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Musings on the Ubiquitous Nature of the r-Process

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How varied are the abundance patterns of the heaviest elements observed in metal-poor stars, and how can this diversity inform our understanding of the assembly of matter on the smallest (i.e., nuclear) and largest (i.e., galactic) scales? With regard to the *r*-process, recent work has shown that (1) there is a dispersion of abundance ratios among the rare earth elements produced in the *r*-process, (2) there is also a dispersion in Y/Eu that is not random but (anti-)correlates with [Eu/Fe], and (3) nearly all metal-poor stars contain detectable traces of Sr and Ba that is not a result of *s*-process nucleosynthesis. If these facts suggest that charged-particle reactions and *r*-process nucleosynthesis are common phenomena in core-collapse supernovae, then charged-particle and *r*-process nucleosynthesis products are inextricably linked to supernova physics. Insofar as this physics can be characterized, it may then be a useful tracer of *standard* chemical evolution rather than its infrequent exception.

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1. Introduction

The two fundamental methods that nature uses to produce significant quantities of the heavy elements are adding neutrons (*n*) to Fe-group seed nuclei on timescales slow (*s*) or rapid (*r*) compared to the average β-decay halflives of unstable nuclei. The *s*-process follows a path near the valley of β stability, whereas the *r*-process follows a path closer to the neutron drip line; the resulting abundance patterns from these two processes are clearly distinct from one another. Variations in the physical conditions, availability of seed nuclei, and timescales involved in each nucleosynthetic event also add nuance to the abundance patterns. If the chemical composition of present-day stars can be used to characterize the nature of their ancestors, this information may then be used to trace the pre-historic journeys of those early generations of stars from their birth in small dark-matter-dominated halos or globular clusters to the halos (?) of massive galaxies. Both the recurring abundance patterns and the deviations from these patterns may be useful tracers of the conditions of nucleosynthesis within stars and supernovae (SNe).

In this Proceeding we recount our recent attempts to characterize the varied *r*-process abundance patterns observed in metal-poor stars and relate them to astrophysical events. We conclude with rampant speculation about how this knowledge, should it be acquired with any moderate degree of confidence, may be used to address the assembly of baryonic matter on large scales.

2. The Ubiquity of *r*-process Abundance Patterns

Building on more than three decades' worth of intensive research into the detailed abundance patterns produced by *n*-capture nucleosynthesis, several recent studies have shown that variations between the light (e.g., Sr, Y, Zr) and heavy (e.g., Ba, La, Eu, Pb, Th) *n*-capture elements produced in the *r*-process abundance pattern can be characterized and related to realistic nuclear astrophysics (e.g., [1, 2, 3, 4]). Our most recent study [4] was based on a large sample of metal-poor ($-3.0 \lesssim$ [Fe/H] $\lesssim -1.4$) stars explicitly purged of any stars with a detectable trace of *s*-process material. The characteristics of the remaining subset of *r*-only stars are summarized as follows.

Stars strongly enriched by the *r*-process, such as the well-known *r*-process standard star CS 22892–052 ([Eu/Fe] $= +1.6$; [5]), are overabundant in the heavy elements relative to the light ones, and stars such as HD 122563 ([Eu/Fe] $= -0.5$ [6]) are deficient in the heavy elements rather than overabundant in the light ones. (See also [6].) These two stars appear to represent the extremes of a continuous range of *r*-process nucleosynthesis patterns.

There is a dispersion of abundance ratios among the rare earth (RE) elements produced in the *r*-process, shown explicitly by the range in La/Eu observed in this *r*-only sample to be at least 0.5 dex. As others have noted [1, 2, 3], there is also a dispersion in Y/Eu of at least 1.6 dex that is not random but (anti-)correlates with [Eu/Fe] (with an intrinsic scatter of 0.2–0.9 dex).

The dispersion in Y/Eu and La/Eu can be reproduced by nucleosynthesis predictions from simulations of the high-entropy neutrino wind (HEW) of a core-collapse SN. This model includes charged particle (CP) freeze-out that produces significant quantities of the Sr-Y-Zr isotopes (but few heavier isotopes), β-delayed neutron emission and recapture, and a traditional *r*-process consisting of high neutron densities (e.g., $10^{23} \leq \mathrm{n}_n \leq 10^{28}$ [7, 8]) that produces all heavy elements.

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At least small amounts of material heavier than the Fe-group (explicitly shown for Sr and Ba) have been detected in nearly all metal-poor stars. The α and Fe-group elements in these metal-poor stars are associated with Type II core-collapse SNe. The simplest explanation for the ubiquitous presence of Sr and Ba in these stars is that the nucleosynthesis mechanisms described by our HEW model are also present in core-collapse SNe, and at least one of these mechanisms is in operation in nearly all core-collapse SN events. If so, then the observed large scatter in, e.g., [Sr/Fe], [Ba/Fe], or [Eu/Fe] ratios at [Fe/H] $\lesssim -3.0$ may be attributed to differing strengths of the *r*-process rather than infrequent occurrences of *r*-process events.

