Observations of r- and s-process elements in Population II stars

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The framework for the interpretation of neutron-capture elements observed in Population II stars, established 20-25 years ago, is that these stars primarily exhibit r-process signatures, due to the inefficiency of the s-process at low metallicity. A view developed later that the r-process might be universal, which is to say that the same r-process element ratios would exist at high and low metallicity. However, observations of s-process abundances in low-metallicity environments, and departures from a universal r-process ratio for the lightest neutron-capture elements have required revisions to the framework. Observations indicating the need for and nature of these changes will be presented.

1. Introduction

Elements beyond the iron peak are formed in neutron-capture reactions. Traditionally these are split into two categories, the slow- (s-) process when beta-decay rates exceed neutron-capture rates, and the rapid- (r-) process when neutron-capture rates are high enough to produce neutron-rich unstable isotopes far from the valley of beta-stability.

The main site for the r-process is currently thought to be supernovae, though neutron-star collisions may have played a role in later stages of Galactic enrichment [1]. The s-process has contributions from two sites: thermally-pulsing (TP-) AGB stars are responsible for the so-called 'main' s-process fraction, while an additional contribution from high-mass He-core-burning stars is required to explain the first neutron-capture peak (nuclei with closed neutron shells having a neutron number $N = 50$; Sr, Y, Zr). A third s-process, the so-called 'strong' s-process, that was invoked to explain the third neutron-capture peak (closed-neutron-shell nuclei with $N = 126$; Pb and Bi), appears now to be associated with metal-poor AGB stars [2].

In metal-poor environments, such as existed during the formation of the oldest stars in the Galaxy, the s-process has long been regarded as unimportant. This interpretation was established some 20-25 years ago. The observational work of Spite and Spite[3] showed that the abundance of Ba dropped faster than the abundance of Eu as progressively more-metal-poor stars were observed. As Eu is an almost pure r-process element, whereas Ba can have contributions from both processes, this was interpreted as evidence for the disappearance of the s-process contribution to Ba in metal-poor stars. The theoretical basis for the framework was provided by Truran[4] who pointed out that the lack of seed nuclei would block the s-process in the metal-poor counterparts of the objects which, at

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solar-metallicity, are primarily responsible for the s-process. The r-process, on the other hand, would be capable of generating its own seed nuclei even in metal-poor environments.

This basic framework was supported by various observations and modelling efforts in subsequent years. Gilroy et al. [5] showed that in metal-poor giants, neutron-capture elements have the same relative abundances as in the inferred r-process contribution to the solar composition. Furthermore, detailed calculations of Galactic chemical evolution [6] show that AGB stars would not contribute significantly to Galactic enrichment of s-process elements until [Fe/H] had climbed to ~ -1.

Observations of [Ba/Eu] ratios were extended to [Fe/H] $\simeq -3$ and showed that the solar r-process ratio persisted [7]. The star CS 22892-052, with [Fe/H] $\simeq -2.5$ and having abundance ratios of r-process to iron-peak elements forty times higher than normal, likewise had a composition in which r-process abundances were seen [8,9]. The relative weakness of iron-peak elements meant that a vast array of neutron-capture elements could be studied, rather than just the more easily detected ones such as Ba and Eu, and hence the existence of an r-process pattern was established far more thoroughly for this star than for any other metal-poor object. This included filling in the gaps in the coverage of elements between the neutron capture peaks [10,11,12].

A view developed that the r-process might be "universal", i.e. that the element yields in the r-process were independent of the metallicity of the gas from which the star providing the site of nucleosynthesis formed. This view was supported by findings that the element ratios near the second neutron-capture peak (closed-neutron-shell nuclei with $N = 126$; e.g. Ba, La) resembled the solar r-process even at low [Fe/H] [5,13,10,9]. As we shall see below, the concept of universality is still entertained, but observations that Sr exhibits a very different behaviour [14,15,7,16] have seen the idea of universality qualified with the restriction that is does not apply to elements in the first neutron-capture peak.

CS 22892-052 soon became, and probably rightly so, one of the most talked about stars in the field of Pop. II nucleosynthesis. Less justifiably, it was often spoken of as an archetypal metal-poor star for the purposes of investigating neutron-capture nucleosynthesis, an epithet which overlooked two key observational results: (1) its fame stemmed from it being *abnormally* rich in neutron-capture elements, very definitely *not* representative of the rest of Pop. II, and (2) it was one of a growing class of carbon-rich, metal-poor stars.

