

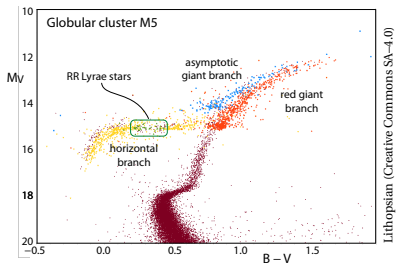
45. RR Lyrae variables

GLOBULAR CLUSTER and other Population II stars more massive than the Sun have long ago evolved into white dwarfs. In contrast, stars of approximately solar mass are common.

Their location in the Hertzsprung–Russell diagram is well accounted for theoretically. After ascending the giant branch, terminating in the helium flash, stars evolve rapidly onto the ‘zero-age horizontal branch’ with masses around $0.6 - 0.8 M_{\odot}$, where they basically comprise a static He-burning core and a H-burning shell.

Their location along the horizontal branch depends on metallicity, from blue in metal-poor clusters, to red in metal-rich clusters, where they merge into the giant branch to form the region of the (red) clump giants.

THE RR LYRAE VARIABLES are a subset of the horizontal branch giants, occurring where the horizontal branch intersects the instability strip. RR Lyrae variables have pulsation periods of around 1 day or less.



Like Cepheids, although less luminous, their distinctive light curves allows detection to large distances, as far as the Galactic centre in the low-absorption Baade Windows, and in crowded fields.

There are two major subgroups: the RRAb, most relevant to the distance scale, are metal-poor spheroidal component stars, with asymmetric light curves, longer periods (above 0.4 day), larger amplitudes (around 0.5–1.5 mag), and pulsating in the fundamental mode.

The less numerous RRC type are old disk component stars, with more symmetric almost sinusoidal light curves, shorter periods (below 0.4 day), smaller variability amplitudes, and pulsating in the first overtone.

There are also double-mode pulsators, denoted RRD, which pulsate simultaneously in the fundamental mode and in the first overtone.

AN UNDERLYING period–luminosity relation has long given RR Lyrae stars a role as standard candles for relatively nearby targets, especially within the Milky Way and Local Group. While typically more common than the Cepheids, there are greater difficulties in accounting for the effects of metallicity, faintness, and blending. RR Lyrae stars also provide tests of evolutionary and pulsation models, and are important kinematic tracers.

Their typically large distances means that useful trigonometric parallaxes have largely been unavailable, and various other methods have been used for luminosity calibration. These include the use of RR Lyrae in Galactic globular clusters whose distances have been derived from main-sequence fitting of subdwarfs, the use of statistical parallaxes, and Baade–Wesselink determinations based on interpretation of the colour, light, and radial velocity variations during the pulsation cycle.

But my goal here is just to look at the *numbers* of RR Lyrae stars that Gaia is discovering, measuring, and characterising.

PRE-GAIA, several thousand Galactic RR Lyrae stars were known. Because of their magnitudes, just 179 were included in the Hipparcos Catalogue.

Hipparcos eventually gave useful parallaxes for only a few, and only that for the class's prototype, RR Lyrae itself, is reasonably accurate, $\pi = 4.38 \pm 0.59$ mas. Bono et al. (2002) later gave a weighted mean of the Hipparcos, HST, and pulsational parallax of 3.87 ± 0.19 mas.

THE HIGH-ACCURACY PARALLAXES from Gaia, combined with the multi-colour multi-epoch precision photometry, makes the mission extremely powerful for identifying and characterising variability across the entire Hertzsprung–Russell diagram.

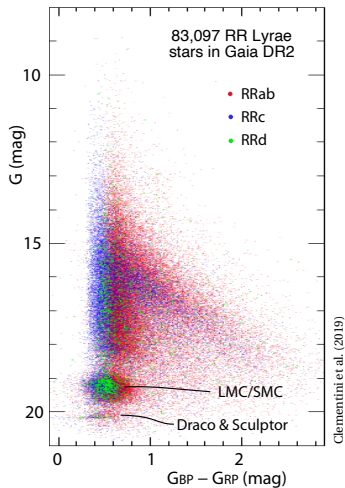
Similarly to what has previously been described here for Cepheid variables, the first Gaia data release, DR1, included 2595 RR Lyrae stars (and 599 Cepheids) in the Large Magellanic Cloud region, which was observed at high cadence during the first 28 days in the ‘ecliptic poles scanning configuration’ (Clementini et al. 2016).

FOR GAIA DR2, covering 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 only in the G band, and subsequently extended to G_{BP} and G_{RP} (Clementini et al. 2019; Rimoldini et al. 2019).

