s- and r-process elements in two very metal-poor stars

SEAN G. RYAN[1], WAKO AOKI[2], LISA A. J. BLAKE[1], JOHN E. NORRIS[3], TIMOTHY C. BEERS[4], ROBERTO GALLINO[5], MAURIZIO BUSSO[6], AND HIROYASU ANDO[2]

[1]*Dept of Physics & Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA, United Kingdom; s.g.ryan@open.ac.uk, l.a.j.blake@open.ac.uk* [2]*National Astronomical Observatory, Mitaka, Tokyo, 181-8588 Japan; aoki.wako@nao.ac.jp, ando@optik.mtk.nao.ac.jp* [3]*Research School of Astronomy and Astrophysics, The Australian National University, Private Bag, Weston Creek Post Office, Canberra, ACT 2611, Australia; jen@mso.anu.edu.au* [4]*Department of Physics and Astronomy, Michigan State University, E. Lansing, MI 48824-1116, USA; beers@pa.ms.edu* [5]*Dipartimento di Fisica Generale, Universitá di Torino, Via P. Giuria 1, 10125 Torino, Italy; gallino@ph.unito.it* [6]*Osservatorio Astronomico di Torino, 10025 Pino Torinese, Italy; busso@to.astro.it*

ABSTRACT. New measurements of neutron-capture elements are presented for two very metal-poor stars ([Fe/H] ~ -3). One (LP 625-44) has an s-process signature believed to be due to mass transfer from a now-extinct metal-poor AGB companion, and the second (CS 22897-008) is one of a number of very metal-poor stars having high [Sr/Ba] ratios which is not expected from the r-process. In the s-process star, many elements including lead have been detected, providing strong constraints on the ^{13}C pocket in the now-extinct AGB star. In the Sr-rich star, Zn, Y, and Zr are also seen to be overabundant, and several possible nucleosynthesis mechanisms are discussed.

1. Introduction

Neutron-capture elements observed in Population II stars are generally interpreted in a framework developed some 20 years ago. Spite & Spite (1978) showed from observations of Ba (a mixture of 80% s- and 20% r-process fractions in the solar system; e.g., Arlandini et al. 1999) and Eu (primarily r-process) that Pop II stars exhibit r-process abundance patterns. Truran (1981) provided a theoretical basis for this result by noting that the s-process needed pre-stellar seed nuclei, whereas an r-process site would produce its own seed nuclei. For this reason, metal-deficient populations would be poor producers of s-process nuclei. It became common to regard neutron-capture elements in Pop II stars as due solely to the r-process. Observational support for this view grew with the work of Gilroy et al. (1988) and McWilliam et al. (1995). The theory is demonstrated numerically in the Galactic chemical evolution (GCE) calculations of Travaglio et al. (1999; see also Busso, Gallino & Wasserburg 1999, Fig. 17) which showed that s-process products do not feature significantly in newly forming stars until [Fe/H] $\gtrsim -1.5$. (See also Raiteri et al. 1999).

Observations of several metal-poor stars enriched in neutron-capture elements have revealed solar r-process patterns. That is, despite their considerable metal deficiency, these stars seem to have experienced an r-process that barely differs from the sum of processes that enriched the pre-solar nebula. This has led to suggestions that r-process production may be independent of the initial metallicity of the site and, to some degree, universal throughout Galactic history (e.g. Cowan et al. 1995; Sneden et al. 1996). Such a finding, if widely substantiated, would have important implications for identifying the r-process site. Theoretical work in the last decade has focussed on the neutrino-heated bubble located above the surface of a newly-formed neutron star (e.g. Woosley et al. 1994; Takahashi, Witti, & Janka 1994), but other sites such as colliding neutron stars may provide an alternative, at least for the heavier r-process nuclei with atomic mass $A > 130$ (e.g. Freiburghaus, Rosswog, & Thielemann 1999).

