69. HD 140283: as old as Methuselah?

UNTIL THE RELEASE of the Hipparcos Catalogue in 1997, a quarter of a century ago, there existed an unsettling paradox regarding the age of the Universe.

From its expansion, its age had been estimated at around 11 Gyr. But some stars within it had ages, derived from their luminosities, and based on evolutionary models, of around 15 Gyr. Clearly something was very wrong for science to be telling us that some of the objects in the Universe were older than the Universe itself.

FROM THE new Hipparcos distances of various nearby Cepheids, Feast & Catchpole (1997) argued that the Large Magellanic Cloud Cepheids were 10% further than previously estimated, and thus brighter.

They concluded that the overall distance scale had to be revised upwards by the same amount, with the implication that globular clusters were more distant than previously thought, that their luminosities were therefore larger, and that their 'turn-off point' (an important distance indicator for much older objects) implied younger ages than previously thought.

Their analysis pushed the age of the Universe up a little, to around 12 Gyr, and brought the oldest stellar ages down to about 11 Gyr. With this consistency better established, astronomers could breath more easily that two foundations of their science—cosmology and stellar evolution—were not, after all, incompatible.

It's not often that scientists get to resolve such a paradox, to wipe a couple of billion years off the face of a cosmic timepiece, or to add a billion years, give or take, to the age of the Universe. And I recall an excited Michael Feast being rushed by taxi from a meeting of the Royal Astronomical Society in London to an interview for BBC radio's *Science in Action* to explain these results to a wider public.

TODAY, THIS AGE TENSION has largely eased, and stellar ages determined from high-accuracy astrometric distances and spectroscopy, combined with state-of-the-art computer-based evolutionary models, generally cap their ages to less than the 13.7 billion years or so that is believed to have elapsed since the Big Bang.

LET ME RECALL here that there are two rather direct measurements, using somewhat distinct approaches, that are considered to provide the most definitive estimates of the age of the Universe today.

One, intimately tied to the 'early Universe' estimates of the Hubble constant (essay #44), is based on precision measurements of the microwave background radiation. This observable relic of the early Universe, most recently and most accurately measured by the Planck satellite, indicates an age of 13.787 ± 0.020 billion years, that is, with a formal uncertainty of a mere 20 million years (Aghanim et al. 2020).

This is estimated in the context of the Lambda–CDM model, where the Universe is assumed to contain normal (baryonic) matter, cold dark matter, radiation (both photons and neutrinos), and a cosmological constant.

The other estimate of its age is based on observations of the 'local' distance scale and expansion rate, which suggest a slightly larger value of the Hubble constant and, correspondingly, a slightly younger age for the Universe. This is both the case for distance measurements based on the younger (Population I) Cepheids (Riess et al. 2018), as well as on the older (Population II) globular clusters (Freedman et al. 2019).

THE ESTIMATE of 13.787 ± 0.020 billion years is considered to be consistent with any of the *lower limits* on its age dictated by the oldest objects within it.

For example, one such constraint comes from the measured temperatures of the coolest white dwarfs. After exhausting their nuclear fuel, white dwarfs simply cool down, albeit very gradually, as they age. The temperature of the coolest white dwarfs, and detailed models of their cooling, over cosmological timescales, must provide a lower limit on the actual age of the Universe.

Another constraint is given by the dimmest 'turnoff point' of main sequence stars in clusters. Low-mass stars spend longer on the main sequence (during their hydrogen-fusion stage) than higher mass stars, such that the lowest-mass stars that have evolved away from the main sequence set another, independent, minimum value for the age of the Universe.

But a small number of individual stars, among the oldest known to date, continue to raise their heads above this impregnable 'age parapet'. Some of these, at several thousand light-years distance, are members of our Galaxy's distant and ancient central bulge population, with estimated ages of around 13.2 Gyr.

HD 164922 is amongst the oldest, but a particular oddity, being a metal-rich main-sequence star at a distance of just 22 pc, but with an estimated age of around 13.4 billion years. It is also one of the most ancient planet-hosting stars known in the Milky Way.

A handful of others, members of our Galaxy's halo population, but which happen to be passing through our solar neighbourhood, are more problematic. Some are sufficiently close, within a few hundred parsecs, that they are particularly well measured.

