Contrib. Astron. Obs. Skalnaté Pleso **54/2**, 234 – 248, (2024)
https://doi.org/10.31577/caosp.2024.54.2.234

Three decades of the OGLE survey

I. Soszyński

Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4,
00-478 Warszawa, Poland (E-mail: soszynsk@astrouw.edu.pl)

Received: November 9, 2023; Accepted: December 17, 2023

Abstract. The Optical Gravitational Lensing Experiment (OGLE) is one of the most extensive sky surveys on a global scale. It focuses on optical astrophysical variability and is carried out using the dedicated 1.3-meter Warsaw Telescope located at Las Campanas Observatory in Chile. Since 1992, the OGLE project has been continuously observing the densest regions of the southern sky, namely, the Galactic bulge, Galactic disk, and Magellanic Clouds. To date, the survey has collected over a trillion individual photometric observations for approximately two billion stars. Throughout its long history, the OGLE project has yielded significant contributions to various fields of astrophysics, including gravitational lensing and microlensing, dark matter, exoplanets, variable stars, the structure of the Milky Way and other galaxies, and more. This article presents the most significant achievements of OGLE over the past 30 years.

Key words: Surveys – Gravitational microlensing – Planetary systems – Variable stars – Cepheids – Galaxy: structure – Catalogs

1. Introduction

The name of the Optical Gravitational Lensing Experiment (OGLE) project reflects its initial objective: the search for gravitational microlensing phenomena. However, over the course of its long history, the project has evolved, and presently, OGLE is a large-scale photometric survey aimed at identifying and studying all forms of variability in the sky. The OGLE project was initiated in 1992 in response to the seminal paper by Paczyński (1986), who introduced the theory of gravitational microlensing and suggested arranging an observational program aimed at monitoring the brightness of at least a few million stars with the goal of detecting the first microlensing events. Such a sky survey was designed to shed light on the nature of dark matter and to serve as a potential source of a substantial number of newly discovered variable stars.

Historically, the OGLE project has been divided into four phases. The initial phase of the survey (OGLE-I; Udalski *et al.*, 1992) was carried out from 1992 to 1995, using the 1-meter Swope telescope at Las Campanas Observatory in Chile. In 1996, a dedicated 1.3-meter Warsaw Telescope was constructed at the same observatory, marking the beginning of the second phase of the OGLE project (OGLE-II; Udalski *et al.*, 1997). The next milestone occurred in 2001,

Table 1. Four phases of the OGLE project

Phase of the project	Camera size [pixels]	Observed area [deg^2]	Number of stars [$\times 10^6$]	Data flow [TB/year]	Main targets
OGLE-I (1992–1995)	4M	1.5	6	0.09	Galactic bulge
OGLE-II (1997–2000)	4M	27	44	0.4	Galactic bulge Magellanic Clouds
OGLE-III (2001–2009)	64M	170	389	3.8	Galactic bulge Magellanic Clouds
OGLE-IV (2010–now)	256M	3600	2000	40	Galactic bulge Galactic disk Magellanic Clouds

when the Warsaw Telescope was equipped with an 8-chip mosaic CCD camera, which initiated the OGLE-III project (Udalski, 2003). Finally, in 2010, Andrzej Udalski, the leader of the OGLE project, designed and constructed a camera consisting of 32 CCD chips. Since then, the fourth phase of the OGLE project (OGLE-IV; Udalski *et al.*, 2015) has been conducted. Tab. 1 shows the progress that has been made between the successive phases of the OGLE project. The initiation of each new stage of the survey was associated with a tenfold enhancement of its observational capabilities. Over the past three decades, the number of monitored stars, the volume of collected data, and the area of the surveyed sky have been expanded by three orders of magnitude. Currently, OGLE ranks among the world's largest sky surveys dedicated to the exploration of celestial variability.

The OGLE-IV project monitors approximately two billion point sources across an area of about 3600 square degrees, encompassing the most densely populated stellar regions of the southern sky, including the central regions of the Milky Way, the Galactic disk, and the Large and Small Magellanic Clouds (LMC and SMC). The OGLE database presently contains approximately $1.2 \cdot 10^{12}$ individual photometric measurements, making it one of the largest photometric database in the history of astronomy. This huge dataset has served as the basis for numerous pioneering discoveries, some of which will be discussed in the following sections of this proceedings contribution.

2. Dark matter

The primary goal of the OGLE survey was to detect gravitational microlensing events in order to validate the hypothesis that dark matter is composed of

