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The OGLE Collection of Variable Stars. Over 450 000 Eclipsing and Ellipsoidal Binary Systems Toward the Galactic Bulge*

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ABSTRACT

We present a collection of 450 598 eclipsing and ellipsoidal binary systems detected in the OGLE fields toward the Galactic bulge. The collection consists of binary systems of all types: detached, semi-detached, and contact eclipsing binaries, RS CVn stars, cataclysmic variables, HW Vir binaries, double periodic variables, and even planetary transits. For all stars we provide the *I*- and *V*-band time-series photometry obtained during the OGLE-II, OGLE-III, and OGLE-IV surveys. We discuss methods used to identify binary systems in the OGLE data and present several objects of particular interest.

Key words: *binaries: eclipsing – Catalogs*

1. Introduction

In recent years, the number of known variable stars in the central regions of the Milky Way has grown significantly, mostly thanks to the publication of an extensive collection of variable stars by the Optical Gravitational Lensing Experiment (OGLE). Hundreds of thousands of pulsating stars (*e.g.,* Soszyński *et al.* 2011b, 2013, 2014) discovered by OGLE have enabled thorough analyses of, both, the stellar pulsation theory and the structure of the Galactic bulge. Eclipsing binary

*Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution for Science.

systems have the potential to play an equally important role in the exploration of the central parts of the Galaxy, although until now only a small fraction of binaries in this region of the sky has been cataloged and studied.

Eclipsing binary systems offer an opportunity to directly measure the fundamental stellar parameters, such as masses, sizes, temperatures, absolute luminosities, and rotation (Andersen 1991). Binary systems serve as testbeds for stellar evolutionary theories, since both components have the same age and chemical composition. Eclipsing binaries are used to study dynamical interactions between stars, mass exchange and loss, stellar magnetic activity, limb darkening, and tidal circularization theories. Moreover, detached eclipsing binaries are accurate distance indicators in the Milky Way and other galaxies (*e.g.,* Paczyński 1997, Kaluzny *et al.* 2013, Pietrzyński *et al.* 2013).

First eclipsing binaries in the region of the Galactic bulge were discovered at the turn of the twentieth century (Roberts 1895, Pickering and Leavitt 1904, Pickering 1908). In subsequent years, thanks to the efforts of many observers (*e.g.,* Parenago 1931, Swope 1938, Ferwerda 1943, Baade 1946, Plaut 1948, 1958, 1971, Gaposchkin 1955, Kooreman 1966), the number of known eclipsing binaries toward the central regions of the Milky Way has grown to about 300.

At the end of the twentieth century with the advent of large-scale variability surveys, this sample has increased significantly. About 1650 eclipsing binary systems have been identified by Udalski *et al.* (1994, 1995ab, 1996, 1997) in the photometric database obtained during the first phase of the OGLE project. This sample was extended by 1575 contact binary systems identified by Szymański *et al.* (2001). Groenewegen (2005) used the OGLE-II photometry of variable stars in the Galactic bulge (Woźniak *et al.* 2002) to select 3053 detached eclipsing binaries, mostly suited for distance determinations. Devor (2005) used the same data to fit over 10 000 models of eclipsing binaries and to identify 3170 detached systems. This list should be supplemented by 59 systems with very shallow eclipses published by Udalski *et al.* (2002ab). Two of these objects, OGLE-TR-10 and OGLE-TR-56, turned out to be planetary systems (Konacki *et al.* 2003, 2005) – the first ones discovered with the transit method. Additionally, a few hundred eclipsing and ellipsoidal binaries toward the center of the Milky Way have been discovered by Pojmański and Maciejewski (2004, 2005) based on the observations gathered by the All Sky Automated Survey (ASAS).

In this paper, we present the OGLE collection of eclipsing and ellipsoidal binary systems in the Galactic bulge. Our collection, consisting of more than 450 000 objects, not only increases the number of known binary stars in the central regions of the Milky Way by two orders of magnitude, but also multiplies the total number of eclipsing binaries known to date in the whole Universe. The first stars from our collection – 242 ultra-short-period binary systems ($P_{\rm orb} < 0.22$ d) – have already been published by Soszyński *et al.* (2015). One of these stars – OGLE-BLG-ECL-000066 – with an orbital period of 0.0984 d is probably the binary system consisting of non-degenerate components with the shortest known orbital period. The paper is structured as follows. In Section 2, we present the photometric data used in the analysis. Section 3 describes the selection and classification of the binary systems in the Galactic bulge. In Section 4, we present the collection itself and estimate its completeness. In Sections 5 and 6, we discuss and summarize our results.

2. Observations and Data Reduction

Our collection of binary systems in the Galactic bulge is based on the photometric data collected by the OGLE survey between 1997 and 2015 at Las Campanas Observatory, Chile, with the 1.3-m Warsaw Telescope. The observatory is operated by the Carnegie Institution for Science. In 1997–2000, during the OGLE-II stage, about 30 million stars in the area of 11 square degrees in the central parts of the Milky Way were constantly monitored. In 2001, with the beginning of the OGLE-III survey, the sky coverage was extended to nearly 69 square degrees and the number of monitored stars increased to 200 million. Finally, from 2010 until today the OGLE-IV project regularly observes about 400 million stars in 182 square degrees of the densest regions of the Galactic bulge. Our search for eclipsing variables was based primarily on the OGLE-IV data.

The Warsaw telescope is currently equipped with a 32-detector mosaic CCD camera covering an area of about 1.4 square degrees on the sky. Most of the observations were made through the Cousins *I*-band filter with an integration time of 100 s. The number of collected data points varies greatly between individual fields, with the least-sampled fields having only about 100 *I*-band observations per star while those most sampled contain over 12 000 observations. The CCD saturation limit is about 13 mag in the *I*-band, while the faintest stars in the OGLE database have $I \approx 21$ mag. Typical photometric uncertainties of individual measurements for bright stars are about 0.005 mag. Up to 10% of the observations were secured in the Johnson *V*-band with the exposure time of 150 s.

