Classical Cepheids in the Milky Way

P. Pietrukowicz, I. Soszyński, and A. Udalski

1 Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

ABSTRACT

We share the most up-to-date, carefully verified list of classical Cepheids residing in the Galaxy. Based on long-term OGLE experience in the field of variable stars, we have inspected candidates for Cepheids from surveys such as ASAS, ASAS-SN, ATLAS, Gaia, NSVS, VVV, WISE, ZTF, among others, and also known sources from the General Catalogue of Variable Stars. Only objects confirmed in the optical range as classical Cepheids are included in the list. We provide Gaia EDR3 identifications of the stars. Purity of the sample exceeds 97 per cent, while its completeness is of about 88 per cent down to a magnitude $G = 18$. The list contains 3352 classical Cepheids, of which 2140 stars are fundamental-mode pulsators. Basic statistics and comparison between the classical Cepheids from the Milky Way, Andromeda Galaxy (M31), and Magellanic Clouds are provided. The list is available at the OGLE Internet Data Archive.

Stars: variables: Cepheids – Stars: oscillations – Galaxy: bulge – Galaxy: disk – Catalogs

1 Introduction

Classical Cepheids are extremely important stellar objects for modern astrophysics (e.g., Pilecki et al. 2021) and cosmology (e.g., Riess et al. 2019, Freedman et al. 2021). These pulsating variable stars serve as distance indicators in the Local Volume (e.g., Bono et al. 2010, Scowcroft et al. 2013) as well as probes for asteroseismology (e.g., Pietrzyński et al. 2010, Smolec and Moskalik 2010, Anderson et al. 2016). Classical Cepheids have been used to map young components of the Milky Way (e.g., Dambis et al. 2015, Skowron et al. 2019a) and nearby galaxies such as the Large Magellanic Cloud (e.g., Jacyszyn-Dobrzeniecka et al. 2016, Inno et al. 2016). Follow-up observations of the Milky Way’s Cepheids have allowed for the determination of metallicity gradients (Genovali et al. 2015) and for precise drawing the rotation curve of the outer Galactic disk (Mróz et al. 2019).

Classical Cepheids are Population I stars of luminosity classes from Ia (luminous supergiants) through Iab (normal supergiants) and Ib (underluminous supergiants) to II (bright giants) and spectral types from F5 to K2. In the Hertzsprung–Russell diagram, the stars lie on the classical instability strip. Classical Cepheids pulsating in the fundamental mode (F) show light variations with periods from about 1 day to over 200 days. Their light curve shapes are usually asymmetric with a rapid rise and a slower decline. In the period range from 5 to 23 days, they are characterized by the presence of an additional bump at location depending on the pulsation period. This effect is known as the Hertzsprung progression and seems to be caused by the 2:1 resonance between the fundamental mode and the second overtone (2O). Light curves of fundamental-mode Cepheids show sharp extrema and have $I$-band amplitudes up to about 1.0 mag (or 1.7 mag in $V$). First-overtone (1O) classical Cepheids have pulsation periods in the range from about 0.23 day up to almost 10 days. They have smoother light curves, round minima, and on average twice lower
amplitudes than those in fundamental-mode stars. Some of the observed classical Cepheids pulsate in two or three radial modes simultaneously. Multi-mode Cepheids have characteristic period ratios which helps to distinguish them from multi-mode RR Lyr-type stars (e.g., Smolec et al. 2017). In some first-overtone Cepheids, additional periodicities corresponding to high-order non-radial modes have been discovered (Soszyński et al. 2008, Moskalik and Kołaczkowski 2009, Rathour et al. 2021). Light curves of Cepheids are very stable over time. Only several Galactic classical Cepheids show definite amplitude and phase modulations, in particular Polaris ($\alpha$ UMi; Bruntt et al. 2008) and V473 Lyr (Molnár and Szabados 2014).

The main purpose of the work here is presentation of the most up-to-date and as pure as possible list of Galactic classical Cepheids that may serve in various astrophysical studies. We plan to update the list once new classical Cepheids are discovered. In this paper, we analyse the whole set of known Milky Way’s Cepheids and compare it with collections of such stars residing in M31 and Magellanic Clouds.

2 Discovering Classical Cepheids

The first classical Cepheids, $\eta$ Aql and $\delta$ Cep (the prototype object of the whole class), were discovered by Edward Pigott and John Goodricke in 1784, respectively. Thirty new Cepheids were found over a century following that discovery. In the first edition of the General Catalogue of Variable Stars (GCVS), there were 473 objects identified as “long-period Cepheids” (Kukarkin and Parenago 1948). Twenty-eight of the stars were marked as uncertain cases. The most recent version (from June 2021) of the fifth GCVS edition (Samus et al. 2017) contains 632 classical Cepheids identified as fundamental-mode (DCEP), first-overtone (DCEPS), and double-mode (beat) pulsators (DCEP(B)). In the catalog, there are also 224 variable sources classified to one of the following ambiguous or uncertain types (colon extension): CEP, CEP(B), CEP:, DCEP:, and DCEPS:. Some of the sources are type II (or Population II) Cepheids. Some classical Cepheids listed in GCVS belong to the Magellanic Clouds.

