188. The tip of the red giant branch

SOME IMPORTANT CONTRIBUTIONS are being made by Gaia in furthering the use of the 'tip of the red giant branch' as a robust distance indicator. These sorts of new insights are becoming ever more crucial in the context of the ongoing 'Hubble tension' debate.

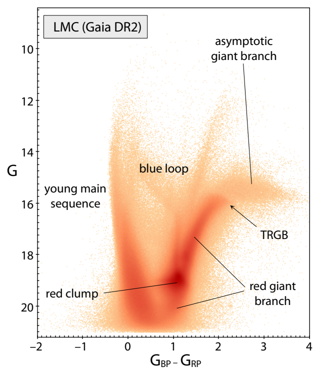
VARIOUS STAGES OF stellar evolution are characterised by well-defined luminosities. This has led to the construction of 'distance ladders' which go far beyond the reach of direct trigonometric parallaxes, and which allow distances to be estimated across our Galaxy, and into the Local Group of galaxies and beyond. Several potential 'standard candles' have been identified over recent decades, amongst them the RR Lyrae, Cepheid and Mira variables, and Type 1a supernovae.

Today, Cepheids lead efforts to calibrate the extragalactic distance scale (essay 122). But it is the discrepancy in the values of H_0 characterising the local ('late Universe') cosmic expansion, inferred from the combined HST and Gaia EDR3 measurements of Cepheids, $H_0 = 73.2 \pm 1.3$ (Riess et al., 2021), compared to that inferred in the 'early Universe' from the Planck satellite measurements of the Cosmic Microwave Background, $H_0 = 67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Aghanim et al., 2020), that sits at the heart of the 'Hubble tension' (essay 44).

Both values are very precise, and both are also considered to be very *accurate*, such that the disagreement, although small, is considered statistically significant.

THE 'tip of the red giant branch' (TRGB) is arguably becoming *the* other leading distance indicator. Unlike the Cepheid scale, which only applies to (Pop I) systems with recent or ongoing star formation, the TRGB method can be used wherever metal-poor red giant branch stars are sufficiently abundant to allow its location to be defined precisely (Beaton et al., 2018).

It provides distance indicators for evolved populations, and can reach the galaxy hosts of SN Type Ia (e.g. M101, M106, NGC 1448, IC 1613), and so can contribute to determining the Hubble constant (e.g. Beaton et al., 2019; Hoyt et al., 2021; Jang et al., 2021; Hoyt, 2023).



The Gaia DR2-based G versus $G_{\mathrm{BP}} - G_{\mathrm{RP}}$ colour–magnitude diagram for the central region (8.°8 radius) of the Large Magellanic Cloud (Clementini et al., 2020). It shows the TRGB location, along with the various stellar populations described by Luri et al. (2021).

Sakai (1999) traces the method to the realisation by Baade (1944) that the brightest resolved red stars in M31 and two companion ellipticals all had the same brightness and colour. Sandage (1971) later proposed that the brightest are at the tip of the first-ascent red giant branch. Here low-mass stars, evolving up the red giant branch, abruptly halt their increasing luminosity at the moment of He-ignition within their core, resulting in a sharp discontinuity in the star's evolutionary track.

Iben & Renzini (1983) showed that the bolometric luminosity at this core He 'flash' for low-mass stars varies by only ~0.1 mag over ages of 2–15 Gyr, and for metallicities most relevant for Galactic globular clusters, $-2.2 \le [\mathrm{Fe/H}] \le -0.7$. More recent models are given by Serenelli et al. (2017), Saltas & Tognelli (2022), and others. A considerable and growing body of observational work continues to confirm the method's potential.

The 'tip' manifests itself as a discontinuity in the population's luminosity function, or colour–magnitude diagram. In the Gaia data it can be seen, for example, as a prominent feature of the G versus $G_{\mathrm{BP}} - G_{\mathrm{RP}}$ colour–magnitude diagram for the central region of the Large Magellanic Cloud (e.g. Luri et al., 2021; Fig. 2). Quantitative methods to estimate the tip's location include edge-detection (Sobel) filters to measure the first derivative of the RGB luminosity function (Lee et al., 1993; Freedman et al., 2019; Scolnic et al., 2023; Anderson et al., 2024).

DETERMINING H_0 using the TRGB then involves determining absolute distances to galaxies that host SN Ia events, but which are also close enough to have their distances measured (whether by TRGB or Cepheids), then using the SN Ia luminosities to infer distances for a sample of galaxies far enough into the Hubble flow that their peculiar velocities are a small fraction of the cosmological recessional velocities.

The Carnegie–Chicago Hubble Program (CCHP) bases its current determination of H_0 on a sample of 10 galaxies over distances 7 Mpc (M101) to 20 Mpc (NGC 1316), which together embrace 11 supernovae from the Carnegie Supernova Project (Krisciunas et al., 2017). HST observations (typically using the F814W filter) establish the TRGB location in the I-band.