The OGLE photometry was carried out using the Difference Image Analysis technique (DIA, Alard and Lupton 1998, Woźniak 2000). The instrumental photometry was calibrated to the standard system with the procedure described by Udalski *et al.* (2015). The accuracy of the zero point of this transformation is at the level of 0.02 mag, however the brightness of some individual stars may be significantly affected by blending, crowding, reflections from bright stars, etc. More details on the OGLE instrumentation, photometric reductions and astrometric calibrations are provided by Udalski *et al.* (2015).

3. Selection and Classification of Binary Systems

The selection of eclipsing and ellipsoidal binary systems from the set of 400 million stars requires the use of automated mechanisms of the variable star classification. However, each light curve included in our collection has been visually inspected by a human at least once, so our procedure can be described as semi-automatic.

In order to detect binary systems, we performed an extensive period search for all stars observed by OGLE toward the Galactic bulge. We applied two different methods of the period search to every *I*-band light curve stored in the OGLE database. The FNPEAKS code[†] computes the Fourier amplitude spectra and provides the most significant periods with their signal-to-noise ratios. The Fourier analysis is better suited to detect periodicities in the magnitude sequences with continuous light variations, *i.e.,* in contact, semi-detached, and ellipsoidal binary systems. On the other hand, the Fourier techniques often fail in the case of detached eclipsing binaries, in particular those with narrow eclipses. Therefore, we additionally applied the Box-Least Squares (BLS) period-search algorithm (Kovács *et al.* 2002) implemented in the VARTOOLS program[‡] (Hartman and Bakos 2016).

The preselection of candidates for binary systems was made with two automatic methods. The first one used the machine-learning technique based on the Random Forest algorithm (Breiman 2001). The details of this method can be found in Pawlak *et al.* (2016). The second method used fitting of the template light curves. As the templates we used *I*-band light curves of bright ($I < 17$ mag) eclipsing and ellipsoidal variables from three best-sampled OGLE-IV fields: BLG501, BLG505, and BLG512. Each light curve from these fields consists of at least 10 000 data points. The Julian Dates of the individual measurements were transformed to the orbital phases and averaged in 1000 bins. The magnitudes were normalized in such a way that the maximum brightness of every template was zero and the amplitude was equal to 1. Fig. 1 presents several template light curves from our set. The full collection consists of 747 templates.

In the last step of the selection procedure, we visually inspected the light curves of the best candidates for binary stars released by the aforementioned automatic methods. Obvious false positives were removed from the sample. We also rejected light curves that mimic eclipsing or ellipsoidal variability, but probably have another origin. These are for example non-eclipsing spotted variables (RS CVn, BY Dra, and Ap stars) or red giant stars exhibiting the long secondary periods, although there are strong arguments that this enigmatic phenomenon is related to binarity (*e.g.,* Soszyński and Udalski 2014). The final collection was supplemented by eclipsing and ellipsoidal binaries identified during previous searches for other types of variable stars, *e.g.,* Cepheids, RR Lyr stars, or long-period variables (*e.g.,* Soszyński *et al.* 2011b, 2013, 2014).

The classification of our stars was mainly based on the light curve template fitting. We divided the sample into three groups: candidates for eclipsing contact binary systems (the status of these stars has to be confirmed spectroscopically),

[†] *http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks*
[‡] *http://www.astro.princeton.edu/~jhartman/vartools.html*

