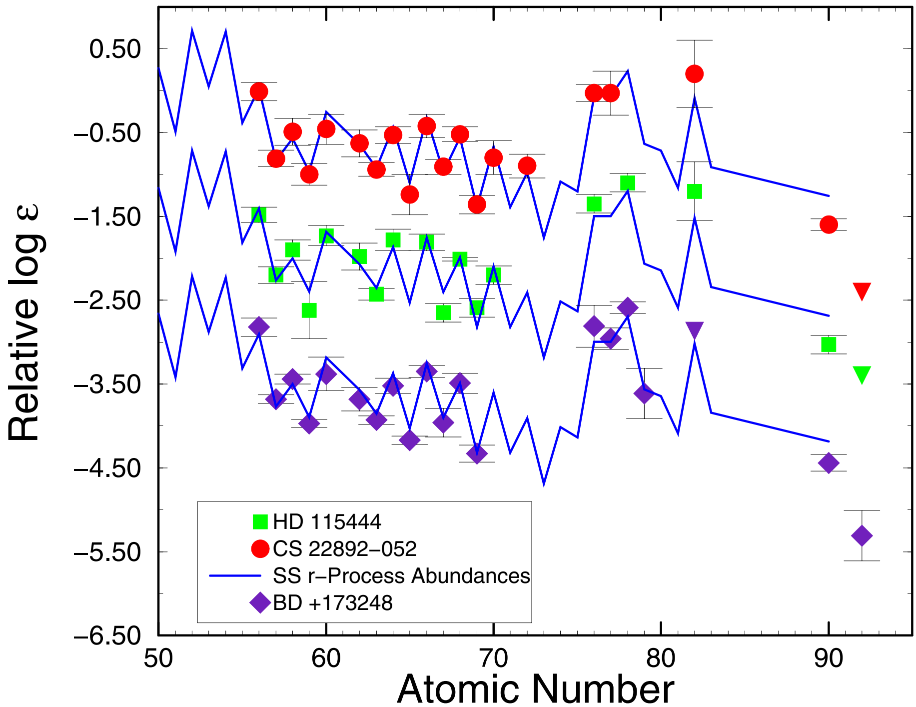

Figure 2. Heavy element abundance patterns for the three r-process rich stars CS 22892-052 (Sneden *et al.* 2000), HD 155444 (Westin *et al.* 2000), and BD +17°3248 (Cowan *et al.* 2002) are compared with the Solar System r-process abundance distribution. (Figure reference: Truran *et al.* 2002).

r-process abundance pattern as well.) The robustness of the r-process mechanism operating in the early Galaxy is reflected in the spectacular agreement of these four stellar patterns (which likely represent the product of at most a relatively small number of progenitors) with the Solar System r-process pattern (which represents the accumulated production of r-process species over billions of years of Galactic evolution). The agreement in the range A $\gtrsim$ 140 is striking. These data provide unambiguous evidence for the operation of a robust r-process in the early Galaxy and strong circumstantial evidence for an r-process synthesis environment associated with massive stars and SNe II.

Observations of halo stars also afford an opportunity to trace the chemical evolution of both r-process and s-process elements over Galactic history. The ratio [La/Eu] from studies of field halo stars (Burris *et al.* 2000), globular cluster stars, and disk stars is displayed as a function of [Fe/H] in Figure 3. This ratio provides a good approximation to that of s-process to r-process elements, since lanthanum is produced primarily by the s-process while europium is produced almost entirely by the r-process. The general trends here are entirely compatible with the early entry of r-process elements from massive stars of short lifetimes and the subsequent introduction of s-process elements from AGB stars on a longer timescale. The general agreement of the trends reflected in the globular cluster data with the halo field stars may hold important implications for models for the origin of globular clusters.