Carbon-rich, metal-poor stars were found [17,18] in follow-up observations of stars originally identified as metal-poor on objective-prism spectra of the Ca H and K and Hϵ lines. The objective prism spectra covered none of the CH or CN molecular features, so contained no information on carbon abundances. However, blue, $\sim$1 Å-resolution spectra obtained subsequently showed that a significant fraction of such objects contained unusually strong CH bands; up to 25% of very metal-poor stars were suspected of having significant carbon excesses. The excesses were eventually shown [19] to extend up to two orders of magnitude, giving [C/Fe] = 2.0.

In work aiming to clarify the relationship between the C and r-process enhancements in CS 22892-052, and with the hope of identifying more stars whose r-process elements could be studied in detail, Norris, Beers and Ryan set out to observe a number of C-rich stars identified from 1 Å-resolution spectra of objective-prism-selected metal-poor objects. Their early observations [20], and extended studies involving many of the other targets

[21,22], showed not a single additional C-rich star with an r-process enhancement, but revealed instead large numbers of metal-poor, C-rich stars with clear s-process signatures (see also [23,24]), as well as others with no neutron-capture anomalies [25].

In the remainder of this paper, we discuss two challenges to the standard framework for understanding neutron-capture nucleosynthesis in Pop. II stars: the existence of a significant number of Pop. II stars with enhanced carbon and s-process elements, and the apparent independence of Sr from the behaviour of Ba.

2. C-rich, metal-poor stars

The abundant s-process elements found in many of the C-rich stars were unexpected given the strong arguments (presented above) that favoured an r-process origin for the neutron-capture species in metal-poor stars. High abundances of C and s-process elements initially suggested that AGB stars may have been active, since AGB stars are the major sites of both C and s-process element production in the Galaxy. However, two of the first few C-rich, metal-poor stars examined in detail were subgiants rather than giants, having being found originally in a study of subdwarfs selected on the basis of high-proper motion [26], so it was shown quickly that the stars being observed with high C and s-process abundances could not themselves be responsible for the enrichment. Since the observed stars could not be AGB stars, and the contribution of AGB stars to Galactic chemical enrichment is believed be insignificant at [Fe/H] ~ -2.5, the search turned for means of directly contaminating them with the products of AGB nucleosynthesis *after* their formation. Suspected mechanisms therefore centred on the accretion of mass lost from an AGB companion, either via Roche-lobe overflow or perhaps more commonly via wind accretion. This mechanism matches the binary mechanism responsible for the origin of Pop. II CH stars and Pop. I Ba stars [27,28,29,30].

If this mechanism were to be able to explain the origins of these stars, we would require binary periods long enough (i.e. separations large enough) to avoid mass transfer on the RGB instead of the AGB, and yet short enough for wind accretion to be efficient. These factors imply periods in the range 1-10 yr [31,29,32]. We would expect to see the chemical signature of a low-metallicity AGB star, and radial velocity variations on the stated timescale due to the presence of a white dwarf companion, being the compact remnant of the AGB star.

A mechanism proposed for the CH stars, before their binarity and its role was discovered, was that the He flash that terminates RGB evolution, or a He shell flash on the TP-AGB, triggered a deep mixing event that refuelled the core and re-ignited core H burning, hence providing it with a second life [33]. Although this possibility fell out of favour, the idea has been revived in a slightly different context, and mixing events triggered by the He flash in zero-metallicity (Pop. III) stars have been investigated more recently [34,35]. They may provide an alternative means of producing C-rich, metal-poor objects.

Observations of s-process enhanced stars have provided mixed support for the binary-star, mass-transfer hypothesis. LP 625-44, which has [Fe/H] $= -2.7$, [C/Fe] $= 2.0$ and [Ba/Fe] $= 2.6$, has been found to have a low-luminosity companion with an orbital period $P \gtrsim 13$ yr ([36]; see also Figure 1 below). Furthermore, the s-process abundance ratios in this object from Ba to Pb are consistent with production in a low-metallicity AGB star (where the efficiency of the s-process is treated as a free parameter) [37]. The observations suggest a low mass for the AGB progenitor.