Gaia DR2 accordingly provides results, along with mean magnitudes and pulsation characteristics, for 140 784 RR Lyrae stars as faint as $G = 20.7$ mag.

This huge sample includes objects in the Milky Way disk, bulge, and halo; in the Large and Small Magellanic Clouds; 1569 distributed over 87 globular clusters; and 417 distributed over 12 dwarf spheroidal galaxies (including seven ultra-faint dwarf galaxies). The largest numbers are in M3 (159), NGC 3201 (83), Sculptor (176) and Draco (176). Including some previously-known objects, not (yet) detected by Gaia, a total of 46 443 lie in the Large and Small Magellanic Clouds.

THE ACCURATE multi-epoch photometry resulted in 121 234 objects whose light curves could be modelled with at least two harmonics, and 67 681 whose light curves could be modelled with at least three harmonics.

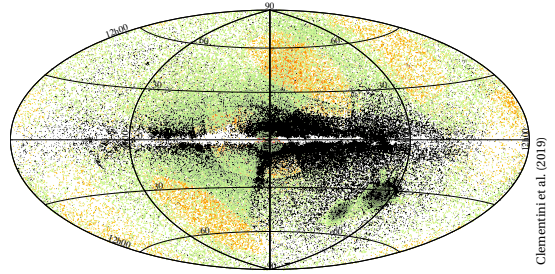


Cross-matching indicate that out of the 140 784 confirmed RR Lyrae stars in Gaia DR2, 90 564 were already known, while 50 220 are new discoveries.

For the 83 097 stars with both G_{BP} and G_{RP} photometry, the colour-magnitude diagram shows the different regions occupied by the RRab, RRc, and RRd classes, along with clumps associated with the Large and Small Magellanic Clouds, as well as the Draco and Sculptor dwarf spheroidals.

THE DISTRIBUTION of all known RR Lyrae stars on the sky (more than 220 000 in total, shown here in Galactic coordinates) are colour-coded as: previously-known RR Lyrae stars without a counterpart in Gaia DR2 (orange); previously-known RR Lyrae stars with a counterpart in Gaia DR2 (green); and new RR Lyrae discovered by Gaia (black).

The latter two groups clearly reflect the pattern of the Gaia scanning law as it stood after the first 22 months of the mission, and suggest that many tens of thousands of additional RR Lyrae stars will be discovered by the end of the mission as the sky coverage densifies.



LET ME TURN briefly to how the Gaia RR Lyrae data, and especially the parallax distances, are being used. Firstly, Molnár et al. (2018) used Kepler mission photometry to conclude that the DR2 catalogue has a completeness of 70–78%.

Several groups have used the data to determine improved period–luminosity–metallicity relations, confirming the parallax quality in the process (e.g. Neeley et al. 2017; Neeley et al. 2019; Muraveva et al. 2018).

Gould et al. (2017) showed that the RR Lyrae yield a meaningful zero-point of the global parallax system, comparable with quasars, despite their smaller number.

Various groups have used the distances and proper motions of several thousand stars to establish the triaxial structure and kinematics of the Galaxy halo, identifying the inner and outer halos with weak prograde and retrograde rotations respectively (Utkin et al. 2018).

Iorio et al. (2018) found no evidence of tilt or offset of the halo with respect to the Galaxy disk, while Iorio & Belokurov (2020) interpreted their density and kinematics as evidence in favour of a scenario in which the bulk of the halo was deposited in a single massive merger event.

THE EXISTENCE of RR Lyrae stars well beyond a system’s tidal radius are providing evidence for tidal disruption and debris stripping, both for Galactic globular clusters (Kundu et al. 2019), and ultra-faint dwarf satellite galaxies (Vivas et al. (2020).

Kervella et al. (2019) combined Hipparcos and DR2 positions to find proper motion anomalies caused by close-orbiting companions, detecting 13 out of a sample of 198, and suggesting a binary fraction of at least 7%.

Ramos et al. (2020) searched for RR Lyrae associated with the Sagittarius tidal stream, finding some 6000–11 000 candidates. Similarly, Prudil et al. (2020) assessed the contributions from the Galaxy disk and from the Gaia–Enceladus stream, out of 314 RR Lyrae in the solar neighbourhood, while Du et al. (2020) studied the kinematics and spatial distribution of 15 599 RR Lyrae stars in the Milky Way bulge.

WHILE THE DR2 RESULTS are already impressive, numbers, accuracies and a vast panorama of detailed studies will continue to grow with the future Gaia data releases.