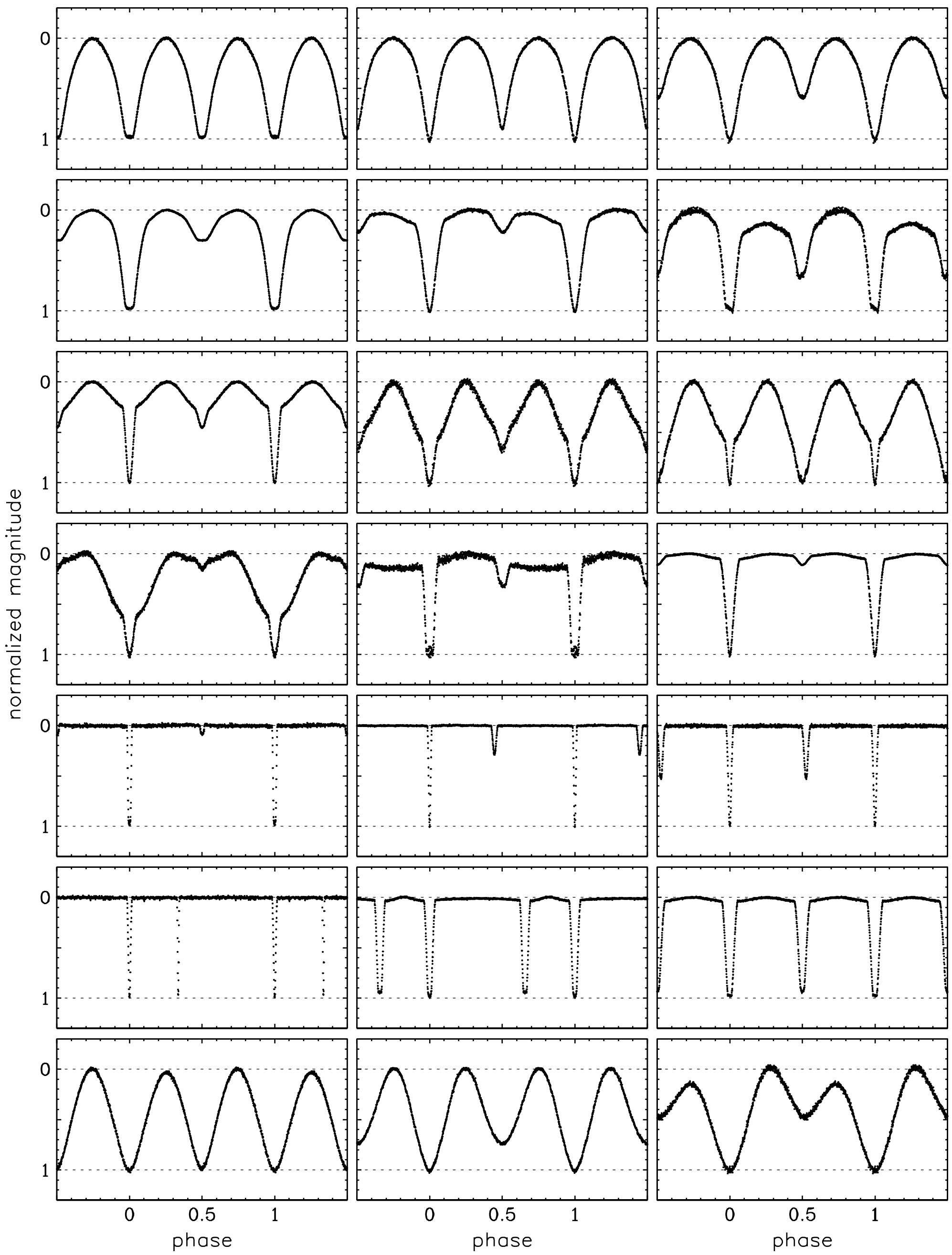

Fig. 1. Examples of template light curves of eclipsing and ellipsoidal binary systems. The templates were obtained from the *I*-band light curves of bright variables detected in three best-sampled OGLE-IV fields: BLG501, BLG505, and BLG512.

non-contact eclipsing systems, and ellipsoidal variables. Additionally, a special designation (CV) was assigned to eclipsing cataclysmic variables – post-novae and dwarf novae – recently cataloged by Mróz *et al.* (2015ab).

4. Binary Systems in the Galactic Bulge

The OGLE collection of eclipsing and ellipsoidal binary systems toward the Galactic bulge contains 450 598 objects, of which 86 560 stars are candidates for contact systems, 338 633 are probable semi-detached and detached binaries (including 18 cataclysmic variables), and 25 405 are non-eclipsing ellipsoidal variables. The data on all these objects are available through the OGLE anonymous FTP sites or via the OGLE web interface:

ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/blg/ecl/
http://ogle.astrouw.edu.pl

Each star has a unique identifier which follows the scheme introduced by Soszyński *et al.* (2015). The identifiers OGLE-BLG-ECL-NNNNNN and OGLE-BLG-ELL-NNNNNN (where NNNNNN is a six-digit number) have been given to the eclipsing and ellipsoidal binaries, respectively. The stars are arranged in order of increasing right ascension, with the exception of the 242 ultra-short-period binaries already published by Soszyński *et al.* (2015). For each object we provide its identifier, J2000 equatorial coordinates, type of variability, *I*- and *V*-band magnitudes at maximum light, orbital period, primary and secondary eclipse depths in the *I*-band, and epoch of the primary eclipse minimum.

We also provide the time-series *I*- and *V*-band photometry collected during the OGLE-II, OGLE-III, and OGLE-IV projects (if available). The light curves from each stage of the survey were independently calibrated to the standard Johnson-Cousins photometric system, however smaller or bigger offsets between the photometric zero points may occur for individual stars. This may be a result of different instrumental configurations, in particular different filters and CCD detectors, used in the three stages of the OGLE project, but also of crowding and blending by unresolved stars which may randomly affect the reference zero point of the DIA photometry. These offsets should be taken into account when merging the light curves from different stages of the project.

The periods and other observational parameters were derived using solely the OGLE-IV light curves collected in the years 2010–2015 or, if the OGLE-IV light curves were unavailable, using the OGLE-II or OGLE-III light curves. The periods were refined using two programs: for the detached systems we applied the BLS algorithm implemented in the VARTOOLS program (Hartman and Bakos 2016), while in the remaining cases the periods were derived with the TATRY code based on the multi-harmonic periodogram (Schwarzenberg-Czerny 1996). One should be warned that only some of the folded light curves have been examined by eye after the final determination of the periods and it cannot be excluded that some of the periods provided in our collection are not real, for example they can be two times longer or shorter than actual orbital periods of the systems. The amplitudes and the luminosities at maximum have been derived fully automatically with the template fitting.

