

A stellar relic from the early Milky Way

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The chemical composition of the most metal-deficient stars reflects the composition of the gas from which they formed. These old stars provide crucial clues to the star formation history and the synthesis of chemical elements in the early Universe. They are the local relics of epochs otherwise observable only at very high redshifts^{1,2}; if totally metal-free (“population III”) stars could be found, this would allow the direct study of the pristine gas from the Big Bang. Earlier searches for such stars found none with an iron abundance less than 1/10,000 that of the Sun^{3,4}, leading to the suggestion^{5,6} that low-mass stars could only form from clouds above a critical iron abundance. Here we report the discovery of a low-mass star with an iron abundance as low as 1/200,000 of the solar value. This discovery suggests that population III stars could still exist, that is, that the first generation of stars also contained long-lived low-mass objects. The previous failure to find them may be an observational selection effect.

The star HE 0107–5240, at coordinates right ascension R.A.(2000.0) = 01h 09m 29.1s and declination $\delta = -52^\circ 24' 34''$, is a giant star of the Galactic halo population with apparent magnitude $B = 15.86$. It was found during medium-

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resolution spectroscopic follow-up observations of candidate metal-poor stars selected from the Hamburg/ESO objective prism survey (HES)^{7,8}. This survey, which covers the entire southern high-galactic-latitude sky to an apparent magnitude limit of $B \approx 17.5$, extends the total survey volume for metal-poor stars in the Galaxy by almost one order of magnitude compared to the total volume explored by previous spectroscopic surveys.

A medium-resolution ($\delta\lambda \approx 0.2$ nm) spectrum of HE 0107–5240 was obtained by M.S.B. with the Siding Spring Observatory 2.3-m telescope on 12 November 2001. The Ca II K ($\lambda = 393.4$ nm) line was barely visible in that spectrum, indicating that the star was likely to be extremely metal deficient. Shortly thereafter, a high-resolution, high signal-to-noise ratio spectrum was obtained with the 8-m Unit Telescope 2 (UT2) of the Very Large Telescope at the European Southern Observatory (ESO), Paranal, Chile.

We derive an effective temperature $T_{\text{eff}} = 5100 \pm 150$ K for HE 0107–5240 by means of broad-band visual and infrared photometry. The absence of Fe II lines, through the Fe I/Fe II ionisation equilibrium, constrains the star to have a logarithmic surface gravity of $\log(g) > 2.0$ dex, while main-sequence gravities are excluded by the relative strengths of Balmer lines, and the strength of the Balmer jump seen in the medium-resolution spectrum. Hence we conclude that the star is located on the red giant branch. By interpolation in a 12-Gyr pre-helium-flash stellar evolutionary track⁹, we estimate the surface gravity of HE 0107–5240 to be $\log(g) = 2.2 \pm 0.3$, and its mass $M \approx 0.8M_{\odot}$. We derive $[\text{Fe}/\text{H}] = -5.3 \pm 0.2$ for HE 0107–5240, where $[A/X] = \log_{10}(N_A/N_X) - \log_{10}(N_A/N_X)_{\odot}$, and the subscript ‘ \odot ’ refers to the Sun. In the determination of the iron abundance, as well as the Fe I/Fe II ionisation equilibrium, we took into account deviations from local thermodynamical equilibrium (LTE) in the formation of iron lines in the atmosphere of the star, which led to a correction of +0.1 dex for the Fe I abundance. The quoted error in the iron abundance includes uncertainties in the derived model atmosphere parameters T_{eff} (resulting in $\delta[\text{Fe}/\text{H}] = \pm 0.20$ dex) and $\log(g)$

