Heavy element synthesis in the oldest stars and the early Universe

John J. Cowan[1] & Christopher Sneden[2]

The first stars in the Universe were probably quite different from those born today. Composed almost entirely of hydrogen and helium (plus a tiny trace of lithium), they lacked the heavier elements that determine the formation and evolution of younger stars. Although we cannot observe the very first stars — they died long ago in supernovae explosions — they created heavy elements that were incorporated into the next generation. Here we describe how observations of heavy elements in the oldest surviving stars in our Galaxy's halo help us understand the nature of the first stars — those responsible for the chemical enrichment of our Galaxy and Universe.

The Big Bang explosion at the start of the Universe was responsible for the production of the light elements hydrogen and helium, along with some fraction of lithium. All of the other elements in nature (except beryllium and boron) are synthesized inside stars, and later ejected back into the interstellar medium where they are incorporated into new generations of stars. Thus, the extinct first stars in our Galaxy and throughout the Universe were essentially composed of only hydrogen and helium — no heavy elements had yet been formed.

The chemical abundances in the oldest surviving stars, however, provide clues about the types or identities of the very first generations of stars in the Galaxy and the Universe (see recent reviews[1–3]). Element formation is closely connected with stellar evolution. Fusion reactions (starting with hydrogen into helium) inside stars synthesize the elements up to iron. The elements heavier than iron, however, cannot be formed by fusion, and instead are synthesized as a result of slow (s-process) and rapid (r-process) neutron-capture reactions. These two nuclear processes are responsible for forming the heavier (also known as n-capture) elements such as platinum and gold. This element formation occurs during the latter stages of a star's life. Low-mass stars, similar to the Sun, live for billions of years, ending their lives as red giants and planetary nebulae. These objects are responsible for producing most of the s-process elements (such as barium), which are then ejected (at relatively low velocities) into the interstellar medium as part of the dying stars.

More massive stars evolve at a much faster rate and typically live only millions of years. During the last brief period of their lives they undergo titanic supernova explosions. It is during this explosion that the r-process elements (such as platinum and gold) are ejected into interstellar gas that will eventually form new stars. Although the general picture of element formation is understood, many questions about the nuclear physics processes and particularly the details of the supernova explosion mechanism remain to be answered[4,5]. So the elements that are observed in the oldest stars were not synthesized internally, but instead are the result of 'seeding' from previous generations of stars. As the first generations of stars no longer exist, we suspect they must have been massive, but the details of their formation are not understood. This is particularly true because their compositions, devoid of elements except hydrogen and helium, make them different from stars like the Sun that have formed more recently. We can also tell something of the history of star formation in our Galaxy from the iron abundance, which astronomers refer to as 'metallicity'. Most of the iron production that occurs today comes from type Ia supernovae. These result from the explosion of white dwarfs, formed from long-lived low-mass stars; thus, the stars that formed early in the history of the Galaxy and the Universe could not have had much iron. In our Galaxy these metal-poor stars are found in the (roughly spherical) halo, whereas the more metal-rich stars like the Sun reside in the flat galactic disk.

Astronomers are using the metal-poor stars in the galactic halo as laboratories for the study of n-capture element synthesis. Their chemical compositions indicate the types of synthesis processes that occurred early in the history of the Galaxy and provide clues about their progenitors, the generations of stars that lived and died before them. These abundance observations have been pushing back to lower and lower metallicities, and, presumably, earlier times. Early observational work[6–15] focused on identifying these n-capture elements in stars with low metallicities, or [Fe/H] < −1. (We adopt the usual spectroscopic notations that $[A/B] \equiv \log_{10}(N_A/N_B)_* - \log_{10}(N_A/N_B)_\odot$, and that $\log \varepsilon(A) \equiv \log_{10}(N_A/N_H) + 12.0$, for elements A and B, where N represents abundance.) More recently, very detailed abundance distributions have been obtained for the stars with metallicities [Fe/H] ≈ −3 and large overabundances of n-capture elements, notably the stars CS22892–052 (ref. 16) and CS31082–001 (ref. 17). More such enriched stars have been identified in recent surveys[18,19].

