Classical Pulsators in Large-Scale Optical Photometric Surveys

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The first large-scale, long-term sky variability surveys – EROS, MACHO, and OGLE – were launched a quarter of a century ago. Such projects have quickly revolutionized the studies on variables stars, in particular on classical pulsators. Hundreds of thousands of new Cepheids, RR Lyrae stars, and other pulsating variables have been discovered. These huge samples of pulsating stars contain objects of very rare and even previously unknown types. Well-sampled, long-term light curves have been used to identify and characterize exotic behaviors, evolutionary changes, and various statistical features of variable stars. The complete catalogs of pulsating standard candles have been used to study the structure and evolution of the Milky Way and other galaxies. We present the latest results on classical pulsating stars from the optical sky surveys, with particular focus on the OGLE project that collected a long-term photometric database for nearly one million variable stars.

1 Introduction

In the last quarter of a century, large-scale ground-based photometric sky surveys has become increasingly relevant for research on stellar pulsation. Three such surveys – EROS, MACHO, and OGLE – were initiated in the early 1990s in response to the Paczyński's (1986) call, who proposed to arrange a search for gravitational microlensing events as a method to detect compact dark matter objects in the Galactic halo. In the following years, these three surveys not only established a new observational branch in astrophysics – the field of gravitational microlensing – but also proved to be a goldmine for stellar variability studies.

The main goal of the microlensing surveys was a constant photometric monitoring of millions of stars in the densest stellar fields of the sky: the Galactic bulge and Magellanic Clouds. All these surveys used 1-meter-class telescopes located in good astronomical sites. EROS (Expérience pour la Recherche d'Objets Sombres, Aubourg et al., 1993) was a French collaboration involving particle physicists and astrophysicists. The project was conducted from 1990 to 2003, and it was divided into two stages: EROS-1 (1990–1994) and EROS-2 (1996–2003). During the second stage, the dedicated 1-meter Marly telescope at the ESO La Silla Observatory was used. The telescope was equipped with two mosaic cameras, allowing simultaneous imaging in two non-standard passbands. EROS-2 collected time-series observations for about 87 million point sources.

MACHO (Alcock et al., 1993) was another microlensing survey, whose acronym stands for MAssive Compact Halo Objects. It was the US-English-Australian collaboration, which used the dedicated 1.3-m telescope at Mount Stromlo Observatory, Australia, from 1992 to 1999. The survey collected about 100 000 images of the Galactic bulge and Magellanic Clouds, monitoring brightness of about 62 million stars.

The third of these pioneering microlensing surveys is still active and recently celebrated its 25th anniversary. The OGLE (Optical Gravitational Lensing Experiment) project has evolved over the years and now, in its fourth phase (OGLE-IV), it is one of the largest variability sky surveys in the world. Since 1997, all observations are taken with the 1.3-m Warsaw telescope located at Las Campanas Observatory, Chile. Since 2010, the telescope is equipped with a mosaic camera consisting of 32 CCD chips (2048×4096 pixels) covering a field of 1.4 square degree. Details of the OGLE telescope, camera, and data reduction pipeline are given by Udalski et al. (2015a).

OGLE has regularly observed a grid of fields that tile the Galactic bulge and disk, and the Magellanic Clouds, in total over 3000 square degrees in the sky. A typical crowded OGLE-IV field may contain up to several million stars, which gives a total number of more than one billion point sources photometrically monitored by the survey. The OGLE database contains about 10^{12} individual measurements in I and V passbands from the standard Johnson-Cousins photometric system. This data set has been a basis of the world's largest collection of variable stars, which currently consists of nearly one million objects in the Milky Way and in the Magellanic Clouds. About one tenth of the OGLE variables are classical pulsators – Cepheids and RR Lyrae stars.

The three pioneering microlensing projects became an inspiration for other large-scale variability surveys started in the next years. All these surveys have provided unprecedented observational material that revolutionized our knowledge of stellar variability. In the last 25 years, the number of known classical pulsators has increased by two orders of magnitudes: from thousands to hundreds of thousands. In this paper, we present the benefits that can be gained from studying such huge samples of pulsating stars: better understanding of their statistical properties, discoveries of extremely rare phenomena or previously unknown types of stellar variability, and thorough analyses of the structure of the Milky Way and other galaxies.