Another important heavy element abundance trend in metal poor stars is clear from Figure 4, in which the ratio [Eu/Fe] is displayed as a function of [Fe/H]. We note specifically that the increasing level of scatter of [Eu/Fe] with decreasing metallicity, most pronounced at values below [Fe/H] $\lesssim -2.0$, indicates that not all early stars are sites for

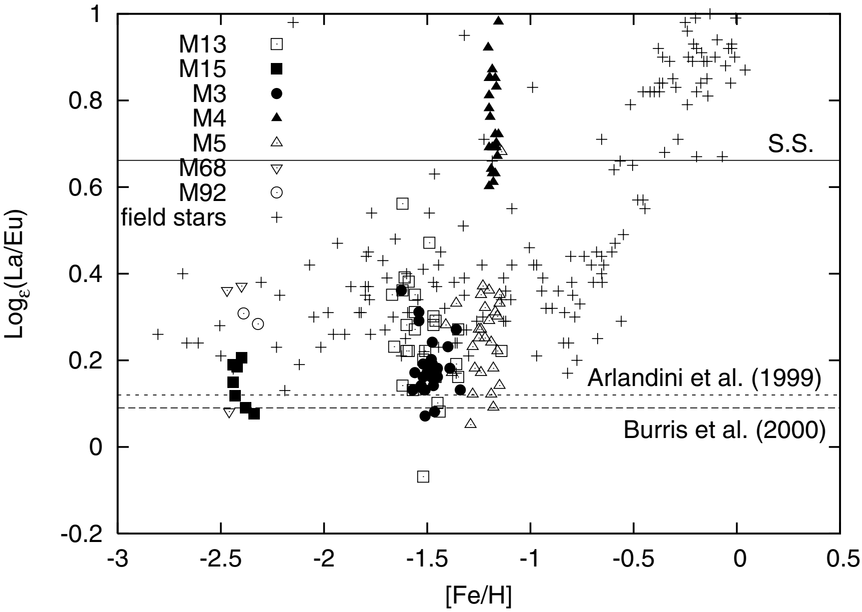

Figure 3. Log_ϵ(La/Eu), which reflects the ratio of s-process to r-process elemental abundances, is displayed as a function of [Fe/H] for a sample of field halo stars, globular cluster stars and disk stars. The solid line is the total Solar System La/Eu ratio. The broken lines are theoretically derived La/Eu ratios of pure r-process elements in the Solar System. Data are shown for globular cluster stars in M3 & M13 (Sneden *et al.* 2004, Cohen&Melendez 2005), M4 (Ivans *et al.* 1999), M5 (Ivans *et al.* 2001, Ramirez&Cohen 2003), M68 (Lee *et al.* 2005), M15 & M92 (Otsuki *et al.* 2005) and for field stars (Honda *et al.* 2004, Simmerer *et al.* 2004, Woolf *et al.* 1995).

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, we conclude from this scatter that only a small fraction of the massive stars that produce iron also produce r-process elements (see, e.g., the discussions by Fields *et al.* (2002) and Qian and Wasserburg (2001)).

Finally, we call attention to several sources of evidence to the effect that their may exist two distinct astrophysical sites for r-process synthesis. This was first suggested by Wasserburg *et al.* (1996), who argued from the inconsistency of the behaviors of the short lived radioactivities ^{129}I and ^{182}Hf for the possible existence of a second r-process that would be responsible for producing most of the r-process nuclei in the mass range A $\lesssim$ 130–140. This is generally consistent with observations of halo stars (see Figure 2), for which the robustness with which the Solar System r-process pattern is reproduced in the mass region above A $\approx$ 140 is not apparent at lower masses. This further complicates our continuing search for an appropriate r-process environment.

4. Discussion and concluding remarks

The detection by Spite & Spite (1978) of the presence of europium in low metallicity stars at levels Eu/Fe consistent with Solar System matter generally confirmed the association of the r-process site with massive star/Type II supernova environments. It has played much the same critical role in this regard – identification of the stellar source – as did the detection of technetium in red giant stars (Merrill 1952). The precise nature of this early r-process unfortunately remains elusive.