The presence of these heavy elements in the observed stars demonstrates that the preceding (massive star and extinct) generation of stars in our Galaxy — perhaps the second generation of stars — was able to synthesize all of the heavy elements, before exploding as supernovae. During the past 3 years intriguing new observations[20,21] have uncovered two stars with metallicities below [Fe/H] = −5. The abundance patterns in these two extremely metal-poor stars (HE0107–5240 and HE1327–2326) are rich in carbon, nitrogen and oxygen but very poor in n-capture elements, quite different from those seen in CS22892–052 and CS31082–001. These differences suggest rapid changes in the synthesis mechanisms early in the history of the Galaxy and shed light on the identity of the first stars: these were probably massive and only able to synthesize the lighter elements such as carbon, nitrogen and oxygen, not the heavy n-capture elements.

[1]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019, USA. [2]Department of Astronomy and McDonald Observatory, University of Texas, Austin, Texas 78712, USA.

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The discovery of radioactive elements such as thorium and uranium in low-metallicity halo stars has led to new chronometric age determinations. Comparing the predicted and observed abundances of these long-lived radioactive elements (with precisely determined, or clock-like, half-lives) can provide a direct stellar age. This technique, originally suggested by Butcher[22], has the advantage of being independent of cosmological and chemical evolution models. Thorium has now been identified in a number of stars[13,18,23–28]. Uranium was first detected in CS31082–0129 and now is seen in several other stars[3,18,26]. These radioactive elements have been used to date the oldest stars in our Galaxy, with typical ages of 13–14 billion years. The age estimates are in accord with determinations of globular cluster and cosmological ages, for instance from WMAP (the Wilkinson Microwave Anisotropy Probe).

In the future, planned large-scale surveys (some of which have already started) will provide new abundances and detections of very metal-poor stars, which will help in identifying the nature of the first stars and the conditions that occurred early in the history of our Galaxy. Additional high-resolution observations of spectroscopic abundances will also lead to the detections of elements never before seen in stars, as well as increasing the number of rarely seen elements such as uranium. New detections of radioactive elements such as thorium and uranium, along with physically more reliable nuclear experimental data for the heaviest, most radioactive nuclei, will also lead to more accurate dating of stellar ages. This will provide more definitive age estimates for the oldest stars, and will ultimately put strong limits on the age of our Galaxy and the Universe.

The formation of the heavy elements

Stars go through a series of fusion reactions in their interiors as they age. Through these reactions, elements from hydrogen to iron can be formed. But iron, with the largest binding energy per nucleon, cannot be fused exothermically. Additionally, as the proton number increases for heavier nuclei, the Coulomb barrier becomes too high to allow charged-particle reactions in stellar environments. So nuclei heavier than iron are synthesized almost exclusively in neutron-capture processes (on heavy target nuclei) where there are no Coulomb barriers to overcome. These neutron-capture elements are produced either solely or by a combination of the slow and rapid processes. Our understanding of how these processes operate in stars began with pioneering work[30,31] in 1957. In the s-process the timescale for neutron capture (τ_n) is much longer than for electron (β) decays (τ_β) from unstable nuclei. Nuclei capturing neutrons will become unstable and undergo β-decay transformations of neutrons into protons, thereby building up heavier elements. The nature of the s-process ensures that it occurs close to stability, meaning the nuclei formed are not very radioactive. The properties of this synthesis process can be determined experimentally. The situation is quite different for the r-process where $\tau_n << \tau$, and the nuclei produced are so unstable and short-lived that experimental information is not generally available.

Nevertheless, much can be learned about how the r-process operates. Observed elemental and isotopic abundance patterns in very old, very metal-poor stars with significant abundances of n-capture elements (see next section) agree very well with the abundance pattern for the relative or 'scaled Solar System' r-process. Happily, the one prominent success of r-process theoretical investigations has been to reproduce the Solar System abundances.

The conclusions reached for the Solar System apparently extend to all metallicities and galactic ages. One recent theoretical attempt is shown in Fig. 1 (K.-L. Kratz, B. Pfeiffer, C.S., J. W. Truran & J.J.C., manuscript in preparation), where an r-process calculation is fitted to the isotopic abundance data for the Solar System. Such calculations are intended to help us to understand the conditions, such as the temperature and neutron number densities (n_n), that are necessary for the production of these isotopes in stellar environments.

