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## 40. The distance of Omega Centauri

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**G**LOBULAR CLUSTERS are tightly bound spherical groups of up to a million or more stars. In contrast to the younger open clusters, which are found mainly in the disk, globular clusters are amongst the oldest populations, contain many more stars, and are more representative of the overall Galaxy population, occurring in the disk, in the bulge, and most prominently in the halo.

There are more than 150 globular clusters known in our own Milky Way, some 20% within a few kpc of its centre, and others extending out to distances of 30–40 kpc. The nearest, M4, is at about 2.2 kpc. Most galaxies of sufficient mass in the Local Group and beyond have their own systems of globular clusters.

Ages of the oldest are comparable to that of the Universe itself, as derived from its expansion rate, suggesting that at least some were formed early in its formation. Others appear to be remnants of the Galaxy's early accretion phase, captured from smaller galaxies during mergers or collisions. And although they represent a negligible fraction of the light and mass of the stellar halo, they are important tracers of our Galaxy's age and dynamics.

**T**HE PROPERTIES of even the nearest globular clusters are such that Hipparcos could make no direct contribution to determining their distances or ages: they lie well beyond the horizon of its parallax measurements, even their brightest stars are too faint, and the average sky density of Hipparcos targets, around 2.5 per square degree, would in any case imply coverage of only one or two cluster stars – even if they had been accessible.

But Hipparcos made important *indirect* contributions to their distances and ages. The distances, and therefore luminosities, of certain nearby stars could be measured and calibrated. Then if these stellar types are also found in globular clusters, their apparent luminosities can be inferred, and used to estimate their distances.

At the same time, globular cluster distances fix the luminosities of stars on the cluster's main sequence, and hence the cluster's age from main-sequence fitting or, more effectively, the main-sequence 'turn-off point' from theoretical models of stellar evolution.

Around 1994, some estimates of the Hubble constant, including those from HST observations of Cepheids out to the Virgo cluster, indicated a value as high as  $H_0 = 80 \pm 17 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , and a resulting Universe expansion age of 8 Gyr. By 2001, further observations gave a revised  $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , and an expansion age of around 12 Gyr (Freedman et al., 2001).

Before the Hipparcos results in 1997, an awkward problem was the 'age paradox': the ages of the oldest globular clusters were estimated to be around 15 Gyr, or even older in the case of NGC 6541.

The disturbing implication for cosmology was that some globular cluster ages appeared to exceed the 'expansion age' of the Universe. Something was wrong.

**A** POSSIBLE SOLUTION to the paradox came from Hipparcos parallaxes for the nearest Cepheids (Feast & Catchpole, 1997). The inference that the Large Magellanic Cloud Cepheids were 10% further than previously estimated, and thus brighter, led to the conclusion that the globular clusters were more distant than previously thought, that their luminosities were larger, and that their ages were younger than previously thought.

The Hipparcos contribution to the ages of globular clusters rested on the observation of nearby subdwarfs, i.e. metal-poor halo stars which happen to be passing close to the Sun at this time. Since they also occur in globular clusters, careful luminosity calibration as a function of metallicity allows them to be used in globular cluster distance determinations through main-sequence fitting.

Independent distance estimates can also be made using the calibrated luminosities of RR Lyrae variables, since these very luminous stars also occur in both the field and in globular clusters. However, even the nearest RR Lyrae are at the limits of the Hipparcos parallaxes.

Whichever way teams tried to tackle the problem, major advances in determining globular cluster distances, ages, and indeed dynamics would have to wait for the arrival of direct trigonometric parallaxes able to reach distances of several *thousands* of parsecs.

OMEGA CENTAURI ( $\omega$  Cen, NGC 5139) is a globular cluster in the constellation of Centaurus, first identified as non-stellar by Edmond Halley in 1677, and one of the few such systems visible to the naked eye.

At a distance of about 5200 pc, it is the largest, most massive globular cluster in the Milky Way. It contains some 10 million stars, with a total mass of 4 million solar masses.

With a diameter of 50 pc, it appears almost as large as the full Moon, and it is thought to have originated as the core remnant of a disrupted dwarf galaxy.

But it is too distant, too crowded, and just too faint, for any of its stars to have been observed by Hipparcos.

