Nucleosynthetic signatures of the first stars

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The chemically most primitive stars provide constraints on the nature of the first stellar objects that formed in the Universe; elements other than hydrogen, helium and traces of lithium within these objects were generated by nucleosynthesis in the very first stars. The relative abundances of elements in the surviving primitive stars reflect the masses of the first stars, because the pathways of nucleosynthesis are quite sensitive to stellar masses. Several models[1−5] have been suggested to explain the origin of the abundance pattern of the giant star HE 0107−5240, which hitherto exhibited the highest deficiency of heavy elements known.[1,6] Here we report the discovery of HE 1327−2326, a subgiant or main-sequence star with an iron abundance about a factor of two lower than that of HE 0107−5240. Both

stars show extreme overabundances of carbon and nitrogen with respect to iron, suggesting a similar origin of the abundance patterns. The unexpectedly low Li and high Sr abundances of HE 1327−2326, however, challenge existing theoretical understanding: none predicts the high Sr abundance or provides a Li depletion mechanism consistent with data available for the most metal-poor stars.

The star HE 1327−2326 (coordinates right ascension, RA = 13 h 30 m 06 s and declination $\delta = -23^\circ\ 41'\ 51''$ at Equinox 2000; apparent visual magnitude $V = 13.5$ mag) was found among 1777 bright ($10 < B < 14$) and apparently metal-poor objects with partly saturated spectra selected from the Hamburg/ESO objective-prism survey (HES)[7]. Its extreme metal-weakness was first appreciated in a medium-resolution ($\delta = 0.5$ nm) follow-up spectrum obtained in April 2003 at the 3.6 m telescope of the European Southern Observatory, Chile. In May and June 2004, observations with the High Dispersion Spectrograph[8] at the Subaru Telescope, Hawaii were taken. Figure 1 shows a portion of this spectrum and gives more details on the discovery.

An important difference between HE 0107−5240 and HE 1327−2326 is their evolutionary status. HE 0107−5240 is a giant and has evolved off the main-sequence and up the red giant branch. Consequently, internal mixing has possibly dredged up processed material (e.g. C, N) from the stellar interior to the surface and altered the abundances of this object. In contrast, HE 1327−2326 is relatively unevolved and located on either the main-sequence or the subgiant branch.

We use model atmosphere techniques and the assumption of local thermodynamical equilibrium (LTE) to perform our chemical abundance analysis with non-LTE corrections where available. There are no significant differences between the subgiant and the main-sequence solution. See Table 1 for more details on the analysis procedure and the derived abundances.

HE 1327−2326 sets a new record for the star with the lowest iron abundance: $[\mathrm{Fe/H}]_{\text{non-LTE}} = -5.4 \pm 0.2$ (where $[\mathrm{A/B}] = \log(N_A/N_B) - \log(N_A/N_B)_\odot$ for the number N of atoms of element A and B and $\odot$ refers to the Sun), derived from four detected weak Fe I lines and corrected for non-LTE. This low value corresponds to $1/250,000$ of the solar Fe value. To illustrate the nature of such extremely Fe-deficient stars, in Figure 2 we compare our abundances with those of HE 0107−52406 ($[\mathrm{Fe/H}]_{\text{non-LTE}} = -5.2$, refs. 1,6 and 9), the only other star known to have $[\mathrm{Fe/H}] < -4.0$. Both objects have very large overabundances of C and N relative to Fe. Although both stars also share a deficiency of Ca and Ti as well as Fe, the Mg and Al abundances relative to Fe in HE 1327−2326 are more than one order of magnitude higher than those of HE 0107−5240.