We know where s-process nucleosynthesis occurs: the sites are stars of low or intermediate mass (0.8–8 solar masses), on the asymptotic (red) giant branch, with evolutionary timescales billions of years long[32]. Identifying the specific astrophysical site for the r-process, however, has

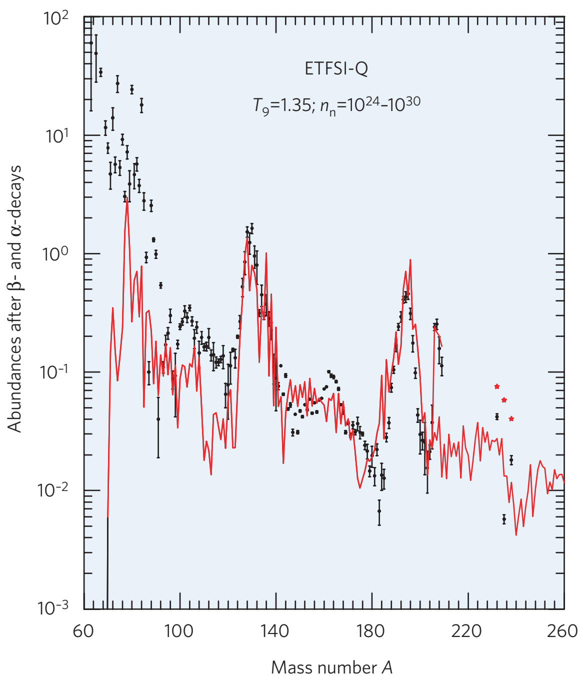

Figure 1 | Abundance comparisons between measured and predicted isotopic abundances. Dots show measured Solar System isotopic abundances (error bars indicate one standard deviation); solid line shows calculated r-process predictions. These theoretical predictions illustrate the stable abundances (after radioactive decays involving α- and β-particles), cover a range of neutron number densities, n_n, and are for a specific theoretical nuclear mass model, ETFSI-Q (K.-L. Kratz, B. Pfeiffer, C.S., J. W. Truran & J.J.C., manuscript in preparation). The temperature, T_9, is in units of 10^9.

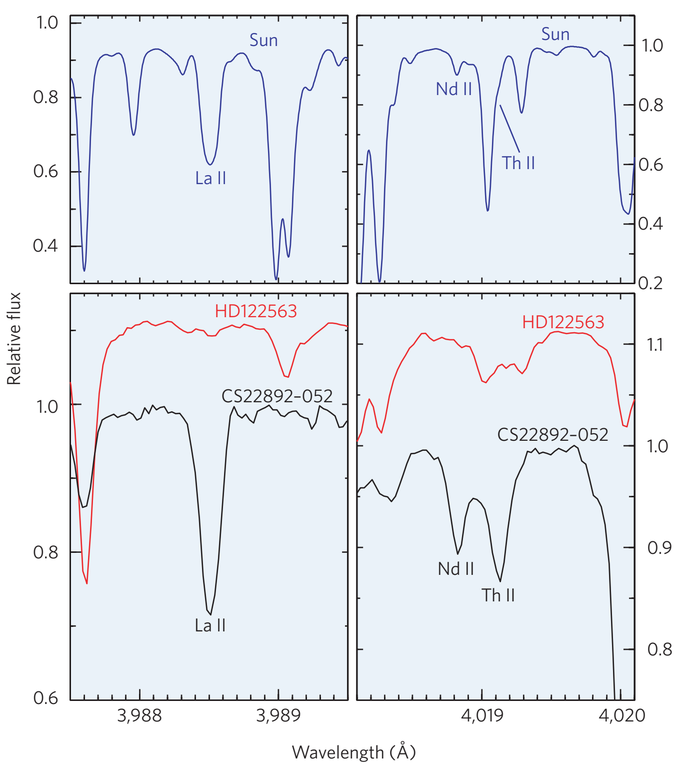

Figure 2 | Spectra featuring three n-capture lines in the Sun and two contrasting low-metallicity stars. The two low-metallicity stars are HD122563 ([Fe/H] = –2.7, [Eu/Fe] = –0.4; from ref. 24) and CS22892–052 ([Fe/H] = –3.1, [Eu/Fe] = +1.6, from ref. 16). Solar spectra are from an integrated flux atlas[83].

