A stellar relic from the early Milky Way

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The chemical composition of the most metal-deficient stars largely 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 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 HE0107−5240, at coordinates right ascension, RA (2000.0) = 01 h 09 m 29.1 s and declination $\delta = -52° 24' 34''$, is a giant star of the Galactic halo population with apparent magnitude $B = 15.86$. It was found during medium-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 HE0107−5240 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 $T_{\rm eff} = 5{,}100 \pm 150$ K for HE0107−5240 by means of broad-band visual and infrared photometry. The absence of Fe II lines, through the Fe I/Fe II ionization 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 track[9], we estimate the surface gravity of HE0107−5240 to be $\log(g) = 2.2 \pm 0.3$, and its mass $M \approx 0.8 M_\odot$. We derive $[{\rm Fe/H}] = -5.3 \pm 0.2$ for HE0107−5240, where $[{\rm A/X}] = \log_{10}(N_{\rm A}/N_{\rm X}) - \log_{10}(N_{\rm A}/N_{\rm X})_\odot$, and the subscript '$\odot$' refers to the Sun. In the determination of the iron abundance, as well as the Fe I/Fe II ionization 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 $T_{\rm eff}$ (resulting in $\delta[{\rm Fe/H}] = \pm 0.20$ dex) and $\log(g)$ ($\delta[{\rm Fe/H}] = \pm 0.02$ dex), the adopted oscillator strengths ($\delta[{\rm Fe/H}] = \pm 0.1$ dex), and in the line-strength measurement uncertainties ($\delta[{\rm Fe/H}] = \pm 0.07$ dex). An LTE analysis, conducted differentially with respect to CD−38° 245 (with $[{\rm Fe/H}] = -3.98$, previously the most iron-deficient giant star known)[1], shows that HE0107−5240 is 1.4 dex more iron-poor. This is in very good agreement with our non-differential LTE value of $[{\rm Fe/H}] = -5.4$ for HE0107−5240.

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 elemental 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 HR4049 and HD52961, which have $[{\rm Fe/H}] = -4.8$. 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 values[11]. For HE0107−5240, on the other hand, we derive an upper limit for the Zn abundance that is significantly below solar ($[{\rm Zn/H}] < -2.7$). We also note that these post-AGB stars occupy a stellar physical parameter space[11] that is not shared by HE0107−5240, that is, $T_{\rm eff} = 6{,}000$–$7{,}600$ K, $\log(g) = 0.5$–1.2. Furthermore, typically many lines in the spectra of post-AGB stars exhibit prominent emission lines 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 HE0107−5240. 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 HE0107−5240 probably formed from a gas cloud with a metal abundance corresponding to $[{\rm Fe/H}] \approx -5.3$. The abundance pattern of elements heavier than Mg can be well fitted by the predicted elemental yields[14] of a 20–25$M_\odot$ star that underwent a type II supernova explosion, indicating that the gas cloud from which HE0107−5240 formed could have been enriched by such a supernova. (See Table 1.) Alternatively, HE0107−5240 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 disk[15].

Table 1 **Elemental abundances for HE0107−5240**

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

Abundance ratios [X/Fe] of HE0107−5240 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 $^{12}C/^{13}C > 30$ from CH A–X lines.

The large overabundances of C and N, and possibly Na, in HE0107−5240 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 stars[16]. 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 mixing 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 1–2$M_\odot$, agree reasonably well with the abundances observed in HE0107−5240, within the large uncertainties arising from the input physics adopted in the model calculations.

Our derived upper limits for Ba and Sr indicate that HE0107−5240 is not strongly overabundant in neutron-capture elements. In this respect, our star is similar to the extremely metal-poor giant[20] CS 22957−27, a star with [Fe/H] = −3.4 and [C/Fe] = +2.2, as well as to the recently discovered class of mildly carbon-enhanced metal-poor stars that are underabundant in neutron-capture elements[21]. 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}C(α,n)^{16}O, giving rise to s-process nucleosynthesis.