2 Classical Cepheids

The importance of classical Cepheids in modern astrophysics cannot be overstated. They serve as precise standard candles, tracers of the young stellar population, and testbeds for the theory of stellar pulsation and evolution. It is significant that the galaxies in which the most numerous samples of classical Cepheids are known as the Large (LMC) and Small Magellanic Clouds (SMC). Recently, the OGLE project presented a virtually complete list of classical Cepheids in the Magellanic System (Soszyński et al., 2017a) containing 9649 objects. Fig. 1 shows the positions of these stars in the sky. This sample is ten times more numerous than the list of all known classical Cepheids in the Milky Way.

The OGLE Cepheids and other variable stars are made publicly available by means of the OGLE Collection of Variable Stars (OCVS). About one million variable stars in the Milky Way and Magellanic Clouds are currently stored in the OCVS. Nearly one hundred thousand of them are classical pulsators. The OCVS is available

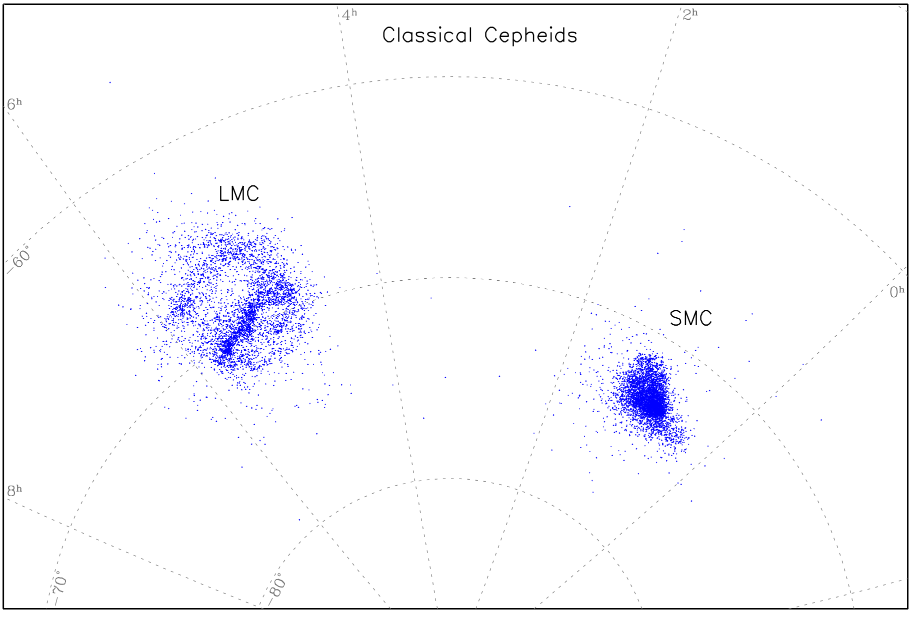

Fig. 1: Sky map showing the positions of virtually all classical Cepheids in the Large and Small Magellanic Clouds (Soszyński et al., 2017a).

through the WWW page or the FTP site:

http://ogledb.astrouw.edu.pl/∼ogle/OCVS/
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/

The catalog data include basic parameters of the stars (coordinates, periods, mean magnitudes, amplitudes, parameters of the Fourier light curve decomposition), time-series *VI* photometry, and finding charts.

The famous period–luminosity (PL) relations for Cepheids were discovered in the Magellanic Clouds (Leavitt, 1908) and both galaxies still play a key role in the calibration of these relations and in the studying of their linearity. The MACHO project was the first who plotted the PL diagram in which two separate relations – for fundamental-mode and first-overtone Cepheids – were clearly visible (Alcock et al., 1999). In the newest diagram (Soszyński et al., 2015), as many as four PL relations obeyed by classical Cepheids can be distinguished. The non-linearity of the PL relation was first noticed in the EROS data (Bauer et al., 1999). Since then, this topic was presented in countless papers (e.g. Ngeow et al., 2009; Bhardwaj et al., 2016), usually using the OGLE collection of Cepheids.

An unbiased view of classical Cepheids in the Magellanic Clouds was used to examine the structure of these galaxies in three dimensions (Jacyszyn-Dobrzeniecka et al., 2016). Several classical Cepheids were also detected in the region between the Magellanic Clouds – in the so called Magellanic Bridge – which confirmed the presence of the young stellar population in this area.

