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Connecting First Stars to Planets
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Constraints on the Nature of the s- and r-processes

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Abstract. Neutron-capture (Z > 30) elements are detected in many very metal-poor halo stars, and so they must have been manufactured by some of the earliest element donors in our Galaxy's history. The bulk amounts of neutron-capture elements with respect to the iron group vary by several orders of magnitude from star to star at low metallicities. Additionally, abundance distributions among these elements are often strikingly different from that of the solar system. Some stars exhibit abundances that must have been made purely in "rapid" neutron-capture events (the r-process), some in "slow" events (the s-process), and some have hybrid mixes. Here we summarize the major observed categories of the neutron-capture abundances in metal-poor stars, and discuss their implications for early Galactic nucleosynthesis.

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

1. Introduction

Stars create most of the lighter elements in charged-particle fusion reactions. The major isotopes of heavier elements, here defined as those with atomic numbers Z > 30, must be created in reactions of the type $^{A}Z + n \rightarrow {}^{A+1}Z$, followed by nuclear transformations of the type $^{A}Z \rightarrow {}^{A}Z{+}1 + \beta^{-}$. Collectively, the content of these so-called "neutron-capture" (*n*-capture) elements is negligible. In the solar system for example, the most abundant *n*-capture element germanium (Z = 32) is about 10,000 times less abundant than iron, and most other *n*-capture elements are orders of magnitude less abundant than germanium. In spite of their small abundances, the *n*-capture elements are important in the quest to understand Galactic chemical evolution. Nearly 20 presentations at this Symposium prominently feature observations and/or interpretations of the *n*-capture elements. Here we comment of some of the unique aspects of these elements at low metallicity. A comprehensive overview is not possible here; we highlight some issues that are discussed at length in the recent review by Sneden, Cowan, & Gallino (2008).

The creation of *n*-capture elements is easily (and probably too neatly) divided into two extreme cases of neutron ingestion and β-decay timescales. If $\tau_n >> \tau_\beta$ then unstable nuclei will have time to execute all β-decays between successive neutron captures by target nuclei, and element production proceeds along the "valley of β stability." This relatively slow nucleosynthesis mechanism is labeled the *s*-process. It normally is a byproduct of quiescent He-burning, most easily accomplished during the asymptotic giant branch (AGB) phase of low-intermediate mass stars. At the opposite extreme, if $\tau_n << \tau_\beta$, target nuclei are (for a few seconds at most) overwhelmed with neutrons, ingesting them out to the "neutron drip line". When the neutron flood stops, β decays occur until stability is reached. This rapid-burst mechanism is labeled the r-process. The site of the r-process is still uncertain, but must be associated with the explosive deaths of high-mass stars. The r- and s-processes yield different, easily distinguished abundance distributions in low metallicity stars.

2. r-Process Stars

Solar-system n-capture abundances result from many generations of stellar element donors of a large mass range. Not surprisingly, they are a complex mix of r- and s-process abundance contributions, as first quantitatively estimated by Cameron (1982), and further developed with data improvements by, e.g., Arlandini *et al.* (1999) and Simmerer *et al.* (2004). Only a few prior nucleosynthesis events could have contributed to the n-capture abundances of very metal-poor stars. This is manifest first in their large star-to-star bulk variations, i.e., the n-capture/Fe values can range over a factor of 1000 at the same metallicity. The detailed abundance distributions also vary, from r-process-dominant, to s-process-dominant, and to many intermediate mixes.