Solar r-process abundance ratios of Ba and Eu are seen in many Pop II stars. In a small number of stars including CS 22892-052 (Cowan et al. 1995; Sneden et al. 1996), an even larger range of elements can be measured and likewise conform to that pattern. However, not all neutron-capture elements are present with solar r-process ratios. In particular, Sr exhibits wide variations not shared by Ba (Ryan et al. 1991, 1996), suggesting that Sr at least does not come from a universal process. Even in CS 22892-052, the light neutron-capture elements Sr (Z=38) to Cd (Z=48) do not match the solar r-process pattern (Sneden et al. 2000), providing more evidence of different processes affecting light and heavy neutron-capture elements.

Although the material from which Pop II stars form is not expected to contain significant s-process contributions, some stars including some subgiants are greatly enriched in carbon and s-process elements (Norris, Ryan, & Beers 1997a; Hill et al. 2000). These are believed to be binary companions of initially more-massive donor stars which have evolved through the thermally pulsing AGB phase and transferred material enriched in C and s-process elements onto the lower mass, longer lived secondary now observed.

In this report, we present the results of two studies of neutron-capture elements in Pop II stars. The first is for a C-rich, s-process-rich star in which many heavy elements including lead have been measured. The second is a Sr-rich Pop II giant, whose abundance patterns we use to search for the nucleosynthesis process responsible.

2. s-process production in Population II stars

Although the s-process contributes little to GCE during the formation of the halo, the measurement of s-process production by metal-deficient objects is important for two reasons. Firstly, s-process yields depend strongly on metallicity (e.g. Busso et al. 1999), so we need to know what this dependence is if we are to compute accurately the onset of s-process contributions to GCE. Secondly, the site of the main s-processing is believed to be thermally pulsing AGB stars. The yields of such stars indicate the conditions in their interiors, providing information on their structure and evolution.

The s-process contribution to the interstellar medium that became locked into newly formed Pop II stars was insignificant, but AGB stars in binaries may transfer material to companions which, if of lower mass and longer lived, may preserve the Pop II s-process products on their enriched surfaces. Two high-proper-motion stars with $[\mathrm{Fe/H}] \simeq -2.7$ and huge carbon excesses $[\mathrm{C/Fe}] \simeq 2.0$ were investigated by Norris et al. (1997a) — LP 625-44 and LP 706-7. By virtue of their proper motions, we infer that they are subgiants (assuming they are bound to the Galaxy). The spectroscopic analysis also suggests subgiant (rather than giant) evolutionary states. In addition to the large carbon over-abundances, the stars have high s-process abundances, with [Ba/Fe] = 2.6 and 2.0 respectively. Norris et al. sought to explain the stars by the mass transfer scenarios described above, but were troubled by the lack of definite radial velocity variations over a time span of several years, which weakened the appeal to a binary mass transfer process as being responsible.

Aoki et al. (2000) have completed a new investigation of LP 625-44 using higher S/N spectra. Definite radial velocity variations have been detected, with a velocity range $\Delta v \geq 10$ km s^{-1} over a period $T \geq 12$ years. This implies a wide orbit separation $a > 5$ AU, consistent with the wide separations found for some CH-subgiants where mass transfer from an AGB donor is believed to occur by wind accretion rather than Roche-lobe overflow (Han et al. 1995). A more detailed element analysis has also become possible, the highlight of which was the detection of lead via the 4057 Å absorption. Comparison of the spectrum of LP 625-44 with that of CS 22957-027, a metal-poor star ([Fe/H] = -3.4) having a strong ^{12}C *and* ^{13}C over-abundances [C/Fe] = 2.2 but no enhancement of neutron-capture elements (Norris, Ryan, & Beers 1997b), verifies that the absorption line is not due to an unrecognised ^{12}CH or ^{13}CH line.