The number of known Galactic classical Cepheids has grown considerably in the era of massive wide-field photometric CCD surveys. One of the first such surveys was the All Sky Automated Survey (ASAS; Pojmanski 1997) operated from the Las Campanas Observatory, Chile, since 1996. ASAS-3 has monitored stars down to $V \approx 14.5$ mag over the entire southern sky up to declination $\delta \approx +28^\circ$. The on-line ASAS Catalog of Variable Stars (ACVS; Pojmanski 2002, 2003, Pojmanski and Maciejewski 2004, 2005, Pojmanski et al. 2005) contains 870 objects classified as authentic classical Cepheids (labeled as DCEP-FU, DCEP-FO, DCEP-FO/DCEP-FU or DCEP-FO/DCEP-FU) and 798 objects as possible classical Cepheids (with uncertain classification or multiple identifications).

A very similar robotic project was carried out from Los Alamos, New Mexico, USA, by the Northern Sky Variability Survey (NSVS; Woźniak et al. 2004). The survey monitored the entire northern hemisphere and also southern fields down to $\delta \approx -38^\circ$ (although with fewer epochs) over one full year (from April 1999 to March 2000). In contrast to ASAS, which used the Johnson $V$ and

*A term “short-period Cepheids” referred to saw-tooth-shaped variables with periods shorter than a day observed mainly in globular clusters and nowadays classified as RR Lyr-type stars.
Cousins $I$ filters, NSVS collected unfiltered photometric data. Hoffman et al. (2009) performed an automated classification of NSVS stars and identified several hundreds of long-period variables including Cepheids. Due to photometric constraints, they were not able to distinguish between classical and type II Cepheids, but nearly one hundred stars were cross-matched with already known classical Cepheids from GCVS. Over a decade several additional objects from the NSVS database were identified as classical Cepheids by various researchers (e.g., Benkő and Csubry 2007, Kuzmin 2008, Khruslov and Kusakin 2016).

Due to a large pixel scale ($\approx 15''$), the ASAS and NSVS instruments were insufficient to resolve stars in dense regions close to the Galactic plane, where the Population I Cepheids reside. These regions have been extensively observed by the Optical Gravitational Lensing Experiment (OGLE) using the 1.3-m Warsaw telescope located at the Las Campanas Observatory since 1997. The third phase of the project (OGLE-III, Udalski et al. 2008), conducted in the years 2001–2009, provided the identification of 32 classical Cepheids in the Galactic bulge (Soszyński et al. 2011) and 20 classical Cepheids in a small part of the Galactic disk (Pietrukowicz et al. 2013). A new wide-field camera installed in 2010 started the fourth phase of the project (OGLE-IV, Udalski et al. 2015) and allowed for a regular deep monitoring of the entire Galactic stripe seen from Las Campanas. A total of 1935 classical Cepheids were reported based on OGLE-IV time-series data (Soszyński et al. 2017, Udalski et al. 2018, Skowron et al. 2019b, Soszyński et al. 2020). Four additional classical Cepheids were found in the OGLE-II data (from years 1997–2000) by three amateur astronomers: R. Jansen in 2009, S. Hümmerich in 2013, and J. Falcón Quintana in 2017. The OGLE observations are collected mainly in the $I$ band and reach $I \approx 21.5$ mag for the inner Galactic bulge and $I \approx 20.5$ mag for the Galactic disk and outer bulge. Regular, long-term, high-quality OGLE photometry, including data for Magellanic Cloud Cepheids (e.g., Soszyński et al. 2008, 2015), has allowed us to verify and properly classify new candidates for Galactic Cepheids from OGLE as well as from other surveys. The OGLE collection of periodic variable stars currently contains over a million objects.

In the 2010s several new large-scale surveys, focused not only on variable star research, started to operate. After 2–3 years of observations the survey teams released their first time-series data and shortly thousands of variable sources and hundreds of candidates for Cepheids were published. One of such surveys, called Asteroid Terrestrial-impact Last Alert System or ATLAS (Tonry et al. 2018), employs two 0.5-m Schmidt telescopes at the Hawaii Haleakala Observatory since 2015 and Mauna Loa Observatory since 2017. For the asteroid search the system use non-standard broad band filters, cyan ($c; 420—650$ nm) and orange ($o; 560—820$ nm). Heinze et al. (2018) reported on the detection of 25 162 candidate pulsating variables with saw-tooth-shaped light curves, including 1140 candidates for Cepheids down to $c \approx 19$ mag, $o \approx 18.5$ mag, or $r \approx 18.5$ mag found between declination $-30^\circ$ and $+60^\circ$.

