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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. XII. Eclipsing Binary Stars in the Large Magellanic Cloud *

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ABSTRACT

We present catalog of 26 121 visually inspected eclipsing binary stars identified in the Large Magellanic Cloud during the third phase of the Optical Gravitational Lensing Experiment. The sample is limited to the out-of-eclipse brightness $I < 20$ mag. The catalog consists mostly of detached eclipsing binaries – ellipsoidal variables were not included.

For stars brighter than $I = 18$ mag the detection rate of eclipsing binaries is 0.5% and for all stars it falls to 0.2%. The absolute completeness of the whole catalog is about 15% assuming the occurrence rate of EBs toward the LMC equal to 1.5%.

Among thousands of regular eclipsing systems we distinguished a subclass of eclipsing binaries – transient eclipsing binaries (TEB) – presenting cycles of appearance and disappearance of eclipses due to the precession of their orbits.

Key words: *binaries: eclipsing – variables: general – Magellanic Clouds*

1. Introduction

This is a successive paper presenting the variable stars treasury from the third part of the Optical Gravitational Lensing Experiment (OGLE). We focused here on the difficult task of identification of eclipsing binary stars. Seven catalogs of eclipsing binaries (EBs) in the Large Magellanic Cloud (LMC) detected by the

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

microlensing surveys have been presented in the past. Grison *et al.* (1995) found 79 candidate EBs from the EROS survey, the MACHO survey identified 611 EBs (Alcock *et al.* 1997). Derekas *et al.* (2007) presented “clean” list of 3 031 EBs from MACHO database and Faccioli *et al.* (2007) published an extension of the preliminary catalog by Alcock *et al.* (1997) containing 4 634 stars.

On the other hand, Wyrzykowski *et al.* (2003) found 2 580 EBs in the OGLE-II survey data. Additionally Groenewegen (2005) and Graczyk and Eyer (2010) identified 178 and 574 new EBs, respectively. In total, using different approaches, 3 332 EBs were identified in the OGLE-II photometric database. However, one should remember that this survey was constrained mostly to the LMC bar.

The OGLE-III survey covers a much larger area so we would expect larger number of detected EBs. OGLE-II survey contained about 7 million sources in the direction to the LMC (Udalski *et al.* 2000) while OGLE-III detected about 32 million LMC sources. Using simple scaling we would expect to find $\approx 15\,000$ EBs. However, our catalog actually contains almost a factor of two more objects. We discuss this result in Section 5 of our paper.

2. Observations and Data Reduction

All the data presented in this paper were collected with the 1.3-m Warsaw telescope at Las Campanas Observatory in Chile. The observatory is operated by the Carnegie Institution for Science. During the OGLE-III phase, the telescope was equipped with a mosaic eight-chip camera, with the field of view of about $35' \times 35'$ and the scale of $0\farcs26$ pixel^{-1}. For details of the instrumentation setup we refer the reader to Udalski (2003).

116 OGLE-III fields in the LMC cover nearly 40 square degrees and about 32 million stars were detected on the collected images. Approximately 500 photometric points per star were secured over a timespan of eight years, between July 2001 and May 2009. About 90% observations were taken in the standard I photometric band, while the remaining measurements were taken in the V-band. The OGLE data reduction pipeline is based on the Difference Image Analysis technique (Alard and Lupton 1998, Woźniak 2000, Udalski 2003). A full description of the reduction techniques, photometric calibration and astrometric transformations can be found in Udalski *et al.* (2008).

3. Method of Identification

Search for eclipsing binaries was done using the method outlined by Graczyk and Eyer (2010). However, some changes to the method were introduced. For 3 332 EBs detected in the LMC during OGLE-II survey only one EB is fainter than $I \approx 20$ mag. The detection rate falls very quickly for stars fainter than $I \approx 19$ mag. Therefore, we limited our search of the candidate eclipsing binaries for stars brighter than $I = 20$ mag. Furthermore, all stars having less than 120 measurements in the *I*-band were excluded from the search. Thus, from a total number of 32 millions sources detected in the LMC, only 12 millions sources were investigated for eclipsing-binary-like variability. To save computational time the period search was restricted to periods longer than 1.0015 day and shorter than 475 days with 70 000 trial periods. Period searches were performed with the PDM method (Stellingwerf 1978) for stars having a skewness parameter less than 1.575, and with the string-length method (Lafler and Kinman 1965) for the remaining stars. Stars having period longer than 6.45 days were additionally investigated using the string-length method for periods within the range of 5.05–2800 days, the last number being the approximate time duration of OGLE-III project.