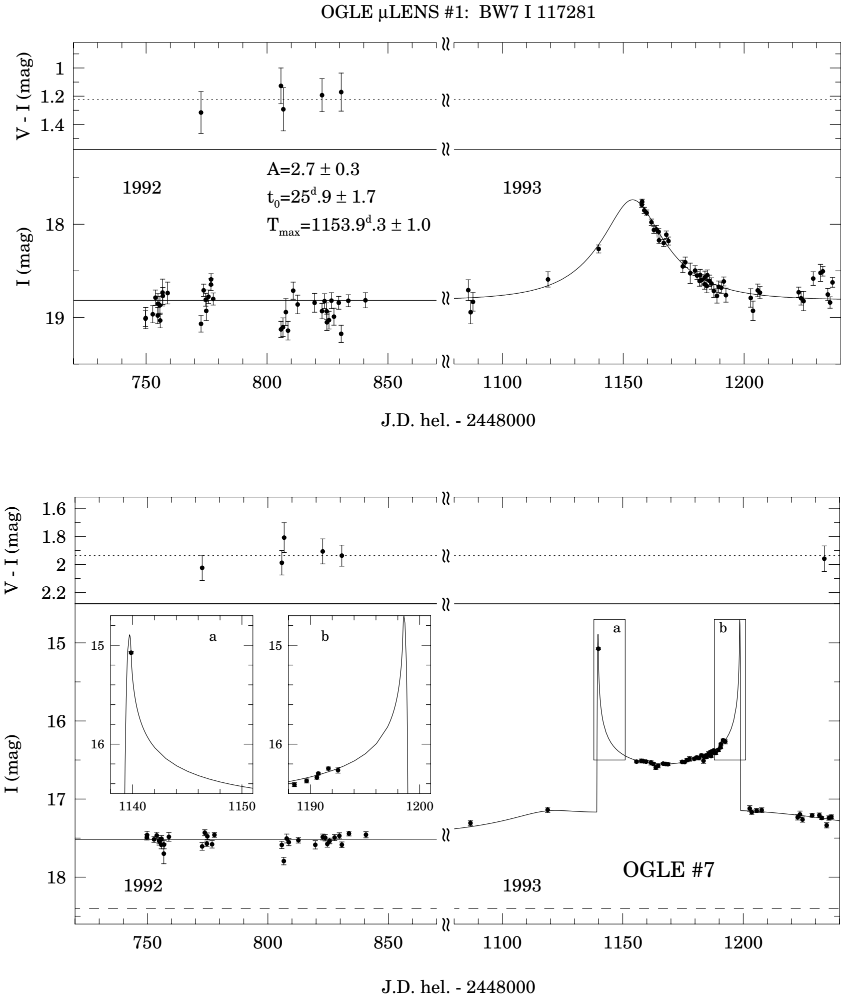

Figure 1. Upper panel: light curve of the first microlensing event detected by OGLE (Udalski *et al.*, 1993). Lower panel: light curve the first known binary microlensing event (Udalski *et al.*, 1994).

MAssive Compact Halo Objects (MACHOs). This term refers to hypothetical non-emitting or extremely faint objects, such as primordial black holes, brown dwarfs, or even free-floating planets, located in galactic halos and contributing to the observed mass of galaxies. A gravitational microlensing event occurs when the light of a background source star is temporarily magnified due to its alignment with a foreground lens object (Einstein 1936). When Paczyński

(1986) proposed using this phenomenon to assess the contribution of MACHOs to dark matter, not a single microlensing event had been observed until then.

The OGLE team announced the discovery of its first microlensing event in September 1993 (Udalski *et al.*, 1993), almost simultaneously with the first-ever gravitational microlens toward the LMC recorded by the MACHO group (Alcock *et al.*, 1993). The upper panel of Fig. 1 displays the light curve of the OGLE's microlensing event number 1. Today, such characteristic light curves are commonly referred to as Paczyński curves. The first OGLE microlensing event was found toward the center of the Milky Way. Currently, the OGLE project routinely detects between 1000 and 2000 gravitational microlensing events per year (depending on the adopted observational strategy), and the overwhelming majority of the lensed stars also reside in the Galactic bulge.

The limited number of gravitational microlensing events detected by OGLE in the direction of the Magellanic Clouds imposes strong constraints on possible explanations for the nature of dark matter. Wyrzykowski *et al.* (2011) analyzed 13 years of the OGLE-II and OGLE-III observations of the LMC and SMC and found only eight candidates for microlensing events, which demonstrated that MACHOs with masses in the range $10^{-2}\,\mathrm{M}_\odot \lesssim M \lesssim 1\,\mathrm{M}_\odot$ cannot constitute more than 10% of dark matter. Much stronger limits have recently been obtained by Mróz *et al.* (2023, in preparation) based on the analysis of light curves of over 78 million stars in the LMC monitored for 20 years by the OGLE-III and OGLE-IV surveys. It was found that MACHOs in the mass range $1.8 \cdot 10^{-4}\,\mathrm{M}_\odot \lesssim M \lesssim 6.3\,\mathrm{M}_\odot$ cannot contribute more than 1% to the dark matter in the Galactic halo, while MACHOs with masses in the range of $1.3 \cdot 10^{-5}\,\mathrm{M}_\odot \lesssim M \lesssim 860\,\mathrm{M}_\odot$ cannot compose more than 10% of dark matter. In fact, all thirteen microlensing events detected by Mróz *et al.* (2023) in the direction of the LMC can be explained by astrophysical objects located in the LMC itself or in the Milky Way disk.

3. Exoplanets

The significance of the OGLE's contribution to exoplanetary research cannot be overestimated. The OGLE observations have been used to the first successful applications of two new techniques for detecting extrasolar planets: gravitational microlensing and transit methods.

Mao & Paczyński (1991) originally proposed the idea that binary stars and planetary systems could be detected through the microlensing phenomena. Binary lenses may produce significantly different light curves than the Paczyński curve, and this effect can be easily detectable even if the companion is a planet. This characteristic is the foundation of the microlensing technique for identifying planetary systems.