Surprisingly, we do not detect the Li I doublet at 670.7 nm in HE 1327−2326, although it is found in similarly unevolved metal-poor stars that permit observational determination of the primordial Li abundance and the associated baryon density of the Universe. Our upper limit for Li of A(Li)= 1.6 (where $\mathrm{A(Li)} = \log(N(\mathrm{Li})/N(\mathrm{H})) + 12.00$) is significantly lower than the primordial Li value of $\mathrm{A(Li)} = 2.62 \pm 0.05$, inferred from the baryon density estimated by the Wilkinson Microwave Anisotropy Probe together with standard Big Bang nucleosynthesis.[10] It is even below A(Li)= 2.0, found by Ryan et al.[11] at $[\mathrm{Fe/H}] = -3.5$. This apparent absence does not result from the evolutionary status of HE 1327−2326, because in more evolved metal-poor subgiants such as HD140283, Li has not been depleted. Li weakness occurs rarely in metal-poor

Figure 1: Comparison of high-resolution spectra of HE 1327−2326 with G64-12 and CS 22876-032. The latter is a double-lined spectroscopic binary. All three stars have similar effective temperature and gravity. In HE 1327−2326 note the absence of the FeI line at 393 nm together with the appearance of CH lines. Our best fit for the Ca II K ($\lambda = 393.4$ nm) and CH band abundances is plotted in red. Additional CH fits (in red) for our carbon abundance [C/Fe]= 4.1 ± 0.2 dex are shown as well. The inset shows our strongest detected Fe I line (0.64 pm equivalent width) at 386 nm in the Subaru data from which we derive $[\mathrm{Fe/H}]_{\text{non-LTE}} = -5.4 \pm 0.2$. From our medium-resolution spectrum we initially estimated [Fe/H]= −4.0 for HE 1327−2326 using the apparent strength of the Ca II K line index KP of Beers et al.[21] and an approximate colour. The high-resolution data revealed the presence of strong interstellar Ca II K which had not been resolved at the lower resolution. See the prominent feature blueward of the Ca II K line. The interstellar Ca is consistent with a colour excess of $E(B-V) = 0.08$ along the line-of-sight to HE 1327−2326. The presence of CH lines near the Ca II K line in HE 0107−5240 caused a similar problem in the initial recognition of its extreme metal-deficiency. These effects should be taken into account in future searches for more stars with similar heavy element deficiency. Our high-resolution (resolving power $R = \Delta\lambda/\lambda = 50,000$), high signal-to-noise ratio ($S/N = 160$ per pixel at 400 nm) data covers the wavelength range of 304 to 674 nm.

Table 1: Abundance ratios of HE 1327−2326. Using colour-effective temperature (T_{eff}) relations[24], we determine an effective temperature of $T_{\mathrm{eff}} = 6180 \pm 80\,\mathrm{K}$ from broad-band $UBVRI$ photometry obtained with the MAGNUM telescope[25], Hawaii, and JHK magnitudes taken from the Two Micron All Sky Survey[26]. To constrain the gravity ($\log g$), we use the proper motion[27] ($\mu = 0.073 \pm 0.006$ arcsec/yr) of HE 1327−2326 to set limits on its distance (assuming that the Galactic escape velocity is $500\,\mathrm{km\,s^{-1}}$ and larger than the transverse velocity). It follows that the absolute V magnitude is $M_V > 2.7$ mag which constrains the evolutionary status of the star and therefore $\log g$. Inspection of a 12-billion-year isochrone with [Fe/H] = −3.5 (the most metal-poor one available[28]) results in two solutions for the surface gravity $\log g$: 3.7 and 4.5 in cgs units. Owing to weak observational constraints on $\log g$, it is currently not possible to determine which of these solutions is correct. T_{eff} and $\log g$ are the input for two different plane-parallel LTE model atmospheres we use to derive the abundances for both gravity solutions; a MARCS model (Gustafsson, B. et al. 2005, manuscript in preparation) tailored for the chemical composition of HE 1327−2326, and a Kurucz model[29]. Both sets of abundances agree to within 0.1 dex. Using spectrum synthesis we determine the C and N abundances from CH and NH molecular bands and the upper limit for O from OH molecular bands in the ultraviolet spectral range. Apart from the molecular features, only 13 weak absorption lines are detected in spectral regions not affected by the wings of the Balmer lines and thus suitable for our abundance analysis. Solar abundances were taken from ref.30. Typical statistical $1\,\sigma$ errors in our abundances are 0.2 dex. Possible systematic errors are judged to be of the same order of magnitude. Non-LTE corrections are included where available[22]. For the calculations of the non-LTE abundance ratios, the non-LTE iron abundance has been used.