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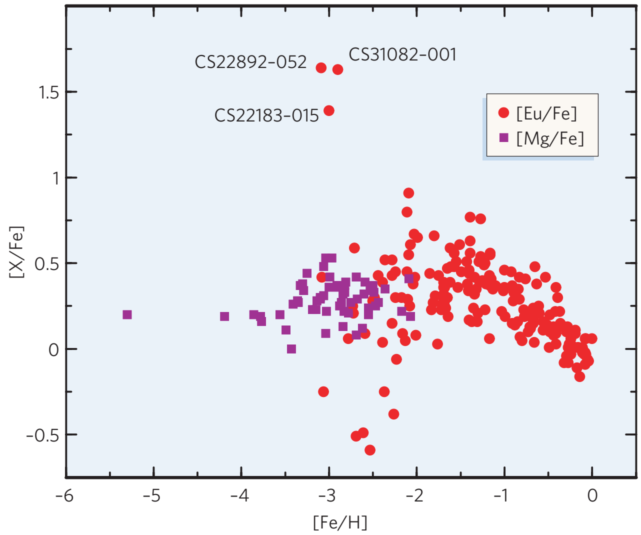

Figure 3 | Elemental ratios for galactic halo and disk stars. The plot shows abundance scatter of elemental ratios [Eu/Fe] (refs 15, 60, 63) and [Mg/Fe] (refs 64, 65) against metallicity (iron abundance) for samples of halo and disk stars in our Galaxy. The iron abundances [Fe/H] are logarithmic and with respect to solar iron. The negative numbers indicate older, metal-poor stars, whereas [Fe/H] = 0 is solar.

been much more difficult[4,33]. The original work on this subject[30] suggested that the neutron-rich regions outside the nascent neutron star in a (type II) core-collapse supernova would be likely sites. More recent work has also pointed to a supernova origin, in this case the 'neutrino wind' streaming out from the central iron-core collapse of a massive star[34,35]. Despite much work, however, the details of the supernova explosion, and the interconnected relationship with the small amount of matter associated with the r-process in this explosion, are still not well understood[4,34,36,37]. The fact that the r-process elements are seen in some of the oldest surviving stars in the Galaxy (particularly those that are rich in heavy elements) strongly suggests that their progenitors — the very early stars that synthesized the r-process elements and ejected them explosively into the interstellar medium where they were incorporated into the halo stars — must have been rapidly evolving. Such a rapid evolution has argued against, although not necessarily ruled out, neutron-star binary mergers as an alternative (non-supernova) site for the r-process[38].

The r-process signatures are clearly seen in stars rich in n-capture elements in the metallicity regime [Fe/H] of approximately –2 to –3. But the two hyper-metal-poor stars discovered[20,21] with [Fe/H] below –5 have very different abundance distributions. These stars, rich in carbon, nitrogen and oxygen with very little evidence of heavier n-capture elements, are similar in that regard to some other r-process-poor stars[39–41]. These observations strongly suggest that some of the very first stars in the Galaxy, the stars that preceded the observed extremely metal-poor stars, must have only been able to synthesize elements up to iron or thereabouts. These new observations might also indicate that the stellar mass ranges of these first stars were not responsible for r-process element formation. There have been many suggestions that the earliest stellar generations in the Galaxy and the Universe were composed of very massive stars[42,43]. For example, there have been arguments that the abundance patterns seen in HE0107–5240 and HE1327–2326 could be explained as coming from the ejecta of black-hole-forming 'faint' supernovae (of the first stars) in the mass range of 20–130 solar masses[44]. The observed absence of the n-capture elements in certain of these halo stars might then be consistent with increasing evidence that r-process synthesis might be associated with lower-mass (8–10 solar mass) supernovae[45–47].

Thus, the first stars might have been massive and unable to form the n-capture elements, but a somewhat later generation of early and perhaps lower-mass stars, existing before [Fe/H] = –3 to –4, could have synthesized the total heavy-element distribution seen, for example, in CS22892–052.

Stellar abundance observations

Low-metallicity stars have widely varying relative abundance distributions. This is most apparent among the heavier n-capture elements ($Z > 55$) whose bulk contents are known to vary by two to three orders of magnitude in stars of similar metallicities. In Fig. 2 small spectral regions surrounding n-capture lines in two very metal-poor giants and the Sun are displayed. Inspection of this figure confirms the relatively simple nature of metal-poor stellar spectra, as well as the gross star-to-star variations in n-capture line strengths. Detection of thorium (strong in CS22892–052 but undetectable among the contaminating features in HD122563) is now commonplace in stars enriched in products of r-process nucleosynthesis. In Fig. 3 the star-to-star variations in n-capture elemental abundances are depicted by plotting relative abundance ratios [Eu/Fe] and [Mg/Fe] against [Fe/H] metallicity.

