244. Searching for ultra-metal-poor stars

METAL-POOR STARS are those with a very low abundance of 'metals' (in astronomy, this refers to elements heavier than H and He), significantly lower than in stars like the Sun. They were amongst the earliest generations of stars in our Galaxy, formed from the gas of the early Universe, before heavier elements were more widely created through successive generations of stars.

They are amongst the oldest (Population II) stars of our Galaxy, found in the halo and in globular clusters, as well as in the oldest disk populations. They are important for understanding the origin and creation of elements heavier than H and He, inferring the properties of the very first stars which must have formed in the early Universe (termed Population III), and tracing the chemical evolution of galaxies more generally.

Stars classed as 'metal-poor' are generally taken to be those with $[Fe/H] \lesssim -2$, where [Fe/H] represents the log number ratio of a star's iron to hydrogen abundance, compared with the same ratio for the Sun. More generally, $[X/H] = \log_{10}(N_X/N_H)_\star - \log_{10}(N_X/N_H)_\odot$ for any element X.

'Extremely metal-poor' are widely taken as stars with $[Fe/H] < -3$, and 'ultra-metal-poor' as $[Fe/H] < -4$.

Ultra-metal-poor stars are rare. Only some 50 are known (Bonifacio et al., 2025), and dedicated programs have been required to find them (e.g. Beers et al., 1992; Roederer et al., 2014). Recent searches include the Pristine, S–PLUS, J–PLUS, and DECam–MAGIC surveys.

WITH METALLICITY increasing with time as a result of nucleosynthesis, stars with the very lowest metallicities are believed to be the direct descendants of Population III stars. And their chemical abundances therefore encode the yields of the first metal-free supernovae (e.g. Ishigaki et al., 2018). Remarkably, their chemistry can often be well-modelled by assuming that all their metals were produced in just a single supernova event.

To underline the importance of these relatively nearby stars, even with the very high-redshift ($z \sim 10$) data from JWST, measured galaxy metallicities rarely extend below $[Fe/H] \sim -2$ (e.g. Curti et al., 2024).

GALACTIC METAL-POOR STARS are typically enhanced in carbon relative to iron, $[C/Fe] \gtrsim +0.7$, with the fraction of carbon-enhanced metal-poor (CEMP) stars *increasing* with decreasing metallicity (e.g. Norris et al., 1997; Aoki et al., 2007). Indeed, nearly all stars with $[Fe/H] \leq -4.5$ are carbon enhanced. Even the most Fe-deficient star known, SMSS J031300.36–670839.3, with $[Fe/H] < -7$, has $[C/Fe] > +4.5$ (Keller et al., 2014).

The first ultra-metal-poor star with a low C abundance was SDSS J102915+172927 (Caffau et al., 2011), with $[Fe/H] = -4.73$ and an upper limit $[C/Fe] < +0.91$ (Caffau et al., 2024). A few others have been found since, both in the Milky Way (e.g. Starkenburg et al., 2018; Placco et al., 2021), and in its satellites Sculptor (Skúladóttir et al., 2021), and the LMC (Chiti et al., 2024).

The chemical diversity of these ultra-metal-poor stars points to a range in properties of the first stars which preceded them (Heger & Woosley, 2010).

DETAILS of the formation of Population III stars remain uncertain. Early studies suggested that the absence of metals would result in the absence of an efficient cooling mechanism, resulting in masses $> 100 M_\odot$. Later models, incorporating supersonic turbulence, fragmentation, and radiation feedback, predict stars with masses $1 - 1000 M_\odot$ (e.g. Lagae et al., 2023).

Some properties of these first stars can be inferred from the (ultra-)metal-poor second-generation (Pop II). Simulations suggest that stars with $[Fe/H] < -3$ could be formed from a cloud enriched by a *single* supernova (Tominaga et al., 2007; Nomoto et al., 2013; Keller et al., 2014; Frebel & Norris, 2015). Hartwig et al. (2018) found that 40% of stars with $-6 < [Fe/H] < -4$ can be modelled as having been enriched by only one such event.

Comparison of the chemical composition of ultra-metal-poor stars with theoretical yields of first-star core-collapse supernovae can constrain the explosion properties and initial mass function of the first stars. These suggest that the progenitors of Pop II stars have masses in the range $10 - 100 M_\odot$ (Tominaga et al., 2014; Placco et al., 2015; Ishigaki et al., 2018; Bonifacio et al., 2025).

WITH THIS BACKGROUND, let me turn to how Gaia is contributing – both by advancing our knowledge of previously-known ultra-metal-poor stars, as well as a remarkable new discovery from the Gaia data.

I referred above to the first known ultra-metal-poor star with a very low carbon abundance, SDSS J102915+172927. This was identified by Caffau et al. (2011) from VLT–XShooter and UVES spectroscopy, although with some uncertainty about its spectral type. Whether it is on the main sequence, or on the sub-giant branch (as suggested by MacDonald et al., 2013), has profound consequences for the origin of its very low metallicity.