Another large-scale survey, the All-Sky Automated Survey for Supernovae (ASAS-SN) started with the installation of the first station at the Haleakala Observatory in Hawaii in 2013. One year later the project was extended for the southern station at the Cerro Tololo Inter-American Observatory, Chile. ASAS-SN patrols the entire sky for supernovae and various transients to a depth of $V \approx 17$ mag (Shappee et al. 2014, Kochanek et al. 2017). In June 2021 the survey database contained information on 666 502 variable stars, of which 2185 objects were classified as classical Cepheids (Jayasinghe et al. 2018, 2019, 2020). Some of the Cepheids are members of the Large Magellanic Cloud (LMC) and Small
Magellanic Cloud (SMC). In the presented here work, the long-term ASAS and ASAS-SN data were particularly useful in the verification of known and recently detected candidates for pulsating stars in less dense regions at higher Galactic latitude.

A deep optical monitoring (down to $g,r \approx 21$ mag, $i \approx 20.5$ mag) of the northern part of the sky ($\delta > -25^\circ$) is conducted by the Zwicky Transient Facility (ZTF; Belm et al. 2019) using the 1.2-m Samuel Oschin telescope at the Palomar Observatory, USA, since 2018. The second data release of the survey (ZTF DR2) allowed for the detection of 781 602 periodic variable stars including 582 candidates for classical Cepheids (Chen et al. 2020). Over 20 long-period Cepheids are stars from M31.

Highly extincted regions close to the Galactic plane are practically inaccessible for optical surveys. In recent years two surveys have obtained near-infrared time-series photometry in the area of the Galactic bulge and adjacent sections of the Galactic disk. Since 2001 the SIRIUS camera installed on the InfraRed Survey Facility (IRSF/SIRIUS) 1.4-m telescope at the South African Astronomical Observatory has collected series of $JHK_s$ images of selected fields near the Galactic equator (Matsunaga et al. 2011). A result of the searches was the detection of about 30 candidates for classical Cepheids among hundreds of long-period (< 60 d) variable stars (Matsunaga et al. 2016, Tanioka et al. 2017). The other near-infrared survey, VISTA Variables in the Via Lactea (VVV; Minniti et al. 2010), is an ESO public survey conducted on the 4.1-m VISTA telescope located at the Paranal Observatory, Chile. The multi-epoch $K_s$-band and single-eclipse $ZYJH$-band observations obtained in years 2010–2019 have brought the detection of 689 candidates for classical Cepheids in the galactic longitude range $-65^\circ < l < +10^\circ$ and latitude range $-2^\circ < b < +2^\circ$ (Dékány et al. 2015ab, 2019).

Since 2014 the whole sky is repeatedly scanned from space by Gaia astrometric mission. Gaia photometry is collected in white-light $G$-band (330–1050 nm) and reaches $G \approx 21$ mag. Based on the second data release (Gaia DR2, Gaia Collaboration et al. 2018) Clementini et al. (2019) informed about 350 candidates for new classical Cepheids. Other space mission which data have been used to search for periodic variables is Wide-field Infrared Survey Explorer (WISE). Chen et al. (2018) reported on the detection of 1312 candidates for Cepheids. However, a weak side of WISE is high angular resolution of its camera and clumping of the time-series observations.

Data from several other surveys have been searched for pulsating stars which led to the discovery of some 20 new classical Cepheids. The surveys were: the Galactic Spiral Arms program in the second phase of Expérience de Recherche d’Objets Sombres (EROS2-GSA; Derue et al. 2002), the Berlin Exoplanet Search Telescope (BEST; Kabath et al. 2008, 2009), the Multitudinous Image-based Sky-survey and Accumulative Observations (MISAO†), Dauban Survey‡, Two Micron All Sky Survey (2MASS; Quillen et al. 2014), Catalina Sky Survey (CSS; Drake et al. 2014), the Super Wide Angle Search for Planets (SuperWASP) program§, and the Convection, Rotation and planetary Transits (CoRoT) space mission (Poretti et al. 2015). Candidates for classical Cepheids were also found during dedicated searches for variable objects in open clusters (e.g., Clark et al. 2015). Turner et al. (2009) informed about a small-amplitude Cepheid that displays remarkably similar properties to Polaris. Discoveries of several classical

---

†http://www.aerith.net/misao/index.html
‡http://www.aspylib.com/newsurvey/
§http://www.superwasp.org/
Cepheids based on NSVS or SuperWASP photometry were reported directly to the Variable Star Index (VSX, Watson et al. 2006) by A. Prokopovich in 2011, A. Ditkovsky in 2015, I. Sergey in 2015, and M. Bajer in 2018.