The abundances of the heavier n-capture elements ($Z \geq 56$) in metal-poor stars with raised abundances of r-process material closely match the Solar System r-process pattern. This is illustrated for CS22892–052 in Fig. 4. Such a clear result has only become possible recently through a combination of excellent stellar spectra and rapid gains in laboratory atomic physics. Indeed, since the publication of the CS22892–052 study, new publications[48,49] have refined and expanded the transition data for several n-capture abundances, shrinking the uncertainties and sharpening the agreement with r-process abundances for the Solar System. This remarkable accord between r-process abundance sets created at the beginning of the Galaxy and in nucleosynthesis events leading to the formation of the Solar System strongly suggests that a unique r-process exists in nature.

Very similar abundance patterns, consistent with the solar r-abundances for the stable elements barium and above (but not necessarily including the radioactive actinides), have now been seen in essentially every other r-process-rich halo star. In Fig. 5 we show this repeated pattern from our studies and others[17,25]. A clearly demonstrated counter-example to this statement has yet to be found. The consistency between Solar System r-process abundances and those of the r-process-rich halo stars has been extended to the isotopic level, as Sneden *et al.*[50] and Aoki *et al.*[51]

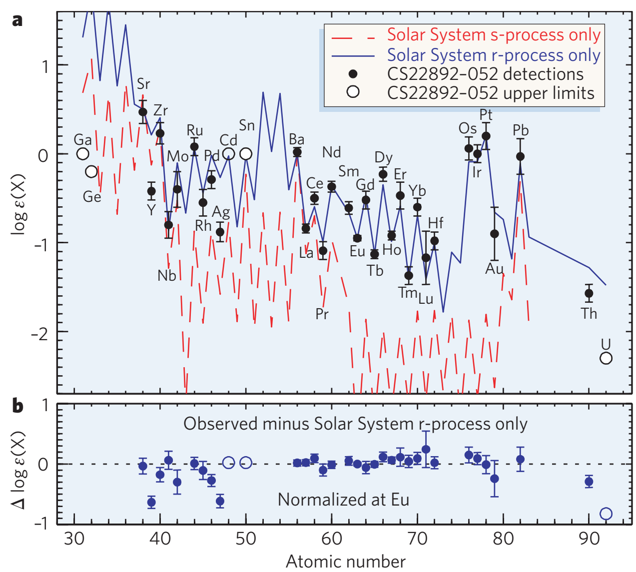

Figure 4 | Abundances in the very metal-poor halo star CS22892–052. This figure is adapted from two figures in ref. 16. The error bars are sample deviations. **a,** Solar System r-process abundance curve[60] has been normalized to the observed Eu abundance, and the non-fitting s-process curve has been shifted so that it roughly matches the observed abundances of the Sr–Y–Zr group. **b,** Differences between the observed CS22892–052 abundances and the scaled Solar System r-process abundances are shown.

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have demonstrated that $N(^{151}Eu)/N(^{153}Eu) \approx 1.0 \pm 0.1$ in several halo stars; the meteoritic ratio of this r-dominant element is 0.478/0.522 = 0.92. Additionally, Lambert and Allende Prieto[52] have found that the ratio of odd-*N* isotopes to even-*N* ones of barium in one low-metallicity star is also consistent with a Solar System r-process-only mix.

However, inspection of Fig. 4 shows that a scaled solar r-process distribution does not seem to extend to the lighter n-capture elements. Several elements, notably silver, appear to be relatively deficient. This anomalous pattern (which also cannot be easily fitted by an abundance distribution from s-process synthesis) is found in many r-process-rich stars[53]. Perhaps we must postulate the existence of two r-process sites[54,55], analogous to the two known s-processes. The formation of the lighter n-capture elements beyond the iron peak may in fact be complicated, and may require (at least in part for certain elements) some other primary synthesis process[56,57].

In addition to the stars within our Galaxy, there have been increasing efforts to identify abundance patterns in other galaxies. For example, metal-poor stars ([Fe/H] < −1) in nearby dwarf galaxies have s- and r-process abundances like those in the galactic halo[58]. In addition, studies of a galaxy at high (redshift) z, with an estimated age of no more than 2.5 Gyr after the Big Bang, have detected the presence of heavy elements[59]. This indicates that star formation and the related element production was rapid in galaxies that formed relatively soon after the Big Bang. This again suggests massive stars as the sites of this nucleosynthesis, during the earliest chemical history of the Universe. Even more striking in these results is that the total elemental abundance pattern seen in this galaxy, formed early in the history of the Universe — and so much older than the Sun — is consistent with a scaled Solar System abundance distribution.