The Pb abundance was measurable in this object because of its overall high abundance of s-process elements. However, it was the *low* value of the [Pb/Ba] ratio ([Pb/Ba] $\simeq 0$) that caused initial surprise. It is well established theoretically and observationally that the ratio of heavy s-process elements around Ba, to lighter s-process elements around Sr, [hs/ls] (defined by Luck & Bond 1981), depends strongly on metallicity. In general, [hs/ls] increases (i.e. Ba becomes over-abundant relative to Sr) as the metallicity is reduced from solar to 1/10 solar, due to the smaller number of seed nuclei for the available neutrons (e.g. Busso et al. 1999, Fig. 16). At still lower metallicities, the models of Busso et al. converge to a [hs/ls] value 3 times solar, though at least some stars have higher values (e.g. Norris et al. 1997a, Fig. 8). However, the observed (low) [Pb/Ba] ratio in LP 625-44 emphasises that the increase in [hs/ls] towards lower metallicities is not necessarily shared by an analogous [Pb/hs] ratio.

In contrast to the observation of LP 625-44, the 'ST' (standard) models of Busso et al. (1999, Fig. 12) indicate a high value [Pb/Ba] $\simeq 1.5$ at [Fe/H] = -2.7. However, the predicted [Pb/Ba] ratio is not uniquely determined by the metallicity of the AGB star but also by the profile of the ^{13}C pocket, which may depend on the mass and rotational properties of the star. Moreover, Busso et al. note (their Fig. 16) that a *range* of ^{13}C-pocket profiles must be adopted in their models to match the range of [hs/ls] values observed in higher metallicity stars. Consequently, the 'ST' model is only one of several possible solutions. A wider range of models (see Figure 1) show the sensitivity of the elements to the extent of the ^{13}C pocket, and indicate for a 1.5 M$_\odot$ star at [Fe/H] = -2.7 that while [Ba/Fe] may be up to 0.5 dex above the 'ST' model prediction, [Pb/Fe] can range over ~ 1.0 dex above and below the 'ST' value. That is, even though the Ba enhancement can be predicted within a narrow range, the [Pb/Ba] ratio depends sensitively on the ^{13}C profile. The low [Pb/Ba] abundance measured in LP 625-44, which initially seemed to challenge the published 'ST' models, may still be within the range of metal-poor AGB models. According to the models shown in Figure 1, this requires

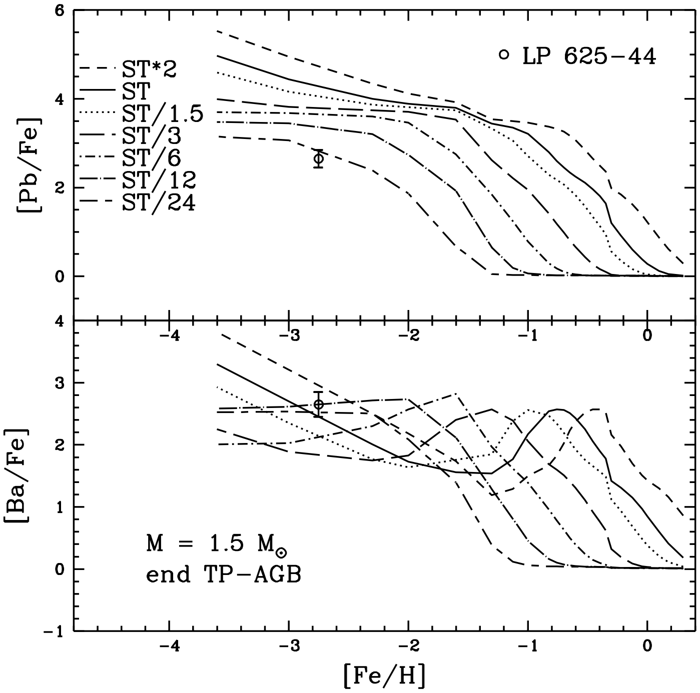

Fig. 1. Metallicity-dependence of [Pb/Fe] and [Ba/Fe] nucleosynthesis in a 1.5 M$_\odot$ AGB star, for different ^{13}C profiles. *Solid curve*: 'ST' (standard) model shown by Busso et al. (1999). *Other curves*: other normalisations of the ^{13}C pocket. At the metallicity of LP 625-44 (shown), the [Ba/Fe] ratio is only weakly sensitive to the ^{13}C pocket, but the [Pb/Fe] value is very sensitive to this choice of parameter.

that only a very weak burning of ^{13}C occurred in the intershell zone, with an efficiency lower by a factor of 20 than in the ST case.