3. The Utility of *r*-process Abundance Patterns

As we have written previously [9], "[a]t low metallicities, *n*-capture enrichment is probably a very localized phenomenon that results in a wide distribution of *n*-capture abundances, and thus it will be extremely difficult to identify any associated large-scale kinematic behaviors of the protostellar clouds from which these stars formed." The observational component of this statement still holds true to the best of our understanding: there is a wide distribution of *n*-capture abundances (in context, the *r*-process) observed in metal-poor stars. Yet less than 2 years after writing this statement we have serious concerns about the remainder of it.

The occurrence of an *r*-process seems to be a frequent if not ubiquitous feature of (almost certainly, but perhaps not exclusively) core collapse SNe [4]. Of course not every metal-poor star has been enriched by a strong *r*-process like that from which CS 22892–052 was enriched. There are other stars that have very low levels of *r*-process enrichment, such as BD +10 2495 ([Eu/Fe] $= +0.1$; see Figure 12 of [10]), whose abundance pattern through the RE domain is also a near-perfect match to the scaled S.S. *r*-process residuals. This is just one demonstration that metal-poor stars need not exhibit a strong *r*-process overabundance to have been enriched by *r*-process material.

If only the most basic features of the HEW model are correct—that a CP reaction occurs alongside the *r*-process in the neutrino wind of a core collapse SN and the heavy element production varies depending on the physical conditions present at the time of nucleosynthesis [4, 11]—then the products of the *r*-process are inextricably linked to SN physics! If so, why should the *r*-process products be any less a tracer of kinematic behavior than, say, the α elements? (The obvious exception is one of observational difficulty: the heavy elements are generally less abundant and require high-resolution spectroscopy to be reliably detected. In principle, with the advent of echelle spectrographs on 6–10m class telescopes this difficulty can be overcome with patience.)

Unlike the lighter elements, which may be produced (and destroyed) by a myriad of processes, there are precious few ways to produce the isotopes of Ba ($A \sim 130$–140) and heavier. With modest effort, the products of the *s*-process can be identified with a high degree of confidence. As far as we know, the *s*-process is the only other mechanism for producing significant amounts of nuclei heavier than $A \sim 130$. If the heavy elements were not produced in an *s*-process, they must be produced in an *r*-process. Should multiple sites prove capable of producing an *r*-process (or be required to explain some aspect of the observations), this could complicate the interpretation, but ultimately it should lead to greater understanding of those additional sites, as well.

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Rather than being viewed as special, infrequent cases of enrichment in the chemical evolution of the Galaxy, products of CP reactions and *r*-process nucleosynthesis may instead be "standard" cases. Their large star-to-star dispersion at low metallicity, in contrast to the generally uniform α or Fe-group abundances, may prove them to be more useful diagnostics of enrichment events. Future models built upon observations will be required to evaluate the utility of this reasoning.

4. A Blessing and a Curse

We conclude with an example and a reminder of the daunting but exciting possibilities before us. Globular clusters, while not the simple stellar populations they were once hoped to be, may play a key role in understanding the relationship between the strength of the *r*-process and the range of *r*-process enrichment levels in stars of a given cluster. The former property may indicate some physical characteristic of the SN event, while the latter may indicate the sphere of influence a particular SN has when enriching the gas from which the next generation of stars form.

Concepts like these may (or may not) be important steps to interpreting the enrichment patterns observed in larger stellar populations, such as the dSph systems and the jumbled collection of orbits of Milky Way field stars. In attempting to obtain detailed chemical knowledge for as many points in the Galaxy as possible, approximately 1500 or 1600 metal-poor field stars have been analyzed (chemically speaking) in detail in the last 15–20 years. The sobering reality is that nearly 95% of the metal-poor field stars that have been analyzed in detail lie within 5 kpc of the Sun. Thus from the standpoint of Galactic chemical evolution it is risky to extrapolate the chemistry of the Solar neighborhood to more distant regions. Somehow we must bridge the gap between individual halo field stars and the in situ outer halo of the Galaxy where a lot of the action is occurring. One straightforward approach is to probe stars in the in situ outer halo itself (e.g., [12]). Indirect approaches involve comparing the compositions of large groups of field stars with contrasting orbital motions (e.g., [9, 13, 14, 15, 16, 17]) or examining the chemistry of individual stars in stellar streams (e.g., [10, 18, 19, 20]).

The day is coming, if it is not already here, when we will have to know the kinematic properties of a given field star in order to place its chemical enrichment pattern in the proper context for interpretation. This is a blessing in that it inextricably links the chemistry of stars with the assembly of galactic structure. Yet it is also a curse, for we are forevermore obligated to examine—at least to the degree to which such information can be obtained—the kinematic properties of whatever stars we are interested in studying. We happily embrace this burden.

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