Mem. S.A.It. Vol. 86, 257

Memorie della

Variable stars from the OGLE survey

I. Soszyński[1], A. Udalski[1], M. K. Szymański[1], M. Kubiak[1], G. Pietrzyński[1,2], Ł. Wyrzykowski[1,3], K. Ulaczyk[1], R. Poleski[1], S. Kozłowski[1], P. Pietrukowicz[1], and J. Skowron[1]

[1] Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
e-mail: soszynsk@astrouw.edu.pl
[2] Universidad de Concepción, Departamento de Astronomía, Casilla 160–C, Concepción, Chile
[3] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

Abstract. Variable stars have long been recognized as excellent tracers of stellar populations. Large and complete samples of variable stars allow to study the spatial distribution of stellar populations of given ages, provide important clues to the star formation history, put constraints on stellar physical properties, and are used to determine distances. We would like to present a unique compilation of variable stars obtained from the long-term observations collected in the course of the Optical Gravitational Lensing Experiment (OGLE). Huge samples of classical, type II and anomalous Cepheids, RR Lyrae stars, long-period variables and other types of variable stars have been discovered in the Magellanic Clouds and in the Galactic bulge. We would also like to present first results from the fourth phase of the OGLE project (OGLE-IV) - a spatial distribution of variable stars in the wide region covering the Magellanic Clouds and the Magellanic Bridge connecting both galaxies.

Key words. Catalogs – Stars: variables: general – Stars: oscillations (including pulsations) – binaries: eclipsing – Magellanic Clouds

1. Introduction

In 1957 Walter Baade began his talk at the seminal Vatican conference with the sentence: "variable stars, in particular the cepheids and the cluster-type variables, have becoming increasingly important in the exploration of our own and other galaxies" (Baade 1958). More than 50 years later, this statement has lost none of its relevance. Variable stars are primary distance markers, traces of various stellar populations and indicators of stellar ages. They are commonly used to study the internal and external structure of stars, measure their masses, sizes, temperatures, chemical composition and other physical properties. When the analyzed samples of variable stars are large and have a high level of completeness, they provide invaluable information about the structure of stellar clusters and galaxies and give insight into the history of star formation.

The Optical Gravitational Lensing Experiment (OGLE) is a large-scale sky survey with a twenty-year-long history. The primary scientific goals of the project is the search for gravitational microlensing events, but a huge amount of high quality photometric data collected by the survey are ideal also for many other astrophysical purposes. During its long history the OGLE project contributed significantly to many various fields of observational astrophysics: gravitational lensing and microlensing, extrasolar planets, cosmic distance scale, structure of the Galaxy and Magellanic Clouds, stellar clusters, interstellar extinction, Kuiper Belt objects, etc. One of the most important results produced by OGLE were large catalogs of variable stars in the Magellanic Clouds, Galactic bulge and other important regions of the sky.

2. The Optical Gravitational Lensing Experiment

Historically, the OGLE project may be divided into several phases, each one connected with major upgrades of the observing capabilities of the survey. The first phase of the OGLE project (OGLE-I) was conducted between 1992 and 1995 on the 1-m Swope telescope at the Las Campanas Observatory in Chile. About 2 million stars were regularly monitored. This part of the survey resulted in catalogs of variable stars toward the Galactic bulge, globular clusters ω Cen and 47 Tuc, dwarf galaxies Sculptor and Sagittarius.

In January 1997 the OGLE survey entered its second phase (OGLE-II). The upgrade included a new 1.3-m Warsaw Telescope at the Las Campanas Observatory. The telescope, which is fully dedicated to the project, was equipped with the "first generation" 2048 × 2048 CCD camera working in the drift-scan mode. Compared to the previous stage, the observing capabilities of the project were increased by a factor of 30. The Magellanic Clouds were added to the list of regularly observed fields. The number of detected variable stars increased significantly in comparison with the OGLE-I project. Thousands of Cepheids, RR Lyr stars, eclipsing binaries and long-period variables were detected in the Magellanic Clouds and Galactic bulge.

The next upgrade of the project occurred in 2001. The Warsaw Telescope was equipped with a new mosaic camera consisting of eight 2048 × 4096 chips, which increased the sky coverage by an order of magnitude. OGLE-III regularly monitored the brightness of about 400 million stars in 170 square degrees of the sky. More than 235 000 frames were collected which occupy about 30 TB of disk space. On average, 500-800 photometric measurements per star were secured, however some fields were observed a few thousand times.