Abundance trends and chemical evolution

Additional clues to the nature of the early synthesis history of the Galaxy are coming from recent studies of chemical evolution. We show in Fig. 6 the abundance trend for the element germanium as a function of metallicity, [Fe/H]. Germanium is normally thought of as an n-capture element with both s- and r-process contributions in Solar System material[60]. Until recently data on Ge have been scarce as the dominant atomic transitions are in the ultraviolet and thus require space-based observations. The abundance behaviour shown in Fig. 6 is surprising in that the Ge abundance in these low-metallicity stars seems to track (and is roughly proportional to) the iron abundance[61]. This seems to imply that Ge is formed, at least at very low metallicities and early times, in some type of charged particle reaction, or other primary process[57], that would occur in massive stars and supernovae before the s-process contribution sets in.

Other chemical evolution studies have focused on a comparison of s- and r-process elemental abundance data. These are designed to help determine the astrophysical sites for both processes and to indicate the metallicities and times for the onset of the bulk of galactic s-process nucleosynthesis. Although Ba/Eu has been used for a number of these studies, known problems in abundance determinations for barium have suggested that La/Eu might be more reliable[60]. We show in Fig. 7 the variation in the ratio of La/Eu as a function of [Fe/H] in a number of galactic halo and disk stars. The dashed line[62] and the dotted line[15] are predictions for the r-process-only ratio of La/Eu, and the square symbols are the values for the r-process rich stars CS22892–052, HD115444, CS31082–001 and BD+17°3248.

There are several trends apparent in this figure. First, there is a general increase in the ratio of La/Eu as the s-process contribution to lanthanum production (europium is an r-process-only element) rises with metallicity and time. This results as lower-mass stars have time to evolve, synthesize and eject s-process material that will be incorporated into new stars. Thus, the metal-rich disk stars, in general, have larger ratios than the halo stars. Second, it is seen that only the most metal-poor stars seem to have La/Eu ratios consistent with the r-process-only ratio. Although the bulk of the galactic production occurs somewhere near [Fe/H] = −2, Fig. 7 suggests that at least some s-process production sets in at relatively early galactic times and low metallicities[15,60]. This clearly has implications for the mass ranges and types of stars that could have been responsible for this synthesis in the early Galaxy.

Returning to Fig. 3, we compare abundance trends as a function of metallicity for the r-process element europium and the α-element (that is, one formed by successive captures of helium nuclei, also known as α-particles) magnesium, synthesized in charged-particle reactions. What is immediately apparent is that there is a very large star-to-star scatter in the Eu/Fe abundances[15,60,63] at low metallicities. This scatter diminishes sharply at higher metallicities. This seems to indicate that at very early times and low metallicities the Galaxy was chemically inhomogeneous in r-process elements. The same is not true for the Mg data[64,65], which show very little scatter at the lowest metallicities. This comparison also

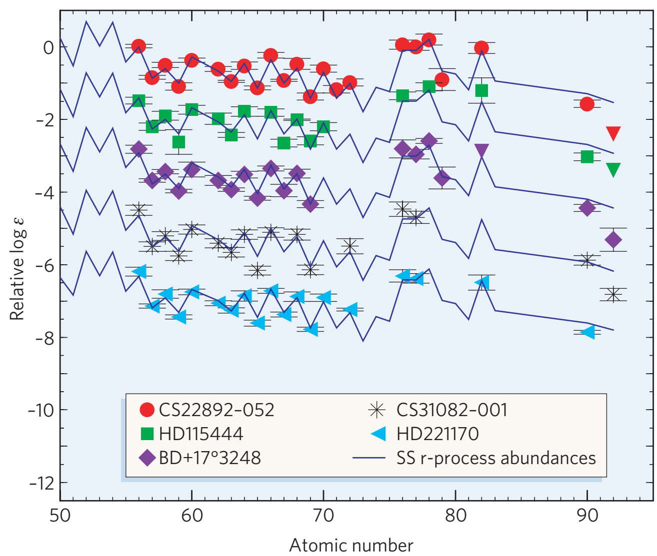

Figure 5 | Elemental abundance patterns in galactic halo stars. The plots show the neutron-capture elemental abundance pattern in the galactic halo stars CS22892–052, BD+17°3248, HD115444, CS31082–001 and HD221170 compared with the (scaled) Solar System (SS) r-process abundances (solid lines). The abundances (with sample deviation error bars) of all of the stars except CS22892–052 have been displaced downwards for display purposes.