3 The List of Galactic Classical Cepheids

With this paper, we share the most up-to-date and carefully verified list of Galactic classical Cepheids. This is a continuation of the work presented in Pietrukowicz et al. (2013) when the list included 841 objects. Since then, several surveys have searched the sky for Cepheids and published their results. In the verification process, we visualized the light curves and checked several observational properties of the stars. Nearly all faint objects (10 < $I$ < 20 mag) come from two surveys, OGLE (southern sky) and ZTF (northern sky). Brighter objects (7 < $V$ < 17 mag) were inspected thanks to long-term $V$-band photometry from the ASAS and ASAS-SN surveys. In the case of about 40 brightest classical Cepheids in the sky, we downloaded $BVI$ light curves obtained by the American Association of Variable Star Observers (AAVSO). We cleaned the light curves from evident outlying points and corrected the periods using the TATRY code (Schwarzenberg-Czerny 1996).

The most important criteria used in the verification process were the characteristic shape and stability of the light curve. In ambiguous cases, we rely on the position of the variable star in the Fourier space (coefficient combinations $R_{21}$, $R_{31}$, $\phi_{21}$, and $\phi_{31}$ vs. pulsation period), its amplitude value, position in the sky, position in the color-magnitude diagram, and spectral type, if were available. In contrast to the fundamental-mode pulsators, first-overtone pulsators are more difficult to confirm, in particular in the period range from 2–3 days. In this range, the light curves have a nearly symmetric, quasi-sinusoidal shape at low amplitude. In the case of multi-mode pulsators, we checked their position in the Petersen diagram. A small fraction of variables detected by ground-based optical surveys like ASAS-SN and ZTF and classified as Cepheids by automatic classifiers are in fact of other types, such as eclipsing binaries and rotating (spotted) variables. Large-amplitude spotted (chromospherically active) variables can often mimic pulsations, but their light curves clearly change from season to season (Pietrukowicz et al. 2015). The automatic classifiers rarely make mistakes in proper classification between classical and type II Cepheids, but very often put anomalous Cepheids to the group of classical Cepheids. Anomalous Cepheids as intermediate-age or old objects can be present at high Galactic latitudes. Long-term ASAS-SN observations show that some GCVS objects require re-classification.

The list of Galactic classical Cepheids is available to the astronomical community through the OGLE Internet Data Archive:

https://www.astrouw.edu.pl/ogle/ogle4/OCVS/allGalCep.listID

In the file, for each Cepheid we provide name of the star together with the source of the name or survey, equatorial and galactic coordinates based on Gaia Celestial Reference Frame (Gaia Collaboration et al. 2021), pulsation mode or modes, period or periods in case of multi-mode pulsators, identifiers in the OGLE, ASAS, ASAS-SN, Gaia EDR3 catalogs, and mean $G$-band magnitude. If the Cepheid has a given GCVS designation, this name is treated as the official one, according to the recommendation of the International Astronomical

¶https://www.aavso.org/data-download
Union. If not, we provide the name given by the discovery survey team. We cross-matched our list of classical Cepheids with the Gaia EDR3 catalog by adopting a matching radius of 0.5′. Over 50 objects without a counterpart were inspected individually. There is no Gaia EDR3 identifier for four classical Cepheids, extremely bright Polaris and three faint classical Cepheids toward the Galactic bulge. There is no G-band information for fifteen Cepheids. According to Gaia Collaboration et al. (2021), the source list published with Gaia EDR3 in December 2020 will be the same for Gaia DR3 planned for the first half of 2022.

In Table 1, we summarize the number of Milky Way’s classical Cepheids discovered by various surveys.

Table 1: Census of known Galactic classical Cepheids with information on the source of data

| Source/Survey | Number |
|---------------|--------|
| GCVS          | 737    |
| ASAS          | 108    |
| NSVS          | 40     |
| OGLE          | 1690   |
| ATLAS         | 139    |
| ASAS-SN       | 161    |
| WISE          | 12     |
| Gaia-DR2      | 5      |
| VVV           | 21     |
| ZTF-DR2       | 422    |
| other         | 17     |
| **Total**     | 3352   |

4 Observational Properties of Classical Cepheids

In this section, we analyse selected observational properties and provide some statistics on the Galactic classical Cepheids. In Fig. 1, we show a map of all known 3352 classical Cepheids in galactic coordinates. These stars as representatives of the young Milky Way’s component (the thin disk) concentrate around the Galactic plane. In the distribution presented in Fig. 2, we count the stars in 8°-wide bins along the galactic longitude. The lowest number of stars is observed, not surprisingly, in the direction of the anticenter. Two maxima, the highest one around $l = -72°$ and a smaller one at $l \approx +48°$, correspond to the inner edge of the tangent lines to the Carina arm and Sagittarius arm, respectively (Vallée 2017). Hundreds of unknown classical Cepheids likely reside between the two tangent lines, but are hidden behind clouds of dust. There is a local minimum in the Cepheid distribution around $l = +80°$, also visible in the map. The minimum coincides with a structure called the Northern Coalsack in constellation Cygnus. It is a unique area in the Galactic disk worth variability exploration in near-infrared bands.