However, LP 706-7, which has almost identical abundance ratios to LP 625-44 ([Fe/H] = −2.7, [C/Fe] = 2.0 and [Ba/Fe] = 2.0) shows no significant radial-velocity variations over 11 years of observation; see Figure 1. LP 706-7 has an effective temperature of 6250 K and lies on the subgiant branch between the main-sequence turnoff and the base of the giant branch. Like most other Pop. II stars in this phase of evolution, it retains the primordial Li abundance. This last point is very difficult to reconcile with either a mass-transfer or mixing scenario for the origin of its C and s-process excesses. The reason is that Li is extremely fragile, and survives only in the outermost few percent (by mass) of the star. Any process which involves mixing of the surface with interior layers, or requires that the surface layers originated in a more evolved star, would fail to account for the existence or primordial abundance of this element. Although Li can be produced in evolved stars, producing it at just the right level to match the primordial value would be a severe challenge, and hence is unlikely to explain this case.

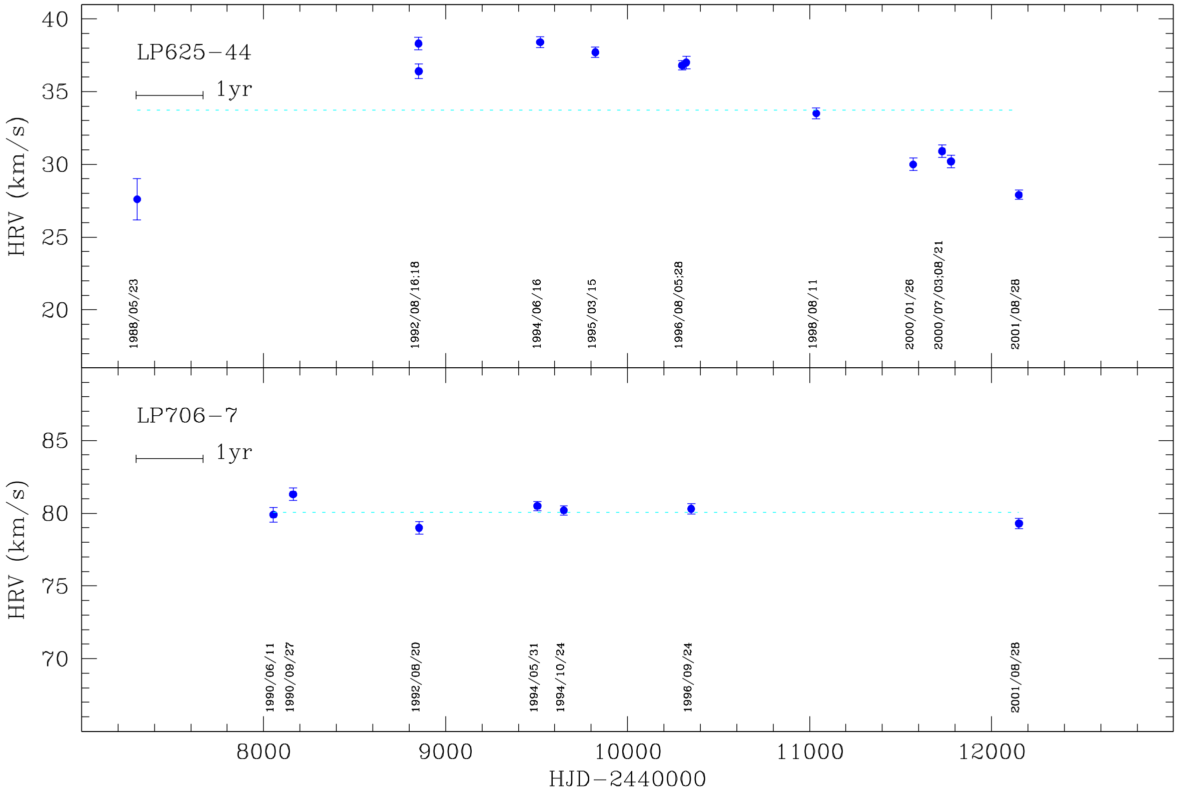

Figure 1. Radial velocity variations of LP 625-44 and LP 706-7 over $\simeq$ 10 yr. Both stars are C rich and s-process rich, and have similar chemical compositions, but LP 706-7 exhibits no significant radial velocity variations and also has a Li/H ratio at the primordial value. The horizontal dashed line gives the mean of the observations. Error bars are 1σ.