The ^{13}C profile is not well constrained, but measurements of many s-process elements in stars like LP 625-44 and LP 706-7, each enriched by a single AGB star, present the opportunity to search amongst the models for the best fit and hence to identify the most likely companion/donor. It is hoped that such studies will advance modelling of AGB stellar structure and nucleosynthesis by providing constraints on actual element yields for AGB stars of low [Fe/H].

A separate series of models for neutron-capture nucleosynthesis is the 1–3.5 M$_\odot$ metal-poor stars ([Fe/H] < -2.5) considered by Fujimoto, Ikeda, & Iben (2000; their Case II'). The helium flash in these metal-poor models drives convection that penetrates into the hydrogen-rich envelope and produces C-rich, N-rich material there. These stars later mix C-rich and s-process-rich material to their surfaces. It remains to be seen

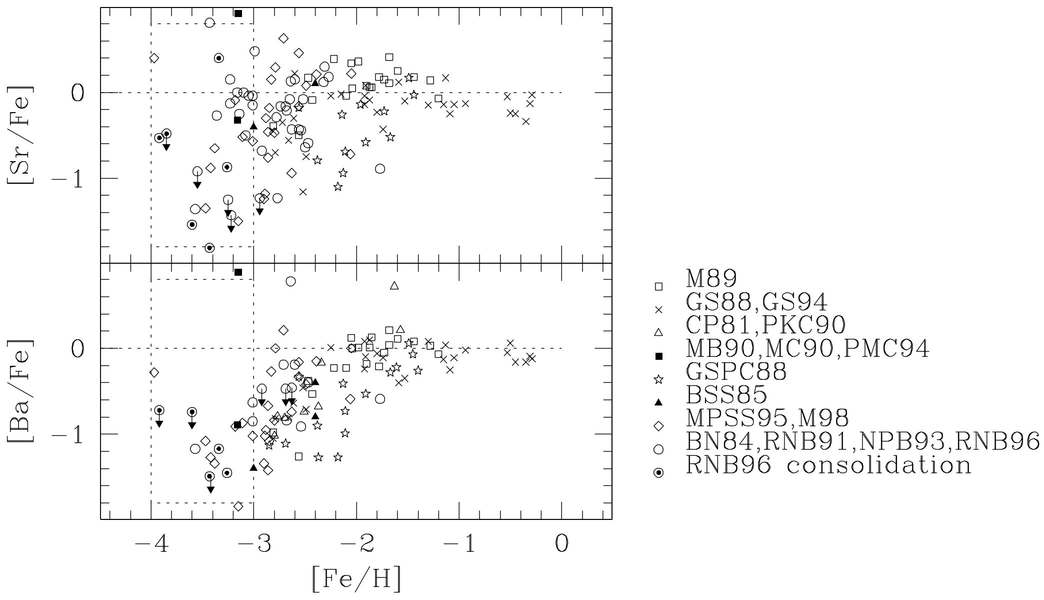

Fig. 2. Abundances of Sr and Ba in halo stars. The dashed box outlines the same region of [X/Fe] and [Fe/H] in each plot. Whereas [Sr/Fe] exhibits a range by a factor of more than 100, [Ba/Fe] has a well-behaved trend towards lower values at the lowest [Fe/H]. (Ryan 2000)

whether the s-process element abundances that such objects would produce are consistent with those observed, and therefore whether this particular mechanism could have affected LP 625-44's mass donor.

3. Non-universal r-process abundances

Pop II neutron-capture elements are believed to originate in the r-process, except in stars enriched after formation by s-process material as discussed in the previous section.[1] Although Ba and heavier elements seem to consistently fit the solar r-process pattern where such data exist (e.g. Gilroy et al. 1988; McWilliam et al. 1995; Cowan et al. 1995; Sneden et al. 1996), at lower atomic numbers a wide variety of element ratios exists (Ryan et al. 1991, 1996), and even in CS 22892-052 they appear not to match the solar r-process (Sneden et al. 2000). Figure 2 shows that at $[\mathrm{Fe/H}] \lesssim -3$, a large range of [Sr/Fe] values exists, spread over 2 dex, whereas [Ba/Fe] occupies a much smaller range.