In 1994, the OGLE group discovered the first-ever binary microlensing event (Udalski *et al.*, 1994; the lower panel of Fig. 1). This was an important step to-

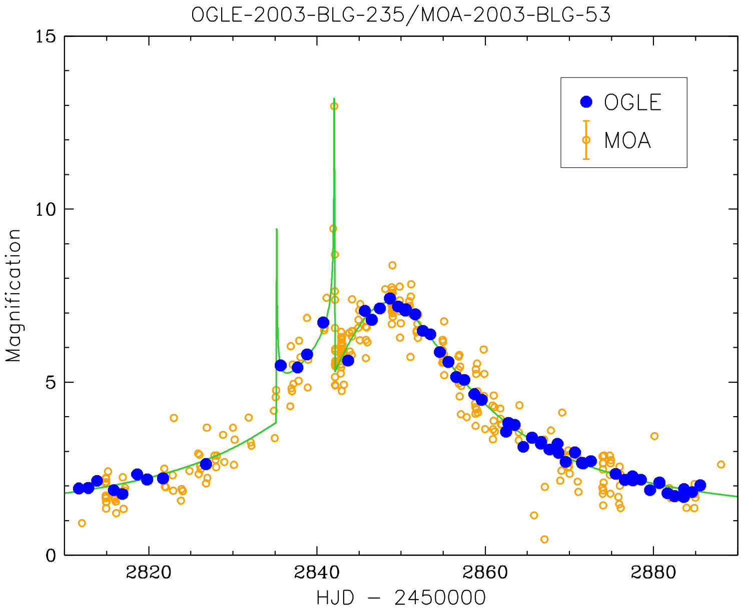

Figure 2. Light curve of OGLE 2003-BLG-235/MOA 2003-BLG-53 – the first planetary microlensing event (Bond *et al.* 2004). The OGLE and MOA measurements are shown as blue and yellow symbols, respectively.

ward detecting the microlensing exoplanets. OGLE-2003-BLG-235/MOA-2003-BLG-53 was the first gravitational microlensing event that yielded a definitive planet identification (Bond *et al.* 2004). This breakthrough discovery was possible thanks to the collaboration between the OGLE survey and the Microlensing Observations in Astrophysics (MOA) project. Fig. 2 presents the light curve of this microlensing event, where the characteristic shape of the Paczyński curve is distorted by an anomaly attributed by the presence of a Jupiter-like planet. Since then, OGLE has participated in the discovery of over a hundred microlensing exoplanets, including the first known cold super-Earth, a scaled analog of the Solar System, planets orbiting brown dwarfs, and planets in binary star systems.

Gravitational microlensing is an effective method for detecting free-floating planets, i.e. worlds that have been ejected from their parent planetary systems and are no longer gravitationally bound to any star. Microlensing events caused by Jupiter-mass planets typically last from 1 to 2 days, whereas Earth-mass lenses last merely a few hours. An in-depth analysis of the OGLE photometric database conducted by Mróz *et al.* (2017) unveiled a notable surplus of very short microlensing events, indicating the presence of a substantial population of Earth-to-Neptune-mass planets that appear to have no host stars. Mróz *et*

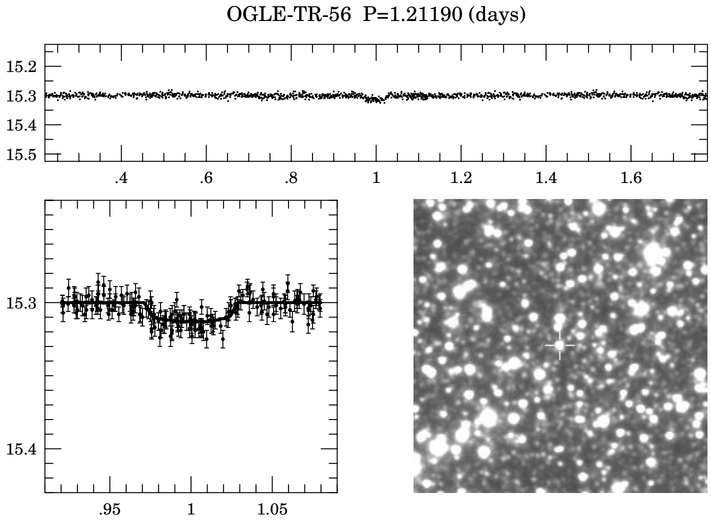

Figure 3. Light curve and finding chart of OGLE-TR-56 – the first exoplanet discovered with the transit method.

al. (2017) estimated that free-floating planets far outnumber stars in the Milky Way.

Finally, the OGLE survey pioneered another technique of detecting extrasolar planets: the transit method. In 2002, the OGLE team published its first list of candidates for planetary transits (Udalski *et al.*, 2002). It was the result of a special observing campaign conducted at the onset of the OGLE-III project. At that time, only one transiting exoplanet was known – HD 209458 b (Charbonneau *et al.*, 2000; Henry *et al.*, 2000) – but this object had been discovered using the spectroscopic method, while the observations of its transits followed afterward.

OGLE-TR-56 b was the first spectroscopically confirmed exoplanet discovered with the transit method (Konacki *et al.*, 2003). Fig. 3 displays the light curve of this system folded with its orbital period of 1.2119 days. In the next several years, seven more OGLE planets were positively verified through spectroscopy. At that time, HD 209458 b and the OGLE planets were the only known transiting planets. Then, dedicated wide-field sky surveys, such as WASP, HAT, and TrES, began to discover transiting planets around much brighter stars, which led to the discontinuation of the OGLE's observing campaigns aimed at searching for transiting planet candidates.