Studies of the multi-mode oscillations of Cepheids benefited the most from the long-term monitoring by the large-scale photometric surveys. In their pioneering work, the MACHO team (Alcock et al., 1995) reported the discovery of 45 double-mode Cepheids – four times more than was previously known. In the latest edition of the OCVS (Soszyński et al., 2015, 2017a) there are more than 750 multi-mode Cepheids, among them previously unknown types of double-mode pulsators (1O/3O and 2O/3O pulsators) and triple-mode Cepheids. Also, the non-radial modes have been reliably identified in classical Cepheids (Dziembowski, 2016).

Eclipsing binary systems containing pulsating components deserve special attention, since they enable the determination of the fundamental physical properties of the stars, like masses and radii, to a high degree of accuracy. About ten classical Cepheids in eclipsing binary systems are currently known in the Universe (although not all of them have been spectroscopically confirmed), and all of them were discovered in the OGLE databases (Udalski et al., 2015b). Extensive follow-up spectroscopic campaigns of these objects has been organized by the "Araucaria" project (Gieren et al., 2005). These studies greatly contributed to the solution of the so-called Cepheid mass discrepancy problem (Pietrzyński et al., 2010).

The number of known classical Cepheids in the Milky Way will soon be significantly increased due to the OGLE Galaxy Variability Survey (Udalski, 2017), which covers the entire Galactic bulge and about 2000 square degrees in the Galactic disk. The already published classical Cepheids toward the Galactic bulge led to the discovery of the flared outer disk of the Milky Way (Feast et al., 2014).

3 Type II Cepheids

Type II Cepheids are much less numerous than their classical cousins, and moreover this class of variable stars is divided into three groups, each one with a different evolutionary history. BL Her stars are on their way from the horizontal to the asymptotic giant branch (AGB), W Vir stars probably move bluewards from the AGB due to thermal pulses, and RV Tau stars evolve away from the AGB towards the white dwarf domain. Actually, this latter group joined other type II Cepheids only when Alcock et al. (1998) discovered the first RV Tau stars in the LMC and showed that they obey the same PL relation as BL Her and W Vir stars.

The OGLE team identified more than a thousand type II Cepheids in the Magellanic Clouds and in the Galactic bulge (Soszyński et al., 2008, 2017b). The greatest achievement in this field was an identification of a new subgroup of type II Cepheids, called peculiar W Vir stars (Soszyński et al., 2008). This group of pulsating stars have distinctive light curves and are brighter and bluer than ordinary W Vir variables. Moreover, a large fraction of peculiar W Vir variables (at least 30%) show eclipsing or ellipsoidal modulation, which indicates that they are members of binary systems. It suggests that the evolution in the binary systems is the factor that led these stars to the instability strip.

4 Anomalous Cepheids

The rarest type of classical pulsators – anomalous Cepheids – are fundamental-mode or first-overtone single-mode pulsating stars with periods ranging from a few tenths to about 2.5 days, and luminosities that place them between classical and type II Cepheids in the PL diagram. For years, anomalous Cepheids have only been observed in nearby dwarf galaxies. Soszyński et al. (2008) discovered the first anomalous