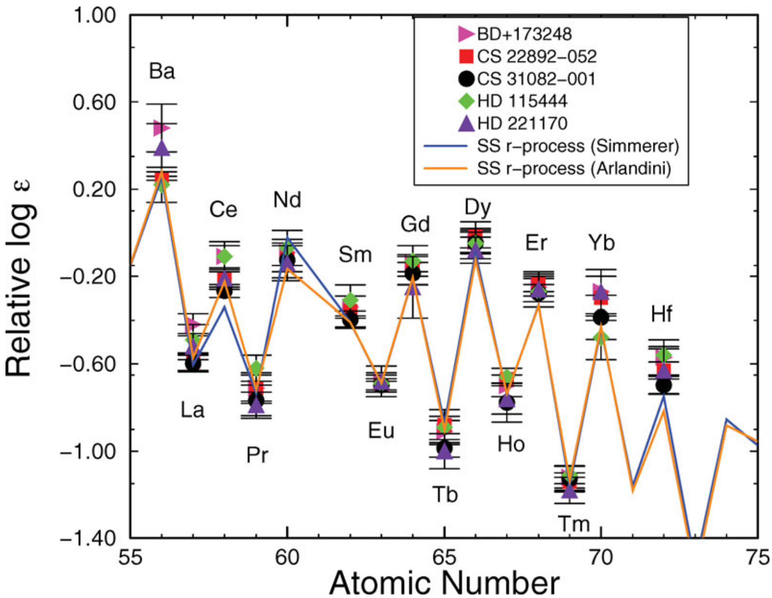

Figure 1. *Figure 8 of Sneden et al. (2009):* rare-earth abundances in five r-rich metal-poor stars (points), and two estimates of the solar-system r-only abundance distribution (lines). All abundance sets have been normalized to agree at Eu. See Sneden *et al.* (2009) for further details.

Enrichment of metal-poor stars by the r-process has been known since the pioneering work of Spite & Spite (1978) and Truran (1981). Abundance studies of halo giant stars HD 115444 (Griffin *et al.* 1982) and HD 122563 (Sneden & Parthasarathy 1983) strengthened the r-process interpretation. Recent studies have demonstrated in excruciating detail the near perfect match between the n-capture abundances of many metal-poor stars and the solar-system r-process-only distribution, especially at the heavy end ($Z \geqslant 56$). We illustrate this agreement for the rare-earth elements in Figure 1; star-to-star scatter in the relative abundances in r-rich stars is now at the $\simeq$0.05 dex level.

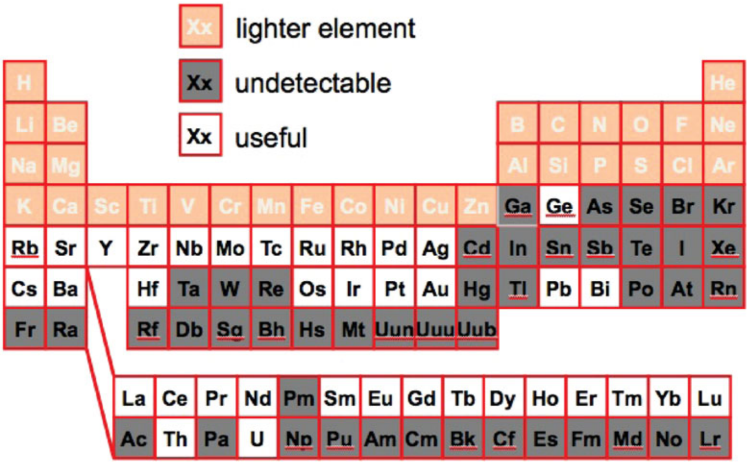

Figure 2. A Periodic Table highlighting the useful n-capture elements, defined here as ones that are accessible in metal-poor stellar spectra and that generally have reliable laboratory transition data.

A prime factor in the increased n-capture abundance precision has been the resurgence of laboratory atomic physics effort on neutral and first ionized species of these elements. In Figure 2 we show a Periodic Table that calls attention to those n-capture elements that have detectable lines in high resolution UV and visible spectra of metal-poor stars. Nearly all of these elements have enjoyed lab analyses since the early 1980's that have resulted in transition probabilities of large numbers of lines to better than 10% accuracy, and in hyperfine and isotopic structure information that largely meet the needs of stellar spectroscopists. Many investigators have contributed to this work, and in particular credit is due to groups in Liège and Wisconsin (especially for the lighter and rare-earth n-capture elements), and Lund (especially for the heaviest elements). Uncertainties in basic transition data have now become fairly minor contributors to the overall error budgets of n-capture abundances in metal-poor stars.

Given the early and repeated attention to HD 122563 and HD 115444, here we consider this pair instead of the more exotic extremely r–rich stars such as CS 31082-001 (Hill *et al.* 2002) or CS 22892-052 (Sneden *et al.* 2003). HD 122563 and HD 115444 seem to have typical r-process patterns, characterized by, e.g, log ϵ(Ba/Eu) $\sim +1.0$ compared with the solar-system $r + s$ total ratio log ϵ(Ba/Eu) $\sim +1.7$. But while their lighter n-capture abundances are similar (e.g., log ϵ(Sr) $\simeq +0.2$ in HD 115444 and -0.1 in HD 122563), their rare-earth contents differ by more than an order of magnitude (e.g. log ϵ(Eu) $\simeq -1.6$ and -2.8, respectively). In Figure 3 we illustrate this contrast by plotting the abundances normalized to Sr. The discrepancy grows with increasing atomic number, as clearly shown by Honda *et al.* (2006, 2007) in a comparison between HD 122563 (and the similar HD 88609) and CS 22892-052.