Table 2. OGLE Collection of Variable Stars

Type of variable stars	Number of stars
Classical Cepheids	11 707
Type II Cepheids	2 010
Anomalous Cepheids	390
RR Lyrae stars	128 472
δ Scuti stars	42 672
Long-Period Variables	403 636
Eclipsing binaries	510 782
Dwarf novae	1 091
R Coronae Borealis stars	23
TOTAL	1 100 783

4. The OGLE Collection of Variable Stars

The light curves of two billion sources observed for decades by the OGLE survey constitute an ideal dataset for detecting and studying variable stars of all types. The OGLE Collection of Variable Stars (OCVS) is a continuously growing catalog of variable stars identified in the OGLE database. Tab. 2 shows a list of different types of variables included in the already published parts of the OCVS. At present, the OGLE catalog contains over 1.1 million variable stars in the Milky Way and Magellanic Clouds. The OCVS is accessible through the WWW and FTP sites:

https://ogle.astrouw.edu.pl → *OGLE Collection of Variable Stars*
https://www.astrouw.edu.pl/ogle/ogle4/OCVS/

The catalog data include observational parameters of the variable stars, such as coordinates, periods, mean magnitudes, amplitudes, etc. Additionally, time-series OGLE photometry in the I and V bands is made available to the astronomical community.

It is worth emphasizing that the OCVS is characterized by exceptionally high levels of completeness and purity because we still employ the traditional method of variable star classification, namely, the visual inspection of their light curves. Each of the over one million variables included in the OCVS has been carefully reviewed by experienced astronomers. This rigorous procedure has not only resulted in an extraordinarily low contamination rate of our collection but has also led to the discovery of new types of variable stars (see Section 6). Therefore, the OGLE catalog is widely used as a training set for machine learning variable star classification algorithms.

5. Classical Cepheids

Due to the limited space of this contribution, I cannot present the full variety of studies on different types of variable stars included in the OCVS. Therefore, for illustrative purposes, I will concentrate on the latest investigations related to only one type of pulsating stars − classical Cepheids − which are relatively young ($\lesssim$400 My) and luminous (10^2–10^5 $L_\odot$) standard candles, 4–20 times more massive than the Sun. Classical Cepheids play a key role as primary distance indicators thanks to the famous relationship between their pulsation periods and intrinsic luminosities, the period–luminosity relation.

Most of the Cepheid pulsators in the Magellanic Clouds (Soszyński *et al.*, 2017), and approximately half of the classical Cepheids currently known in the Milky Way (Pietrukowicz *et al.*, 2021), were identified in the OGLE photometric databases. At present, the OGLE collection comprises a virtually complete census of Cepheids in the LMC and SMC, thus our group concluded the task of cataloging these variable stars initiated by Henrietta Leavitt in the early 20th century.

The OCVS contains 4713 and 4954 classical Cepheids in the LMC and SMC, respectively. These are the largest known samples of such variables detected in any galaxy, including the Milky Way, so classical Cepheids in the Magellanic Clouds have been the subject of extensive studies in recent decades. These two satellite galaxies are close enough to us that individual stars are easily distinguishable for ground-based telescopes, but they are far enough that their stellar populations can be considered to be located at the same distance from us. Moreover, the distance to the LMC is known with unprecedented accuracy of about 1% (Pietrzyński *et al.*, 2019). Consequently, the Magellanic Clouds, particularly the LMC, serve as anchors for the cosmic distance scale.

Fig. 4 shows the period–Wesenheit index[1] diagram for classical Cepheids in the LMC. The four ridges visible in this diagram are attributed to the stellar pulsations in the fundamental, first-, second-, and third-overtone modes. Cepheids in the Magellanic Clouds play a crucial role in the calibration of the period–luminosity, period–luminosity–color and period–Wesenheit index relations across a wide range of wavelengths, spanning from optical to mid-infrared domains (e.g., Macri *et al.*, 2015; Riess *et al.*, 2019; Chown *et al.*, 2021). In addition, a thorough exploration of the non-linearities of the period–luminosity relations (e.g., García-Varela *et al.*, 2013; Bhardwaj *et al.*, 2016) and the correlation of the zero-points of these relations with the metallicity of Cepheids (e.g., Wielgórski *et al.*, 2017; Gieren *et al.*, 2018; Breuval *et al.*, 2022) has been conducted to assess their influence on the cosmic distance scale, particularly in the context of the Hubble constant measurements.

---

[1] The Wesenheit index is an extinction-free quantity, defined as $W_I = I - 1.55(V - I)$, where I and V are apparent mean magnitudes of the stars.

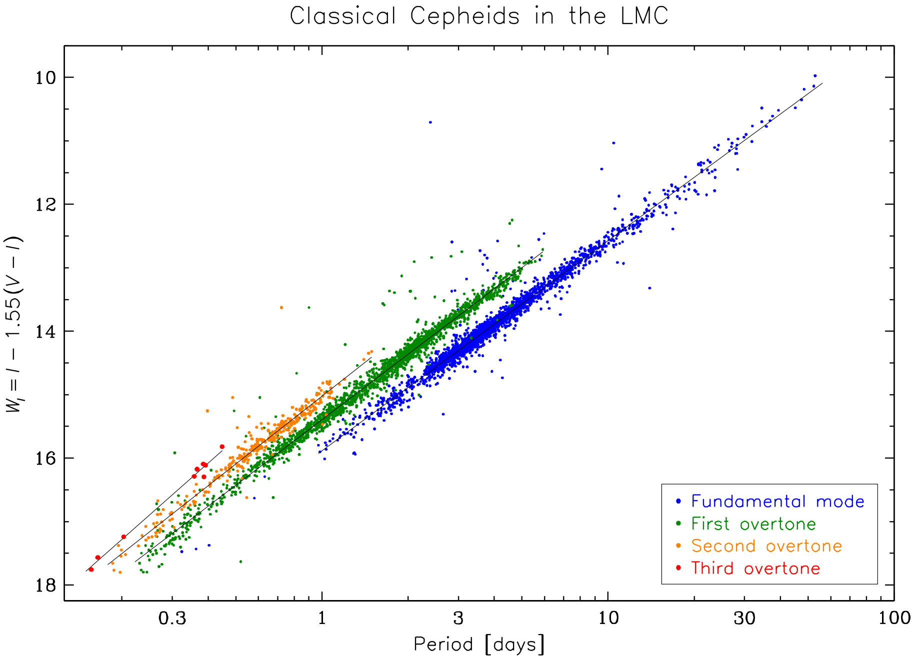

Figure 4. Period–Wesenheit index diagram for classical Cepheids in the LMC. Blue, green, orange, and red dots mark the fundamental, first-, second-, and third-overtone pulsation modes, respectively.