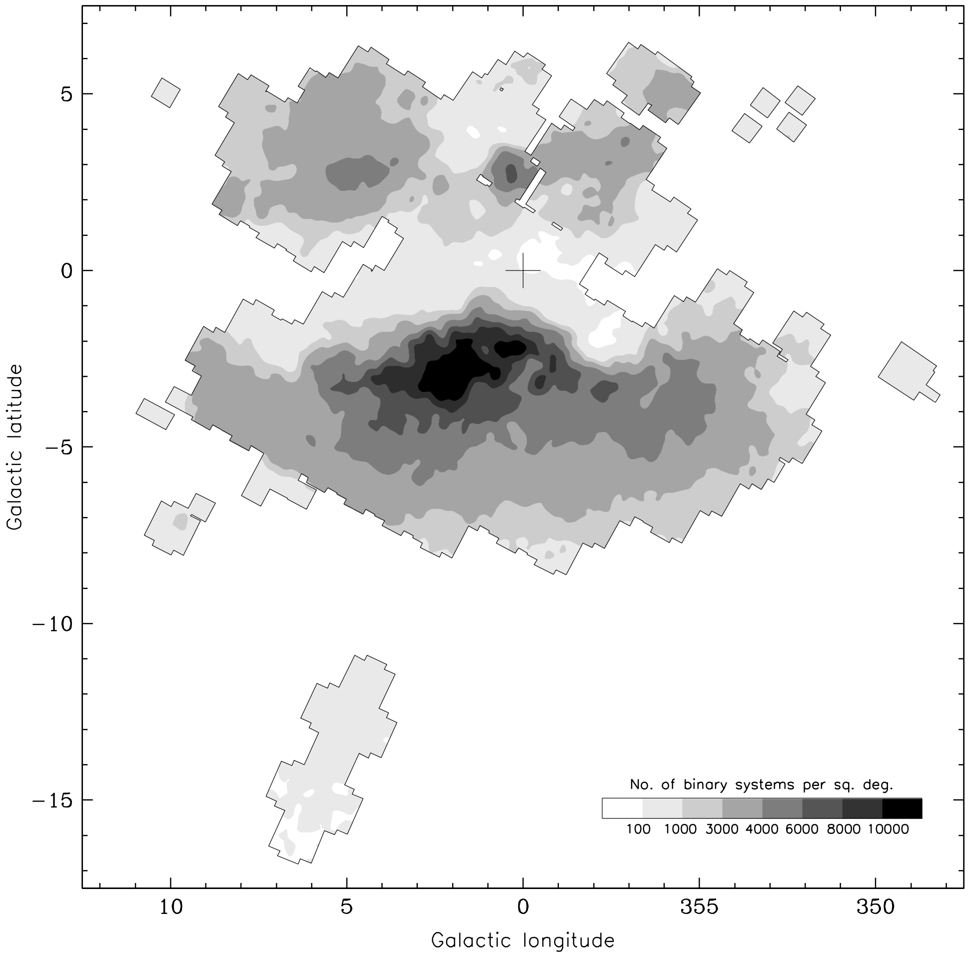

Fig. 2. Spatial distribution of eclipsing and ellipsoidal binary systems in the OGLE fields toward the Galactic bulge.

In Fig. 2, we present the surface density map of the binary systems from the OGLE collection. As one might have expected, the highest density is observed around the Galactic coordinates $(l,b) = (2^\circ,-3^\circ)$, since these are the densest and the most frequently observed OGLE fields. The number of objects in our sample drastically decreases near the Galactic plane due to large interstellar extinction in this region. All systems observed here are likely located in the foreground of the Galactic bulge.

We estimated the completeness of our sample using stars located in the overlapping parts of adjacent OGLE-IV fields. Such stars have double entries in the OGLE database, since they were recorded twice, independently in both fields. Note, that in the final version of our collection each star is represented by a single OGLE-IV light curve, usually the one with larger number of data points.

We found *a posteriori* that 10 118 binaries in our collection have such double entries in the OGLE database (assuming that both light curves must consist of at least 100 points), so we had a chance to detect 20 236 counterparts. We independently identified 16 174 of them, which implies the completeness of the whole sample at the level of 75%. Of course, the completeness is a strong function of the number of data points obtained for a given star, brightness, amplitudes, and light curve morphology. For example, the completeness for binary systems brighter than $I = 18$ mag is about 83%, while for fainter stars it drops to 64%. Obviously, these estimates relate only to the binary systems which brightness, amplitudes and light curve shapes are sufficient to be potentially identified and classified with the OGLE photometry.

5. Discussion

Our collection contains eclipsing and ellipsoidal binary stars of all types: detached, semi-detached, and contact eclipsing binaries, ellipsoidal variables, eclipsing RS CVn stars (exhibiting additional variations due to stellar spots), cataclysmic variables, HW Vir binaries (consisting of a cool main-sequence star and a B-type subdwarf), double periodic variables (Mennickent *et al.* 2003), and even planetary transits (Udalski *et al.* 2002ab). The orbital periods of the systems range from 75 minutes (0.05 d) to over 7 years (2600 d). For about twenty eclipsing binaries we cannot currently determine the periods, since these stars exhibited only one or two eclipses during the whole time span of the OGLE survey. Their periods are probably longer than 8–20 years (depending on whether the star was monitored during the OGLE-IV project only or also during the previous stages of the survey). Detected variability amplitudes range from milimagnitudes to several magnitudes.

The list of potential astrophysical application of our collection is long. Time-series, standard OGLE photometry together with multi-epoch spectroscopic observations may provide a complete set of parameters of both components: their radii, masses, and effective temperatures. Our sample contains many detached eclipsing binaries with deep eclipses which are ideal for distance determinations, so they can be used to trace the structure of the bulge. In turn, statistical properties of the collection provide a useful window into the history of formation and evolution of binary systems in the central regions of our Galaxy.

Fig. 3 presents the distribution of orbital periods of the entire sample. The number of objects shown in the linear scale (the upper panel of Fig. 3) illustrates the proportions of various periods, while the logarithmic scale (the lower panel of Fig. 3) is better suited to show details of the distribution. The bulk of our systems