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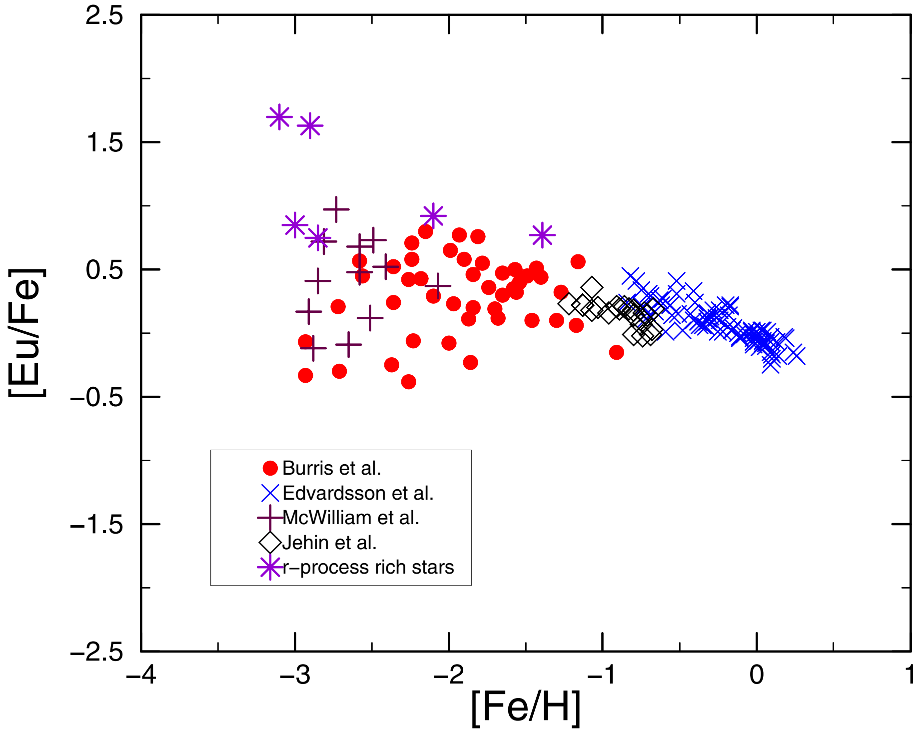

Figure 4. The ratio [Eu/Fe] is displayed as a function of [Fe/H] for a large sample of halo and disk stars (Burris *et al.* 2000; Jehin *et al.* 1999; Edvardsson *et al.* 1993; McWilliam *et al.* 1995, McWilliam 1998). *r*-process rich stars from Westin *et al.* (2000); Sneden *et al.* (2003), Hill *et al.* 2002 and Cowan *et al.* (2002). (Figure reference: Truran *et al.* 2002).

Driven by this early discovery, subsequent studies of r-process stars have provided important clues to the history of the r-process:

• Early Galactic synthesis of the heavy (A>130) r-process isotopes occurred in an r-process which robustly reproduces the pattern identified in Solar System matter.

• The observed trends in Ba/Eu and La/Eu in both halo field stars and globular cluster stars generally reflect expected chemical evolution s-process/r-process trends: early entry of r-process contributions (dominating at metallicities below [Fe/H] ~ -2) and subsequent input of s-process elements from lower mass (and longer lived) red-giant stars.

• The scatter in [Eu/Fe] (or equivalently [r-process/Fe]) at low metallicities strongly suggests that the synthesis of heavy r-process isotopes occurs in only a relatively small fraction of the stars that produce iron-peak nuclei. The robustness of the r-process mechanism can, in our view, be more easily understood if this occurs in a relatively narrow stellar mass range, consistent with the lower mass range of massive stars.

• Spectroscopic studies of early stars and levels of extinct radioactivities in the early Solar System both suggest the existence of more than one r-process site.

• Further studies of r-process trends in globular cluster stars can serve to provide interesting constraints on models for the formation and early evolution of the halo clusters.

Currently, the sites of r-process synthesis are neither cleanly defined nor thoroughly understood. It seems likely that the next breakthrough will again be derived from observations.

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