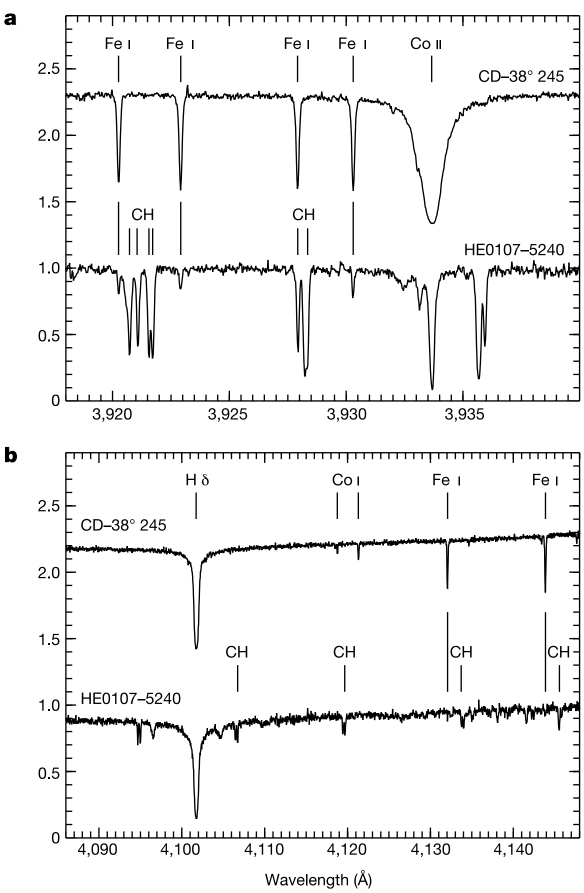

Figure 1 A portion of the spectrum of HE0107−5240, shown compared to the spectrum of CD−38° 245, the previously most iron-poor giant star known. Both spectra were obtained with VLT-UT2, and the Ultraviolet-Visual Echelle Spectrograph (UVES). We note the strong molecular CH and C_2 lines and extremely weak lines of Fe I in the spectrum of HE0107−5240. The spectra used in our analysis have a resolution of $R = \lambda/\Delta\lambda = 40{,}000$, and a signal-to-noise ratio (S/N) 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.

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 [Fe/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 HE0107−5240 were then known. This view received support from early objective-prism surveys[3] that failed to detect significant numbers of low-mass stars with [Fe/H] < −2.5. For the past two decades, more extensive surveys have pushed the low-metallicity limit to [Fe/H] = −4.0, that is, the iron abundance of CD−38° 245, but no lower[4]. On the basis of the numbers of metal-poor stars thus far identified in these surveys, which include some 1,000 stars with [Fe/H] < −2.0, a simple extrapolation of the distribution of metal abundances suggested that if stars with [Fe/H] < −4.0 existed in the Galaxy, at least a handful should have been found. The dwarf carbon star G77−61 has been suggested to have[24] [Fe/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 HE0107−5240. However, the analysis of the cool ($T_{\rm eff}$ = 4,200 K)[24] dwarf G77−61 is much less certain than the analysis of HE0107−5240, because the spectrum of the former is dominated by molecular bands of carbon that are much stronger than in HE0107−5240. Clearly, the existence of at least one example of a star with an iron abundance as low as [Fe/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, $Z_{\rm crit} \approx 10^{-4} Z_\odot$ ([Fe/H] = −4), our discovery provides evidence in favour of other studies suggesting that the FMF included not only very massive stars but also lower-mass stars[25]. The FMF may also have been bimodal[26] and may have included stars with masses around 1$M_\odot$ as well as around 100$M_\odot$. Other authors[27] 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 HE0107−5240 and other extremely metal-poor stars may represent the period of reheating and re-ionization, when star formation was strongly suppressed owing to the destruction of the molecular hydrogen that was needed for cooling. As an alternative, it remains possible that the [Fe/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 HE0107−5240 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 [Fe/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 type II supernova 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 [Fe/H] < -4.0, we may be able to use nucleochronometry[29] 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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Measurement of the conductance of a hydrogen molecule

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Recent years have shown steady progress towards molecular electronics[1,2], in which molecules form basic components such as switches[3–5], diodes[6] and electronic mixers[7]. Often, a scanning tunnelling microscope is used to address an individual molecule, although this arrangement does not provide long-term stability. Therefore, metal–molecule–metal links using break-junction devices[8–10] have also been explored; however, it is difficult to establish unambiguously that a single molecule forms the contact[11]. Here we show that a single hydrogen molecule can form a stable bridge between platinum electrodes. In contrast to results for organic molecules, the bridge has a nearly perfect conductance of one quantum unit, carried by a single channel. The hydrogen bridge represents a simple test system in which to understand fundamental transport properties of single-molecule devices.

Here we use a mechanically controllable break junction[12,13] at low temperatures (4.2 K) to produce pure metallic contacts of atomic size. Figure 1 inset shows a typical conductance curve for a clean Pt contact that was recorded while gradually decreasing the contact size by increasing the piezovoltage (black curve). (We concentrate here on results obtained for Pt wires, but conductance histograms suggest similar behaviour for Pd.) The conductance is expressed in terms of the quantum unit, $G_0 = 2e^2/h$, with e the electron charge and h Planck's constant. The jumps in conductance are the result of sudden atomic rearrangements in response to the applied strain[14]. After the conductance has dropped to a value corresponding to a single atom—which for Pt is in the range 1.2–$2.3G_0$—the contact suddenly breaks. In order to extract the common features of these conductance curves, we collect the data of a large series of conductance curves into a conductance histogram. The main panel in Fig. 1 shows such a histogram for Pt contacts (black). It is dominated by a large peak at 1.4–$1.8G_0$, which represents the range of conductance values for contacts having a single atom in cross-section (for a recent review, see ref. 15). The histogram drops sharply to zero for lower conductance values, as is typically found for Pt contacts in the absence of adsorbates and impurities.

The character of the conductance curves and the shape of the resulting histogram change markedly when a small quantity of hydrogen gas is admitted to the vacuum vessel (grey curves). The critical amount is difficult to establish, as most hydrogen is expected to condense on the walls of the container (the equilibrium H_2 gas pressure at a temperature of 4.2 K is about 10^{-6} mbar), but the results are not very sensitive to the precise quantity. The peak at the position characteristic for Pt disappears, and a large weight is added in the entire range below that value. On top of this background a distinct peak close to $1G_0$ is found, which grows for larger currents through the contact, while the background is suppressed. For still larger bias voltages, above 200 mV, we recover the histogram for clean Pt. The low-conductance tail and the peak at $1G_0$ reappear

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