One of the oldest, at 300 pc distance, is BD +17° 3248, an ultra-metal-poor Population II star. Based on its thorium and uranium abundances, its cosmochronological age is estimated at 13.8 Gyr, but with an uncertainty of about 0.4 Gyr, large enough to still be interpreted as younger than the age of the Universe (Cowan et al. 2002).

Of great interest in this context is HD 140283, an extremely metal-deficient and high-velocity subgiant in the solar neighbourhood. It occupies a location in the Hertzsprung–Russell diagram where absolute magnitude is most sensitive to stellar age.

Currently, one of the latest and best estimate of its age, at 13.7 ± 0.7 Gyr, places it amongst the very oldest known stars in our Galaxy, and in *potential* conflict with the accepted age of the Universe (Creevey et al. 2015). Accordingly, the star has become informally known as Methuselah (the idiom *'As old as Methuselah'*, meaning extremely old, is based on the biblical character, the grandfather of Noah, who died at the age of 969!).

Today, in the era of very large surveys covering millions of stars, placing them in a detailed evolutionary context depends on the accurate knowledge of their fundamental physical parameters (notably effective temperature, surface gravity, metallicity, and radius). This, in turn, relies on stellar models which are tested and refined against a sample of 'benchmark stars', determined independently. Interest in HD 140283 has been compounded by its selection as one of the 34 FGK-type benchmark stars selected as the 'pillars of calibration' for Gaia (Jofré et al., 2014; Karovicova et al., 2020).

Before proceeding, let me emphasise the important difference in science, and so crucial in astrometry, between the terms 'accuracy' and 'precision'. An example is perhaps sufficient. If my height were quoted as 2.35 ± 0.01 m (or 7 ft 8.5 ± 0.5 inches in our quaint imperial system), it is clearly claimed to be a very *precise* measurement, but it is evidently not at all *accurate*.

The true *precision* of any scientific measurement may be very difficult if not impossible to quantify with rigour. Any estimates of the precision can be affected by both random and (unknown) systematic errors, and always have to be viewed with due caution.

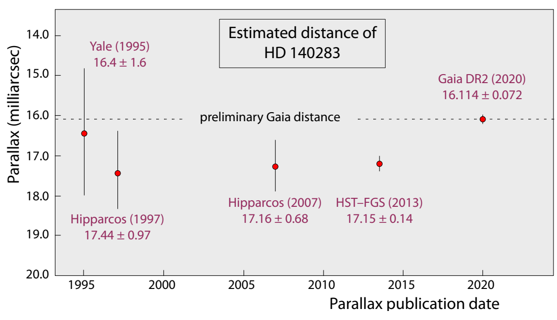
Thus if the age of Methuselah (13.7 ± 0.7 Gyr) is actually 13.0 Gyr (-1σ), we could relax. If it's 13.7 Gyr, it might be surprising, but perhaps still plausible. But if it's 14.4 Gyr ($+1\sigma$), well, Houston, we have a problem!

Interest in HD 140283, from the point of view of its metal deficiency and therefore its age, dates back at least to the work of Burbage & Burbage (1956). By 2000, evolutionary models which included observed enhancements in the α-elements, provided 'strong evidence' in favour of an age older than 14 Gyr (Vandenberg, 2000).

A decade later, Bond et al. (2013) used a parallax from the Hubble Space Telescope Fine Guidance System, of 17.15 ± 0.14 milli-arcsec, *'five times more precise than that from Hipparcos'* (17.16 ± 0.68). They included the effects of He diffusion and enhanced O abundance, to infer an age of 14.46 ± 0.31 Gyr, where this specified error includes *only* the parallax uncertainty.

Further high-quality spectra, used to derive the surface abundances of O, Fe, Mg, Si, and Ca, resulted in a Universe-busting age of 14.27 ± 0.38 Gyr, again with the error including only the parallax uncertainty (Vandenberg et al. 2014). More recent estimates appear less in conflict (Joyce & Chaboyer, 2018; Tang & Joyce, 2021).

As of April 2022, I have not seen an age estimate for Methuselah derived using the Gaia DR2 parallax. And I will not embarrass myself by attempting to derive one.



Today, most astronomers would probably place their bets on the microwave background providing the most secure estimate of the age of the Universe, with any apparent conflict with stellar ages pointing to errors in the measured properties of the star, or to inadequacies in the theoretical models used to infer their ages.

But a secure conflict could point to important omissions in the theory of stellar evolution, or even to errors in our understanding of cosmology.

Future Gaia data releases, with improved parallaxes, will be an important contribution to this debate.