From the beginning of our work, we were aware that a final visual inspection of candidates would be necessary to produce a "clean" catalog of eclipsing binaries. For this reason we decided to look for periods longer than 1.0015 days only. If an eclipsing binary has shorter period we can still find it as a EB candidate. Such object is found with a longer period being a multiplication of a real period – see Fig. 1. During the visual inspection most of these short period binaries were easy to recognize and to assign the real period. In practice this method worked reasonably well for EBs having orbital periods longer than 0.25 day because we have found only one eclipsing binary with a shorter period. On the other hand we would expect a sharp cut-off in the distribution for periods shorter than ≈ 0.2 days (Paczyński *et al.* 2006). Inspection of Fig. 2 from Ficcioli *et al.* (2007) can shed some light on this. Their period distribution also has sharp cutoff near the period of 0.25 days like our one (see Fig. 4 in this paper), however, they could detect about 20 close eclipsing binaries with a period below that limit. Thus our searching algorithm introduces a bias for the shortest period binaries (periods $P < 0.25$ day). However, because all of them are foreground Galactic systems we can still consider our method suitable for the LMC eclipsing binaries.

Quite large number of stars are semiregular long period variables (P>500 days) or high proper motion objects. When their light curve is folded with trial periods, such stars often produce spurious detections as eclipsing binaries, usually with periods being close to one day or a multiplication of one day. We account for this effect by employing strong filters for stars having periods close to a small whole number of days: only stars with high variability index *pvi* could pass the filter. Some real EB could have been removed from the sample this way but much smaller sample of stars for visual inspection was a clear advantage of this approach.

All candidate stars were cross-checked against other previously published catalogs of variable stars from OGLE-III survey, *i.e.*, Cepheids (Soszyński *et al.* 2008a, 2008b), RR Lyr stars (Soszyński *et al.* 2009a) and Long Period Variables (Soszyński *et al.* 2009b). The purpose of this comparison was to remove from the candidate sample all the remaining pulsating and long period semiregular variables. We finished with a sample of about 79 000 of candidate stars.