In spring 2010 the OGLE project entered its fourth phase (OGLE-IV). The eight-chip CCD camera was replaced with the next generation 32-chip mosaic camera covering the whole field of view of the Warsaw telescope – 1.4 square degrees. With much shorter reading time and better sensitivity the new camera has led to an order of magnitude larger data flow compared to OGLE-III. The new instrumental setup enables observations of much larger area of the sky and monitoring of selected fields with much better time resolution, up to 30 times per night. The number of regularly observed objects increased to about one billion, and the total size of collected raw images exceeds 30 TB per year. With these capabilities the OGLE-IV survey is among the largest optical surveys worldwide.

3. The OGLE Catalog of Variable Stars

The extraordinary data set collected by OGLE is a base of the most ambitious project currently conducted in the field of variable stars – the OGLE Catalog of Variable Stars (OCVS). The main goal of this project is to detect and classify all variable sources in the fields monitored by the OGLE survey. This area includes the bulge of the Milky Way, selected regions in the Galactic disk, and the Large (LMC) and Small Magellanic Clouds (SMC) with their far outskirts and the Magellanic Bridge connecting both galaxies. All parts of the OCVS published up to now contain in total over 400 000 variable stars, thus it is the largest catalog of variable stars in the history of astronomy. Table 1 lists all the parts of the OCVS published to date. All of these samples of variable stars were discovered from the photomet-

Table 1. Published parts of the OGLE Catalog of Variable Stars

Type of variable stars	Environment	Number of stars	Reference
Classical Cepheids	LMC	3 375	Soszyński et al. (2008a)
	SMC	4 630	Soszyński et al. (2010a)
	GB	32	Soszyński et al. (2011c)
Type II Cepheids	LMC	203	Soszyński et al. (2008b)
	SMC	43	Soszyński et al. (2010b)
	GB	335	Soszyński et al. (2011c)
Anomalous Cepheids	LMC	83	Soszyński et al. (2008b)
RR Lyrae stars	LMC	24 906	Soszyński et al. (2009a)
	SMC	2 475	Soszyński et al. (2010c)
	GB	16 836	Soszyński et al. (2011a)
Long-period variables	LMC	91 995	Soszyński et al. (2009b)
	SMC	19 384	Soszyński et al. (2011b)
	GB	234 260	Soszyński et al. in prep.
δ Scuti stars	LMC	2 786	Poleski et al. (2010a)
R CrB stars	LMC	23	Soszyński et al. (2009c)
Double-periodic variables	LMC	125	Poleski et al. (2010b)
Eclipsing variables	LMC	26 121	Graczyk et al. (2011)

ric data collected during the OGLE-III and earlier phases of the survey.

Most parts of the OCVS contain the largest sets of Cepheids, RR Lyrae stars, long-period variables, etc. found so far in any stellar environment. Analysis of large samples of variable stars in different stellar environments provides many benefits. First, a large number of objects of a given type allows to study their statistical properties. For example, the OGLE photometry is used to study in detail the period–luminosity relations for Cepheids (e.g. Storm et al. 2011; Matsunaga et al. 2011; Ngeow et al. 2012) and to detect new period–luminosity sequences followed by pulsating red giants (e.g. Soszyński et al. 2007). Second, large and complete samples of variable stars can be used to study the structure and evolution of stellar environments in which they are located, as well as to measure the distance to them and examine the distribution of interstellar matter along the line of sight (e.g. Pejcha & Stanek 2009; Haschke et al. 2012; Pietrukowicz et al. 2012).

Third, in huge samples of variable stars it is more likely to find objects of very rare subtypes or even those previously completely unknown. Many such exceptional objects were found in the OGLE databases. For example, Soszyński et al. (2008b) distinguished a new subclass of type II Cepheids (so called peculiar W Virginis stars), Soszyński et al. (2008a) found a new type of double-mode classical Cepheids (pulsating simultaneously in the first and third overtones), Soszyński et al. (2008a, 2010a, 2011c) discovered in total ten cases of very rare triple-mode Cepheids, Mennickent et al. (2003) discovered a new phenomenon in some semi-detached binary systems – the secondary long periods on average 33 times longer than the orbital ones.