The complete samples of classical Cepheids have been employed to investigate the three-dimensional geometry of the LMC and SMC (e.g. Jacyszyn-Dobrzeniecka *et al.*, 2016; Ripepi *et al.*, 2022). These studies are vital for gaining insights into past interactions between the Magellanic Clouds and between the Magellanic System and the Milky Way.

An analogous analysis of the structure of the Milky Way's disk was performed by Skowron *et al.* (2019) using the sample of about 2500 Galactic classical Cepheids, significantly expanded thanks to the observations carried out by the OGLE survey (Udalski *et al.*, 2018). In particular, OGLE was the first survey that identified a significant number of Cepheids in the outskirts of the Milky Way, which was used to construct of a three-dimensional map of the Galactic disk. This map unambiguously revealed that the disk is not flat but exhibits a warp, beginning at galactocentric distances of about than 8 kpc, and extending to the edge of the Milky Way, approximately 20 kpc from the center. Moreover, the spatial distribution of Cepheids was utilized to assess the disk's flaring, its scale height, and pinpoint the Sun's location within the disk. Additionally, the relationship between periods and ages for classical Cepheids was employed to obtain an age tomography of the young stellar population in the Milky Way. Finally, this analysis was supplemented by Mróz *et al.* (2019) who used the OGLE Cepheids with their proper motions and radial velocities from the Gaia database to construct the most precise rotation curve for the outer regions of our Galaxy.

6. New types of variable stars

The huge OGLE photometric database contains light curves of variable stars belonging to all categories, including types that have remained entirely unknown. Thanks to our individualized approach to the analysis of observational data, the OGLE team discovered several new classes and subclasses of variable stars, for example the so-called peculiar W Virginis stars (Soszyński *et al.*, 2008), anomalous double-mode RR Lyrae stars (Soszyński *et al.*, 2016), type II Cepheids pulsating in the first overtone (Soszyński *et al.*, 2019), and the first known multimode anomalous Cepheid (Soszyński *et al.*, 2020).

A completely new class of pulsating stars was extracted from the OGLE database by Pietrukowicz *et al.* (2017). These stars, known as Blue Large Amplitude Pulsators (BLAPs), are hot subdwarfs with temperatures around 30 000 K, pulsating in the fundamental mode with periods ranging from 3 to 75 minutes. The light curves of BLAPs (Fig. 5) resemble those of Cepheids or RR Lyrae stars. The uniqueness of BLAPs lies in the fact that they are the only known type of fundamental-mode pulsating stars situated on the blue side of the Hertzsprung-Russell diagram. Recently, the total number of known BLAPs has been significantly increased, reaching 80 objects at present (Borowicz *et al.*, 2023). However, the evolutionary status of these stars still remains a mystery.

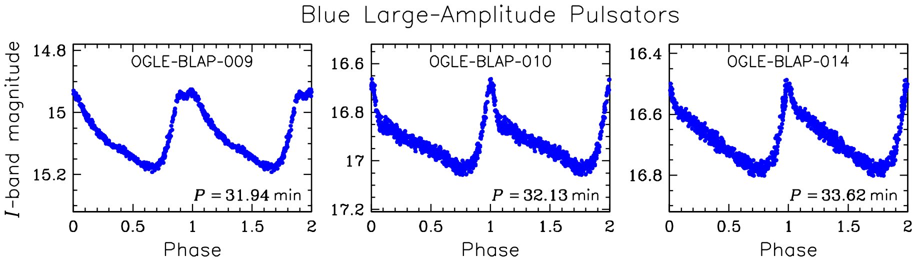

Figure 5. *I*-band light curves of three example Blue Large Amplitude Pulsators (Pietrukowicz *et al.*, 2017).

Another new type of pulsating stars was discovered in the OGLE database by chance. OGLE-BLG-RRLYR-02792, as its name suggests, was initially classified in the OCVS as an RR Lyrae star due to its short period ($P \approx 0.6275$ days) and characteristic light curve morphology (Fig. 6). This pulsating star stood out as

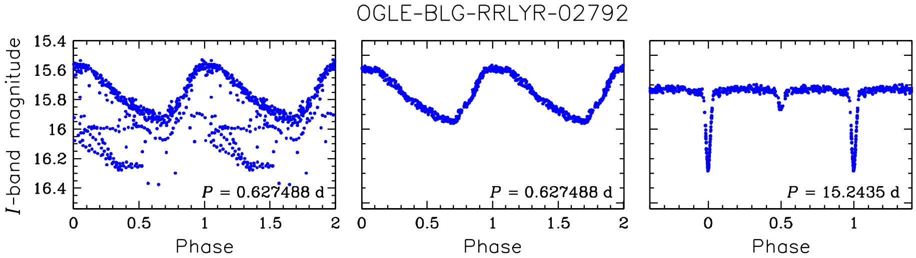

Figure 6. Light curves of the Binary Evolution Pulsator OGLE-BLG-RRLYR-02792 (Pietrzyński *et al.*, 2012). The left panel displays the original light curve folded with the pulsation periods, while the middle and right panels show the disentangled pulsation and eclipsing light curves of the same object.

it is a component of an eclipsing binary system, providing an opportunity for the first direct determination of the RR Lyrae's mass. Pietrzyński *et al.* (2012) obtained highly precise spectroscopic observations for this system and measured the mass of the pulsating component, which turned out to be surprisingly small – only 0.26 $M_\odot$. Such low mass indicates that OGLE-BLG-RRLYR-02792 is not an RR Lyrae variable but rather a representative of a new category of pulsating stars that mimic RR Lyrae stars. Because these stars pulsate as a consequence of their evolution in binary systems, they have been named Binary Evolution Pulsators.

