228. Cepheid variables: an update

I described Gaia's early contributions to the study of Cepheid variables in essay 43, where I gave a broad introduction, and essay 44, where I focussed on their part in determining the Hubble constant. These were written at the end of 2021, before Gaia Data Release 3. Before bringing the topic up-to-date, let me recall the state of knowledge at that time, about three years ago.

Cepheids are bright pulsationally unstable stars, located in a narrow region of the Hertzsprung–Russell diagram, with typical periods of 1–30 days, but extending towards 100 days. There are two sub-classes. Classical Cepheids (or δ Cephei stars) are high-mass core He-burning supergiants, young Population I objects found in the Galactic plane, notably in spiral arms and in open clusters. Type II Cepheids are low-mass metal-poor Population II objects found at high Galactic latitudes, in the Galactic bulge, and in globular clusters, and sub-divided by period into BL Her, W Vir, and RV Tau-type variables.

Their importance as distance indicators is due to their strong period–luminosity correlation, discovered empirically by Henrietta Leavitt (1908), and subsequently explained theoretically. A historical review is given by Fernie (1969). The relationship nevertheless shows a significant scatter about the mean line, even when corrected for reddening, due to the finite (temperature) width of the instability strip. If a colour-term is introduced, the scatter is significantly reduced.

While the Cepheid period–luminosity relation has traditionally provided the most accurate method to derive distances to nearby galaxies, various complications are encountered in practice. A key goal of Cepheid studies is to establish the slope and zero-point of the period–luminosity relation, such that an observed period yields the object's luminosity, and hence its distance.

An important and related question is whether the period–colour and period–luminosity relations for classical Cepheids in the Large and Small Magellanic Clouds have the same slopes and zero-points as the Galactic Cepheids; differences would greatly complicate their use for the extragalactic distance scale.

As well as their use as distance indicators, the fact that Cepheids can be seen to very large distances, and the fact that they reflect the young population of the Galaxy, means that they also provide an important tracer of spiral arms. For similar reasons, their proper motions also provide a powerful measure of Galactic rotation. Important information is also encoded in their vertical distribution above and below the Galactic plane, and its age dependence. In a simplified picture, Cepheids with very young ages are found preferentially close to the Galactic plane, their assumed birth sites.

The Gaia results, pre-DR3, that I outlined in essay 43, already made major contributions. For Gaia DR2 (using the first 22 months of mission data), a 'Specific Object Study' pipeline was used to validate and characterise Cepheids and RR Lyrae stars, originally using the period–amplitude and period–luminosity relations in the G band, and subsequently extended to $G_{\rm BP}$ and $G_{\rm RP}$ (Clementini et al., 2019; Rimoldini et al., 2019).

Accordingly, Gaia DR2 provided results, with mean magnitudes and pulsation characteristics, for 9575 Cepheids, of which 3767 are in the LMC, 3692 in the SMC, and 2116 are elsewhere. The majority of those in the Magellanic Clouds were already known from OGLE, although Gaia DR2 identified 118 new objects. The all-sky sample includes Cepheids in 87 globular clusters and 14 dwarf galaxies, of which 350 were new discoveries. Other analyses of the DR2 Cepheid selection were made by Ripepi et al. (2019), and Molnár et al. (2018).

Kervella et al. (2019) combined the Hipparcos and Gaia DR2 positions to determine the mean proper motion of a sample of classical Cepheids, searching for proper motion anomalies caused by close-in orbiting companions. They concluded that their binary fraction is likely to be above 80%. Other pre-DR3 studies were used to characterise Galaxy rotation (Mróz et al., 2019; Kawata et al., 2019; Ablimit et al., 2020), the component of their velocities perpendicular to the Galactic plane (Skowron et al., 2019b), and as probes of our Galaxy's structure more generally (Skowron et al., 2019a).

CONCERNING THEIR USE in determining the Hubble constant (essay 44), the latest pre-DR3 studies by Riess et al. (2021) used 75 Milky Way Cepheids with HST photometry and the greatly improved Gaia EDR3 parallaxes. Applied to the calibration of Type Ia supernovae, it gave $H_0 = 73.0 \pm 1.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Combined with the best complementary sources of Cepheid calibration, they found $H_0 = 73.2 \pm 1.3\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, reaching 1.8% precision, but still a 4.2σ difference with the estimate from the Planck microwave background observations.

WITH GAIA DR3, came new radial velocities, and a wealth of astrophysical data derived from Gaia's BP/RP photometry and RVS spectroscopy. These allowed further unprecedented identification of variability across the HR diagram more generally (Gaia Collaboration et al., 2023; Maíz Apellániz et al., 2023).