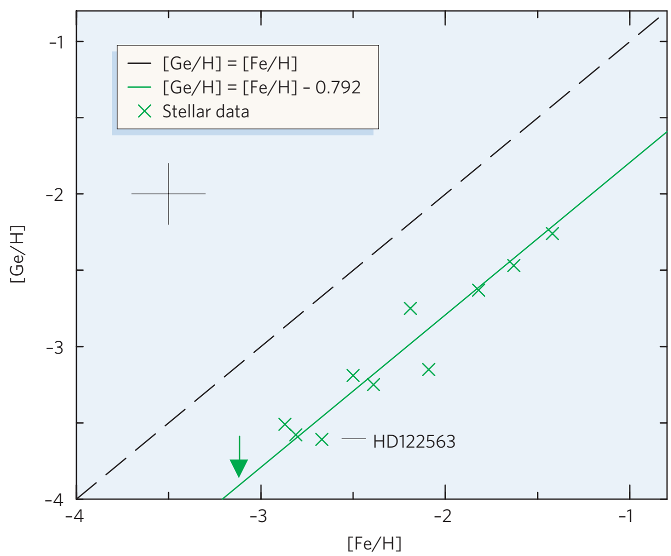

Figure 6 | Relative abundances of the elemental ratio [Ge/H] as a function of metallicity (Fe). Data are for a sample of 11 galactic halo stars (after ref. 61). The arrow represents the derived upper limit for CS22892–052. The dashed line indicates the solar abundance ratio of these elements, [Ge/H] = [Fe/H], and the solid green line shows the derived correlation [Ge/H] = [Fe/H] – 0.79. A typical error (1σ) is indicated by the cross.

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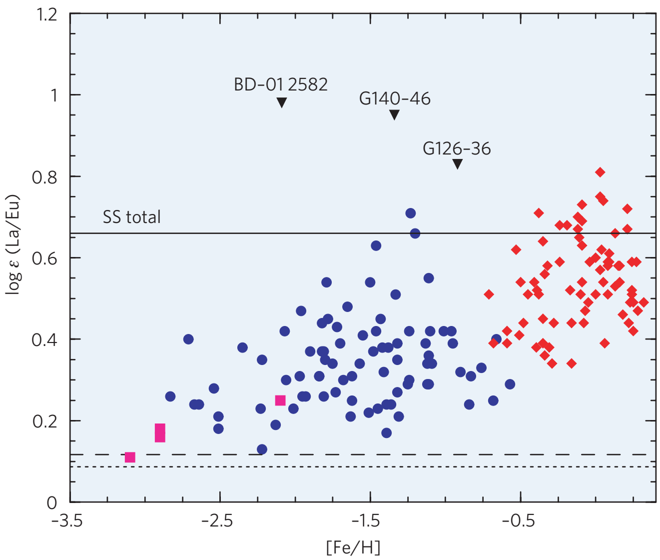

Figure 7 | Abundance trends for the ratio La/Eu in galactic stars. Abundance trends are shown with respect to metallicity for the elemental ratio La/Eu in a large number of stars in our Galaxy (after ref. 60). The filled circles are halo stars (ref. 60), the filled diamonds are disk stars (ref. 63). The dashed (from ref. 62) and dotted (from ref. 15) lines are predictions for r-process-only ratios, and the solid line shows the total Solar System abundances. The labelled stars are all s-process rich. Pink squares represent well-studied r-process-enhanced stars.

suggests that Mg is commonly produced in most (or perhaps all) massive-star supernovae[66,67], whereas Eu is created more rarely in perhaps a restricted (and low-mass) supernova range.

The ages of the stars

The detection of radioactive elements such as Th, with its very long half-life of 14 Gyr (see Fig. 2), offers a promising means of determining ages. This chronometric technique depends only on determining the initial and measured abundances of these elements, usually in ratios to minimize errors. Because the low-metallicity halo stars were formed so early in the Galaxy, chemical evolutionary effects before that formation are not important. Furthermore, these stellar age estimates of the oldest stars will set a lower limit on the age of the Galaxy and hence the Universe, and these estimates will not depend on any particular cosmological model. The ideal chronometer pair is U/Th, both with long half-lives, nearby in nuclear mass and both made entirely in the r-process. The ratio U/Th has been successfully used to date CS31082–001 (12.5 ± 3 Gyr, ref. 29; 14 ± 2.4 Gyr, ref. 17; 15.5 ± 3.2 Gyr, ref. 68; 14.1 ± 2.5 Gyr, ref. 69) and BD+17°3248 (13.8 ± 4 Gyr, ref. 26). Recent estimates of the age of the Galaxy have also been made[70] by determining the production ratio of U/Th.