Not all n-capture elements will cooperate by having accessible transitions in the visible spectral region. Further insights must rely on gathering high-resolution spectra in the UV, and the Hubble Space Telescope STIS is the instrument of choice. In Figure 4 we continue the HD 115444 and HD 122563 comparison with the spectra of two prominent r-process lines. The Eu II line contrast in the left-hand panel reinforces the large abundance difference for this element discussed previously. The Pt I line strength contrast in the right-hand panel is just as large; the line in HD 122563 cannot be reliably detected. But the abundance analyses of this and most other n-capture lines that occur

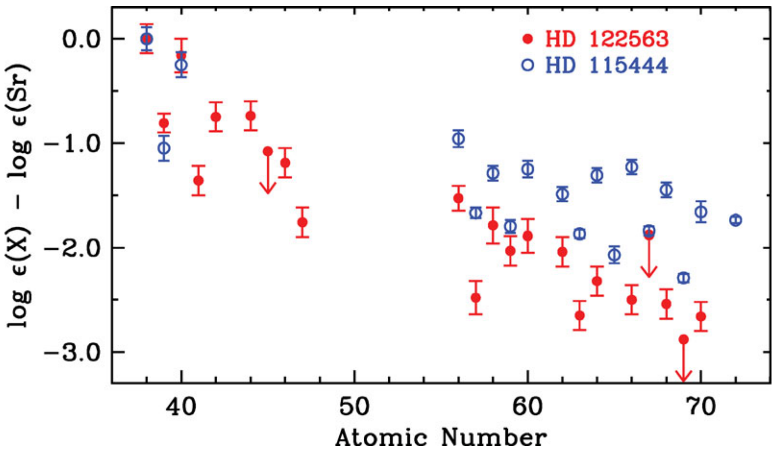

Figure 3. n-capture abundances in HD 115444 (Westin *et al.* 2000, Sneden *et al.* 2009) and HD 122563 (Honda *et al.* 2007), normalized to the Sr abundances for each star.

at short wavelengths ($\lambda < 4000$ Å) is difficult due to line contamination that increases with decreasing wavelength. Certainly caution is warranted in interpretation of n-capture abundances determined from a single transition in the UV.

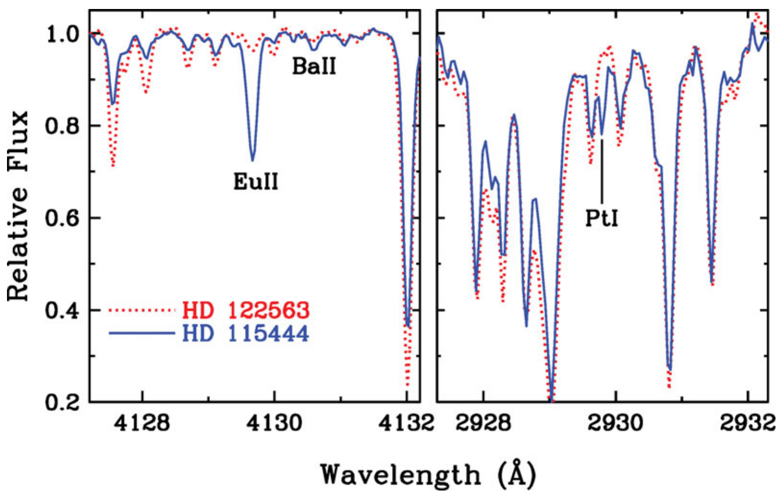

Figure 4. n-capture lines in HD 115444 and HD 122563. The visible-wavelength spectra (left–hand panel) were obtained with the Keck I HIRES, and the UV spectra were obtained with the HST STIS. Cowan *et al.* (2005) has details about these spectra and their analyses.