Element	[Element/Fe], A(Li), [Fe/H]	
	Subgiant	Dwarf
Li	< 1.6	< 1.6
C	4.1 ± 0.2	3.9 ± 0.2
N	4.5 ± 0.2	4.2 ± 0.2
O	< 4.0	< 3.7
Na (LTE)	2.4 ± 0.2	2.4 ± 0.2
Na (non-LTE)	2.0 ± 0.2	2.0 ± 0.2
Mg (LTE)	1.7 ± 0.2	1.7 ± 0.2
Mg (non-LTE)	1.6 ± 0.2	1.6 ± 0.2
Al (LTE)	1.3 ± 0.2	1.3 ± 0.2
Al (non-LTE)	1.7 ± 0.2	1.7 ± 0.2
Ca I	0.1 ± 0.2	0.1 ± 0.2
Ca II	0.9 ± 0.2	0.8 ± 0.2
Ti	0.6 ± 0.2	0.8 ± 0.2
Fe (LTE)	-5.6 ± 0.2	-5.7 ± 0.2
Fe (non-LTE)	-5.4 ± 0.2	-5.5 ± 0.2
Sr (LTE)	1.0 ± 0.2	1.2 ± 0.2
Sr (non-LTE)	1.1 ± 0.2	1.3 ± 0.2
Ba (LTE)	< 1.4	< 1.7
Ba (non-LTE)	< 1.4	< 1.7

stars near the main sequence turn-off: at effective temperature $T_{\rm eff} = 6200\,{\rm K}$ only 1 in ~ 20 shows this effect.[11] In HE 1327−2326, the weak lines show no evidence for rotational broadening and offer no support for the ultra-Li depleted rapid rotator model[12], which assumes membership of a binary system, or for rotationally induced mixing in general.[13] Other explanations might include gravitational settling[14] or diffusion, but these have not operated efficiently in other metal-deficient stars of similar temperature and gravity.

Another surprising result is the high Sr abundance (see Figure 2). Our observed lower limit for the Sr/Ba ratio ($[{\rm Sr/Ba}]_{\text{non-LTE}} > -0.4$) suggests that Sr was not produced in the main "slow" neutron-capture (s-) process occurring in asymptotic giant branch (AGB) stars, given that the typical ratio in Fe-deficient, C-rich and s-process enhanced stars is[15] $[{\rm Sr/Ba}]_{\text{non-LTE}} < -1.0$. The weak s-process occurring in formerly more massive stars ($M > 10\,M_{\odot}$ might yield Sr with little or no Ba, although theoretical calculations suggest that this process is inefficient at low metallicity.[16] Alternatively, the main "rapid" neutron-capture (r-) process might have produced the Sr, given that $[{\rm Sr/Ba}]_{\text{non-LTE}} > -0.4$ is consistent with the ratio observed in metal-poor, r-process enhanced stars, in which[17] $[{\rm Sr/Ba}]_{\text{non-LTE}} \sim -0.3$ (non-LTE corrections were applied as for HE 1327−2326). It is therefore possible that the Sr was formed in a type II supernova (SNII), currently believed to be a site of the main r-process, that expelled material from which HE 1327−2326 formed. Another possibility is the recently proposed process that might have provided light neutron-capture elements in the early Galaxy.[16] Although the site and details of this newly suggested process are not yet known, it might provide an explanation for the excesses of light neutron-capture elements, including Sr, seen in very metal-poor stars. To discriminate the contribution of such processes, further constraints on the Ba abundance, as well as further information on other neutron-capture elements, from higher quality data, are needed.