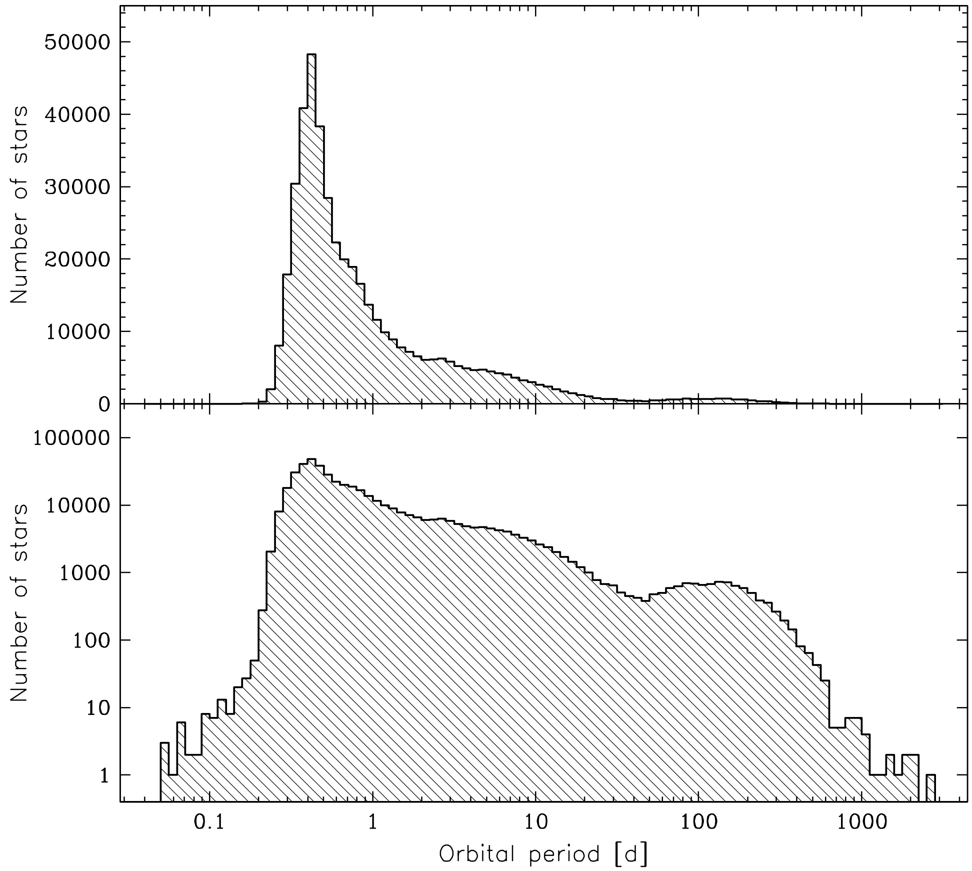

Fig. 3. Distribution of orbital periods of the OGLE collection of binary systems in the Galactic bulge. The number of stars is presented in the linear (*upper panel*) and logarithmic scale (*lower panel*).

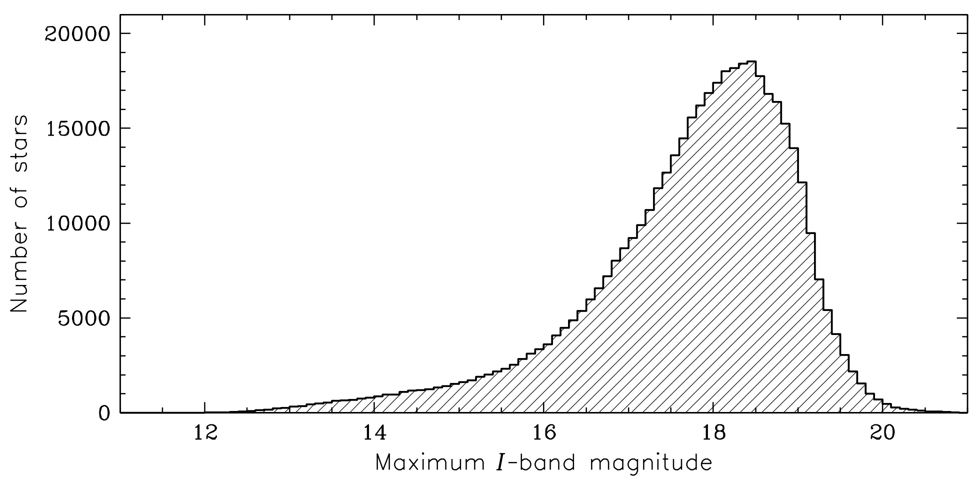

Fig. 4. Distribution of out-of-eclipse *I*-band magnitudes of the OGLE collection of binary systems in the Galactic bulge.

have orbital periods below 1 day and most of them are close binary systems consisting of main-sequence stars. The period distribution has a strong maximum at about 0.40 d. A well-known sharp cut-off at a lower limit around 0.22 d is also visible. The long-period binaries are dominated by very detached binaries or close systems (usually ellipsoidal variables) consisting of red giant stars. Such long-period ellipsoidal variables are responsible for a local flat maximum visible in the distribution for periods between 100 d and 200 d. Red giants in close binary systems form period-luminosity relations (*e.g.*, Pawlak *et al.* 2014). The distribution of apparent I-band magnitudes at maximum light is shown in Fig. 4. The distribution peaks at 18.4 mag, but it is clear that the completeness of our collection begins to decrease at $I = 18$ mag. It is in agreement with our tests of completeness presented in Section 4.

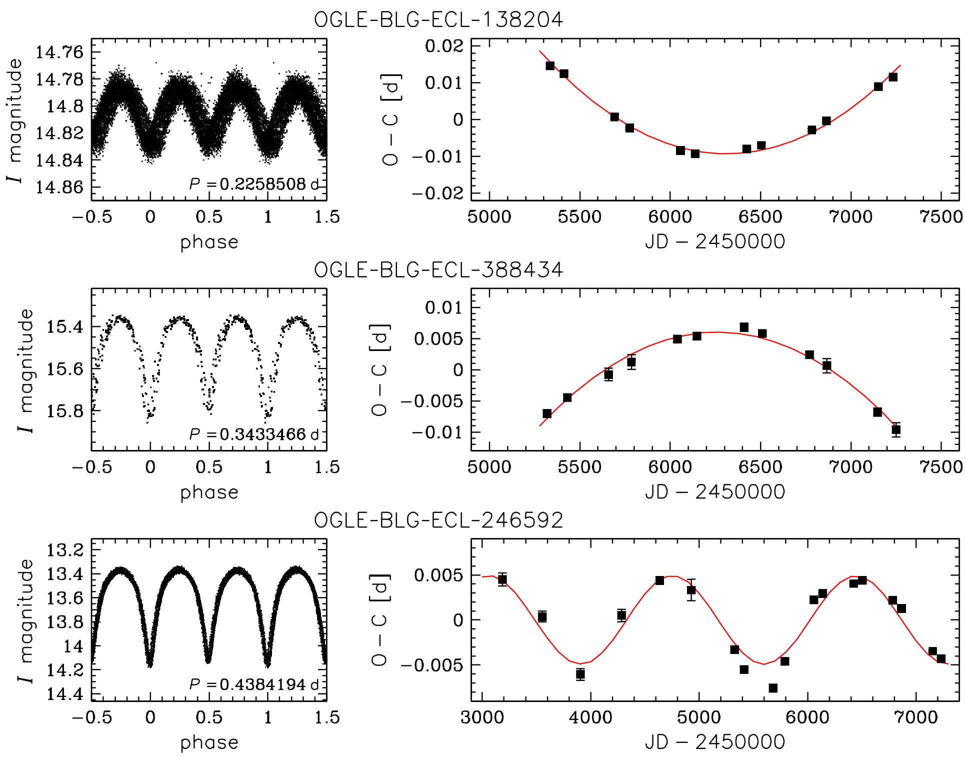

Fig. 5. Examples of three close binary systems with prominent period changes. *Left panels* show light curves folded with the best constant periods. *Right panels* present $O-C$ diagrams obtained for these stars.