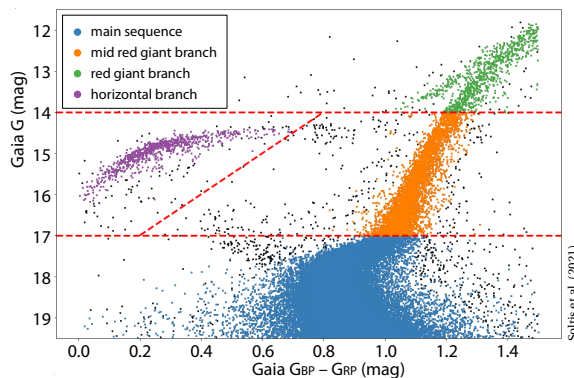
G AIA IS NOW transforming our understanding of this important stellar system. As Soltis et al. (2021) stated: *‘The recent Gaia Early Data Release 3 opens a new chapter in the measurement of parallaxes, placing the precise and accurate determination of the distances to nearby Galactic globular clusters within reach. None may be more prized than that of  $\omega$  Cen... A precise determination of its distance will characterise the luminosity of a broad sample of stellar types.’*

An important feature of the Hertzsprung–Russell diagram (or colour–magnitude diagram) seen in globular clusters is the ‘tip of the red giant branch’. This is the point of maximum brightness for red giant branch stars, and this tip originates from the sudden start of helium fusion in low-mass stars. After this ‘helium flash’, stars quickly expand and dim, resulting in a rapid decline in numbers at magnitudes brighter than the tip.

Once calibrated, it provides an important distance indicator for evolved stellar populations that can be used to reach the galaxy hosts of Type Ia supernovae, and so influence determination of the Hubble constant.

Because the tip of the red giant branch is not the identity of some individual star, but rather a feature of the entire globular cluster population, its luminosity has not been easy to determine in the past. This is partly because of the impossibility, before Gaia, of determining the individual parallaxes of such distant objects. But also because, since bright red giants are relatively rare, few clusters contain enough stars to reasonably define the position of this ‘tip’.

In practice,  $\omega$  Cen provides the best opportunity in the Milky Way, in part because it is ‘relatively’ nearby, but also because it contains nearly 200 stars within a magnitude of the tip, enough for a rather good definition.



Colour–magnitude diagram of 66 467 members of  $\omega$  Cen.

The numbers of stars available with Gaia is spectacular. Soltis et al. (2021) selected 178 548 from EDR3 within 45 arcmin of the cluster centre. They estimated a mean cluster proper motion of  $\mu_\alpha = -3.25 \mu\text{as}$ ,  $\mu_\delta = -6.76 \mu\text{as}$ , in good agreement with the value found for DR2 (Baumgardt et al. 2019).

Selecting stars participating in this common space motion then resulted in 108 054 candidate members. Further restriction according to their location in the colour–magnitude diagram resulted in 66 467 members with good Gaia astrometry and 2-colour photometry.

Their resulting mean parallax of  $\omega$  Cen is  $0.191 \pm 0.001 \text{ mas}$ , corresponding to a distance of  $5236 \pm 28 \text{ pc}$ , and in good agreement, for example, with the classical photometric distance of 5.2 kpc from Harris (1996).

WHAT DOES this mean for cosmological distance calibrations based on the tip of the red giant branch? Soltis et al. (2021) estimate that its  $I$ -band absolute magnitude is  $M_I = -3.97 \pm 0.06 \text{ mag}$ . This is slightly fainter, by 0.07 mag, than the calibration used in recent determinations of the Hubble constant (Freedman et al. 2019).

This change raises the value of  $H_0$  by 3.2%, so yielding a Hubble constant from the SN Ia distance ladder, based on this ‘tip’, of  $72.1 \pm 2.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

This is in good agreement with other local measures, including those from Cepheids. But it is significantly larger than that predicted by the Planck mission’s cosmic microwave background data used to calibrate  $\Lambda$ CDM models (Verde et al., 2019). The ‘age paradox’ may have disappeared, but this ‘Hubble Tension’ remains.

THE DETERMINATION of the parallax of  $\omega$  Cen represents a new milestone of distance measurements in astronomy.

But while the focus here has been on the cluster’s distance, Gaia has also already thrown much new light on various properties of  $\omega$  Cen not touched on here, including the cluster’s three-dimensional structure and depth; its orbit around the Galaxy; and the tidal stellar streams torn off the cluster as it orbits the Milky Way.