Observations of other C-rich, metal-poor stars close to the main-sequence turnoff [38] likewise show a significant lack of radial-velocity variations. This, combined with the problem of Li survival in LP 706-7, emphasises that while the AGB mass-transfer explanation for the C-rich, s-process-rich stars may be attractive in that it fits with established phenomena in the evolution of stars, clearly it is not the answer for all of the s-process-rich, C-rich Pop. II stars. Even if AGB stars can produce the element ratios seen in these objects, the problem of how it is incorporated into the atmospheres of these objects is not yet resolved.

3. Neutron-capture elements in C-normal, very metal-poor stars

As discussed in the introduction, wide variations (up to a factor of 100) in the [Sr/Fe] and [Sr/Ba] ratios of stars with [Fe/H] < -3 have been observed [14,15,7,16]. Star-to-star variations in [r/Fe] have also been seen for a range of other r-process elements, e.g. [5], but these seem to only rarely reach large extremes, whereas Sr regularly exhibits large variations. It was the decoupling of the behaviour of Sr from that of Ba which first indicated that a universal r-process could not exist. Current evidence is consistent with a universal r-process for stable elements at the second neutron-capture peak and above, but clearly not for the first neutron-capture peak. At present there are too few observations of elements between the first and second peaks in stars with [Fe/H] < -3 to know at which atomic number universality is established. That is, we do not know whether silver correlates with Sr, with Ba, or with neither in the most metal-poor stars.

The lack of data on Ag may be expected since observations of the lines of this element, which are in the UV, are extremely rare. Europium, on the other hand, is frequently measured in the blue spectra of Pop. II stars, but the lines become very weak at [Fe/H] < -3. Unfortunately, that is precisely where the Sr anomalies become most evident. The result of this lack of data on Eu in very metal poor stars is that we do not usually have measurements much above the second r-process peak in the most metal-poor stars. As Eu is almost a pure r-process element, it avoids any ambiguity associated with the s- and r-process fractions of Ba. The origin of Ba was called into question when analysis of its hyperfine structure suggested an odd-to-even isotope ratio more in keeping with the s-process than the r-process [39], though this result has been challenged by new observations [40]. More importantly, Eu probes a different region of the chart of nuclides than Ba.

The lack of observations of Eu has until very recently [41,42] meant that the region with [Fe/H] < -3 was devoid of Eu detections, constrained only by quite high upper limits on [Eu/Fe]. In addition to the new data cited, observations with the new HDS spectrograph on the Subaru telescope have permitted an extension of the observations down towards [Fe/H] $= -3.4$. These observations [43] confirm that [Eu/Fe] is only slightly sub-solar, $\simeq -0.2$. This, combined with the previously known [Ba/Fe] decline at low metallicity, indicates that [Ba/Eu] is close to the solar r-process fraction in these objects. In contrast, [Sr/Eu] remains above the solar r-process fraction.

This finding, combined with the high and unpredictable [Sr/Fe] values in such metal-poor stars, adds weight to the suggestion that the r-process sets a lower limit on the production of Sr, which one may infer from the [Sr/Ba] ratio that would be found if the r-process contribution were truly universal even for elements at the first neutron-capture peak. On top of this, an additional Sr source is required that appears to be highly variable from one nucleosynthesis site to the next [44].

Possible mechanisms [45] are split between the known and the unknown. The former category includes the weak s-process, which is known to produce only first neutron-capture-peak elements, but which requires pre-existing metals both as the ^{22}Ne neutron source and for the neutron-capture seed nuclei, and hence is expected to be ineffective in very metal-poor stars. The alpha-process (alpha-rich freeze-out) may be an alternative if nucleosynthesis can extend to Sr in significant numbers. Unknown processes that may mimic the weak s-process yields include a weak-r-process [46], and possibly a neutron-capture process that resembles neither of the traditional extremes (s- and r-) of neutron-capture timescales.

