X-shooter Finds an Extremely Primitive Star

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Low-mass extremely metal-poor (EMP) stars hold the fossil record of the chemical composition of the early phases of the Universe in their atmospheres. Chemical analysis of such objects provides important constraints on these early phases. EMP stars are rather rare objects: to dig them out, large amounts of data have to be considered. We have analysed stars from the Sloan Digital Sky Survey using an automatic procedure and selected a sample of good candidate EMP stars, which we observed with the spectrographs X-shooter and UVES. We could confirm the low metallicity of our sample of stars, and we succeeded in finding a record metal-poor star.

According to the standard Big Bang theory, the primordial matter of the Universe was made of hydrogen, helium and traces of lithium. Almost all of the other (heavier) elements (metals), including those forming our bodies, were subsequently created in quiescent and explosive stellar nucleosynthesis. The first stars were formed by the condensation of clouds from the matter of the primordial Big Bang: the absence of metals in these condensing clouds makes their cooling more difficult, favouring the formation of high-mass stars. Such stars evolved rapidly, and disappeared in explosions (supernovae) that enriched the surrounding matter in metals. If low-mass stars (less than 0.8 $M_{\odot}$) had also been formed (e.g., Clark et al., 2011; Greif et al., 2011), they would still remain on the main sequence today, and, owing to their very slow and moderate evolution, their atmospheres would still display their initial abundances: the Big Bang abundances. No such star has been observed as yet.

The first stars, formed from primordial matter, composed only of material produced in the Big Bang nucleosynthesis, played an essential role in the first epochs of the Universe: the most massive ones produced the re-ionisation of the Universe and synthesised the first metals. The chemical composition of their descendants brings unique information about these first stars. The most ancient stars of the Milky Way galaxy are the direct descendants of the first stars and contain a fossil record of the first epochs of the Universe. For four decades, astronomers have been looking for stars with chemical compositions as close as possible to the primordial material, in order to understand the very first step of the build-up of the chemical elements, and also to establish whether stars with this primordial composition still exist. It is therefore essential to find and analyse these primitive stars.

In the Milky Way galaxy, a few low-mass, extremely metal-poor stars have been found: here the primordial matter has been slightly enriched in metals by the ejecta of the first stars. Among them, three stars are known to be extremely deficient in iron (less than 1/10 000 of the solar abundance): HE 0107-5840 (Christlieb et al., 2002), HE 1327-2326 (Frebel et al., 2005)and HE 0557-4840 (Norris et al., 2007). These stars are usually designated by the name of the first author of the discovery paper, thus: Christlieb's star, Frebel's star, and Norris's star. But in these stars the extreme deficiency in iron is *not* matched by a similar deficiency in lighter elements such as carbon and oxygen, which are enhanced by two to three orders of magnitude. It has been then suggested that the formation of such low-mass, iron-poor stars has been made possible only by the presence of some extra C and O (Bromm & Loeb, 2003). A sample of only three stars, however, is too small to draw any firm conclusions and needs to be extended.

A good selection

To look for very rare objects, a first selection has been performed on a very large sample of low-resolution spectra from the Sloan Digital Sky Survey (SDSS; York et al., 2000). A selection method has been built and applied to the SDSS spectra. The selection, described in Caffau et al. (2011c), is based on an automatic abundance determination, where the stellar parameters are derived from the SDSS photometry, while the metallicity is derived from line profile fitting of the metallic features present in the spectra. The most metal-poor objects ([Fe/H] < −2.5) are inspected by eye. We applied this selection to SDSS, Data Release 7, resulting in a sample of very metal-poor candidates.