The long-term OGLE photometry can be used to test the stability of the orbital periods of individual systems. Binary stars may change their periods due to a mass transfer between the components, mass ejections from the system, or a presence of an unseen tertiary companion. In Fig. 5, we present three examples of close binary systems with prominent period changes: monotonically increasing, decreasing, and cyclically varying periods. A careful analysis of the entire sample should shed light on the problems of short-period cut-off in contact binary systems, the role of magnetic breaking in the evolution of close systems, and the abundance of triple and other multiple systems.

The latter issue can also be examined using double binaries – objects in which two superimposed eclipsing or ellipsoidal modulations are simultaneously visible. Our sample contains at least several dozen such stars. Four light curves of this type are presented in Fig. 6. Double binaries can be blended stars observed on the same

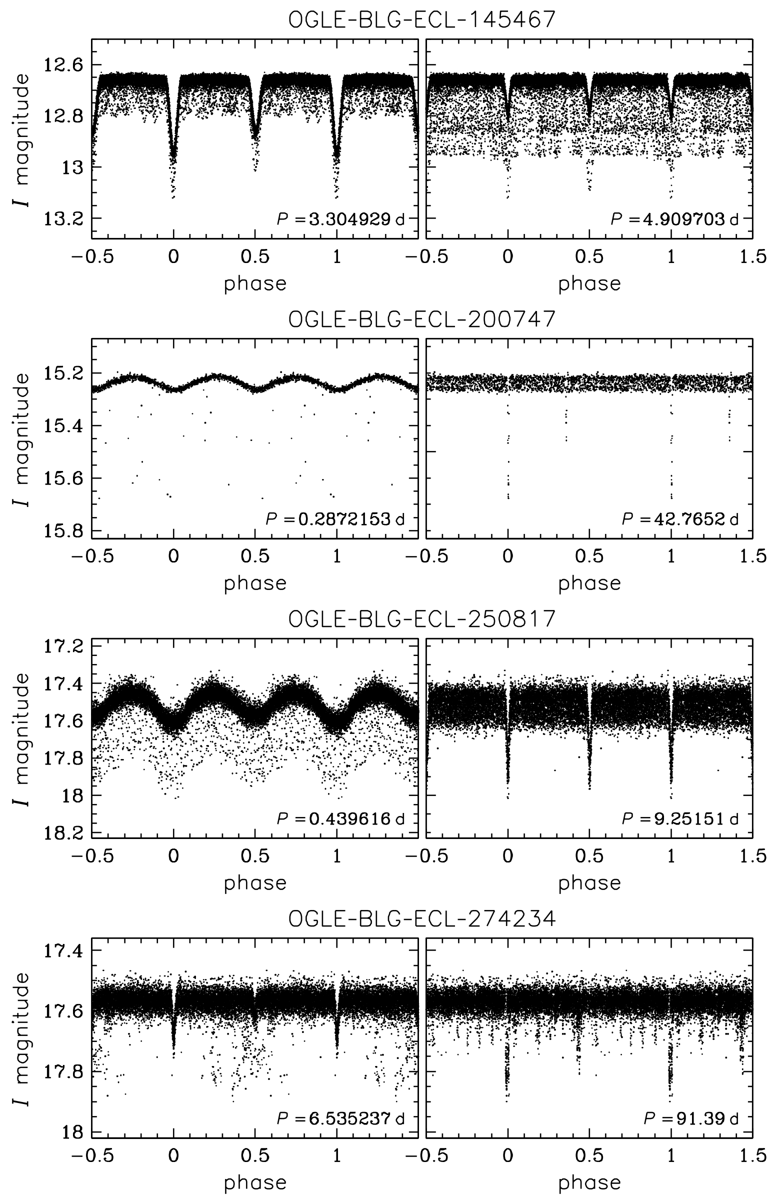

Fig. 6. Examples of four double binaries. Each pair of *left* and *right panels* show the same light curve folded with different periods.

line of sight or can be physically bound triple or quadruple systems. Significant changes of the orbital period observed for example in OGLE-BLG-ECL-274234 (lower panel of Fig. 6) suggest that in this case we deal with an interacting multiple system. Binaries that ceased or began their eclipsing variations can also be used to study triple systems. Graczyk *et al.* (2011), who discovered such stars in the Large Magellanic Cloud, called them transient eclipsing binaries. Three light curves of transient eclipsing binaries in the Galactic bulge are shown in Fig. 7.