In Fig. 3, we present mean G-band brightness distributions for all (but the mentioned fifteen) known Galactic classical Cepheids and, separately, for stars pulsating in the fundamental mode only. Both distributions have the maximum around $G = 16$ mag. We divided each of the two sets of stars into two complementary parts, stars from highly reddened Galactic area ($-80° < l < +50°$, $-2° < b < +2°$) and stars outside this area. The maximum of the distribution for
Fig. 1. Distribution, in Galactic coordinates, of 3352 optically confirmed classical Cepheids residing in the Milky Way.
fundamental-mode Cepheids in the highly-reddened regions reaches $G \approx 18$ mag (red histogram in the lower panel in Fig. 3). The distribution for fundamental-mode pulsators from mildly reddened regions (blue histogram in the same panel) is nearly symmetric around $G = 14.5$ mag, which suggests that searches for Cepheids in those regions are highly complete.

In Fig. 4, we compare period distributions of fundamental-mode and first-overtone classical Cepheids from four galaxies in the Local Group: the Large and Small Magellanic Clouds (Soszyński et al. 2015), Milky Way (this work), and M31 (Kodric et al. 2018). The distributions of fundamental-mode pulsators from the Milky Way (2140 stars) and M31 (1662 stars) look remarkably similar to each other. The differences are that the maximum of the M31 distribution is slightly shifted toward longer periods and that there is a notable deficit of Milky Way’s Cepheids around $P \approx 10$ d. The number of known M31 first-overtone Cepheids is three times smaller than the number of Galactic pulsators of this type (307 vs. 924). Due to low luminosity of short-period Cepheids, the current sample of M31 overtone Cepheids is far from being complete and its period distribution starts at a relatively high value, from about $P \approx 1.5$ d. It seems that there are missing first-overtone Cepheids around the maximum in the distribution for Milky Way or stars with periods of about 3 days. In contrast to the Milky Way and M31, the collections of classical Cepheids for nearby Magellanic Clouds are complete. The shapes of the distributions for the two irregular galaxies are quite similar to each other, but differ from the distributions for the large spirals. The former are skewed toward shorter periods. The period shift in the distributions is evident in the fundamental-mode as well as first-overtone Cepheids. This effect results from different metallicity of the investigated galaxies—the higher metal content, the longer period of the maximum distribution.

In Fig. 5, we present a period–amplitude diagram based on $I$-band observations from the OGLE survey for 1027 fundamental-mode and 540 first-overtone Milky Way’s classical Cepheids. Nearly all variables have full amplitudes higher than 0.1 mag in $I$. There are fundamental-mode stars with amplitudes reaching 1.0 mag, but most of this type of pulsators have amplitudes between 0.3 and 0.8 mag. The first-overtone Cepheids usually pulsate with amplitudes from 0.1 to 0.35 mag, but may reach 0.6 mag. We cannot exclude that there are more
Fig. 3. Mean $G$-band brightness distributions (black histograms) for all known (upper panel) and fundamental-mode Galactic classical Cepheids (lower panel). In each panel, stars are divided into two complementary groups depending on their location in the sky: highly obscured regions (red) and mildly obscured regions (blue), as shown in the inset maps.

Cepheids with amplitudes below 0.1 mag.

Fig. 6 shows where we can find fundamental-mode and first-overtone classical Cepheids in the Fourier parameter space. The following Fourier parameter combinations were calculated for $I$-band light curves from OGLE: $R_{21} = A_2/A_1$, $R_{31} = A_3/A_1$, $\phi_{21} = \phi_2 - 2\phi_1$, and $\phi_{31} = \phi_3 - 3\phi_1$, where $A_i$ and $\phi_i$ are parameters of the cosine Fourier series fitted to the light curves. Parameters derived from $V$-band observations may differ slightly. Fundamental-mode Cepheids with periods around 10 days have nearly symmetric light curves. Similar situation is for first-overtone Cepheids with periods at approximately 3 days. Around these periods, the $R_{21}$ and $R_{31}$ ratios are close to zero, $\phi_{21}$ and $\phi_{31}$ combinations dramatically change around zero, and amplitudes of the stars are lower (see Fig. 5).

Multi-mode Cepheids have specific period ratios. This is illustrated in the Petersen diagram in Fig. 7, in which we plot the shorter-to-longer period ratio in the function of logarithm of the longer period for classical Cepheids from the Milky Way, LMC, and SMC. The points form characteristic sequences for various period ratios. The sequence representing 1O+2O pulsators is tight, in contrast to the sequence for F+1O pulsators which is strongly metal-dependent. This is well seen when one compares stars from the three galaxies. The sequences
Fig. 4. Pulsation period distributions for fundamental-mode (upper panel) and first-overtone classical Cepheids (lower panel) from the SMC, LMC, Milky Way, and M31.

shift with the metallicity. In general, the period ratios are higher for stars in more metal-poor environments at a given period.