We had the opportunity to observe twenty of the most promising candidates at higher resolution. Fifteen were observed with the UVES spectrograph and six with the X-shooter spectrograph mounted at the Cassegrain focus of the Kueyen VLT Unit Telescope (Vernet et al., 2011), taking advantage of its high efficiency, and using the Franco–Italian guaranteed observing time (GTO). One of these stars, whose 2D spectrum taken with X-shooter is represented in Figure 1, seemed particularly interesting, since the only metallic lines clearly detectable were the strong Ca II K lines at 3933 Å and 3968 Å. Owing to the peculiarity of this interesting star, additional telescope time was requested from the ESO Director General's discretionary time to study the star's light at higher resolution with

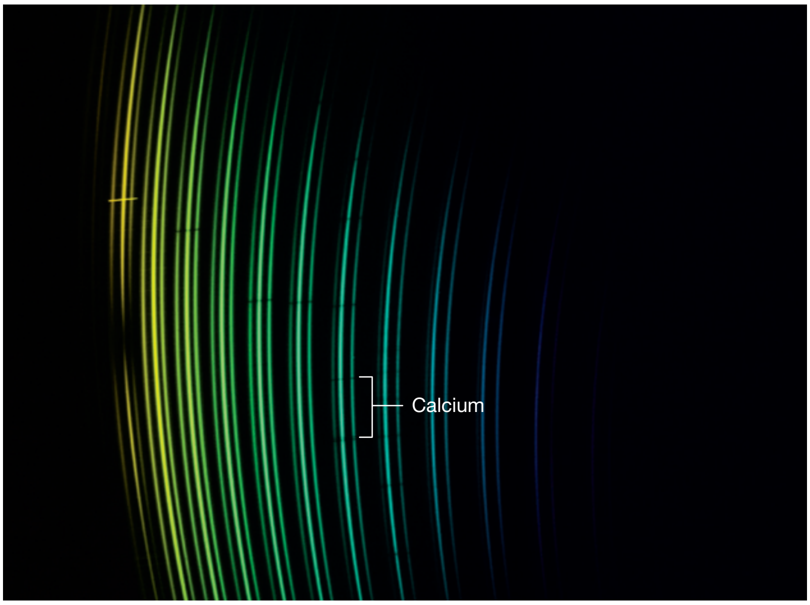

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Figure 1. A 2D echellogram of the spectrum of SDSS J102915+172927 taken with X-shooter in the UVB range.

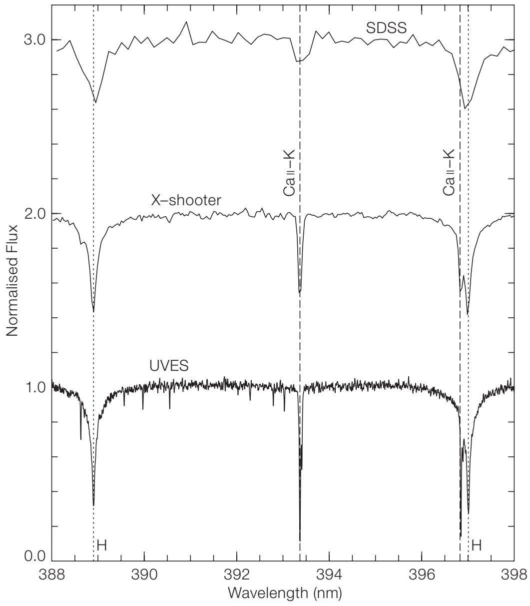

Figure 2. The SDSS, X-shooter and UVES spectra (from top to bottom) of SDSS J102915+172927 in the region of the Ca II K and H lines.

the UVES spectrograph to try to find other (faint) metallic lines in the spectrum. Figure 2 shows the three available spectra (SDSS, UVES, and X-shooter).

The high resolution analysis confirms the metallicity determination derived from the SDSS spectra. All the stars happen to be extremely metal-poor ([Fe/H] < –3). For the stars above [Fe/H] > –3.5, there is a good agreement between the metallicity derived from low and high resolution spectra, within 0.5 dex. At lower metallicity, the disagreement is much larger, about 1 dex, but the low metallicity derived from SDSS spectra is still confirmed (see Figure 3).