As the lower envelopes to the [Sr/Fe] and [Ba/Fe] values seem similar, and because of the observational and theoretical arguments that Ba is an r-process product in these stars, it seemed reasonable to regard the lower Sr abundances as also produced by the r-process. We then seek processes that produce an excess of Sr but not Ba in some

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[1] Note, however, Magain's (1995) finding of s-process-like isotope ratios in HD 140283.

metal-poor stars, giving rise to the stars with the higher [Sr/Fe] values. It also seemed more natural to hypothesise an additional source of Sr rather than a means of destroying Ba. Since the wide ranging [Sr/Fe] ratios are seen in both dwarfs and giants, we consider processes in the objects that enriched the material from which these stars formed, rather than self-enrichment or other processes affecting them after their formation.

We sought high S/N, high resolving power spectra, to verify previous abundance estimates and to seek additional elements, in particular Zn (Z=30) which lies just above the Fe-peak and can be produced along with Sr. Means of Zn production include (e.g. Woosley & Weaver 1995, §4.7): (1) the α-rich freeze-out from explosive Si-burning, where the density is low enough to avoid complete nuclear statistical equilibrium [NSE] with the result that excess α-particles combine with iron-peak nuclei to extend the distribution up to Zn, also producing much Ni (Sneden & Crocker 1988; Arnett 1995); and (2) the weak s-process in core-He-burning stars which also produces Sr, Y, and Zr but not heavier species (Prantzos, Hashimoto, & Nomoto 1990). However, quantitative models of GCE do not currently reproduce zinc observations well, and we cannot be certain that we understand its production. For example, Nomoto et al's (1997) SN II calculations averaged over the IMF for 10–50 $M_\odot$ stars (their Fig. 8) underproduces the solar Zn abundance by $\gtrsim 1$ dex, as foreshadowed by their earlier comments (Thielemann, Nomoto, & Hashimoto 1996) that additional Zn is produced in the s-process and possibly in SN Ia. The GCE calculations of Timmes, Woosley & Weaver (1995, Fig. 35) similarly fail to match the observations, though Woosley & Weaver (1995, §4.7) specifically note that they regard the probable source of the dominant solar isotope, ^{64}Zn, to be an extreme α-rich freeze-out which was *not* included in their study.

Blake et al. (2000a,b) report results for CS 22897-008, a giant selected for its high [Sr/Fe] and low [Ba/Fe] values.[2] Through échelle spectra with S/N = 47–129, and $\lambda/\Delta\lambda$ = 50000, earlier Sr, Y, Zr, and Ba measurements have been improved, and the first detection of Zn in this object was obtained. Abundances, calculated using WIDTH6 (Kurucz & Furenlid 1979) and a Bell et al. (1976) model for parameters $T_{\rm eff}/\log g/[{\rm Fe/H}]/\xi = 4850/1.8/-3/1.9$, are shown in Figure 3. They confirm that Sr, Y, Zr, and also Zn ([Zn/Fe] = +0.7) are more abundant in this star than most others of the same [Fe/H].

There is an additional caveat for Zn in addition to the usual uncertainties in the atmospheric parameters and models. The 'normal' value of [Zn/Fe] in stars at [Fe/H] = −3.3 is not well known, due to the paucity of measurements in such metal-poor objects. Primas et al. (2000) show only one object with [Fe/H] < -3.0, for which they give *preliminary* values [Fe/H] = −3.5, [Zn/Fe] = 0.45. It will be interesting to see whether their final sample reveals an increasing overabundance of [Zn/Fe] in more-metal-poor stars, as their preliminary sample suggests and as Johnson (2000) also identifies.