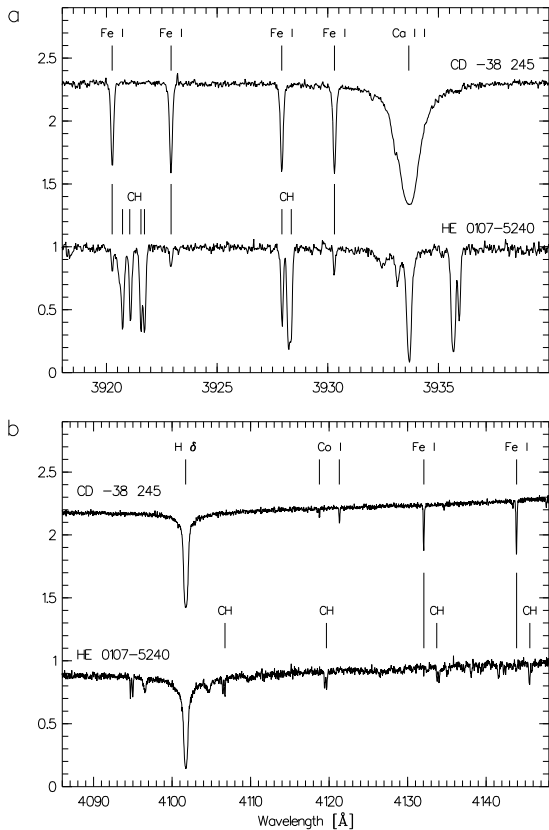


Figure 1: A portion of the spectrum of HE 0107–5240, shown compared to the spectrum of CD –38° 245, the previously most iron-poor giant star known. Both spectra were obtained with VLT-UT2, and the Ultraviolet-Visual Echelle Spectrograph (UVES). We note the strong molecular CH and C₂ lines and extremely weak lines of FeI in the spectrum of HE 0107–5240. The spectra used in our analysis have a resolution of $R = \lambda/\Delta\lambda = 40,000$, and a signal-to-noise ratio of more than 100 per pixel at $\lambda > 400.0$ nm. The covered wavelength ranges are 329.0–452.0 nm, 478.0–576.0 nm, and 583.0–681.0 nm.

($\delta[\text{Fe}/\text{H}] = \pm 0.02$ dex), the adopted oscillator strengths ($\delta[\text{Fe}/\text{H}] = \pm 0.1$ dex), and in the line-strength measurement uncertainties ($\delta[\text{Fe}/\text{H}] = \pm 0.07$ dex). An LTE analysis, conducted differentially with respect to CD –38° 245 (with $[\text{Fe}/\text{H}] = -3.98$, previously the most iron-deficient giant star known)¹, shows that HE 0107–5240 is 1.4 dex more iron-poor. This is in very good agreement with our non-differential LTE value of $[\text{Fe}/\text{H}] = -5.4$ for HE 0107–5240.

Extreme iron deficiencies have also been observed in some post-asymptotic giant branch (post-AGB) stars^{10,11}. However, extensive studies have revealed that their observed elemen-

tal abundances were altered substantially from their primordial compositions by selective dust depletion and subsequent radiation-driven gas-dust separation^{10,12}. The most extreme cases are HR 4049 and HD 52961, which have $[\text{Fe}/\text{H}] = -4.8$. Other elements, such as Ca and Mg, are depleted by a similar amount, while the abundances of elements such as C, N, O, and Zn are close to the solar values¹¹. For HE 0107–5240, on the other hand, we derive an upper limit for the Zn abundance that is significantly below solar ($[\text{Zn}/\text{H}] < -2.7$). We also note that these post-AGB stars occupy a stellar physical parameter space¹¹ that is not shared by HE 0107–5240, that is, $T_{\text{eff}} = 6,000\text{--}7,600$ K, $\log(g) = 0.5\text{--}1.2$. Furthermore, typically many lines in the spectra of post-AGB stars exhibit prominent emission features owing to a strong stellar wind, while other lines have a complex absorption structure resulting from the presence of circumstellar gas^{11,13}. Such features are not seen in the spectrum of HE 0107–5240. Finally, we note that infrared photometry of our star does not reveal any indications of an excess of infrared flux due to hot dust.