7. V1309 Scorpii – a “Rosetta stone” for stellar mergers

V1309 Scorpii (Nova Scorpii 2008) was discovered in September 2008 when it underwent an outburst, increasing its brightness by about 10 mag. This event represented a rare case of a so-called “red nova” – a class of variable stars for which there was no definitive explanation at that time. Fortunately, V1309 Scorpii had been observed by the OGLE-III project for seven years prior to the eruption. Using the OGLE time-series photometry, Tylenda *et al.* (2011) demonstrated that the progenitor of V1309 Sco was a contact binary with an orbital period decreasing at an accelerating rate.

Fig. 7 displays the light curve of V1309 Scorpii, obtained within 20 years of the OGLE monitoring. After the outburst, there are no signs of binarity, proving that Nova Scorpii 2008 and, consequently, other red novae were stellar-merger events. Because of the pivotal role played by V1309 Scorpii in clarifying the process of star mergers, this object has been dubbed a “Rosetta stone” for the interpretation of red novae.

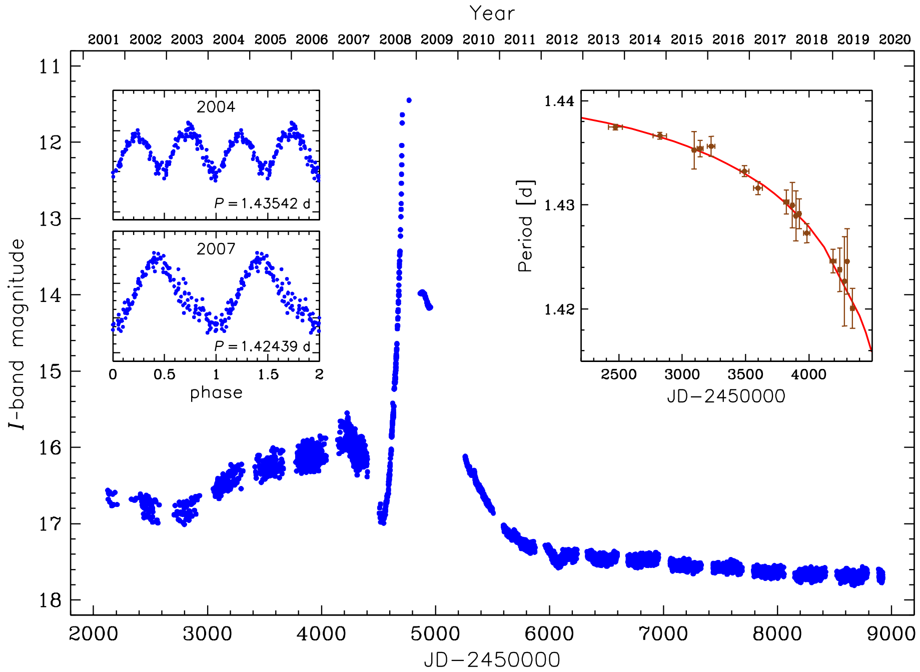

Figure 7. OGLE light curve of V1309 Scorpii (Tylenda *et al.*, 2011). The insets on the left side display detrended and phased light curves observed four years and one year prior to the outburst, respectively. The inset on the right side shows the evolution of the orbital period of the V1309 Scorpii progenitor.

8. Summary

In this proceeding, I have presented a subjective overview of the most fascinating achievements of the OGLE project. I have outlined OGLE's research in the area of gravitational microlensing, dark matter, extrasolar planets, variable stars, and the structure of galaxies. Nevertheless, over the last three decades, the OGLE survey has made a substantial contribution to many other fields of astrophysics. OGLE observations have been widely used to establish cosmic distance scale, analyze star clusters, investigate both old and young stellar populations, identify unique modes of stellar oscillations, and produce maps of interstellar extinction. The OGLE team has been involved in the discovery of free-floating black holes, thousands of novae and supernovae, hundreds of quasars, Cepheids in eclipsing binary systems, as well as transneptunian objects in the Solar System.

Acknowledgements. This work has been funded by the National Science Centre, Poland, grant no. 2022/45/B/ST9/00243. For the purpose of Open Access, the author

References

Alcock, C., Akerlof, C.W., Allsman, R.A., Axelrod, T.S., Bennett, D.P., Chan, S., Cook, K.H., Freeman, K.C., Griest, K., Marshall, S.L., Park, H.-S., Perlmutter, S., Peterson, B.A., Pratt, M.R., Quinn, P.J., Rodgers, A.W., Stubbs, C.W., Sutherland, W.: 1993, *Nature* **365**, 621, DOI: 10.1038/365621a0

Bhardwaj, A., Kanbur, S.M., Macri, L.M., Singh, H.P., Ngeow, C.-C., Ishida, E.E.O.: 2016, *Monthly Notices of the RAS* **457**, 1644, DOI: 10.1093/mnras/stw040