In Table 2, we provide information on numbers of Galactic classical Cepheids pulsating in various modes and their combinations. Single-mode pulsators is the most common group of stars (91.4 per cent), while triple-mode pulsators are very rare (0.3 per cent). In the whole set of variables, fundamental-mode pulsators constitute 63.8 per cent. A detailed comparison between the collections of classical Cepheids from the Milky Way, M31, and Magellanic Clouds is presented in Table 3. If the real fraction of first-overtone Cepheids is slightly higher than one-third, as observed in the Magellanic Clouds, then many such pulsators in our Galaxy are yet to be discovered. Observations of the Magellanic Clouds also indicate that second-overtone Cepheids are not extremely rare and more of them should exist in the Milky Way. Very recently, Rathour et al. (2021) performed a frequency analysis of OGLE-IV photometry for Galactic classical Cepheids and detected possible additional radial and non-radial modes in nearly forty pulsators. However, the presence of new frequencies requires confirmation once new brightness measurements are collected.

Below, we provide some interesting records referring to the Galactic classical Cepheids.

\footnote{Due to the Covid-19 pandemic, OGLE stopped regular observations on 18 March 2020.}
Fig. 5. Period–amplitude diagram for fundamental-mode (red points) and first-overtone Galactic classical Cepheids (blue points).

Table 2: Census of Galactic classical Cepheids pulsating in various modes and their combinations: fundamental mode (F), first overtone (1O), second overtone (2O), and non-radial 0.62-mode (X)

| Mode(s)        | Number of stars |
|----------------|-----------------|
| F             | 2140            |
| 1O            | 924             |
| 2O            | 1               |
| F+1O          | 93              |
| 1O+2O         | 180             |
| 1O+X          | 1               |
| 2O+3O         | 2               |
| F+1O+2O       | 3               |
| 1O+2O+3O      | 8               |
| **Total**     | **3352**        |

- $\beta$ Dor has the highest absolute galactic latitude ($b = -32.77^\circ$).
- The brightest classical Cepheid in the sky is Polaris.
- S Vul is a fundamental-mode pulsator with the longest period of 68.651 d.
Fig. 6. Fourier coefficient combinations $R_{21}$, $R_{31}$, $\phi_{21}$, and $\phi_{31}$ as a function of the logarithm of the pulsation period for fundamental-mode (red points) and first-overtone Galactic classical Cepheids (blue points) observed by the OGLE survey. Only objects with at least 50 $I$-band measurements and brighter than $I = 18$ mag are shown.

Table 3: Incidence rates for known classical Cepheids in four Local Group galaxies

| Galaxy     | Total | F (%) | 1O (%) | 2O (%) | multi-mode (%) |
|------------|-------|-------|--------|--------|----------------|
| Milky Way  | 3352  | 2410  | (72.2) | 924 (27.6) | 1 (0.03)       |
| M31        | 1969  | 1662  | (84.4) | 307 (15.6) | ?              |
| LMC        | 4706  | 2477  | (52.6) | 1776 (37.7) | 26 (0.55)       |
| SMC        | 4944  | 2754  | (55.7) | 1791 (36.2) | 91 (1.84)       |

- OGLE-GD-CEP-1628 is a first-overtone pulsator with the longest period of 9.437 d.
- V473 Lyr is the only known single-mode Cepheid pulsating in the second overtone.

5 Purity and Completeness of the List

It is difficult to determine purity of a list of objects constructed based on various catalogs. To estimate it, we can use the most reach and uniform source of Galactic classical Cepheids, the OGLE collection. We found that 10 detections
Fig. 7. Petersen diagram with the positions of multi-mode radially pulsating classical Cepheids from the Milky Way (black filled symbols), LMC (dark green open symbols) and SMC (open orange symbols). Circles represent double-mode pulsators (F+1O, 1O+2O, and 2O+3O), while triangles represent triple-mode pulsators (F+1O+2O and 1O+2O+3O). Location of the sequences of stars clearly depends on the metal content of the environment.

out of 1973 stars were in fact artifacts in the vicinity of much brighter real Cepheids saturated in OGLE-IV images. Additional 47 objects were noted as uncertain cases in Soszyński et al. (2020). This means that 1916 variables or 97.1 per cent of the sample are bona fide classical Cepheids. The purity of Cepheids pulsating in the fundamental mode solely is even higher, 1179/1201 or 98.2 per cent. The OGLE collection contains on average fainter objects than those from other optical catalogs, thus the estimated values can be treated as lower limits.