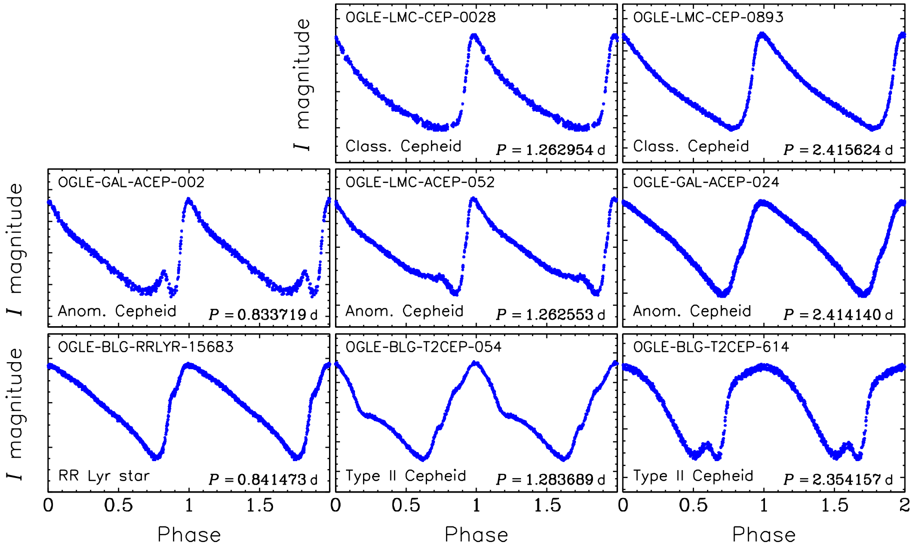

Fig. 2: How to distinguish between different types of classical pulsators? Example *I*-band light curves of fundamental-mode classical pulsators: classical Cepheids (upper panels), anomalous Cepheids (middle panels), an RR Lyrae star and type II Cepheids (lower panels). Each column contains light curves with similar periods.

Cepheids in the LMC and in the latest edition of the OCVS (Soszyński et al., 2017a) as many as 262 such stars in both Magellanic Clouds have been included. This sample has multiplied the number of known anomalous Cepheids in the Universe.

The richest known samples of Cepheids and RR Lyrae stars in the Magellanic Clouds allowed us to study the morphology of their light curves (Fig. 2). It resulted in the development of a method of distinguishing between various types of classical pulsators based on their light curve shapes quantified by the Fourier coefficients ϕ_{21} and ϕ_{31}. We used this method to identify in the OGLE data 27 anomalous Cepheid belonging to the Milky Way: 7 in the foreground of the Magellanic Clouds (Soszyński et al., 2017a) and 20 in the Galactic bulge (Soszyński et al., 2017b). These are the first unambiguously identified anomalous Cepheids in the field of our Galaxy.

5 RR Lyrae Stars

RR Lyrae stars have been widely used as a tool for determining distances inside and outside the Milky Way and studying the history of star formation and structure of our and other galaxies. To date, OGLE detected more than 80 000 RR Lyrae stars in the Galactic bulge and Magellanic Clouds. The homogeneous, long-term OGLE photometry was used for the identification of unique objects, such as triple-mode pulsators (Smolec et al., 2015; Soszyński et al., 2017b), RR Lyrae stars showing non-radial modes (Netzel et al., 2015), objects that experienced a mode switching (from RRd to RRab or vice versa, Soszyński et al., 2014), or light-time effects in binary system hosting RR Lyrae stars (Hajdu et al., 2015).

Careful analysis of the double-mode RR Lyrae variables led to the discovery of a new sub-class, tentatively called anomalous RRd stars (Soszyński et al., 2016). This group of pulsators are characterized with different period and amplitude ratios than "regular" RRd stars and usually the presence of the Blazhko modulation.

The OGLE RR Lyrae stars in the Magellanic Clouds and Galactic bulge were used to map the structures of these stellar environments built by the oldest stars (Pietrukowicz et al., 2015; Jacyszyn-Dobrzeniecka et al., 2017). Rich populations of RR Lyrae stars were also found by various surveys in the Galactic halo. The solar neighborhood has been sampled by shallow all-sky surveys, like ASAS and SuperWASP. The ASAS project (All-Sky Automated Survey, Pojmanski, 1997) is historically one of the first such shallow surveys aimed at monitoring a large part of the sky for variability. The ASAS Catalog of Variable Stars increased the number of known variable stars brighter than 13 mag by an order of magnitude. Szczygieł et al. (2009) investigated 1455 nearby (up to 4 kpc from the Sun) RR Lyrae stars from the ASAS project. They found a clear manifestation of the Oosterhoff dichotomy among field RR Lyrae stars in the surroundings of the Sun.

Nearly 5000 bright RRab stars were recently found by Greer et al. (2017) in the SuperWASP database. The SuperWASP (Wide Angle Search for Planets) project (Pollacco et al., 2006) is a sky survey dedicated to the search for exoplanets, but due to the impressive short cadence, the SuperWASP data are very useful also for the variable star analyses. The project uses two robotic observatories (located in the Canary Islands and in South Africa), each consisting of eight wide-angle 20-cm cameras. The project monitors the entire sky with the exception of the Galactic plane. Greer et al. (2017) performed a statistical analysis of the Blazhko variables, which constitute about 20% of the total SuperWASP sample.