An element that may help resolve the origin of the Sr excesses is zinc. At atomic number $Z_{\rm Zn} = 30$, this lies between the iron peak ($Z_{\rm Fe} = 26$) and Sr ($Z_{\rm Sr} = 38$). Contributions to its nucleosynthesis come from both the alpha-process and the weak-s-process, and hence it may be able to indicate whether one or other of these processes has been active.

The possible link between Zn and Sr was first tested with the star CS 22987-008 [47,48], which was previously discovered to be very Sr-rich [7]. The star was indeed found to have [Zn/Fe] above solar, but around the same time evidence emerged that so may large numbers of very metal-poor stars [49,50]. The comparison in Figure 2 shows data for CS 22897-008 [48] and the normal star HD 140283 [51] against metal-poor giants investigated by Johnson and Bolte [52,53]. Although [53] could not calculate Sr abundances, they found high [Y/Ba] values in several of their objects. One might expect these same objects to have high [Sr/Ba] values; this could be tested. The high-Y stars have been highlighted in the figure. Although the genuinely Sr-rich giant, CS 22897-008, has a [Zn/Fe] value even higher than the rising trend, the high-[Y/Ba] stars do not. If high-Sr and high-Y stars do belong together, then the lack of distinction between the Y-rich and Y-normal stars in the [Zn/Fe] vs [Fe/H] diagram may indicate that the high Zn abundance of CS 22897-008 is not related to its high Sr. Analysis of these objects is continuing, but it appears that the interpretation of the observations will not be simple! The nucleosynthesis of elements above the iron peak retains at least some of its secrets 20 years after the framework for understanding metal-poor stars was established.

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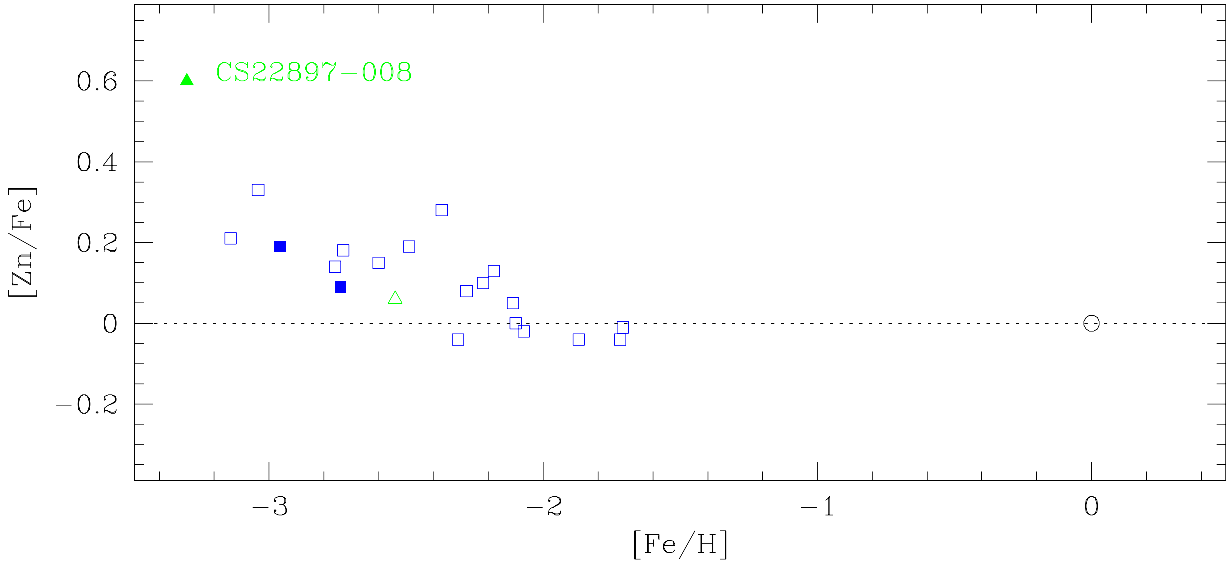

Figure 2. Zn and Fe abundances for normal giants (open squares [52]), Y-rich giants (filled squares [53]), HD 140283 (open triangle [51]), and the Sr-rich giant CS 22897-008 (filled triangle [48]).

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