Several nucleosynthetic sites that may produce the overabundances shown in Figure 3 will be discussed below, with quantitative calculations presented elsewhere (Blake et al. 2000b). Whatever produces Zn, Sr, Y, and Zr abundantly in CS 22897-008 and other stars must avoid producing much Ba. If this is a neutron capture process, then a small exposure, or a small number of neutrons per seed, is required.

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[2] It has only a moderate carbon abundance ([C/Fe] = 0.34; McWilliam et al. 1995) so is unlikely to be related to the C-rich, s-process-rich stars investigated by Norris et al. (1997a) or to the r-process-rich object CS 22892-052 (Sneden et al. 1995).

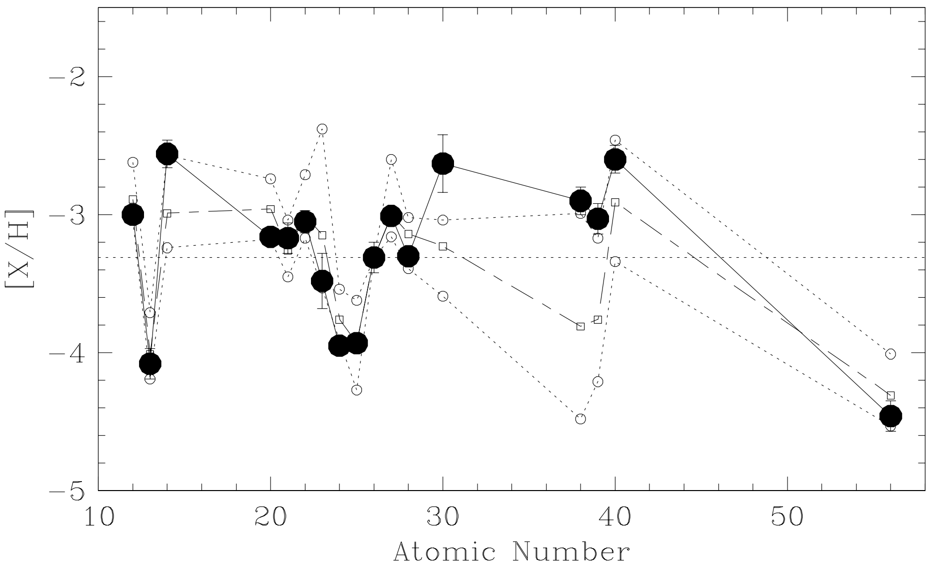

Fig. 3. [X/H] for a range of elements in CS 22897-008 (solid symbols). The horizontal line passes through Fe; displacements from this line give [X/Fe]. The squares (connected by the dashed line) give [X/H] values typical of other stars at the same [Fe/H], while open circles approximate the upper and lower quartiles of the spread. (For V, Zn, and Zr, where few similarly metal-poor stars have been observed, comparison values are based on higher metallicity objects.)

3.1. The weak s-process

The weak s-process occurs during He- and C-burning in massive stars ($M \gtrsim 10$ M$_\odot$), producing only the first s-process peak, the $N = 50$ closed shell at Sr-Y-Zr, but not the $N = 82$ peak at Ba-La (e.g. Prantzos et al. 1990). It differs in both site and yield from the main s-process associated with thermally-pulsing AGB stars (e.g. Busso et al. 1999). Prantzos et al. show (their Fig. 7) that sufficiently massive stars will produce a strong overabundance of elements from Zn to Zr, as would be needed to explain the elements enhanced in CS 22897-008 (Figure 3). Furthermore, this nucleosynthetic component would be more obvious in the ejecta of massive stars, the mass range appropriate to the enrichment of the most metal-poor stars. However, it depends strongly on metallicity, and is not expected to be significant in metal-poor objects with [Fe/H] < -3, due to the greater relative importance of *primary* neutron poisons like ^{12}C, ^{16}O, and ^{20}Ne (Prantzos et al. 1990; Raiteri et al. 1991a,b, 1992; Travaglio et al. 1996).