The final critical step is to establish the absolute zero-point of the TRGB colour–magnitude diagram using some more fundamental distance measure. The latest CCHP determination uses a distance modulus of 18.477 mag for the LMC based on 20 detached eclipsing binaries (Pietrzyński et al., 2019), to yield an I-band TRGB absolute magnitude of $M = -4.049$ mag. A similar value is found using the Megamaser-anchored distance to NGC 4258 (Jang et al., 2021).

The latest CCHP value, $H_0 = 69.8 \pm 0.8$ (± 1.1% stat) $\pm$ 1.7 (± 2.4% sys) km s^{-1} Mpc^{-1}, appears compatible with both Cepheid and Planck values (Freedman et al., 2019; Freedman, 2021). But the recent determination by Scolnic et al. (2023), anchored to NGC 4258, gives $H_0 = 73.22 \pm 2.06$ km s^{-1} Mpc^{-1}, favouring the Cepheid value.

Freedman et al. (2019) note that their *'ultimate goal for the absolute calibration is the geometric parallax measurements for Milky Way red giant branch stars being obtained by Gaia'*, although they were still waiting for a more robust estimate of the Gaia parallax zero point.

I will not go deeper into this topic, which includes effects of age, metallicity, and extinction, but refer the reader to recent more in-depth reviews (Freedman, 2021; Freedman & Madore, 2023; Lee, 2024).

ONE OF THE MAIN WAYS that Gaia is contributing is by determining the TRGB absolute magnitude using geometrical parallaxes of Milky Way stars. Working with Gaia DR2, Mould et al. (2019) showed that the high Galactic latitude colour–magnitude diagram, drawn from our Galaxy's thick disk and inner halo, is consistent with the CCHP calibrations of the TRGB.

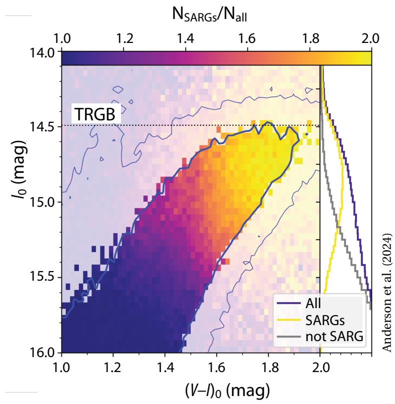
Soltis et al. (2021), in their wider Gaia EDR3 study of the Milky Way globular cluster ω Cen (essay 40), emphasised its merits for anchoring the TRGB calibration: the direct use of trigonometric parallaxes, well-calibrated extinction, and with nearly 200 stars within a magnitude of the tip. They estimated an I-band TRGB magnitude $M_I = -3.97 \pm 0.06$ mag, fainter by 0.07 mag than that used by Freedman et al. (2019), and yielding $H_0 = 72.1 \pm 2.0$ km s^{-1} Mpc^{-1}, closer to the Cepheid value.

Li et al. (2022) used a maximum likelihood method to calibrate the brightness of the TRGB using Gaia EDR3 parallaxes of Milky Way field giants at high Galactic latitude, finding $M_I = -3.91 \pm 0.05 \pm 0.09$ mag. Li et al. (2023), used DR3 and Gaia synthetic photometry (essay 187) to better constrain the luminosity function, yielding $M_I = -3.970^{+0.042}_{-0.024} \pm 0.062$ mag.

Dixon et al. (2023) used high Galactic latitude halo stars to minimise effects of metallicity, dust, and crowding, and used PARSEC isochrones (instead of Sobel edge detection) to find $M_I = -4.042 \pm 0.041 \pm 0.031$ mag.

TWO OTHER CONTRIBUTIONS illuminate some additional complications in using the TRGB as distance indicator. Anderson et al. (2024) noted that stars near the TRGB are typically regarded as non-variable. But, in a detailed study of the LMC, they show that all stars near the TRGB are small-amplitude red giants (SARG) that follow several period–luminosity sequences.

While their variability data is (presently) only from OGLE, the contributions of Gaia (DR3) were to remove foreground stars by astrometric cuts, to remove blended stars, and to provide synthetic photometry in the HST–ACS/F814W passband. They concluded that this variability population diversity affects the TRGB at a level exceeding the stated precision, and that both luminosity function smoothing and edge detection weighting can further bias the measurements. They derived $M_I = -4.025 \pm 0.014 \pm 0.033$ mag, assuming the geometric distance to the LMC given by Pietrzyński et al. (2019).



ANOTHER POSSIBLE COMPLICATION is that the location of the tip of the red-giant branch would be affected by any energy loss leading to a larger core mass at He-ignition, and thus to a brighter luminosity than predicted by standard models. From the Gaia DR2 distance of ω Cen, Capozzi & Raffelt (2020) gave a limit on the neutrino dipole moment of $\mu_\nu < 1.2 \times 10^{-12} \mu_B$, and on the axion–electron coupling of $g_{ae} < 1.3 \times 10^{-13}$.

THERE ARE many challenges in using the TRGB. Gaia is certain to contribute much more in the future.