Much deeper photometry is produced by the Catalina Sky Survey (Larson et al., 2003), which is devoted to a search for near-Earth objects with a particular emphasis on potentially hazardous asteroids. The project is conducted since 2003 using three telescopes located in the USA and Australia. The survey covers most of the sky with the exception of regions within 15 degrees of the Galactic plane.

Drake et al. (2013b,a, 2017) and Torrealba et al. (2015) found in total about 43 500 RR Lyrae stars of all types, including about 33 000 RRab variables, in the Catalina databases. These objects were used to study the structure of the Galactic halo and to trace halo streams and nearby dwarf galaxies.

An even larger sample of about 45 000 RRab stars in the Galactic halo was found in the databases collected by the Pan-STARRS1 3π survey (Chambers, 2011). This deep optical survey covers about three-quarters of the sky (declination $> -30°$). Sesar et al. (2017a) succeeded to select a significant sample of RR Lyrae stars in a time series containing only up to 12 epochs per filter. The purity and completeness of the sample was estimated to be 90% and 80%, respectively, for RRab stars at the distance 80 kpc from the Sun and for Galactic latitudes $|b| > 10°$. These data set was used by Sesar et al. (2017b) for a detailed study of the Sagittarius Stream morphology.

6 Conclusions

Ground-based, large-scale, optical sky surveys revolutionized the variable star research in the last two decades. This breakthrough is clearly visible in Fig. 3, which shows how many classical pulsators have been known in the Magellanic Clouds since

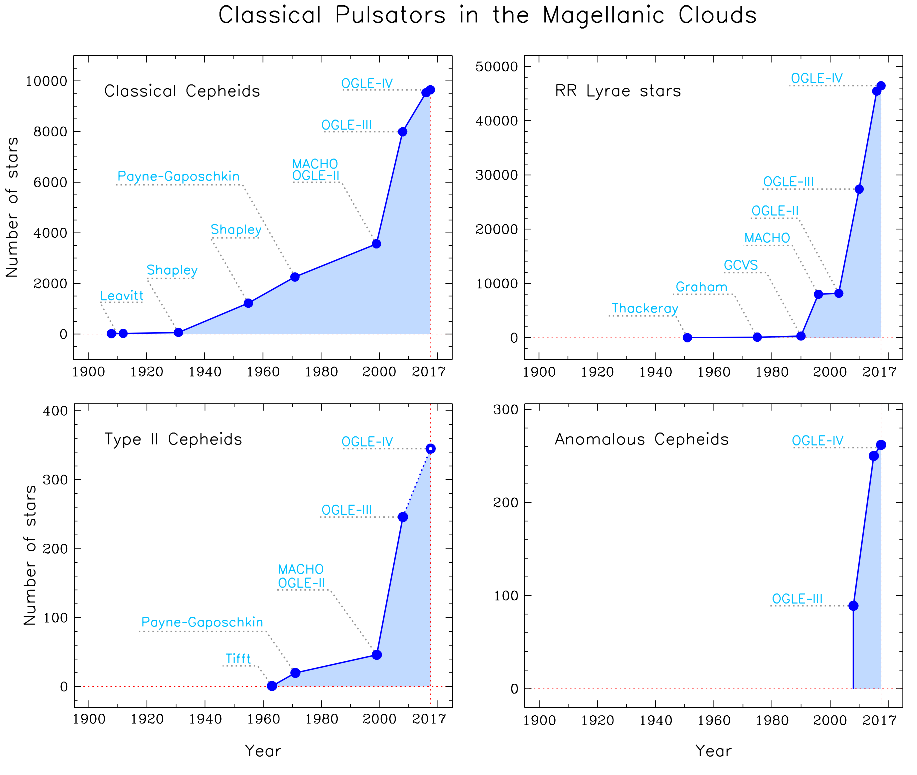

Fig. 3: Number of known classical pulsators in the Magellanic Clouds since the beginning of the twentieth century. Successive panels show: classical Cepheids, RR Lyrae stars, type II Cepheids, and anomalous Cepheids.

the beginning of the twentieth century. The sky variability surveys, in particular the OGLE project, have multiplied the number of known Cepheids and RR Lyrae stars in the Magellanic System, and now the distributions presented in Fig. 3 have reached almost the maximum value – practically all classical pulsators in these galaxies are already cataloged. Moreover, the long-term light curves in the standard *VI* passbands of these stars are publicly available through the OCVS.

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