We conclude that HE 0107–5240 likely formed from a gas cloud with a metal abundance corresponding to $[\text{Fe}/\text{H}] \approx -5.3$. The abundance pattern of elements heavier than Mg can be well fit by the predicted elemental yields¹⁴ of a 20–25 M_{\odot} star that underwent a type II supernova explosion, indicating that the gas cloud from which HE 0107–5240 formed could have been enriched by such a supernova. (See Table 1.) Alternatively, HE 0107–5240 could have formed from a zero metallicity gas cloud, with its present metallicity being due to accretion of material during repeated passages through the Galactic disc¹⁵.

The large overabundances of C and N, and possibly Na, in HE 0107–5240 can be explained by either mass transfer from a previously more massive companion during its AGB phase, or else by self-enrichment. The mass-transfer scenario has been proposed as the likely explanation for the so-called metal-poor CH stars¹⁶. Recent model computations of the structure, evolution and nucleosynthesis of low-mass and intermediate-mass stars of zero or near-zero metallicity have shown^{17–19} that such stars undergo extensive mix-

ing episodes at or shortly after the helium-core flash, resulting in a dredge-up of helium burning and CNO-cycle processed material to their surfaces, especially carbon and nitrogen. The surface abundance ratios of CNO, Na, and Mg, predicted by Siess *et al.*¹⁹ for stars in the mass range $1\text{--}2M_{\odot}$, agree reasonably well with the abundances observed in HE 0107–5240, within the large uncertainties arising from the input physics adopted in the model calculations.

Our derived upper limits for Ba and Sr indicate that HE 0107–5240 is not strongly overabundant in neutron-capture elements. In this respect, our star is similar to the extremely metal-poor giant²⁰ CS 22957–27, a star with $[\text{Fe}/\text{H}] = -3.4$ and $[\text{C}/\text{Fe}] = +2.2$, as well as to the recently discovered class of mildly carbon-enhanced metal-poor stars that are underabundant in neutron-capture elements²¹. This abundance pattern implies that helium burning and some CNO burning may have occurred. However, if this scenario is correct, the observations suggest that the reactions involved have produced little ^{13}C , or that the ^{13}C produced has been consumed by proton captures. We note that if α captures on ^{13}C were dominant, neutrons would have been produced through the reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$, giving rise to s-process nucleosynthesis.

It was once believed that the lowest-metallicity objects to have formed in the Galaxy (at least those that survived until the present) were the halo globular clusters, such as M92, with $[\text{Fe}/\text{H}] = -2.5$, a factor of 300 times below the solar value. This belief was based on several assumptions, most importantly that star formation in the early Galaxy would have been strongly inhibited at low masses, owing to the difficulty of forming stars from nearly primordial gas without cooling channels arising from heavy elements such as iron. A number of early studies^{22,23} suggested that cooling from molecular species including hydrogen might allow low-mass star formation before the production of heavy metals significantly polluted the interstellar medium, but no examples of stars approaching such low metallicities as HE 0107–5240 were then known. This view received support from early objective-prism surveys³ that failed to detect significant numbers

Element	[X/Fe]
Li	< 5.3
C	4.0
N	2.3
Na	0.8
Mg	0.2
Ca	0.4
Ti	-0.4
Ni	-0.4
Zn	< 2.7
Sr	< -0.5
Ba	< 0.8
Eu	< 2.8

Table 1: Abundance ratios $[\text{X}/\text{Fe}]$ of HE 0107–5240 as derived from a high-resolution, high-S/N UVES spectrum. In our analysis, we used a custom plane-parallel model atmosphere with the most recent atomic and molecular opacity data. Typical errors in the logarithmic abundances, resulting from uncertainties in the stellar parameters and oscillator strengths, are 0.1–0.2 dex. Possible systematic errors are judged to be of the same order of magnitude. The abundances of C, N, and Ca have been derived from spectrum synthesis, using the C_2 band at $\lambda = 516.5$ nm, the CN band at $\lambda = 388.3$ nm (assuming a C abundance as listed above), and the Ca II H+K lines, respectively. We measure a carbon isotopic ratio of $^{12}\text{C}/^{13}\text{C} > 30$ from CH A-X lines.