Uranium, however, is inherently weaker and more difficult to detect in stellar spectra than thorium. Originally, Th/Nd (ref. 22) and later Th/Eu (ref. 71) were suggested as chronometer pairs. In spite of being widely separated in mass number from Th, Eu is easily detected from ground-based observations and made almost exclusively in the r-process[60]. Following the early work[23], chronometric ages based on Th/Eu have been obtained for a number of halo stars[13,16,24–26,28,72–74], typically with age ranges of 11–15 Gyr and with average age uncertainties of 3–4 Gyr. This approach has also yielded a similar age for one globular cluster[75]. These stellar values are consistent with age determinations for the Galaxy based on main-sequence turn off ages for globular clusters[76,77] and recent cosmological age estimates from WMAP[78] and type Ia supernovae[79,80].

The stellar chronometric age estimates, however, sensitively depend on the initial predicted values of Th/Eu, which, in turn, depend on the nuclear mass formulae and r-process calculations used in making those determinations (see discussion in refs 4 and 68). Typical r-process calculations such as the one illustrated in Fig. 1 are intended to reproduce the isotopic (and elemental) abundance distribution of the Solar System. These same calculations that reproduce the stable Solar System (and stellar) elemental abundances can then be used to determine the radioactive abundances, and thus the Th/Eu ratio, at time of formation in an r-process site (a supernova). Although Th/Eu has been used in this manner for a number of stars, in at least one case (CS 31082–001) its use leads to unreasonably low age estimates. In contrast, U/Th does predict an age consistent with other ultra-metal-poor halo stars. Owing to this result and the wide separation in mass number between Th and Eu, the use of Th/Eu as a chronometer has been called into question (see discussion in ref. 28). It is not clear yet, however, whether CS31082–001 with large overabundances of Th and U is anomalous or part of a class of stars with such enhancements. We also note, however, that the reported lead abundance[81], which predominantly results from α-decay of Th and U isotopes, in this star seems to be too low with respect to such high abundance values of these radioactive elements[82]. Clearly more stellar observations, particularly the detection of U, and additional theoretical and nuclear experimental studies of very neutron-rich nuclei will be required to strengthen this technique and reduce the chronometric age uncertainties.

The future

New stellar abundance observations are pushing back to lower and lower metallicities and earlier and earlier times in the history of our Galaxy. There is a concerted effort in, for example, large surveys (in progress and planned) to identify additional extremely metal-poor stars ([Fe/H] < –5), the generation that followed the first stars in our Galaxy. Such new observations will provide details of the synthesis histories and possible mass ranges for those first stars in our Galaxy and throughout the Universe. Additional observations will also be needed to bridge the gap between these very n-capture-poor stars at [Fe/H] < –5 and stars in the metallicity regime of –3 to –4 that already show complete r-process abundance signatures. Determining how the first stars exploded as supernovae will also be critical to our understanding of the nature of these early generations. The explosion mechanism (and the associated microphysics such as neutrino transport) for supernovae is still not well understood.

More work will also be required to improve our understanding of the r-process. We still, for example, do not know the astrophysical site for this process, despite decades of work. We also lack physically reliable data for the most n-rich (or radioactive) elements: perhaps new experiments such as the Radioactive Ion Accelerator, RIA, will provide this. It also remains to determine precisely the conditions that occur in the r-process, and how that affects the abundance predictions, particularly for the most radioactive nuclei. That will be especially critical in reducing the uncertainties in and allowing more precise determinations of chronometric ages. More reliable observations of the radioactive elements Th and U in the most metal-poor stars will also be needed. Together these should provide increasingly stringent constraints on estimates of the ages of our Galaxy and the Universe. ■

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Acknowledgements We dedicate this paper to the memory of Al Cameron, who was a giant in this field and who taught us much about nuclear astrophysics and life. We thank our colleagues for discussions and insights, and Jason Collier and Randi Worhatch for their help with the paper. We also acknowledge support from the National Science Foundation and the Space Telescope Science Institute.

Author Information Reprints and permissions information is available at npg.nature.com/reprintsandpermissions. The authors declare no competing financial interests. Correspondence should be addressed to J.J.C. (cowan@nhn.ou.edu) or C.S. (chris@verdi.as.utexas.edu).

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