Particularly interesting objects discovered from the OGLE observations are pulsating stars that are components of eclipsing binary systems. Such objects allow measuring directly the physical parameters of pulsating stars, such as dynamical masses and radii. Recently, two

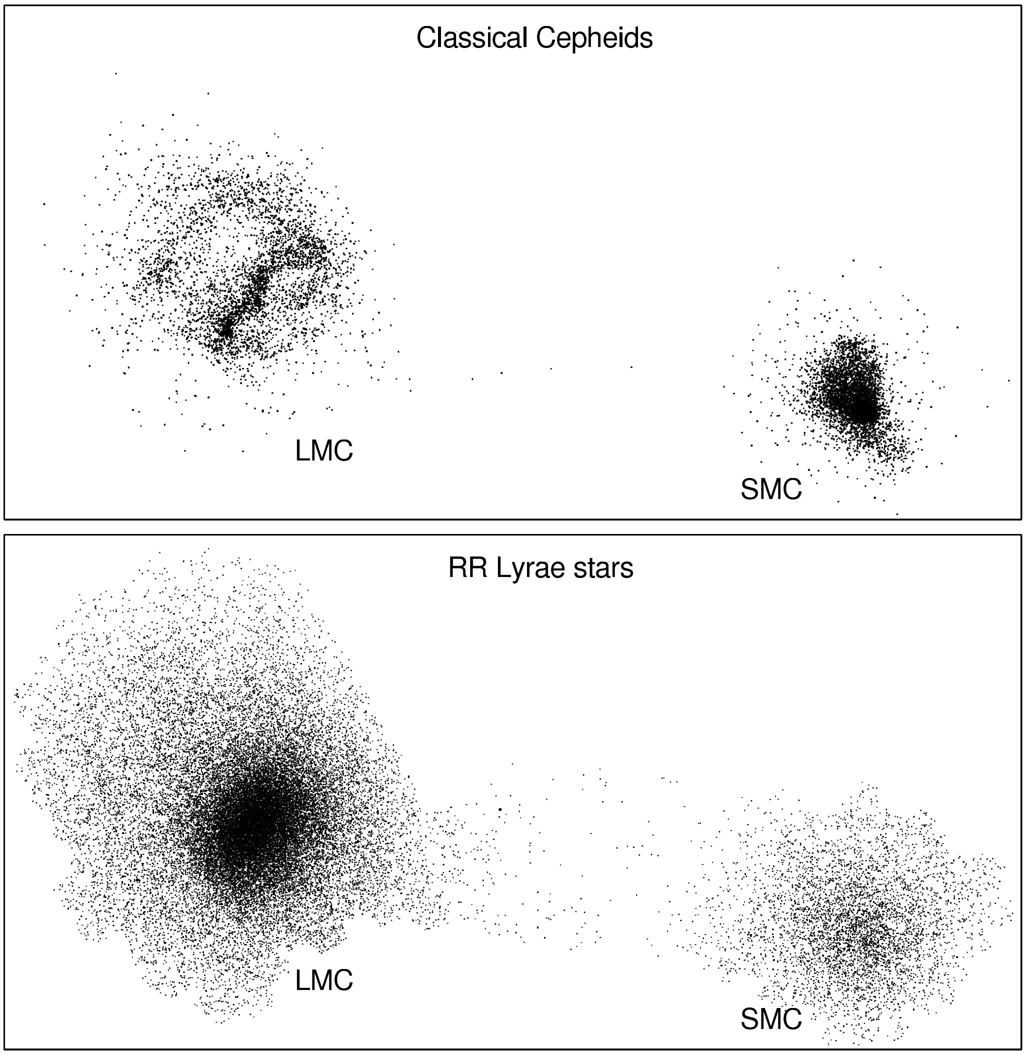

Fig. 1. Spatial distribution of classical Cepheids (upper panel) and RR Lyrae stars (lower panel) in OGLE-IV fields in the Magellanic System.

of the classical Cepheids in the eclipsing binary systems discovered by the OGLE survey (Soszyński et al. 2008a) were used to measure the Cepheid masses with unprecedented accuracy of 1% (Pietrzyński et al. 2010, 2011). This measurement solved the Cepheid mass discrepancy problem – the long-lasting disagreement between mass estimates obtained from pulsational and stellar evolution models.

