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Milky Way's structure based on thousands of Cepheids and RR Lyrae stars from OGLE

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Abstract. Classical Cepheids and RR Lyrae-type variable stars are widely-used tracers of young (<300 Myr) and old (>10 Gyr) stellar populations, respectively. These stars also serve as distance indicators allowing for Galactic structure studies. Robust detection of pulsating variables requires precise and relatively frequent observations over several years. Recently, the OGLE survey has discovered nearly 1,300 new genuine classical Cepheids and 15,000 RR Lyrae stars along the southern Galactic plane. Here, we present the picture of the Milky Way's thin disk drawn with the Cepheids and the view of the Galactic old population that emerges from the set of known RR Lyrae stars.

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Our Galaxy, the Milky Way, is a complex formation of dark matter, gas, dust, and stars representing various populations. Studies of the Milky Way are difficult due to the location of our Sun close to the Galactic plane toward which the interstellar dust is concentrated. Only luminous distance indicators allow investigating the structure of the Milky Way's disk. Such stellar distance indicators are classical Cepheids. These pulsating variable stars are supergiants with luminosities between 100 and 10,000 $L_{\odot}$. They are younger than 300 Myr and obey period-luminosity as well as period-age relations. Robust detection of a Cepheid often requires a hundred of measurements taken over two or more years. That is because spotted stars can mimic pulsating variables. Spots on the surface of a star evolve which results in slow changes of the observed light curve shape and amplitude (Iwanek *et al.* 2019). Light curves of Cepheids are stable over time.

Since 1992 the Optical Gravitational Lensing Experiment (OGLE) monitors dense stellar regions of the sky in searches for any kind of variable objects, including pulsating stars such as Cepheids, RR Lyrae-type stars, Long-Period Variables. The target regions are the Galactic bulge, Galactic disk, and Magellanic Clouds. Since 1996 the survey operates the 1.3-m Warsaw telescope at Las Campanas Observatory, Chile. With the installation of a 32-detector camera with a total field of view of 1.4 deg^2, in 2010 OGLE became a truly large-scale variability survey (Udalski *et al.* 2015). Currently, every clear night OGLE monitors about 2 billion stars over an area of 3,600 deg^2. Observations are conducted mainly in I band, while some additional frames are taken in V band to secure color information. Long-term optical monitoring conducted from the site with superb photometric conditions allows us to release pure and highly complete collections of variable sources. So far, the survey has detected and classified over one million variable stars of various types (e.g., Soszyński *et al.* 2014, 2015).

Recently, OGLE discovered 1,300 new Galactic classical Cepheids and increased the number of all known such objects to 2487 (Udalski *et al.* 2018). The whole list is available at http://www.astrouw.edu.pl/ogle/ogle4/OCVS/allGalCep.listID. This is a significant upgrade of the set of Cepheids presented in Pietrukowicz *et al.* (2013). Fig. 1 shows the

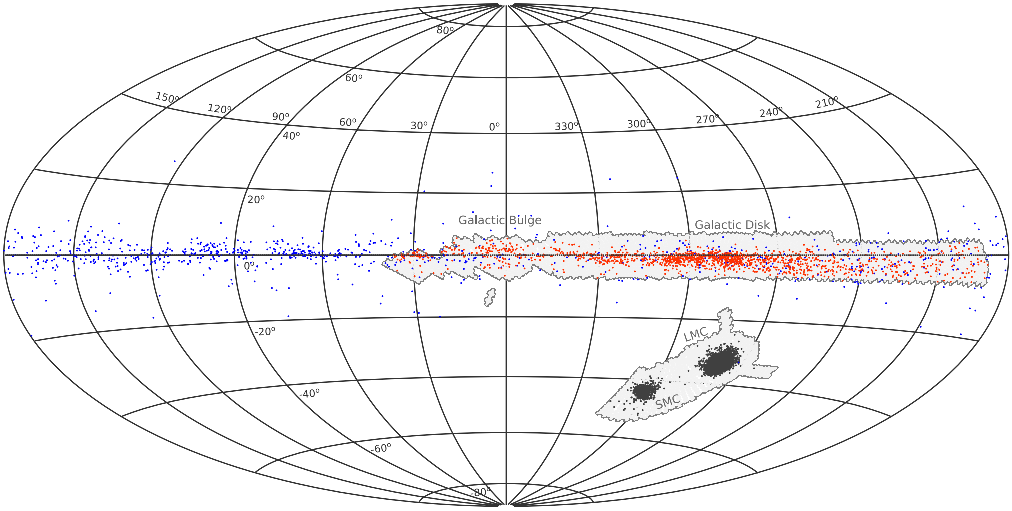

Figure 1. Map of the sky with the positions of all optically confirmed classical Cepheids from the Milky Way and Magellanic Clouds. The contours mark the OGLE survey area of the Galactic plane and Magellanic System. Red dots represent Galactic classical Cepheids discovered by OGLE. The warped disk is noticeble.