Bonifacio et al. (2018) used the Gaia DR2 parallax, $\varpi = 0.734 \pm 0.073$ mas, to place it securely on the main sequence. Its low carbon content then puts it below the critical abundance required for metal-line cooling, confirming the need for dust cooling and fragmentation to explain its formation (Caffau et al., 2012; Schneider et al., 2012; Klessen et al., 2012).

Several studies subsequently made use of the Gaia DR2 and DR3 astrometric and photometric data (including the revised DR3 parallax, $\varpi = 0.6482 \pm 0.0598$ mas) as inputs to models of its atmosphere ($T_{\rm eff}$ and $\log g$), and its evolutionary status. These provided evidence for both rotation and mixing (Lombardo et al., 2021), and suggest a mass $0.65 M_\odot$ (Caffau et al., 2024).

Studies of its kinematics, using Gaia DR2 and subsequently DR3, indicate that SDSS J102915+172927 is on an almost circular prograde orbit around the Galaxy ($e = 0.09 \pm 0.02$), and confined to within 2.36 ± 0.60 kpc of the Galactic plane (Sestito et al., 2019; Di Matteo et al., 2020; Dovgal et al., 2024; Caffau et al., 2024).

THESE DETAILS ARE IMPORTANT because it is still unclear whether these rare ultra-metal-poor stars originate in protogalactic fragments that formed the early Milky Way, or in low-mass satellites accreted later, or whether they formed *in situ* in the Galactic plane. As summarised by Sestito et al. (2019): *'The combination of the exquisite Gaia data and surveys of the very metal-poor sky opens an exciting era in which we can trace the very early formation of the Milky Way'.*

THE RARITY AND RELEVANCE of ultra-metal-poor stars makes the discovery of others particularly noteworthy, and it is perhaps superficially surprising that Gaia can contribute in this way. But a new discovery was recently announced, independently, both from Gaia DR3, as GDR3 526285 (Limberg et al., 2025), and from SDSS, as SDSS J0715–7334 (Ji et al., 2025).

Ji et al. (2025) identified it from an analysis of the SDSS-III low-resolution BOSS spectra, with high-resolution follow-up using Magellan–MIKE. Of particular interest in the context of Gaia-based results, Limberg et al. (2025) were able to identify it from the Gaia DR3 XP (Gaia's low-resolution BP/RP spectra) catalogue of candidate very metal poor stars, [Fe/H] < −2, constructed by Yao et al. (2024). They specifically focused on the Yao et al. 'golden sample' of 70 000 red giant-branch stars, and with follow-up high-resolution spectroscopy also using the Magellan–MIKE spectrograph.

Both discovery papers underline its extremely low iron abundance, of [Fe/H] = −4.3 to −4.8 respectively, along with the relatively low upper limit on its carbon abundance, [C/Fe] < −0.2 or < +0.50 respectively, compared with other stars at a similar [Fe/H]. Again, based on this low [C/H] abundance is the conclusion that it likely formed from gas cooling via dust grains, rather than by fine-structure line-cooling.

Its kinematics, from Gaia DR3, suggests that it was either dynamically perturbed by the infall of the Magellanic system, or was formerly a member of the Magellanic Clouds which was later stripped by the Milky Way (Limberg et al., 2025). Its detailed chemical composition implies a supernova progenitor with initial mass $30 M_\odot$ (Ji et al., 2025).

Ji et al. (2025) emphasise that this latest discovery is a factor 10 more metal-poor than the most metal-poor high-redshift galaxies found by the James Webb Space Telescope, some of which have been suggested as being possibly metal-free.

As for the future discoveries that might be made by Gaia, Limberg et al. (2025) conclude that *'Our results showcase the potential of an all-sky search for low-metallicity targets with Gaia XP, and confirm that the methodology described here is a useful 'treasure map' for finding additional ultra-metal-poor stars'.*

OTHER SEARCHES and analyses for these ultra-metal-poor stars are benefiting from Gaia, with much more to say on the physics of the pre-cursor Pop III stars, and their location and provenance within our Galaxy.

These include: • the ESO Large Program, 'First Stars' (Bonifacio et al., 2009), where their kinematics and orbital properties have shown that some probably belong to the thick disk, partially heated to halo kinematics, with others being members of the accreted Gaia Sausage–Enceladus stream (Di Matteo et al., 2020); • as part of the candidate selection from the S-PLUS survey (Almeida-Fernandes, 2023; Perottoni et al., 2024); • as distances for 111 000 very metal-poor candidates from the LAMOST DR9 survey, including 702 extremely metal-poor stars, [Fe/H] < −3.0, and 30 ultra-metal-poor stars, [Fe/H] < −4.0 (Hou et al., 2024); • as further candidates based on the Gaia DR3 XP spectra, including a strontium-rich ultra-metal-poor star that belongs to the ancient so-called Atari disk component (Mardini et al., 2024); and • to assist candidate selection in the DECam–MAGIC survey (Placco et al., 2025).