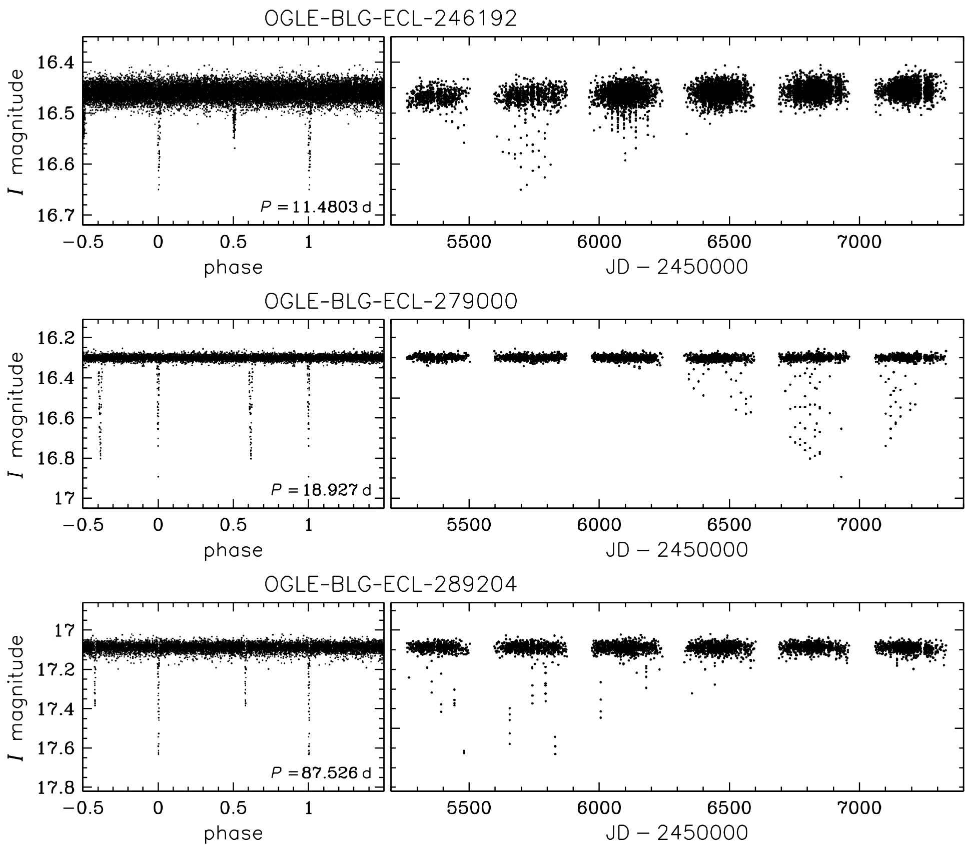

Fig. 7. OGLE-IV *I*-band light curves of three eclipsing binaries that ceased or began their eclipsing variations due to precession of the orbital planes. *Left panels* show light curves folded with the orbital periods. *Right panels* show the same, unfolded light curves.

Eclipsing or ellipsoidal binaries that exhibit superimposed additional types of variability deserve special attention, since such stars may provide solutions to many astrophysical problems. For example, OGLE-BLG-RRLYR-02792 – a variable initially classified by Soszyński *et al.* (2011a) as an RR Lyr star in an eclipsing binary system – turned out to be a first representative of a new type of pulsating stars – so called binary evolution pulsators (Pietrzyński *et al.* 2012). OGLE-BLG-RRLYR-02792, as an eclipsing binary, is also included in the present collection and designated as OGLE-BLG-ECL-108266.

Our collection contains many other binary systems with additional modulation of light. These objects are flagged in the remarks of the collection. Fig. 8 shows light curves of four sample stars of this type. The collection includes at least several eclipsing variables with δ Sct-like variations, one more star classified as an RR Lyrae star (OGLE-BLG-ECL-172630 = OGLE-BLG-RRLYR-06807), many long-period variables (pulsating red giants), and several microlensing events. Probably, some of these objects are blends with unresolved variables.

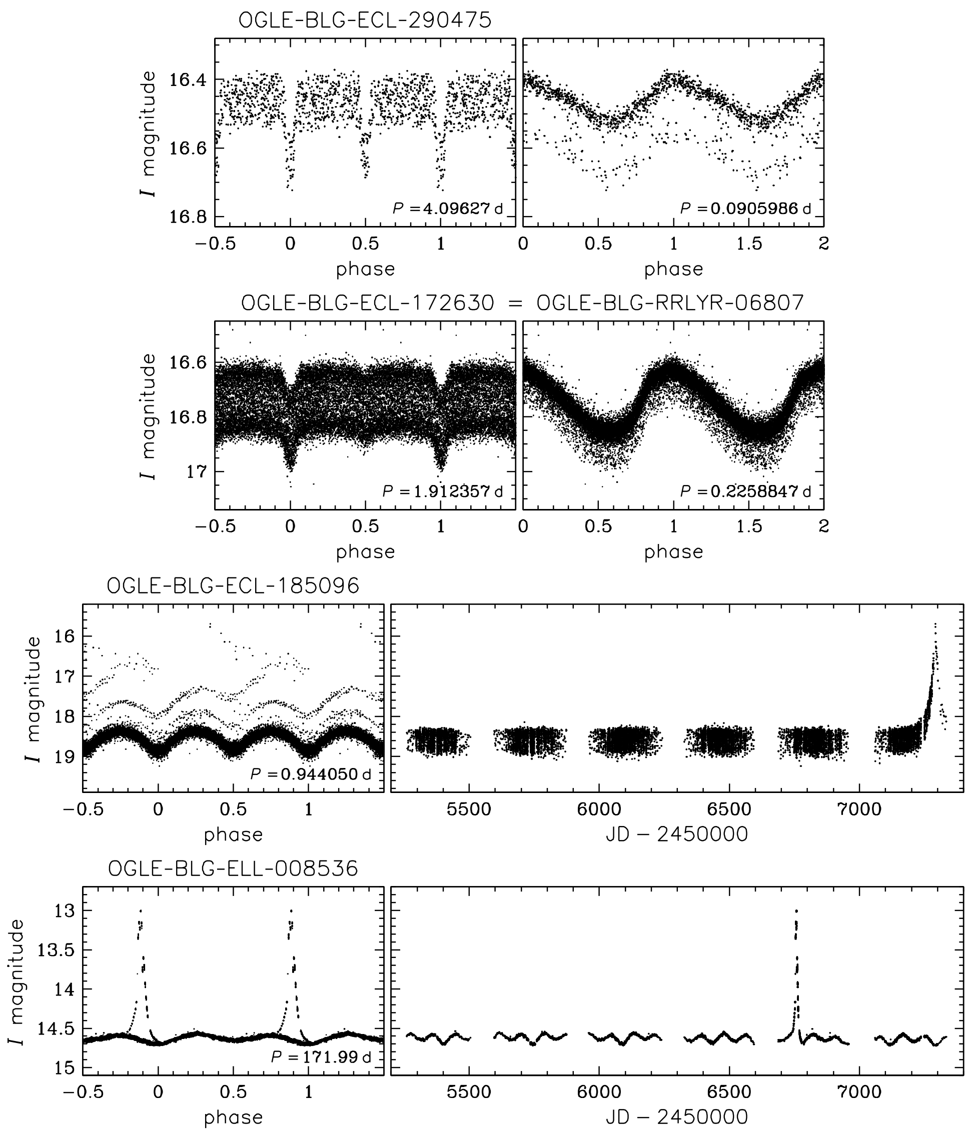

Fig. 8. OGLE-IV light curves of four eclipsing or ellipsoidal binaries with a superimposed additional variability. Each pair of panels show the same light curves. Two *upper panels* show pulsating stars (δ Sct and RR Lyr stars), while *lower panels* display microlensing events.