distribution of all *bona fide* Cepheids in Galactic coordinates. The warp is well seen. To investigate the spatial distribution of the Cepheids, we applied period-luminosity relations to periods derived from the optical observations and brightness measurements determined in several mid-infrared bands from *Spitzer* and *WISE* satellites (Skowron *et al.* 2019). The obtained distances are accurate to 5% or better. The distribution of Cepheids as seen from the Galactic pole is presented in Fig. 2. This is the first real map of the Milky Way's young disk with distances calculated to each object individually. The newly discovered pulsating stars allowed us to explore the outer parts of the Galactic disk. Previously known set of classical Cepheids covered a region up to 5 kpc from the Sun. By looking at the map, one can say that the near side of the Milky Way, in contrast to the far side, seems to be complete with classical Cepheids. The stars form pronounced structures reaching 15 kpc from the Galactic center. Fitting models to the data brought us the information on the disk scale height ($H = 73.5 \pm 3.2$ pc) and Sun elevation over the Galactic plane ($z_0 = 14.4 \pm 3.0$ pc). The new data show that the Galactic warp starts at the galactocentric distance of 10 kpc. At 15 kpc it departes by almost 1 kpc from the geometrical plane. Flaring of the young disk is significant. It has a full thickness of about 0.2 kpc at 8 kpc from the center and about 1 kpc at 12 kpc (Skowron *et al.* 2019).

The new extended collection of classical Cepheids was used to construct the rotation velocity curve of our Galaxy (Mróz *et al.* 2018). For this purpose, we cross-matched the whole collection of Cepheids with Gaia DR2 catalog. For 773 pulsators it was possible to obtain reliable information on kinematics. The curve is nearly flat with a very mild decrease. We confirm the presence of a dip at the galactocentric distance of about 10 kpc. The measured rotation speed of the Sun $\Theta_0 = 233.6 \pm 2.8$ km/s, assuming the distance to the Galactic center $R_0 = 8.122 \pm 0.031$ kpc recently obtained by the Gravity Collaboration (Abuter *et al.* 2018).

RR Lyrae-type variable stars are at least 10 Gyr old. They strongly concentrate toward the Milky Way's center (Soszyński *et al.* 2014). The analysis of over 27,200 fundamental-mode (type ab) RR Lyrae stars from OGLE showed that the inner old bulge has the shape of a triaxial ellipsoid with the major axis inclined at an angle of $20 \pm 3°$ with respect to the line Sun–Galactic Center (Pietrukowicz *et al.* 2015). The determined angle is close to

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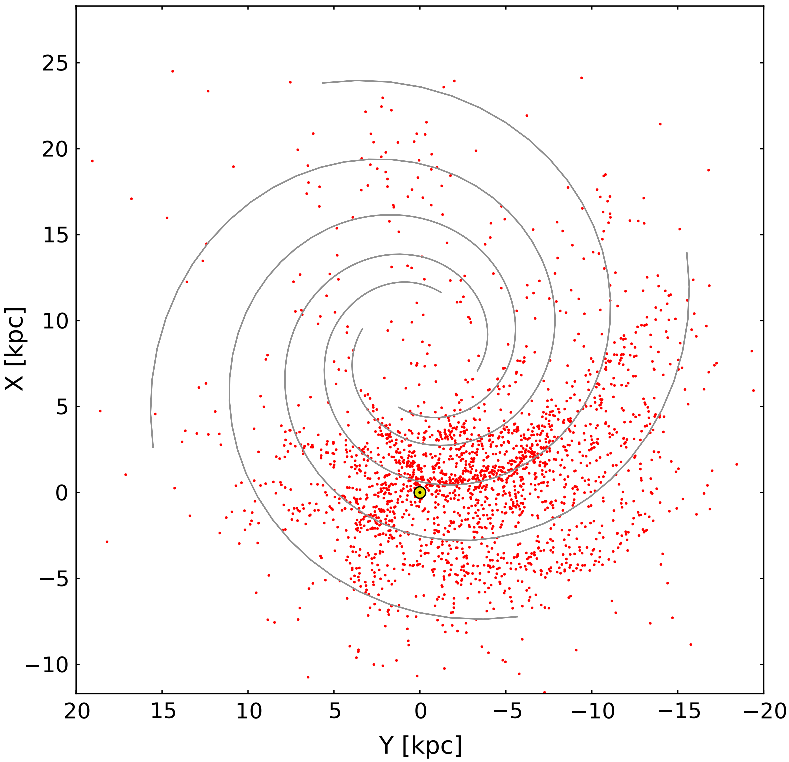

Figure 2. Face-on view of the Milky Way drawn with the classical Cepheids. The Sun is marked with a yellow dot at the origin of the coordinate system. The logarithmic spirals represent a four-arm galaxy model consistent with the measurements of neutral hydrogen (Vallée *et al.* 2017).