Bond, I.A., Udalski, A., Jaroszyński, M., Rattenbury, N.J., Paczyński, B., Soszyński, I., Wyrzykowski, L., Szymański, M.K., Kubiak, M., Szewczyk, O., Żebruń, K., Pietrzyński, G., Abe, F., Bennett, D.P., Eguchi, S., Furuta, Y., Hearnshaw, J.B., Kamiya, K., Kilmartin, P.M., Kurata, Y., Masuda, K., Matsubara, Y., Muraki, Y., Noda, S., Okajima, K., Sako, T., Sekiguchi, T., Sullivan, D.J., Sumi, T., Tristram, P.J., Yanagisawa, T., Yock, P.C.M.: 2004, *Astrophysical Journal, Letters* **606**, L155, DOI: 10.1086/420928

Borowicz, J., Pietrukowicz, P., Mróz, P., Soszyński, I., Udalski, A., Szymański, M.K., Ulaczyk, K., Poleski, R., Kozłowski, S., Skowron, J., Skowron, D.M., Rybicki, K., Iwanek, P., Wrona, M., Gromadzki, M.: 2023, *Acta Astron.* **73**, 1, DOI: 10.32023/0001-5237/73.1.1

Breuval, L., Riess, A.G., Kervella, P., Anderson, R.I., Romaniello, M.: 2022, *Astrophysical Journal* **939**, 89, DOI: 10.3847/1538-4357/ac97e2

Charbonneau, D., Brown, T.M., Latham, D.W., Mayor, M.: 2000, *Astrophysical Journal, Letters* **529**, L45, DOI: 10.1086/312457

Chown, A.H., Scowcroft, V., Wuyts, S.: 2021, *Monthly Notices of the RAS* **500**, 817, DOI: 10.1093/mnras/staa3186

Einstein, A.: 1936, *Science* **84**, 506, DOI: 10.1126/science.84.2188.506

García-Varela, A., Sabogal, B.E., Ramírez-Tannus, M.C.: 2013, *Monthly Notices of the RAS* **431**, 2278, DOI: 10.1093/mnras/stt325

Gieren, W., Storm, J., Konorski, P., Górski, M., Pilecki, B., Thompson, I., Pietrzyński, G., Graczyk, D., Barnes, T.G., Fouqué, P., Nardetto, N., Gallenne, A., Karczmarek, P., Suchomska, K., Wielgórski, P., Taormina, M., Zgirski, B.: 2018, *Astronomy and Astrophysics* **620**, A99, DOI: 10.1051/0004-6361/201833263

Henry, G.W., Marcy, G.W., Butler, R.P., Vogt, S.S.: 2000, *Astrophysical Journal, Letters* **529**, L41, DOI: 10.1086/312458

Jacyszyn-Dobrzeniecka, A.M., Skowron, D.M., Mróz, P., Skowron, J., Soszyński, I., Udalski, A., Pietrukowicz, P., Kozłowski, S., Wyrzykowski, Ł., Poleski, R., Pawlak, M., Szymański, M.K., Ulaczyk, K.: 2016, *Acta Astron.* **66**, 149, DOI: 10.48550/arXiv.1602.09141

Konacki, M., Torres, G., Jha, S., Sasselov, D.D.: 2003, *Nature* **421**, 507, DOI: 10.1038/nature01379

Macri, L.M., Ngeow, C.-C., Kanbur, S.M., Mahzooni, S., Smitka, M.T.: 2015, *Astronomical Journal* **149**, 117, DOI: 10.1088/0004-6256/149/4/117

Mao, S., Paczyński, B.: 1991, *Astrophysical Journal, Letters* **374**, L37, DOI: 10.1086/186066

Mróz, P., Udalski, A., Skowron, J., Poleski, R., Kozłowski, S., Szymański, M.K., Soszyński, I., Wyrzykowski, Ł., Pietrukowicz, P., Ulaczyk, K., Skowron, D., Pawlak, M.: 2017, *Nature* **548**, 183, DOI: 10.1038/nature23276

Mróz, P., Udalski, A., Skowron, D.M., Skowron, J., Soszyński, I., Pietrukowicz, P., Szymański, M.K., Poleski, R., Kozłowski, S., Ulaczyk, K.: 2019, *Astrophysical Journal, Letters* **870**, L10, DOI: 10.3847/2041-8213/aaf73f

Paczyński, B.: 1986, *Astrophysical Journal* **304**, 1, DOI: 10.1086/164140

Pietrukowicz, P., Dziembowski, W.A., Latour, M., Angeloni, R., Poleski, R., di Mille, F., Soszyński, I., Udalski, A., Szymański, M.K., Wyrzykowski, Ł., Kozłowski, S., Skowron, J., Skowron, D., Mróz, P., Pawlak, M., Ulaczyk, K.: 2017, *Nature Astronomy* **1**, 0166, DOI: 10.1038/s41550-017-0166

Pietrukowicz, P., Soszyński, I., Udalski, A.: 2021, *Acta Astron.* **71**, 205, DOI: 10.32023/0001-5237/71.3.2

Pietrzyński, G., Thompson, I.B., Gieren, W., Graczyk, D., Stępień, K., Bono, G., Moroni, P.G.P., Pilecki, B., Udalski, A., Soszyński, I., Preston, G.W., Nardetto, N., McWilliam, A., Roederer, I.U., Górski, M., Konorski, P., Storm, J.: 2012, *Nature* **484**, 75, DOI: 10.1038/nature10966