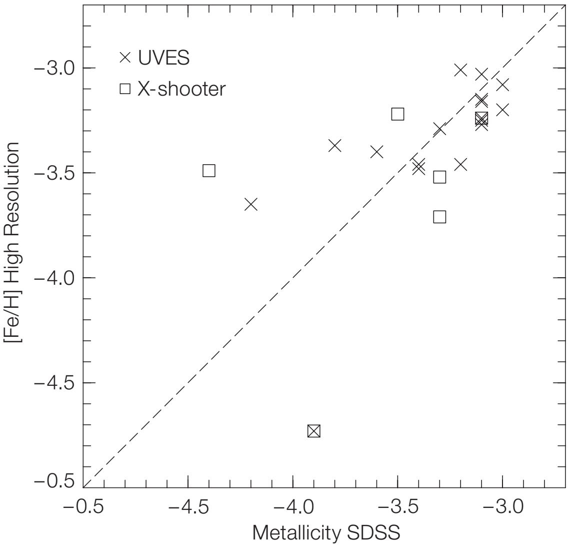

Figure 3. The metallicity derived from SDSS spectra for the sample of extremely metal-poor stars is here compared to the [Fe/H] values derived from higher resolution spectra (UVES data shown by crosses and X-shooter by squares).

An extremely metal-poor star indeed!

The star SDSS J102915+172927 in the constellation of Leo is faint, with a *g*-band magnitude of 16.92, a *g*–*z* colour of 0.59 mag (0.53 after reddening correction) and is compatible with the colour of a turn-off star. Its distance is about 1.3 kiloparsecs (kpc). The stellar orbit is elongated, so the star belongs to the halo. This star has a mass smaller than that of the Sun and therefore a slow evolution rate, so that its photosphere still displays the unaltered chemical composition of the cloud of interstellar matter from which it formed: a cloud made of the primordial matter of the Big Bang, slightly enriched by the ejecta of the first massive stars. The star is old, probably more than 13 billion years, following several arguments: such stars belong to old populations; comparable stars are directly found to be old by radiochronometry; and the matter of the Galaxy has been submitted to efficient mixing processes so that the formation of these stars had to take place before the rapid enrichment in metals by the ejecta of numerous supernovae.

The star turns out to be extremely metal-poor: it is less iron-poor than two of the three well-known stars quoted before, but it has not been affected by an inflow of C and N, so it is also C-poor. Oxygen is not measured in the star, but since the star is not enhanced in C and N, we assume that it is not O-rich. Metal-poor stars show a constant ratio [O/Fe] of about 0.4 dex, irrespective of their metallicity. We assume for this star [O/Fe] = +0.6, adding +0.2 dex to the expected value, to be conservative.

Stars have generally been classified taking into account only their iron abundance (the most easily measured abundance). We are compelled to use here a more general parameter, the metallicity, Z (used in stellar structure theory). Z is the mass fraction of elements heavier than helium (i.e., the mass fraction of metals). The metallicity of the Sun is around $Z = 0.0153$ (Caffau et al., 2011a). The metallicity of SDSS J102915+172927 is less than 6.9×10^{-7} (i.e., about 4×10^{-5} times the Solar metallicity). The metallicities of the other three well-known EMP stars are larger than 10^{-5}. The metallicity of SDSS J102915+172927 is much lower, and hence nearer to the Big Bang metallicity (see Caffau et al., 2011b).

How was this star formed?

A large and massive cloud condenses easily and rapidly into a massive star, but it is difficult for a small cloud to form a low-mass star rapidly, so that a slowly condensing cloud of primordial matter is at risk of being contaminated by the ejecta of massive supernovae (SNe). The main difficulty is to find efficient mechanisms that can cool the gas cloud during its collapse. Without such a mechanism the thermal energy of a small cloud is sufficient to halt its collapse. Metals are efficient cooling agents, and thus, because of an observed absence of stars with a metallicity $Z < 1.5 \times 10^{-5}$, it has been suggested that low-mass stars cannot form from the primitive interstellar medium until it has been significantly enriched in metals.