3.2. A weak r-processes

In view of the difficulties faced by the weak-s-process, it is natural to hypothesise an analogous weak-r-process (e.g. Ishimaru & Wanajo 2000) that produces only the lighter neutron-capture species abundantly, but at the high neutron densities associated with a primary r-process. Wasserburg, Busso & Gallino (1996) were prompted by the $^{129}\mathrm{I}/^{127}\mathrm{I}$ and $^{182}\mathrm{Hf}/^{180}\mathrm{Hf}$ ratios in the early solar system to hypothesise two distinct r-process sites to explain light ($A \leq 130$) and heavy ($A > 130$) nuclei. Qian, Vogel & Wasserburg (1998) and Wasserburg & Qian (2000) developed the idea further, and associated light r-element production with lower frequency, higher yield events above a new neutron-star remnant, while heavy r-element production occurred in higher frequency but lower yield events associated with the formation of black hole remnants.

3.3. The α-process

The α-process — an α-rich freeze-out (e.g. Woosley, Arnett, & Clayton 1973) from explosive Si-burning which avoids complete nuclear statistical equilibrium in the low density, high temperature neutrino bubble above a 1–10-second-old neutron star — is capable of producing not only excess Zn but also Sr-Y-Zr (Woosley & Hoffman 1992; Witti, Janka & Takahashi 1994; Woosley et al. 1994). One of the challenges of explaining the excess Sr in the stars at $[\mathrm{Fe/H}] < -3$ is that it appears in some but not others, and with varying magnitude. That is, the data exhibit a large spread in [Sr/Fe], not simply a bimodal distribution.[3] The existence of a wide spread, covering $\gtrsim 2$ dex, suggests that the efficacy of whatever mechanism is responsible is strongly dependent upon some key factor(s). Takahashi et al. (1994) show that a reduction in the density of the neutrino bubble by a factor of 5 would allow the normal r-process to proceed rather than the α-process. With such a small variation in density required to toggle between the Sr-Y-Zr-producing α-process and the r-process, it may be possible to switch between normal and excessive production of these species with just the natural variation in density. This is an attractive feature of the α-process possibility.

3.4. Neutron-star mergers

Freiburghaus et al. (1999) have shown that neutron-star mergers could be an important site for the production of r-process elements with $A > 130$ in the Galaxy. The Y_{e} range explored in their work finds underproduction of $A < 130$ species, which fits qualitatively the data of Sneden et al. (2000) for CS 22892-052. However, this result is in the opposite sense to that found for the stars we are investigating, which in contrast have high Sr and low Ba abundances. That is, while neutron-star mergers may prove responsible for much of the r-processing in the Galaxy, they do not, by current calculations, describe the nucleosynthesis that has produced high Sr abundances in the most metal-poor stars.

4. Concluding remarks

These stars emphasise that element analyses of neutron-capture elements in very metal-poor stars can constrain the nucleosynthesis processes and sites that have operated in the Galaxy. This will provide a greater degree of realism in the models and hence to our

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[3] The bimodality in the [Ba/Fe] distribution discussed by Ryan et al. (1996) was eliminated (see Figure 3) by McWilliam's (1998) revision of the Ba abundances for his sample.

computations of the chemical evolution of the Galaxy. In the case of very metal-poor stars, we hope to constrain models of sites that may no longer be observed directly.

Caution is also needed to avoid overinterpreting the observations. In many discussions of heavy-element production, the element abundances in CS 22892-052 are cited as if they were a definitive record of early Galactic nucleosynthesis. While these data are exquisite, and many of the recent advances in our understanding of neutron-capture elements have been based on this star's composition, people should bear in mind that this is a very *a*typical star. It has a carbon overabundance of a factor of ten, and is one of few metal-poor stars showing strong r-process overabundances, again by a factor of $\gtrsim 10$ (depending on exactly which element is measured). It is precisely because it is such an *unusual* star that it has been able to be studied in such detail. We must be cautious that we do not infer that the typical products of nucleosynthesis in the early epoch of *Galaxy* are those seen in such an unusual and atypical single object.

Acknowledgements

It is a pleasure to acknowledge many valuable discussions with Drs Y. Ishimaru, C. Travaglio, and S. Wanajo.

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