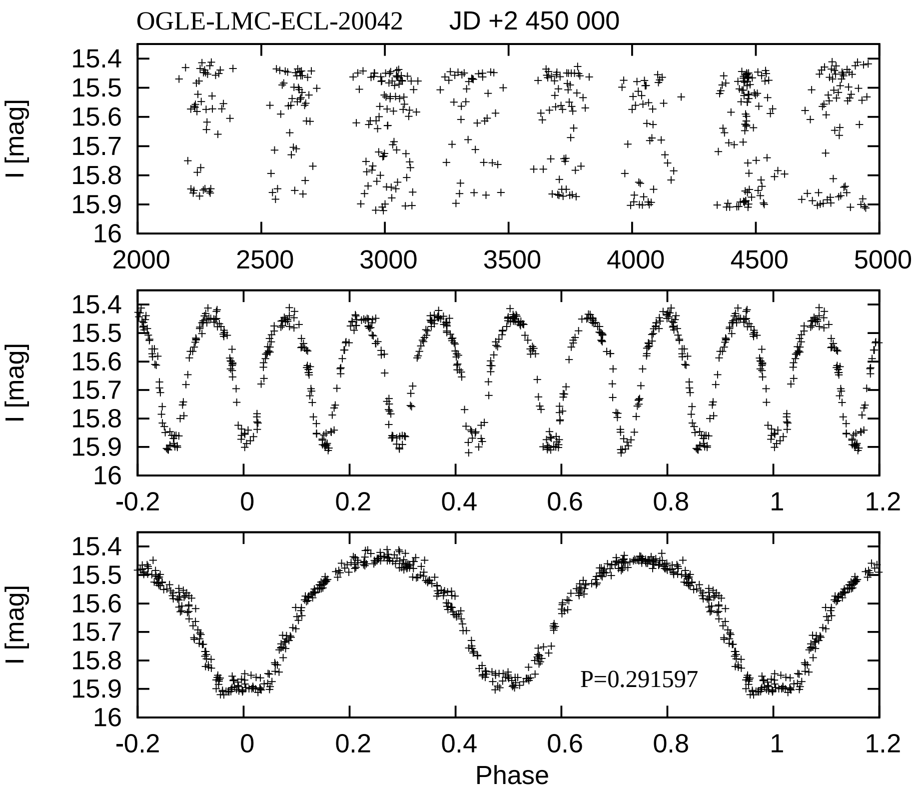

Fig. 1. *Upper panel:* light curve of OGLE-LMC-ECL-20042. *Middle panel:* light curve of OGLE-LMC-ECL-20042 folded with the original period 1.02059 days found by our period finding algorithm. The star was classified as an eclipsing binary candidate. During the visual inspection it turned out that its true period is 2/7th of the original one. *Bottom panel:* light curve of OGLE-LMC-ECL-20042 folded with the real period of 0.291597 days indicating a W UMa type eclipsing binary.

The next and the most tedious part was a visual inspection. The inspection was done using VARTOOL program (written by M.K. Szymański) which has a nice graphic interface. VARTOOL can show the raw and the folded light curve of candidate star at the same time. The period used for folding light curve can be easily modified, and each scrutinized star can be assigned a type of variability. Verification of the orbital period was necessary for many stars, usually by multiplying or dividing it by a factor of 2. Almost 14% of candidate stars turned out to be ellipsoidal variables or their artifacts, 35% of the sample were false detections caused by some noise in the photometry of fainter stars. 15% turned out to be non-eclipsing very long period variables and artifacts of pulsating stars or eclipsing binaries. About 29 000 objects passed visual inspection as eclipsing binaries.

During visual inspection only the most clear artifacts of EBs were removed. Some of the bright eclipsing binaries had as much as 5 artifacts which passed the inspection. To remove them, the cross-correlation index of time series measurements was calculated for all stars from a given OGLE-III field having similar period (within 0.2%). All star pairs with such an index larger than 0.72 were inspected visually to find which star is a true variable. The criteria were: the quality of the light curve (more noisy light curves belong to artifacts), the flux amplitude (the star having the larger amplitude is probably the true variable) and the brightness (in about 90% of cases the true variable is the brighter one). Almost 1 200 objects turned out to be artifacts of some neighboring EBs. Afterwords we checked all the remaining stars from the sample against the presence of artifacts using another method: those stars being in the same field within $2''$ of each other and having similar period (within 0.1%) were again inspected. In this manner we found about 500 more artifacts.

The last part was cross-identification of eclipsing binaries from neighboring fields. 1 051 stars were found in two fields and 16 were found in three fields. The final number of 26 121 stars classified as eclipsing binaries constitutes the present catalog.

4. Classification and Basic Parameters

The catalog provides 26 121 entries, one for each detected eclipsing binary star. For each EB we provide: 1) identification, 2) orbital period, 3) epoch of the primary minimum, 4) mean out-of-eclipse *I*-band magnitude, 5) $V-I$ color, 6) the depth of the primary minimum, 7) the standard deviation, 8) the skewness, 9) the kurtosis, 10) *V*-band magnitude (from OGLE-III photometric maps), 11) *I*-band magnitude (from OGLE-III photometric maps), 12) right ascension (J2000.0), 13) declination (J2000.0), 14) the periodic variability index *pvi*, 15) classification. Positions 7, 8 and 9 refer to the first three statistical moments of the light curve.