We decided to include in our list only classical Cepheids confirmed in the optical range. Verification of candidates for Galactic Cepheids from near-infrared VVV observations showed that more than a half of the objects are of other variability type. Out of 689 candidates for classical Cepheids in Dékány et al. (2019), 197 stars are present in OGLE images, of which 136 objects show periodic variations in the optical range. It turns out that only 63 variables are real classical Cepheids. The remaining variables are type II Cepheids (5 stars), rotating (23 stars) and eclipsing variables (17 stars), and stars of uncertain variability type (28). Accordingly, the purity of the near-infrared observations is only 46.3 per cent. The reason for this very low success rate is that near-infrared
light curves of pulsating stars have smoother, nearly-sinusoidal shapes, on average lower amplitudes, and more often can be confused with variables of other types. Large number of measurements and long-term stability of the light curve are required to properly classify the variables as classical Cepheids.

It is even more complicated to assess completeness of the presented list of classical Cepheids. The OGLE mosaic camera covers about 93 per cent of each OGLE-IV field. The remaining area are gaps between the CCD detectors. From the brightness distributions presented in Fig. 3 (drawn in red), we see that the census of Galactic fundamental-mode classical Cepheids is highly complete down to \( G = 18 \) mag. In mildly reddened regions (blue histograms in Fig. 3), practically all Cepheids are known. However, Fig. 4 shows that there are missing objects in the period distributions. There is a deficit of about 100 fundamental-mode pulsators with periods around 10 days and about 50 first-overtone pulsators with periods around 2.5 days. This is about 5 per cent of the F and 1O samples. Moreover, we cannot exclude that there are yet undiscovered low-amplitude Cepheids (<0.1 mag), similar to Polaris, that are entering or exiting the main instability strip. Several relatively bright (\( I < 12.5 \) mag) unknown classical Cepheids are expected to exist in the nearby Sagittarius arm since OGLE has conducted only a deep monitoring of the inner Galactic bulge. Overall, we can estimate that the completeness of the presented list of Cepheids is of about \( 0.95 \times 0.93 \) or 88 per cent down to \( G = 18 \) mag. This result refers to stars observed in the optical range, while hundreds of unknown classical Cepheids likely reside at the far side of the Milky Way’s disk hidden behind thick clouds of interstellar dust along spiral arms.

Acknowledgments. We thank Prof. Nikolai N. Samus for sending us information on Cepheids in the first GCVS edition. This research has been supported by the National Science Centre, Poland, grant MAESTRO 2016/22/A/ST9/00009 to I.S.

We used data from the European Space Agency (ESA) mission Gaia, processed by the Gaia Data Processing and Analysis Consortium (DPAC). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