Pietrzyński, G., Graczyk, D., Gallenne, A., Gieren, W., Thompson, I. B., Pilecki, B., Karczmarek, P., Górski, M., Suchomska, K., Taormina, M., Zgirski, B., Wielgórski, P., Kołaczkowski, Z., Konorski, P., Villanova, S., Nardetto, N., Kervella, P., Bresolin, F., Kudritzki, R. P., Storm, J., Smolec, R., Narloch, W.: 2019, *Nature* **567**, 200, DOI: 10.1038/s41586-019-0999-4

Riess, A.G., Casertano, S., Yuan, W., Macri, L.M., Scolnic, D.: 2019, *Astrophysical Journal* **876**, 85, DOI: 10.3847/1538-4357/ab1422

Ripepi, V., Chemin, L., Molinaro, R., Cioni, M.-R.L., Bekki, K., Clementini, G., de Grijs, R., De Somma, G., El Youssoufi, D., Girardi, L., Groenewegen, M.A.T., Ivanov, V., Marconi, M., McMillan, P.J., van Loon, J.T.: 2022, *Monthly Notices of the RAS* **512**, 563, DOI: 10.1093/mnras/stac595

Skowron, D.M., Skowron, J., Mróz, P., Udalski, A., Pietrukowicz, P., Soszyński, I., Szymański, M.K., Poleski, R., Kozłowski, S., Ulaczyk, K., Rybicki, K., Iwanek, P.: 2019, *Science* **365**, 478, DOI: 10.1126/science.aau3181

Soszyński, I., Udalski, A., Szymański, M.K., Kubiak, M., Pietrzyński, G., Wyrzykowski, Ł., Szewczyk, O., Ulaczyk, K., Poleski, R.: 2008, *Acta Astron.* **58**, 293

Soszyński, I., Smolec, R., Dziembowski, W.A., Udalski, A., Szymański, M.K., Wyrzykowski, Ł., Ulaczyk, K., Poleski, R., Pietrukowicz, P., Kozłowski, S., Skowron, D., Skowron, J., Mróz, P., Pawlak, M.: 2016, *Monthly Notices of the RAS* **463**, 1332, DOI: 10.1093/mnras/stw1933

Soszyński, I., Udalski, A., Szymański, M.K., Wyrzykowski, Ł., Ulaczyk, K., Poleski, R., Pietrukowicz, P., Kozłowski, S., Skowron, D.M., Skowron, J., Mróz, P., Pawlak, M.: 2017, *Acta Astron.* **67**, 103, DOI: 10.32023/0001-5237/67.2.1

Soszyński, I., Smolec, R., Udalski, A., Pietrukowicz, P.: 2019, *Astrophysical Journal* **873**, 43, DOI: 10.3847/1538-4357/ab04ab

Soszyński, I., Smolec, R., Udalski, A., Szymański, M.K., Pietrukowicz, P., Skowron, D.M., Skowron, J., Mróz, P., Poleski, R., Kozłowski, S., Iwanek, P., Wrona, M., Gromadzki, M., Ulaczyk, K., Rybicki, K.: 2020, *Astrophysical Journal, Letters* **901**, L25, DOI: 10.3847/2041-8213/abb817

Tylenda, R., Hajduk, M., Kamiński, T., Udalski, A., Soszyński, I., Szymański, M.K., Kubiak, M., Pietrzyński, G., Poleski, R., Wyrzykowski, Ł., Ulaczyk, K.: 2011, *Astronomy and Astrophysics* **528**, A114, DOI: 10.1051/0004-6361/201016221

Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., Mateo, M.: 1992, *Acta Astron.* **42**, 253

Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., Krzemiński, W., Mateo, M., Preston, G.W., Paczyński, B.: 1993, *Acta Astron.* **43**, 289

Udalski, A., Szymański, M., Mao, S., Di Stefano, R., Kałużny, J., Kubiak, M., Mateo, M., Krzemiński, W.: 1994, *Astrophysical Journal, Letters* **436**, L103, DOI: 10.1086/187643

Udalski, A., Kubiak, M., Szymański, M.: 1997, *Acta Astron.* **47**, 319

Udalski, A., Paczyński, B., Żebruń, K., Szymański, M., Kubiak, M., Soszyński, I., Szewczyk, O., Wyrzykowski, Ł., Pietrzyński, G.: 2002, *Acta Astron.* **52**, 1

Udalski, A.: 2003, *Acta Astron.* **53**, 291

Udalski, A., Szymański, M.K., Szymański, G.: 2015, *Acta Astron.* **65**, 1

Udalski, A., Soszyński, I., Pietrukowicz, P., Szymański, M.K., Skowron, D.M., Skowron, J., Mróz, P., Poleski, R., Kozłowski, S., Ulaczyk, K., Rybicki, K., Iwanek, P., Wrona, M.: 2018, *Acta Astron.* **68**, 315, DOI: 10.32023/0001-5237/68.4.1

Wielgórski, P., Pietrzyński, G., Gieren, W., Górski, M., Kudritzki, R.-P., Zgirski, B., Bresolin, F., Storm, J., Matsunaga, N., Graczyk, D., Soszyński, I.: 2017, *Astrophysical Journal* **842**, 116, DOI: 10.3847/1538-4357/aa7565

Wyrzykowski, L., Skowron, J., Kozłowski, S., Udalski, A., Szymański, M.K., Kubiak, M., Pietrzyński, G., Soszyński, I., Szewczyk, O., Ulaczyk, K., Poleski, R., Tisserand, P.: 2011, *Monthly Notices of the RAS* **416**, 2949, DOI: 10.1111/j.1365-2966.2011.19243.x