Different theories exist as to the physical mechanism providing the cooling. Bromm & Loeb (2003) postulate the need for a minimum amount of carbon and oxygen that can provide efficient cooling through the fine structure transitions of ionised carbon and neutral oxygen. Another theory postulates that dust grains are instead responsible for the cooling and make it possible for a cloud of large mass to fragment and form low-mass stars (Schneider et al., 2011). The issue is far from being settled and competing theories exist, predicting that low-mass stars can form even without any metals to guarantee the cooling (Clark et al., 2011; Greif et al., 2011).

Element	A(X) 3D	[X/H] 3D	[X/Fe] 3D	[X/H] 1D	Number of lines	A(X)$_\odot$
Li	≤ 1.1				1	1.03
C	≤ 4.2	≤ −4.3	≤ +0.7	≤ −3.8	*G*-band	8.50
N	≤ 3.1	≤ −4.8	≤ +0.2	≤ −4.1	*NH*-band	7.86
Mg I	2.95	−4.59 ± 0.10	+0.40	−4.68 ± 0.08	4	7.54
Si I	3.25	−4.27 ± 0.10	+0.72	−4.27 ± 0.10	1	7.52
Ca I	1.53	−4.80 ± 0.10	+0.19	−4.72 ± 0.10	1	6.33
Ca II	1.48	−4.85 ± 0.11	+0.14	−4.71 ± 0.11	3	6.33
Ti II	0.14	−4.76 ± 0.11	+0.23	−4.75 ± 0.11	6	4.90
Fe I	2.53	−4.99 ± 0.12	+0.00	−4.73 ± 0.13	44	7.52
Ni I	1.35	−4.88 ± 0.11	+0.11	−4.55 ± 0.14	10	6.23
Sr II	≤ −2.28	≤ −5.2	≤ −0.21	≤ −5.1	1	2.92

Table 1. The chemical abundances of SDSS J102915+172927 (A(X) for 12 + log (A/H) and [X/H] or [X/Fe] for log abundances relative to Solar) derived from the UVES spectrum.

The abundances in SDSS J102915+172927 (Table 1) and the assumption [O/Fe] = +0.6 strongly support the idea that, at least in some cases, low-mass stars can also form at lower carbon and oxygen abundances than the current estimates for the critical values in the theory of Bromm & Loeb (2003). The metallicity of SDSS J102915+172927 is compatible with the critical metallicity predicted in the case of dust cooling (Schneider et al., 2011). It is clearly interesting to see if stars of much lower metallicity can be found, and would thereby yield support to theories that do not predict any critical metallicity for the formation of low-mass stars.

Where has the lithium gone?

Another very interesting finding is the lack of lithium in SDSS J102915+172927. Such an old star should have a composition similar to that of the Universe shortly after the Big Bang, thus including traces of lithium, with a few more metals. But we found that the proportion of lithium in the star was at least fifty times less than expected in the material produced by the Big Bang. The warm, unevolved old stars in the Galactic halo display a constant abundance of lithium — the Spite Plateau (Spite & Spite, 1982). The upper limit for lithium in SDSS J102915+172927 is well below the value of the Spite plateau. The reasons for this lack of lithium are not understood: it could be the extension of the "meltdown" described by Sbordone et al. (2010). Lithium is also depleted in the most iron-poor star HE 1327–2326 (Frebel et al., 2005). What is certain is that, in order to destroy the lithium produced in the Big Bang, the material we are observing in these stars must have been processed at temperatures exceeding two million degrees.

How many of these stars are there?

Stars similar to SDSS J1029151+172927 are probably not very rare. Between 5 and 50 stars with similarly low, or even lower, metallicity than SDSS J1029151+172927 are expected to be found among the candidates accessible from the VLT, and many more in the whole SDSS sample. The high efficiency of X-shooter, and of its integral field unit mode, holds the promise that a large number of candidates can be scrutinised in a limited amount of time.

We are still involved in the Italian GTO for X-shooter, and we hope to continue observing the best candidates during during the next few semesters. We have also applied for more observation time with both X-shooter and UVES, to increase the sample of extremely metal-poor stars.

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