With its distinctive chemical composition, HE 1327−2326 is an ideal tool for "stellar archaeology" and a better understanding of the early enrichment history, and the first mass function of stars in the Universe. Although two stars, HE 1327−2326 and HE 0107−5240, are now known with $[{\rm Fe/H}] < -5.0$, none has been found in the range $-5 < [{\rm Fe/H}] < -4$. This is suggestive of an underlying, yet to be explored, fundamental physical mechanism in the formation of the first stellar objects[2] which may differ from that for stars more metal-rich than $[{\rm Fe/H}] = -4.0$.

HE 1327−2326 permits exploration of the many formation theories of the earliest stars proposed for HE 0107−5240. One idea is the pre-enrichment of the gas clouds from which the two stars formed by a first generation "faint" type-II supernova ($M \sim 25\,M_{\odot}$) experiencing mixing and fallback[3], or rotating, massive objects ($M \sim 200 - 300\,M_{\odot}$, ref.18) In this case, HE 1327−2326 would be an early Population II star, formed from gas enriched by one (or possibly a few) of the first SNII. In particular, the quantitative predictions of abundance patterns by updated models of "faint" SNII (N. Iwamoto, H. Umeda, N. Tominaga, K. Maeda, private communication) agree with the chemical abundance patterns of HE 1327−2326. The diversity of Mg/Fe ratio found in HE 1327−2326 and HE 0107−5240 is easily explained by the variety of mixing and fallback. A remaining problem is the Sr whose production is not yet included in these type-II supernova models.

Another idea is the accretion of heavy elements from the ISM onto first generation low-mass stars (Population III).[19,1,2] In this case, however, the high abundances of lighter elements

Figure 2: Abundance patterns of HE 1327−2326 (subgiant solution, filled circles) and HE 0107−5240 (open squares). Typical $1\,\sigma$ errors of 0.2 dex are shown in the plot. Upper limits are indicated by an arrow. We adopt the same non-LTE correction for both stars[22], which lead to the modification of the published abundances of HE 0107−5240. Consequently, we adopt $[\mathrm{Fe/H}]_{\text{non-LTE}} = -5.2$ (ref. 9) as the iron abundance of HE 0107−5240. These two most Fe-poor stars both have very large C enhancement relative to Fe by a factor of $\sim 5,000$ (HE 0107−5240) and $\sim 10,000$ (HE 1327−2326). N/Fe is $\sim 30,000$ times the solar value (considering the subgiant solution) in HE 1327−2326 whereas it is ~ 200 times the solar value in HE 0107−5240. The upper limit for the O abundance of HE 1327−2326 is $[\mathrm{O/Fe}] < 4.0$. Oxygen in HE 0107−5240 has recently been determined[23] to be $[\mathrm{O/Fe}] = 2.3$ which is of the same order as its [N/Fe] value. These enormous overabundances in CNO elements suggest that both stars belong to a group of objects sharing a common formation scenario. HE 1327−2326 and HE 0107−5240 have Ca/Fe and Ti/Fe abundance ratios which are enhanced by factors less than 10 compared to the Sun. The light element ratios Na/Fe, Mg/Fe and Al/Fe, as well as, surprisingly, Sr/Fe, are all enhanced by factors of ~ 10 to ~ 100 in HE 1327−2326. Of these four elements only Na and Mg are detected in HE 0107−5240 with element/Fe ratios close to the solar value. As for several other elements an upper limit for Ba has been measured in both stars. The Sr/Ba ratio is crucial to identify the origin for the Sr and other heavy elements.

must be explained by other processes. The unevolved status of HE 1327−2326, the scenario in which internal mixing processes lead to the dredge-up of processed material can be excluded. A remaining possibility is mass transfer from an AGB star within a binary system.[1,5] Mass transfer could naturally account for the Li depletion[20] found in HE 1327−2326. The high Sr abundance is problematic, along with the non-detection of Ba, which can not be explained by the s-process expected to occur in AGB stars. A crucial test for this scenario is to check the binarity of this object, for which long period radial velocity monitoring is required.

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