of low-mass stars with $[\text{Fe}/\text{H}] < -2.5$. For the past two decades, more extensive surveys have pushed the low-metallicity limit to $[\text{Fe}/\text{H}] = -4.0$, that is, the iron abundance of CD $-38^{\circ}245$, but no lower⁴. On the basis of the numbers of metal-poor stars thus far identified in these surveys, which include some 1,000 stars with $[\text{Fe}/\text{H}] < -2.0$, a simple extrapolation of the distribution of metal abundances suggested that if stars with $[\text{Fe}/\text{H}] < -4.0$ existed in the Galaxy, at least a handful should have been found. The dwarf carbon star G 77–61 has been suggested to have²⁴ $[\text{Fe}/\text{H}] = -5.5$, if a logarithmic solar Fe abundance of 7.51 (on a scale where the logarithmic abundance of hydrogen is 12) is adopted, as we did for our analysis of HE 0107–5240. However, the analysis of the cool ($T_{\text{eff}} = 4,200$ K)²⁴ dwarf G 77–61 is much less certain than the analysis of HE 0107–5240, because the spectrum of the former is dominated by molecular bands of carbon that are much stronger than in HE 0107–5240. Clearly, the existence of

at least one example of a star with an iron abundance as low as $[\text{Fe}/\text{H}] = -5.3$ provides evidence that the limiting metallicity of halo stars may not yet have been reached.

This has implications for the nature of the first mass function (FMF) of early star formation. Although some studies^{5,6} have suggested that metal-poor gas clouds fragment into low-mass objects only above a certain critical metallicity, $Z_{\text{crit}} \approx 10^{-4} Z_{\odot}$ ($[\text{Fe}/\text{H}] = -4$), our discovery provides evidence in favor of other studies suggesting that the FMF included not only very massive stars but also lower-mass stars²⁵. The FMF may also have been bimodal²⁶ and may have included stars with masses around $1M_{\odot}$ as well as around $100M_{\odot}$. Other authors²⁷ have speculated on the possible presence of ancient (presumably extremely low metallicity) objects that could have formed before re-ionization of the early Universe. In this view, the ‘gap’ between the iron abundance of HE 0107–5240 and other extremely metal-poor stars may represent the period of reheating and re-ionization, when star formation was strongly suppressed owing to destruction of the molecular hydrogen that was needed for cooling. As an alternative, it remains possible that the $[\text{Fe}/\text{H}] = -4.0$ ‘limit’ is an artefact caused by the brighter magnitude limits of surveys that have been carried out up to now. Indeed, it may be no coincidence that the fainter magnitude limit of the HES allowed for the detection of HE 0107–5240 at a distance of about 11 kpc from the Sun, whereas most previous surveys have been limited to searches for extremely metal-poor stars within the inner halo of the Galaxy. Further tests of this hypothesis are currently targeting the faintest giants from the HES, which extend to 20 or more kpc from the Sun. If additional stars with iron abundances substantially lower than $[\text{Fe}/\text{H}] = -4.0$ are identified, these will provide important new tools with which, for example, we could directly compare observed elemental abundance patterns with the predicted yields of the first generation of supernova type II explosions, make a definitive measurement of the primordial lithium abundance (which strongly constrains ‘big bang’ nucleosynthesis)²⁸, and obtain tighter constraints on the nature of the FMF. If any examples of the so-called r-process-enhanced

stars are found with $[\text{Fe}/\text{H}] < -4.0$, we may be able to use nucleochronometry²⁹ to obtain a direct estimate of the epoch of first star formation in the Universe, possibly resulting in an improved lower limit for the age of the Universe.

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