253. The oldest stars

The best estimate of the age of the Universe is generally taken to be that based on precision measurements of the microwave background radiation by the Planck satellite. This points to an age of 13.787 ± 0.020 billion years, i.e. with a formal uncertainty of just 20 Myr (Aghanim et al., 2020). More 'local' measurements of the Universe's distance scale and expansion rate give a slightly larger value of the associated Hubble constant, and a slightly younger age for the Universe. According to current ΛCDM cosmology, therefore, even the very oldest stars should not exceed this maximum age.

Methods used to estimate stellar ages include those based on gyrochronology, and on lithium depletion. Estimates for the oldest stars rely primarily on isochrone fitting in the Hertzsprung–Russell diagram, asteroseismology (from the H/He ratio), or nucleocosmochronology (based on the radioactive decay of U and Th).

Age estimation through isochrone fitting is complicated by the fact that stars can appear very similar over billions of years, and an old star can look similar to a young star with high metal content.

More specific and robust age indicators are given by the main-sequence turnoff region of the Hertzsprung–Russell diagram (where stars begin to move away from the main sequence), and by the nearly-horizontal subgiant branch, the transition region from the main sequence to the red giant branch (marked by core hydrogen depletion and the onset of core helium burning).

I discussed some early Gaia results on the oldest known stars in essay 69 (25 April 2022), including specific mention of the metal-poor (Pop II) subgiant HD 140283, informally referred to as Methuselah.

While long considered as problematically old (e.g. Burbidge & Burbidge, 1956), continued interest is compounded by its inclusion as one of 34 FGK-type benchmark stars selected as Gaia's 'pillars of calibration', important for stellar models due to its proximity (61.47 ± 0.10 pc), brightness (V = 7.2), low reddening, and low metallicity, [Fe/H] = –2.3 dex (Jofré et al., 2014; Karovicova et al., 2020). But age estimates continue to be plagued by effects such as metallicity and convection.

Pre-Gaia ages of HD 140283 have put it as: older than 14 Gyr (VandenBerg, 2000); 14.46 ± 0.31 Gyr from HST (Bond et al., 2013); 13.49 ± 0.47 Gyr (Schönrich & Bergemann, 2014, Table 2); 14.27 ± 0.38 Gyr (VandenBerg et al., 2014); 13.7 ± 0.7 Gyr (Creevey et al., 2015); and 12.5–14.9 Gyr (Joyce & Chaboyer, 2018). But as noted by Sahlholdt et al. (2019), *'its position in the HR diagram is so close to the 14 Gyr isochrone that it would take only a small change in the observed parameters, or in the isochrones, to move it below the age of the Universe.'*

Indeed, more recent estimates appear to be less in conflict, with $\tau = 12 \pm 0.5$ Gyr based on the MESA evolutionary models given by Tang & Joyce (2021), and $\tau = 12.3$ Gyr based on the Liège Stellar Evolution code, tailored abundances, and the star's Gaia DR3 parallax, $\varpi = 16.26 \pm 0.026$ mas, by Guillaume et al. (2024).

But the latest TESS-based asteroseismic analysis still yields 14.2 ± 0.4 Gyr (Lundkvist et al., 2025), although, as the authors state, an age nonetheless *'in agreement with the upper limit set by the age of the Universe within 1σ'.*

While Methuselah is perhaps the most celebrated problem case, several others are of comparable age. Two from cosmochronology are the r-process enhanced very metal-poor 2MASS J22132050–5137385, at 13.6±2.6 Gyr (Roederer et al., 2024), and the ultra-metal-poor BD +17° 3248, at 13.8 ± 0.4 Gyr (Cowan et al., 2002). For the thin disk 2MASS J18082002–5104378, models based on the Dartmouth code give 13.535 ± 0.002 Gyr (Schlaufman et al., 2018; Dovgal et al., 2024).

In a wider study of the ages of the oldest Galactic stars and globular clusters, white dwarfs, and the ancient ultra-faint galaxies and dwarf spheroidals in the Local Group, Cimatti & Moresco (2023) concluded that *'the most ancient stars in the present-day Universe are significantly older than 13 Gyr, but with uncertainties (dominated by systematic errors) from 0.5 to $\gtrsim 1$ Gyr'.*

Accurate ages are, of course, also important for disentangling the formation history of the Milky Way, including the time of formation of the thin and thick disks, and of its various accreted halo streams.

A TRUE CONFLICT between the ages of these individual stars, and the age of the Universe, is probably unlikely. But definitive conclusions are hampered by the small number of suitable diagnostic stars, metallicities based on inhomogeneous spectroscopy, with ages derived from different methods, and drawing on different isochronal models. But recent Gaia studies of much larger samples is providing some further insight.