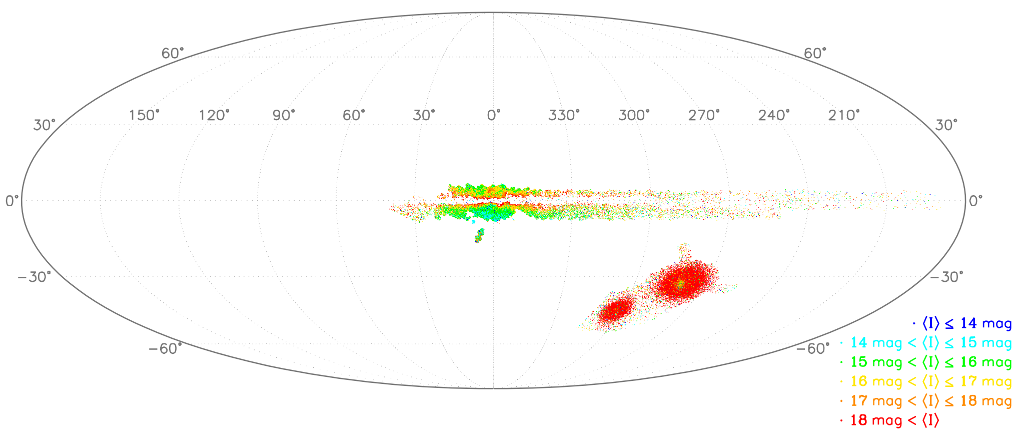

Figure 3. Distribution of RR Lyrae stars from the OGLE collection. Objects from the Milky Way and Magellanic System are shown. Colors code the observed I-band brightness of the variables. Regions close to the Galactic plane are practically unaccessible for exploration in the optical regime due to extremely high extinction by interstellar dust.

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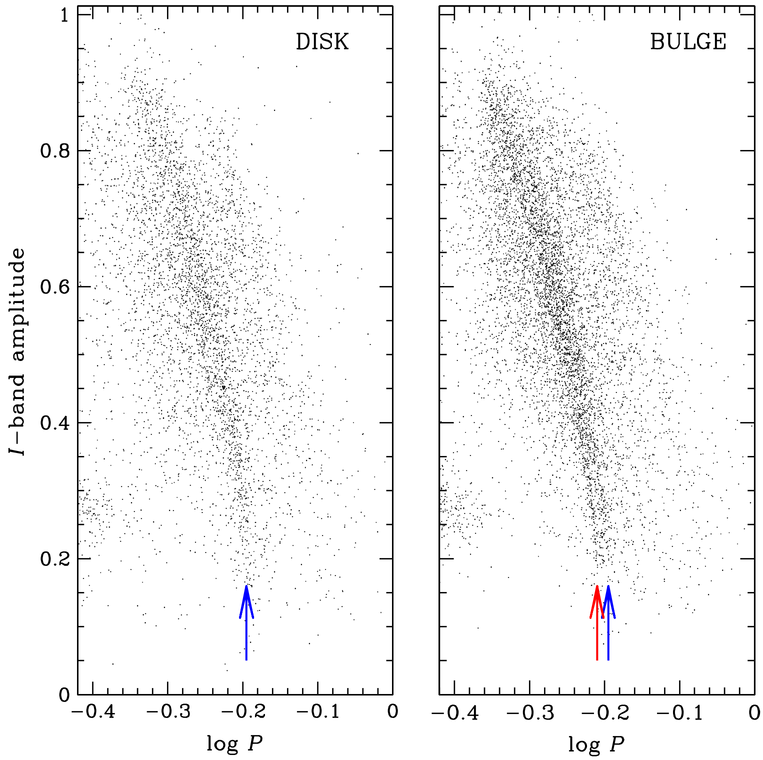

Figure 4. Period-amplitude diagram for RR Lyrae stars from the Galactic disk (on the left) and Galactic bulge (on the right). Note the absence of the shorter-period sequence in the disk.

the inclination angle of the bar (≈ 27°, Cao *et al.* 2013). Very likely, the much less massive old component, possesing about 5% of the total bulge mass, follows the orientation of the more massive intermediate-age bar.

One of the most interesting results from the analysis of the OGLE RR Lyrae stars are two close sequences in the period-amplitude diagram. This result is interpreted as the presence of two major (and in general multiple) old bulge (or inner halo) populations that slightly differ by metallicity. Perhaps, those are remnants of two large (and other smaller) ancient galaxies that collided and formed the early Milky Way. In Fig. 3, we show a map of the bulge RR Lyrae stars and recently found new pulsating variables of this type along the Milky Way's disk between the Galactic longitudes −170° and +40°. By comparing the period-amplitude diagrams for the bulge and disk area (Fig. 4), we can notice that one of the two sequences does not exist in the disk. Lack of the shorter-period sequence translates to the absence of a more metal-rich population in the thick disk. With more data coming in 2020, particularly for the outer bulge, we should be able to trace the changes in the old stellar populations with more details. This picture will be then very complementary to the view of the Galactic halo obtained by other surveys.

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