43. Cepheid variables

CEPHEIDS ARE pulsationally unstable stars, located in a narrow region of the HR diagram, with typical periods of 1–30 days, but extending up to about 100 days.

There are two sub-classes. Classical Cepheids (or δ Cephei stars) are young high-mass core He-burning supergiants, 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).

The immediate precursors of the classical Cepheids are massive young O and B main-sequence stars. As they evolve rapidly off the main sequence, they pass through a zone (termed the 'instability strip') where their outer atmospheres are unstable to periodic radial oscillations. High-mass stars pass through the instability region at higher luminosities (cooler temperatures) than lower-mass stars, resulting in a Cepheid instability strip which slants upwards and to the right in the HR diagram.

Basic physics considerations lead to the existence of a mass–luminosity relation for Cepheids, and hence also a radius–luminosity relation. However, since neither mass nor radius are easily observable for the majority of stars, the mass–luminosity relation cannot be used to predict luminosities, nor therefore distances.

THE IMPORTANCE OF Cepheid variables as distance indicators is that there exists a correlation between period and luminosity, discovered empirically by Henrietta Leavitt in 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 to be the most accurate method to derive distances to nearby galaxies, various complications have been encountered in practice.

THERE IS AN ENORMOUS literature on Cepheid variables, and their application to the determination of the astronomical distance scale, both within the Galaxy, and beyond.

One main 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 thereby its distance. Until the Hipparcos results, the most accurate zero-point for the period–luminosity relation came from Cepheids in open clusters and associations through main-sequence fitting.

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

IN ADDITION TO THEIR USE as distance indicators, the fact that Cepheids can be seen to 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, while their proper motions provide a powerful probe of Galactic rotation.

Pre-Hipparcos studies of Galactic rotation could only sample a small region around the Sun. The first such contribution making use of the Hipparcos data to explore a significant region of the Galactic disk was by Feast & Whitelock (1977). They used 220 Cepheids with Hipparcos astrometry to derive the Oort constants A and B from the first-order expression for Galactic rotation.

Interesting information is also encoded in the vertical distribution of Cepheids above and below the Galactic plane, and its age dependence. In a simplified picture, Cepheids with a very young age are found preferentially close to the Galactic plane, their assumed birth sites. Evolving in scale height with age as a result of their initial vertical velocity component, they reach their maximum distance and return to the plane after times depending on the local mass density, somewhere in the range of 70–100 Myr.

The Hipparcos Catalogue contained 280 Cepheids, of which 32 are either Type II (mainly W Vir stars) or double-mode Cepheids. Of the 248 classical Cepheids, 32 are first-overtone pulsators.

The mean standard error of the 223 Hipparcos Cepheid parallaxes considered by Feast & Whitelock (1977) is about 1.5 mas. The majority are beyond about 500 pc, such that the parallaxes are typically very small, and of limited individual value. The closest is Polaris (α UMi), with $\pi = 7.56 \pm 0.48$ mas or $d = 132 \pm 8$ pc. Polaris is too bright to appear in current Gaia data releases.

The Gaia results are transforming all of these areas of study. The high-accuracy parallaxes, combined with the multi-colour multi-epoch precision photometry, makes Gaia extremely powerful for identifying and characterising variability across the entire HR diagram.

Gaia DR1 included 599 Cepheids (and 2595 RR Lyrae stars) in the Large Magellanic Cloud region, observed at high cadence during the first 28 days in the 'ecliptic poles scanning configuration' (Clementini et al. 2016).

For Gaia DR2 (the first 22 months of the mission), 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).

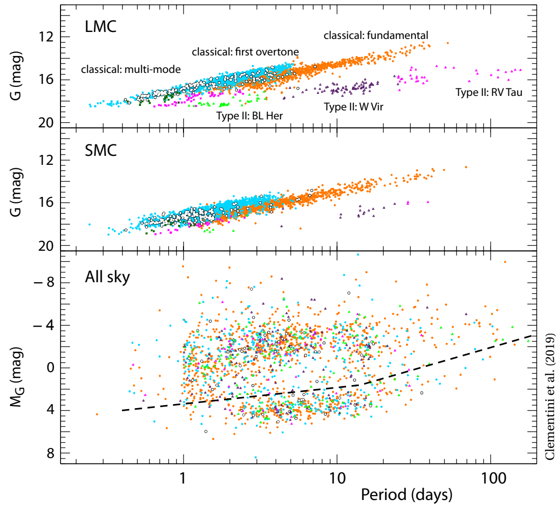
Gaia DR2 provides results, along with mean magnitudes and pulsation characteristics, for 9575 Cepheids, of which 3767 are in the LMC, 3692 are in the SMC, and 2116 are elsewhere ('all-sky'). The majority of those in the Magellanic Clouds were already known from the OGLE survey, although Gaia DR2 lists 118 new objects.

The all-sky sample includes Cepheids and RR Lyrae variables in 87 globular clusters and 14 dwarf galaxies (the Magellanic Clouds, 5 classical and 7 ultra-faint dwarfs), of which 350 Cepheids are new discoveries.

Metallicities derived from the Fourier parameters of the light curves are also given for 3738 fundamental-mode classical Cepheids with periods below 6.3 days.

In addition to the classical and Type II Cepheids, the Gaia 'Specific Object Study' pipeline also identifies the less common double-mode Cepheids (which are observed to pulsate in two modes at the same time, usually the fundamental and first overtone), as well as the shorter-period high-mass 'anomalous Cepheids', whose evolutionary status is somewhat unclear.

The figure shows the period–luminosity relation for all Cepheids identified in DR2 by Clementini et al. (2019), divided into three sky regions, and shown as a function of apparent magnitude for theLMC and SMCs, and as a function of absolute magnitude for the all-sky sample. All are uncorrected for reddening.



The colour coding, identical in all panels, is divided into the classical Cepheids (sub-divided into fundamental-mode, first-overtone, and multi-mode pulsators), and the Type II Cepheids (sub-divided by period into BL Her, W Vir, and RV Tau-type variables).

A much larger scatter is seen in the all-sky period–luminosity distribution. Clementini et al. (2019) already considered that many of the sources below the dashed line are likely to be a combination of mis-classifications, sources with very high reddening, or the consequences of a simplified treatment of binary/multiple sources.

A further more detailed analysis has subsequently been undertaken by Ripepi et al. (2019), while an independent analysis of the purity of the DR2 Cepheid sample is discussed by Molnár et al. (2018).

I will make only a brief mention of some of the other analyses that have been based on the Cepheid data from Gaia DR2, through to the end of 2020. Specific application to the estimation of the Hubble constant is taken as a separate topic elsewhere.

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 the binary fraction of classical Cepheids is likely to be above 80%.

Other studies have used the Gaia Cepheid data to characterise our Galaxy's rotation curve (e.g. Mróz et al. 2019; Kawata et al. 2019; Ablimit et al. 2020), as well the vertical component of the velocity vector (Skowron et al. 2019a), and our Galaxy's structure more generally (Skowron et al. 2019b), which I will look at separately.

Marconi et al. (2020) derived theoretical mass-dependent 'period–Wesenheit' (reddening-free) relations in the various Gaia photometric bands, from which they derive the individual mass of each pulsator.