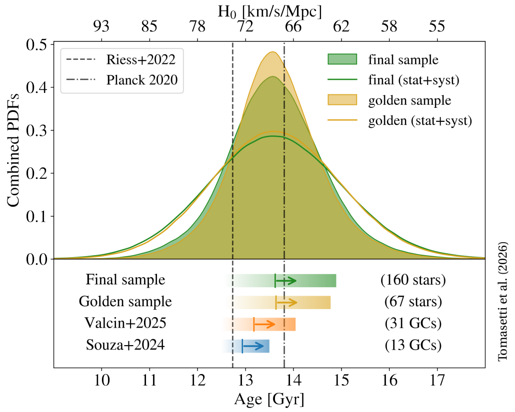
The starting point here is the Gaia DR3-based catalogue of accurate and homogeneous atmospheric parameters and abundances for 886 080 stars observed with Gaia's Radial Velocity Spectrograph (RVS). Guiglion et al. (2024) developed a convolutional neural network that combined the RVS spectra, photometry (G, G_{BP}, G_{RP}), parallaxes, and XP (BP/RP) coefficients to derive atmospheric parameters ($T_{\rm eff}$, $\log g$), as well as overall ([M/H]) and detailed ([Fe/H] and [α/M]) abundances. A major result from their work was a characterisation of the [α/M]–[M/H] bimodality, stretching from the Milky Way's inner regions to its outer parts.

This catalogue was used by Nepal et al. (2024) to select a subsample of 565 606 stars with 6D phase space information (positions and velocities) and high-quality stellar parameters, of which 8500 have $[{\rm Fe/H}] < -1$. Further restricted to 200 000 main sequence turn-off and subgiant branch stars (whose relevance for age estimation is noted above), they computed distances and ages with a mean precision of 1% and 12% respectively, using the `StarHorse` code[1].

Amongst their results, they confirmed the existence of metal-poor stars in thin-disk orbits[2]. The majority are very old (> 10 Gyr), and more than 50% have ages > 13 Gyr. The oldest thin disk component extends across a wide range of metallicities, from metal-poor to super-solar stars. They concluded that the thin disk formed less than 1 Gyr after the Big Bang, and continuously built up in an inside-out manner, with the metal-poor stars in disk orbits reported by previous studies belonging to this old thin disk, and with a fraction heated to thick disk velocities by a massive merger event such as the Gaia Sausage–Enceladus infall, GSE (essay 197).

A RECENT STUDY BY Tomasetti et al. (2026) extends efforts to formalise cosmological constraints provided by bulk age estimates for stars (e.g. Jimenez et al., 2019; Boylan-Kolchin & Weisz, 2021) and globular clusters (e.g. Tomasetti et al., 2025; Valcin et al., 2026).

Again, they start with the catalogue of Nepal et al. (2024), now restricted to 202 384 stars with precise parallaxes (<1%) and extinctions (<0.2 mag), and composed of just 160 high-quality main-sequence turnoff and subgiant branch stars, based on their position in the Kiel ($\log g$ versus $T_{\rm eff}$) diagram. But in contrast to the ages estimated by Nepal et al. (2024), where they were constrained by a cosmological prior of 13.73 Gyr, ages derived by Tomasetti et al. (2026) were estimated without any imposed upper bound, instead permitting the full range of the isochrone models, between 0.025–20 Gyr.



The figure shows the age distribution for their final sample of 160 stars, and their more restricted 'golden' sample of 67 stars. The distributions including the systematic component of the error are shown with solid lines in the same colours. The upper axis shows the corresponding H_0 value, assuming a formation redshift $z = 20$. In the lower panel, the age ranges and their means are compared with the oldest (>12.5 Gyr) globular clusters from Valcin et al. (2026), and the oldest bulge globular clusters from Souza et al. (2024).

The age distribution of their final sample peaks at $13.6 \pm 1.0({\rm stat}) \pm 1.4({\rm syst})$ Gyr. Assuming a maximum formation redshift for these stars of $z = 20$, corresponding to a delay of about 0.2 Gyr, they obtained a lower bound on the age of the Universe of $13.8 \pm 1.0({\rm stat}) \pm 1.4({\rm syst})$ Gyr. At the 90% confidence level, 70 stars favour a lower bound of 13 Gyr, while none exceeds 14.1 Gyr. For the upper envelope to fall below 13 Gyr, a shift of nearly the full systematic term would be required.

They note that their work presents the first statistically significant use of individual stellar ages as cosmic clocks, and represents a new independent approach for cosmological studies. Future Gaia data releases, they conclude, will enable even larger and more precise stellar samples, further strengthening these constraints.

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[1] `StarHorse`, originally developed in the context of RAVE, SEGUE and APOGEE (Santiago et al., 2016; Queiroz et al., 2018), is being widely used to find the (Bayesian) posterior probability over a grid of stellar evolutionary models, distances, and extinctions, given a set of observations plus a number of priors, such as the initial mass function, density laws for the thin disk, thick disk, bulge, and halo, as well as broad metallicity and age priors.

[2] Until recently, very metal-poor stars were expected to trace the halo, debris from past galaxy-scale mergers, and the metal-weak thick disk. I refer to their introduction (§1) for further background to this interesting topic, itself being much advanced by Gaia (e.g. Sestito et al., 2019; Sestito et al., 2020; Carollo et al., 2023; Fernández-Alvar et al., 2024).