Another interesting object was a candidate for an RR Lyrae star in an eclipsing binary system discovered in the Galactic bulge by Soszyński et al. (2011a). This case was recently spectroscopically investigated by Pietrzyński et al. (2012), who found a very unexpected low mass value for the pulsating component of only 0.26 $M_{\odot}$, incompatible with the theoretical predictions. Thus, the pulsating star cannot be a classical RR Lyrae variable (i.e. a star burning helium to carbon in its core), although it is indistinguishable in its period and light curve shape from a typical RR Lyrae star. This object is the first representative of a new evolutionary channel of the pulsating stars production – habitants of the classical instability strip which mimic classical RR Lyrae variables, but have a completely different origin. Thus, there is still no any definitive RR Lyrae star discovered in an eclipsing binary system, so our knowledge of the masses of these important standard candles relies completely on stellar models.

4. First results from the OGLE-IV project

Currently conducted fourth phase of the OGLE project allows us to detect and study variable stars over a much larger area than in the previous stages of the project. Preliminary results of a search for classical Cepheids and RR Lyrae stars in the OGLE-IV fields covering the Magellanic System are presented in Fig. 1. The spatial distribution of classical Cepheids indicates that OGLE-IV fields cover the whole young stellar population in Large and Small Magellanic Clouds, thus our catalog contains nearly complete list of Cepheid in these galaxies. It is worth noting that in the Magellanic Bridge spreading between both Clouds we identified several classical Cepheids. This fact is important for the investigations on the history of star formation and the interactions between both galaxies.

On the other hand, the distribution of RR Lyrae stars shown in the lower panel of Fig. 1 suggests that the OGLE-IV fields do not entirely cover the extended halos of old stellar population in the Magellanic Clouds. Therefore, we recently decided to significantly expand our sky coverage in the Magellanic System by adding additional fields around the existing fields. On a time scale of one year we should collect enough amount of data to search for RR Lyrae stars and other variables in these far outskirts of the Magellanic Clouds.

Acknowledgements. The OGLE project has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement no. 246678 to AU. This work has been supported by the Polish National Science Centre grant no. DEC-2011/03/B/ST9/02573.

References

Baade, W. 1958, Ricerche Astron., 5, 165
Graczyk, D., Soszyński, I., Poleski, R., et al. 2011, Acta Astron., 61, 103
Haschke, R., Grebel, E. K., & Duffau, S. 2012, AJ, 144, 106
Matsunaga, N., Feast, M. W., & Soszyński, I. 2011, MNRAS, 413, 223
Mennickent, R. E., et al. 2003, A&A, 399, L47
Ngeow, C.-C., Citro, D. M., & Kanbur, S. M. 2012, MNRAS, 420, 585
Pejcha, O., & Stanek, K. Z. 2009, ApJ, 704, 1730
Pietrukowicz, P., et al. 2012, ApJ, 750, 169
Pietrzyński, G., et al. 2010, Nature, 468, 542
Pietrzyński, G., et al. 2011, ApJ, 742, L20
Pietrzyński, G., et al. 2012, Nature, 484, 75
Poleski, R., et al. 2010a, Acta Astron., 60, 1
Poleski, R., et al. 2010b, Acta Astron., 60, 179
Soszyński, I., et al. 2007, Acta Astron., 57, 201
Soszyński, I., et al. 2008a, Acta Astron., 58, 163
Soszyński, I., et al. 2008b, Acta Astron., 58, 293
Soszyński, I., et al. 2009a, Acta Astron., 59, 1
Soszyński, I., et al. 2009b, Acta Astron., 59, 239
Soszyński, I., et al. 2009c, Acta Astron., 59, 335
Soszyński, I., et al. 2010a, Acta Astron., 60, 17
Soszyński, I., et al. 2010b, Acta Astron., 60, 91
Soszyński, I., et al. 2010c, Acta Astron., 60, 165
Soszyński, I., et al. 2011a, Acta Astron., 61, 1
Soszyński, I., et al. 2011b, Acta Astron., 61, 217
Soszyński, I., et al. 2011c, Acta Astron., 61, 285
Storm, J., et al. 2011, A&A, 534, A94