REFERENCES

Anderson, R.I., Saio, H., Ekström, S., Georgy, C., and Meynet, G. 2016, *Astron. Astrophys.*, 591, A8.
Bellm, E.C. *et al.* 2019, *P.A.S.P.*, 131, 018002.
Benkő, J.M., and Csabry Z. 2007, *Acta Astron.*, 57, 73.
Bono, G., Caputo, F., Marconi, M., and Musella, I. 2010, *Astrophys. J.*, 715, 277.
Bruntt, H., Evans, N.R., Stello, D. *et al.* 2008, *Astrophys. J.*, 683, 433.
Chen, X., Wang, S., Deng, L., de Grijs, R., and Yang, M. 2018, *Astrophys. J. Suppl. Ser.*, 237, 28.
Chen, X., Wang, S., Deng, L., de Grijs, R., Yang, M., and Tian, H. 2020, *Astrophys. J. Suppl. Ser.*, 249, 18.
Clark, J.S., *et al.* 2015, *Astron. Astrophys.*, 584, L12.
Clementini, G., *et al.* 2019, *Astron. Astrophys.*, 622, A60.
Dékány, I., *et al.* 2015a, *Astrophys. J.*, 799, L11.
Dékány, I., *et al.* 2015b, *Astrophys. J.*, 812, L29.
Dékány, I., Hajdu, G., Grebel, E.K., and Catelan, M. 2019, *Astrophys. J.*, 883, 58.
Dambis, A.K., *et al.* 2015, *Astronomy Letters*, 41, 489.
Deiries, F., *et al.* 2002, *Astron. Astrophys.*, 389, 149.
Drake, A.J., *et al.* 2014, *Astrophys. J. Suppl. Ser.*, 213, 9.
Freedman, W.L. 2021, *Astrophys. J.*, arXiv:2106.15656.
Gaia Collaboration, *et al.* 2018, *Astron. Astrophys.*, 616, 1.
Gaia Collaboration, et al. 2021, Astron. Astrophys., 649, A1.
Genovali, K., et al. 2015, Astron. Astrophys., 580, A17.
Heinze, A.N., et al. 2018, AJ, 156, 241.
Hoffman, D.I., Harrison, T.E., and McNamara, B.J. 2009, Astron. J., 138, 466.
Inno, L., et al. 2016, Astrophys. J., 832, 176.
Jacyszyn-Dobrzeniecka, A.M., et al. 2016, Acta Astron., 66, 149.
Jayasinghe, T., et al. 2018, MNRAS, 477, 3145.
Jayasinghe, T., et al. 2019, MNRAS, 486, 1907.
Jayasinghe, T., et al. 2020, MNRAS, 491, 13.
Kabath, P., et al. 2008, Astron. J., 136, 654.
Kabath, P., et al. 2009, Astron. J., 137, 3911.
Kochanek, C.S., et al. 2017, P.A.S.P., 129, 104502.
Kodric, M., et al. 2018, Astron. J., 156, 130.
Khruslov, A. V., and Kusakin, A. V. 2016, arXiv:1605.01313.
Kukarkin, B.V., and Parenago, P.P. 1948, Peremenye Zvezdy Prilozhenie, Izdatel’stvo AN SSSR, 80.
Kuzmin, M. L. 2008, General Catalogue of Variable Stars, First Edition, Moscow and Leningrad, Izdatel’stvo AN SSSR, 654.
Kuzmin, M. L. 2008, Peremennye Zvezdy Prilozenienie, 8, 1.
Matsunaga, N., et al. 2011, Nature, 477, 188.
Matsunaga, N., et al. 2016, MNRAS, 462, 414.
Minniti, D. et al. 2010, New Astronomy, 15, 433.
Mohlář L., and Szabados L. 2014, MNRAS, 442, 3222.
Moskalik, P., and Kohaczewski, Z. 2009, MNRAS, 394, 1649.
Mróz, P., et al. 2019, Astrophys. J., 870, L10.
Pietrukowicz, P., et al. 2013, Acta Astron., 63, 379.
Pietrukowicz, P., et al. 2015, Astrophys. J., 813, L40.
Pietrzyński, G., et al. 2010, Nature, 468, 542.
Pilecki, B., et al. 2021, Astrophys. J., 910, 118.
Pojmanski, G. 1997, Acta Astron., 47, 467.
Pojmanski, G. 2002, Acta Astron., 52, 397.
Pojmanski, G. 2003, Acta Astron., 53, 341.
Pojmanski, G., and Maciejewski, G. 2004, Acta Astron., 54, 153.
Pojmanski, G., and Maciejewski, G. 2005, Acta Astron., 55, 97.
Pojmanski, G., Pilecki, B., and Szczygiel, D.M. 2005, Acta Astron., 55, 275.
Poretti, E., et al. 2015, MNRAS, 454, 849.
Quillen, A.C., et al. 2014, MNRAS, 441, 2691.
Rathour, R.S., Smolec, R., and Netzel, H. 2021, MNRAS, 505, 5412.
Riess, A.G., Casertano, S., Yuan, W., Macri, L.M., and Scolnic, D. 2019, Astrophys. J., 876, 85.
Samus, N.N., Kazarovets, E.V., Durlevich, O.V., Kizieva, N.N., and Pastukhova, E.N. 2017, Astronomy Reports, 61, 80.
Schwarzenberg-Czeny, A. 1996, Astrophys. J., 460, L107.
Scowcroft, V., et al. 2013, Astrophys. J., 773, 106.
Shappee, B.J., et al. 2014, Astrophys. J., 788, 48.
Skowron, D.M., et al. 2019a, Science, 365, 478.
Skowron, D.M., et al. 2019b, Acta Astron., 69, 305.
Smolec, R., and Moskalik, P. 2010, Astron. Astrophys., 524, A40.
Smolec, R., et al. 2017, EPJ Web of Conferences, 152, 06003.
Soszyński, I., et al. 2008, Acta Astron., 58, 163.
Soszyński, I., et al. 2011, Acta Astron., 61, 28.
Soszyński, I., et al. 2015, Acta Astron., 65, 297.
Soszyński, I., et al. 2017, Acta Astron., 67, 297.
Soszyński, I., et al. 2020, Acta Astron., 70, 101.
Tanioka, S., Matsunaga, N., Fukue, K., Inno, L., Bono, G., and Kobayashi, N. 2017, Astrophys. J., 842, 104.
Tonry, J.L., et al. 2018, P.A.S.P., 130, 064505.
Turner, D.G., Majaess, D.J., Lane, D.J., Percy, J.R., English, D.A., and Huziak, R. 2009, Bulletin of the American Astron. Soc., 41, 302.
Udalski, A., et al. 2008, Acta Astron., 58, 69.
Udalski, A., et al. 2015, Acta Astron., 65, 1.
Udalski, A., et al. 2018, Acta Astron., 68, 315.
Vallée, J.P. 2017, Astronomical Review, 13, 113.
Watson, C.L., Henden, A.A., and Price, A. 2006, Soc. Astron. Sci. Annu. Symp., 25, 47.
Woźniak, P.R., et al. 2004, Astron. J., 127, 2430.