The orbital periods of all EBs from the catalog were refined using the string-length method. Typical relative precision of the period determination is about 10^{-4}, but it varies considerably depending on the light curve quality. For eclipsing binaries having only one eclipse observed we provide the shortest possible orbital period. The precision of the ephemeris varies from about 0.05% to 2% of the orbital period. Mean out-of-eclipse *I*-band magnitudes were calculated for orbital phases around 0.25 or/and 0.75. The $V-I$ colors and coordinates were adopted from the LMC photometric maps. The preliminary classification of EBs based on the Fourier series coefficients of the light curves was done using LC_CLASS program written by Pojmański (2002). Only one fourth of the classified cases were visually inspected, so a number of misclassified stars can be expected. We traditionally divided EBs into three main subclasses according to the light curve shape: detached (ED), semi-detached (ESD) and contact (EC). Furthermore we distinguished some other types: ED/VAR – detached with superimposed other kind of variability, ED/ESD – detached/semidetached binaries, ED/TEB – detached Transient Eclipsing Binaries (see Section 7), ELL/EC – ellipsoidal/contact binaries. The last type was singled out by identifying eclipsing binaries having ellipsoidal effects dominating their light curve and eclipses which are usually very shallow and almost grazing. The catalog also contains 30 entries in common with the Double Periodic Variables catalog in the LMC (Poleski *et al.* 2010). The eclipsing binaries with Cepheid components which were detected previously by Soszyński *et al.* (2008a, 2008b) are not included in the present catalog, *i.e.*, OGLE-LMC-CEP-0227, -CEP-1718, -CEP-1812, -CEP-2532 with population I Cepheids and OGLE-LMC-T2CEP-021, -T2CEP-023, -T2CEP-052, -T2CEP-077, -T2CEP-084, -T2CEP-093, -T2CEP-098 with type-II Cepheids.

5. Detection Rate and Completeness of the Catalog

To assess the completeness of our catalog we employed two methods. The first one providing "absolute completeness" is based on the estimated total number of eclipsing binary systems brighter than our limiting magnitude in all our observed LMC fields. To derive this number we should know the occurrence rate of eclipsing binaries in the LMC. However, it is still an open question how double stars form and how such processes depend on a population of stars, their metallicity and a structure of particular galaxy. Therefore the occurrence rate should be rather estimated based on an empirical determination.

Until now, the only reliable estimate of the occurrence rate of eclipsing systems was presented by Prša *et al.* (2011) who calculated the detection rate of EBs from the Kepler space mission to be about 1.5% in the direction of Cygnus-Lyra constellation. The population of stars in the LMC is certainly different from that of the Galactic disk (star-birth history, metallicity, space distribution), but both are relatively young. If we assume the same rate of double stars, and consistently EBs, in both populations and furthermore that the detection rate from Kepler is a good estimation of the real occurrence rate we can make a first guess – we would expect to find 180 000 EBs in the LMC from the OGLE-III survey. So the completeness of our catalog, in an absolute sense, would be just 15%. However, for stars brighter than 17.8 mag the number of detected sources is 1.7 millions and the number of identified EBs is about 8 500 giving the detection rate of eclipsing binaries of 0.50% (see Fig. 2) and the absolute completeness of 35%. In fact, these ratios are even higher because a number of identified sources, searched for EBs, are artifacts of bright stars.

The second method providing "relative completeness" is based on the number of EBs which could be detected from non-continuous, sparse ground-based photometry. Our catalog was cross-correlated against the MACHO catalogs of eclipsing binaries (Derekas *et al.* 2007, Faccioli *et al.* 2007) and the OGLE-II catalogs of eclipsing binaries (Wyrzykowski *et al.* 2003, Graczyk and Eyer 2010). In the area covered by the OGLE-III survey there are 2 888 entries from Derekas *et al.* (2007) and 3 819 entries from Faccioli *et al.* (2007) catalogs, respectively. It gives in total 4 861 stars because 1 846 entries are common to both catalogs. 651 entries were not