Concerns about the reliability of individual n-capture abundances cannot obscure the general trends seen in the HST spectra. In Figure 5 we summarize the abundances for 11 r-rich giants from Cowan *et al.* (2005). The correlations are with Europium, the traditional r-process indicator. Relative [X/H] values are used instead of log ϵ in order to inter-compare the abundance enhancements of different elements. In the left-hand panel we plot the abundances of Ge, Zr, and La against Eu. While [La/H] tracks [Eu/H] extremely well, the trends with Zr and especially Ge are poor. This is in line with the differences between lighter and heavier n-capture abundances of HD 115444 and HD 122563 (Figure 3). Much cleaner correlations are shown between the 3^{rd} r-process-peak elements

Os, Ir, and Pt with Eu (Figure 5, right-hand panel. This panel also shows the La abundance with an addition of 0.45 dex. This offset "corrects" it for the solar-system s-process fraction, so that [La/H] + 0.45 = $[\mathrm{La/H}]_{r-only}$. The [La_{r-only},Os,Ir,Pt/H] abundance trends with [Eu/H] are all consistent with a single, nearly one-to-one relationship.

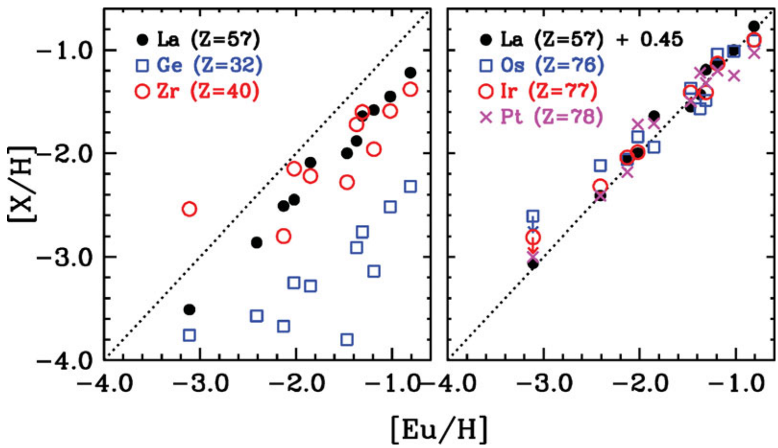

Figure 5. Correlations of light and heavy n-capture abundances with Eu in 11 r-process-rich stars (Cowan *et al.* 2005). In the left-hand panel, "light" Ge and Zr are shown along with the rare earth La. In the right-hand panel, "heavy" Os, Ir, and Pt are compared to La, after adding 0.45 dex to compensate for the loss of La's s-process solar-system contribution.

Abundance comparisons like those shown in Figure 5 have lent support to suggestions for multiple astrophysical nucleosynthesis processes. It seems clear that the heaviest n-capture elements , *i.e.*, Ba and above, are correlated, and are consistent with a (scaled) Solar System r-process abundance pattern. This r-process pattern exists in a very large number of r-process-rich stars (see Sneden *et al.* 2008, and references therein). On the other hand the abundances of the lighter n-capture elements in these same stars are not correlated − thus, the large scatter of the abundances of Ge and Zr with respect to Eu in the left-hand-panel of Figure 5. Much recent work has explored various scenarios to explain these lighter n-capture elemental abundances. There have been a number of suggestions that it will require at least two r-processes − a "main" one for the heavier n-capture elements and a second, or "weak" r-process for the lighter n-capture elements from Z=40 to $\leqslant$ 50 (Kratz *et al.* 2007).

The abundances of the elements Sr-Y-Zr also seem to require multiple synthesis sources, suggesting the possibility of a Light Element Primary Process (LEPP), which could result from either neutrons or charged particles (Travaglio *et al.* 2004). A combination of the main r-process and the LEPP could then explain the abundances of the lighter n-capture elements (Montes *et al.* 2007). The Ge abundances of Cowan *et al.* (2005) − see Figure 5 − do not correlate with r-process abundances, and instead scale with the metallicities of stars, at least for [Fe/H] $\leqslant$ –2. From this, Fröhlich *et al.* (2006) have suggested a new synthesis origin for Ge early in the history of the Galaxy: the ν-p process, involving neutrino scattering in supernovae that could produce protons to be captured on Fe nuclei. Finally, very recent work suggests that various conditions (i.e., entropies) in the high entropy wind of supernovae might be able to reproduce both the heavy and light n-capture abundances (Farouqi *et al.* 2009). Clearly more observational and theoretical studies will be required to discern the origin of these various n-capture elemental regimes.