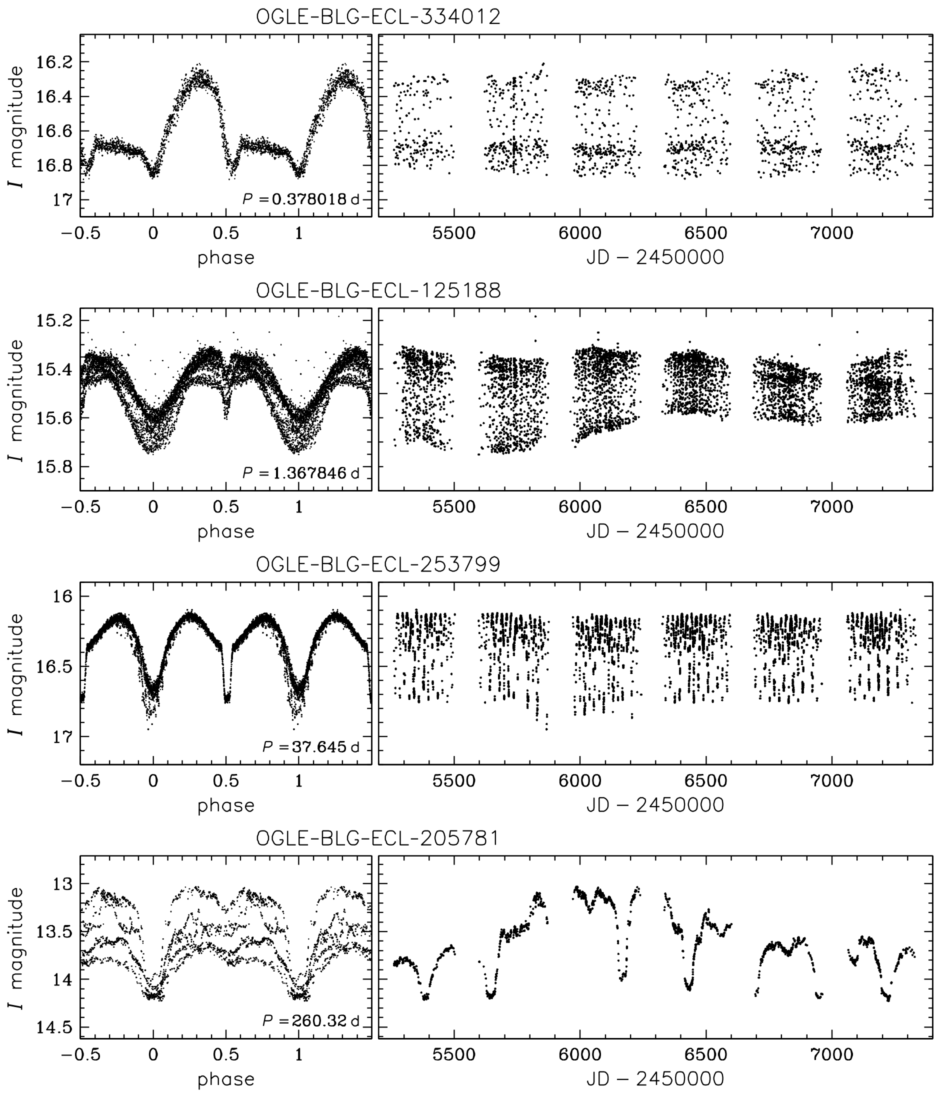

Fig. 9. Four examples of eclipsing binary systems with peculiar light curves. *Left panels* show light curves folded with the orbital periods. *Right panels* show the same, unfolded light curves.

Hundreds of eclipsing RS CVn stars – chromospherically active binary systems – have been included in the OGLE collection. Their light curves usually exhibit two periodicities: the orbital period (manifested by the eclipses) and the brightness fluctuation caused by the rotation of a spotted star. The amplitudes and shapes of the out-of-eclipse light curves gradually change from cycle to cycle due to changes of the spot distribution on the stellar surface. Usually, both periods are similar due to the synchronization of the orbital and rotation cycles, but there are also RS CVn stars in our collection which show very different periodicities. For all RS CVn stars we provide the orbital periods of the systems, even if the variations due to spot surface coverage have larger amplitudes than the amplitudes of eclipses.

6. Conclusions

We presented the OGLE collection of eclipsing and ellipsoidal binary systems in the Galactic bulge. Our sample multiplies the number of known binary systems in this environment and in all other stellar environments. Together with the collection of binary systems in the Magellanic Clouds (Pawlak *et al.* 2016) and in the Galactic disk (Pietrukowicz *et al.* 2013) the OGLE Collection of Variable Stars contains about half a million binary systems. For each object we provide the long-term time-series OGLE photometry in the I and V standard photometric bands, well suited for studying properties of the individual systems and the stellar environment in which they are located.

Such a huge collection of binary stars contains objects of particular interest: systems with secular and cyclic period changes, double binaries, transient eclipsing binaries, other types of variable stars in the eclipsing configuration, systems with accretion disks, and many other peculiar eclipsing and ellipsoidal variables. In Fig. 9, we present four such unusual light curves. In the future, we plan to extend the OGLE collection of the newly found systems in the same bulge fields and in the additional fields covering practically the entire Galactic bulge with its far outskirts. We also expect to discover hundreds of thousands of binary systems in the Galactic disk, which is currently extensively observed by the OGLE-IV Galactic Variability Survey.

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