Dedicated processing of the Cepheids, again using the 'Specific Object Study' Cepheid/RR Lyrae pipeline, is detailed by Ripepi et al. (2023). It resulted in 15 006 Cepheids of all types: 4663 in the LMC, 4616 in the SMC, 321 in M31, 185 in M33, with the other 5221 objects elsewhere over the sky. The sample includes Cepheids in the Galactic field, in open clusters, and in a number of small satellite galaxies. Among them, 327 objects were previously known as variable stars but with a different classification, while 474 were new Gaia discoveries.

Studies of the period–luminosity relation continue (e.g. Trentin et al., 2024; Bras et al., 2024; Das et al., 2024; Musella et al., 2024). I will not attempt a synthesis here!

AN IMPORTANT FOCUS of these more recent DR3-based Cepheid studies has been to better establish their membership of open clusters and associations (and to identify new open clusters associated with known or newly discovered Cepheids), to aid in distance estimation (e.g. Majaess & Turner, 2024; Majaess et al., 2024). Amongst these studies, Hao et al. (2022) associated 50 classical Cepheids with 45 open clusters, while Wang et al. (2024) found 43 Cepheid–cluster memberships.

The high-quality sample of Cruz Reyes & Anderson (2023) identified 34 Cepheids in 28 open clusters, of which 27 are pulsating in the fundamental mode, and 7 in overtones. They found three new cluster Cepheids (V0378 Cen, ST Tau, and GH Lup), and corrected the host cluster for three others. They found the fraction of Cepheids occurring in open clusters within 2 kpc to be about 9%. Cluster parallaxes could be determined to around 7 micro-arcsec in the range $G = 12.5 - 17$ mag.

Their combined cluster and field Cepheids yield a calibration of the period–luminosity relation for several photometric passbands, providing excellent (0.3σ) agreement with the latest Hubble Space Telescope (SHOES) distance ladder (Riess et al., 2022), confirming the continuing early/late Universe 'Hubble tension'.

THE GAIA DR3 CEPHEIDS have been applied to several important studies of Galactic structure. As part of a much bigger mapping of the Galactic disk, Drimmel et al. (2023) used 2800 classical Cepheids younger than 200 Myr to show that its spiral features extend outwards as far as 10 kpc from the Sun.

High-resolution ground-based spectroscopy by da Silva et al. (2023) gave metal abundances for 70 of the Gaia Cepheids, covering a wide range of Galactocentric distances, pulsation modes, and pulsation periods. This allowed them to trace the elemental O, S, and Fe abundance gradients across the disk. They presented detailed conclusions about their radial gradients, which are in turn used as inputs to models of Galactic kinematics and chemical enrichment history of the thin disk.

A detailed programme of ground-based all-sky radial velocity observations (from CORALIE and HERMES, between 2010–22), comprising 18 225 measurements of 258 classical Cepheids, is providing detailed insight into their pulsation properties, spectroscopic variability, and offsets with respected to Gaia's own RVS radial velocity estimates (Anderson et al., 2024).

Bobylev (2023) used 200 Gaia Cepheids to estimate the Sun's distance from the Galactic centre, $R_0 = 8.24 \pm 0.20$ kpc, and the rotation velocity at the solar circle, $V_0 = 268 \pm 8\,\mathrm{km\,s^{-1}}$. Further details of the rotation curve, based on 1705 Cepheids amongst 700 000 young disk stars out to 19 kpc, were given by Beordo et al. (2024).

FOR THE LARGE AND SMALL Magellanic Clouds, the improved Gaia Cepheid samples have been used to verify neural network classifiers of SMC membership (Jiménez-Arranz et al., 2023), to investigate the so-called 'flux-weighted gravity' versus luminosity relation (Groenewegen & Lub, 2023), and as structural diagnostics of the LMC (Bhuyan et al., 2024).

THERE ARE various outstanding questions about the detailed physics of Cepheid variables. Amongst these, ultralow amplitude (ULA) Cepheids are a poorly understood class, near the edges of the classical instability strip. For six CoroT candidates in the Galactic plane, Tarczay-Nehéz et al. (2023) used Gaia distances and magnitudes to rule out their pulsating nature, instead attributing their variability to rotation.

An interesting case of Gaia's mis-classification is the ultra-long period (ULP) Cepheid OGLE–GD–CEP–1884, classified as a Cepheid from 10 years of OGLE monitoring (Soszyński et al., 2024), but as a long-period variable in Gaia DR3. With a pulsation period of 78.14 days, nearly 10 d longer than the previous record holder, S Vulpeculae, it is perhaps the most luminous, youngest, and most massive Cepheid known in our Galaxy. Possible implications for understanding the Hubble tension are detailed by Musella et al. (2024).