3. *s*-Process Stars

A large fraction ($\sim$20%) of halo stars with metallicity [Fe/H] < -2 are C-rich, [C/Fe] > 1 (e.g., Beers & Christlieb 2005; Lucatello *et al.* 2006). Such stars are called Carbon Enriched Metal Poor (CEMP) stars. High resolution spectroscopic studies further divide CEMP stars into four subclasses: CEMP-s, enhanced in *s*-process elements; CEMP-sr, enhanced in both *s*-process and *r*-process elements; CEMP-r, enhanced in *r*-process elements, and CEMP-no, with no *n*-capture element overabundances. The majority of CEMP stars are enhanced in *s*-process abundances (both CEMP-s or CEMP-sr).

Heavy *s*-process nuclei (Y$\rightarrow$Pb) are synthesized by a long-lived low mass ($\sim$1.3–5 $M_\odot$) star during its late Asymptotic Giant Branch (AGB) phases, where the star undergoes a series of recurrent Thermal Pulse (TP) instabilities in the He shell. The TP-AGB phase lasts $\sim 10^6$ years, while the envelope, enriched in carbon and *s*-process elements, is progressively lost by intense stellar winds (see Sneden *et al.* 2008 and references therein). The contribution of *s*-process elements to the Galactic interstellar medium thus can occur only later in the halo or in the disk, not early in the halo, at [Fe/H] < -2. Nearly all CEMP-s stars belong to close binary systems, where the observed star, a dwarf or a giant far from the TP-AGB phase, of mass $\sim$0.9 $M_\odot$, became enriched in C and s-process elements by mass transfer from the winds of the more massive companion while on the TP-AGB phase (which now is presumably an unseen white dwarf).

Elements mostly fed by the *s*-process are grouped in three peaks around neutron magic numbers: the light peak (ls: Sr, Y, Zr) at N = 50; the heavy peak (hs: Ba. La, Pr, Ce, Nd) at N = 82; and Pb at N = 126, at the termination of the *s*-process path. The relative elemental abundances of the three *s*-process peaks mainly depends on the initial Fe content (the seed for the *s*-process) and the strength of the major source of neutrons, driven by the $^{13}C(\alpha,n)^{16}O$ reaction. A small number of protons are assumed to penetrate from the bottom of the convective envelope into the radiative He-rich and C-rich inner zone during a third dredge up (TDU) episode. Production of ^{13}C proceeds from proton capture on ^{12}C at H re-ignition ("^{13}C pocket"; Bisterzo *et al.* 2009). A spread in ^{13}C-pocket efficiencies, defined as a multiple/fraction of the "ST" case that reproduces the solar-system main *s*-process component, is needed in order to account for different *s*-process distributions observed at a given metallicity (Bisterzo *et al.* 2009b, Husti *et al.* 2009). The ^{13}C neutron source in principle does not depend on metallicity, being the result of proton capture on newly synthesized ^{12}C. Consequently, at low metallicities the number of neutrons captured by Fe seeds favors the production of very heavy Pb at the termination of the *s*-process path with respect to ls and hs abundances.

Here we give three examples of how the detailed observed abundance patterns can be used to constrain the parameters of C-rich, *s*-rich binary stars Figure 6 compares an *s*-process distribution generated from an AGB model of initial mass 1.5 $M_\odot$ generated with the FRANEC code (Chieffi & Straniero 1989), to observed abundances of the CEMP-s star HE 2158-0348 Cohen *et al.* (2006). For this star the observed [La/Eu] =0.8 is in agreement with *s*-process predictions. La is mostly contributed by the *s*-process ($\sim$70% in the solar-system), whereas Eu is mostly contributed by the *r*-process ($\sim$95% in the solar system). An initial [Eu/Fe] = 0.5 has been assumed, consistent with the average enhancement of Eu in unpolluted low metallicity stars. The agreement between theoretical predictions and observations are obtained after diluting one part of the AGB envelope over 20 parts of the envelope of the envelope of the present star (*dil* = 1.35 dex).

Figure 7 compares *s*-process predictions with abundances in the CEMP-sr star CS 22898-027. The initial AGB mass has been assumed to be 1.3$\odot$. The exceptional [Eu/Fe] $\sim$ 2, and similarly large enhancements of other hs elements (e.g., [La/Eu] $\sim$ 0)

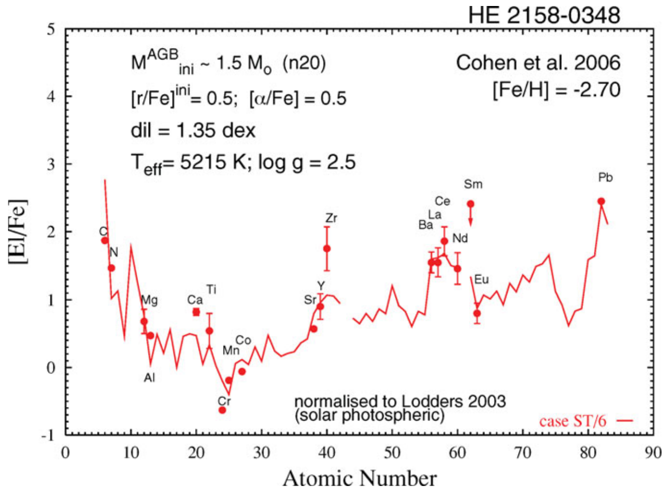

Figure 6. Observed HE 2158-0348 abundances compared with the best-fit model abundance distribution (computed with mass 1.5 $M_\odot$, ^{13}C pocket efficiency ST/6, and dilution factor dil = 1.35 dex.

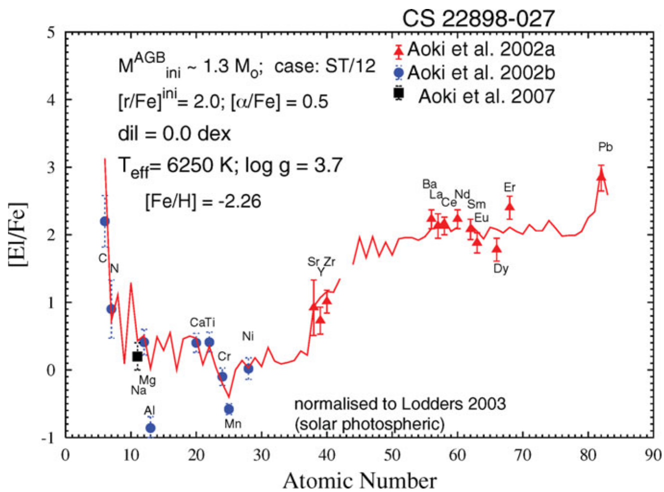

Figure 7. Observed and best-fit model abundance distributions for CS 22898-027.

can only be reconciled by assuming that the initial cloud from which the binary system formed was already locally polluted by ejecta from a very r-process-rich Type II SN.

Figure 8 shows the theoretical prediction of Pb for the CEMP-s star HE 1135+0139. All predicted n-capture element abundances are in excellent agreement with the observation by Barklem *et al.* (2005). We emphasize that the observed abundances in these CEMP stars, such as those illustrated here, can be reproduced by models with relatively few parameters and under reasonable physical conditions.

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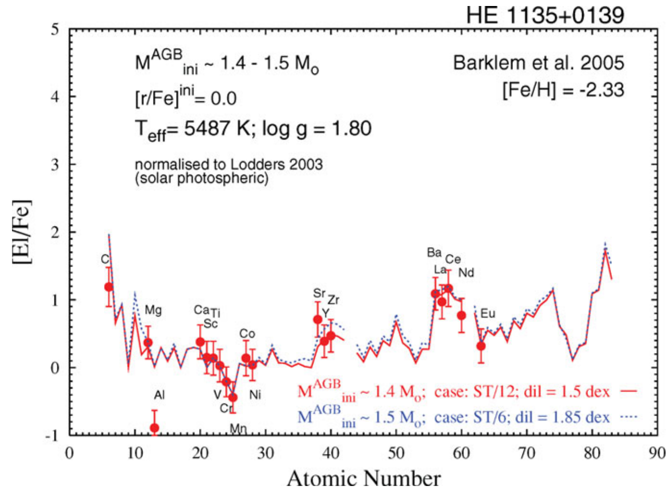

Figure 8. Observed Observed and best-fit model abundance distributions for HE 1135+0139.

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