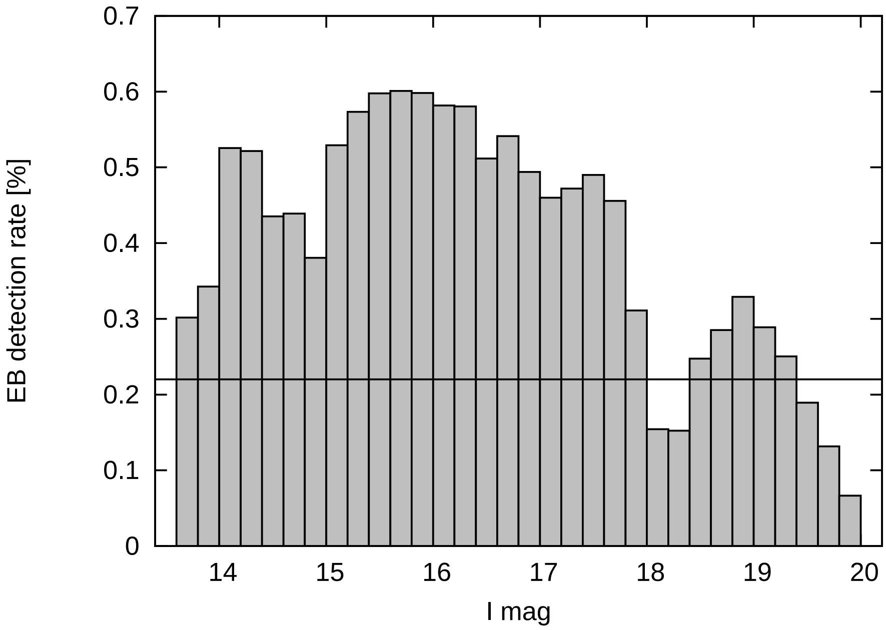

Fig. 2. Detection rate of eclipsing binaries in the OGLE-III survey. The mean value for the whole catalog is 0.22% – horizontal line. However, for EBs brighter than $I \approx 17.8$ mag the rate is substantially larger and equal to 0.50%. The dip around 18.2 mag is caused by numerous red clump stars for which the detection rate is low. Also for stars fainter than $I \approx 19$ mag one can note a clear deficiency of the detection rate.

found in our catalog. Inspection of the individual cases revealed that most of them were ellipsoidal variables (excluded from our catalog by definition) and only 205 were genuine EBs. That gives the relative completeness of $\approx 95\%$. Comparison with the OGLE-II catalogs shows that 290 EB were not found in the present catalog which constitutes the relative completeness of around 91%. Taking a conservative limit, we regard the completeness of our catalog at the level of 90% in comparison with previous ground based surveys.

There are 3 332 eclipsing binaries identified in the LMC from the OGLE-II survey among ≈ 3.5 million sources brighter than $I \approx 20$ mag. This provides the detection rate of almost $\approx 0.1\%$. A similar calculation for the OGLE-III survey in the LMC results in the detection rate slightly larger than 0.2%. What is the origin of this difference?

First of all, the OGLE-III survey time span is twice that of the OGLE-II one giving the chance to detect variability in larger number of stars, especially those having longer periods. The number of measurements is typically larger by a factor of only 1.25 per star in the OGLE-III survey, but its photometry quality is superior to that of OGLE-II. This again provides an opportunity to detect larger number of low amplitude variables. Combining these two effects we can understand the higher detection rate of the present catalog.

6. Statistical Properties of the Catalog

16 443 entries from the catalog were classified as detached systems (it constitutes almost 63%), 1 681 entries as ED/ESD binaries (6%), 6 502 entries as semidetached systems (25%) and only 1 614 as contact or ellipsoidal/contact binaries (6%). It is interesting to compare these numbers with the numbers from Kepler Eclipsing Binary Stars catalog (Prša *et al.* 2011, Slawson *et al.* 2011), remembering that in our catalog ellipsoidal variables were excluded. If we account for their missing contribution the distribution of the types in the Kepler catalog is the following: 62% detached EBs, 8% semidetached systems, 23% contact binaries and 7% of uncertain type. It is worth noting that the relative number of detected, detached systems is remarkably similar in both catalogs and very high in comparison, and in clear contrast, with previous catalogs of eclipsing binaries from ground-based surveys.

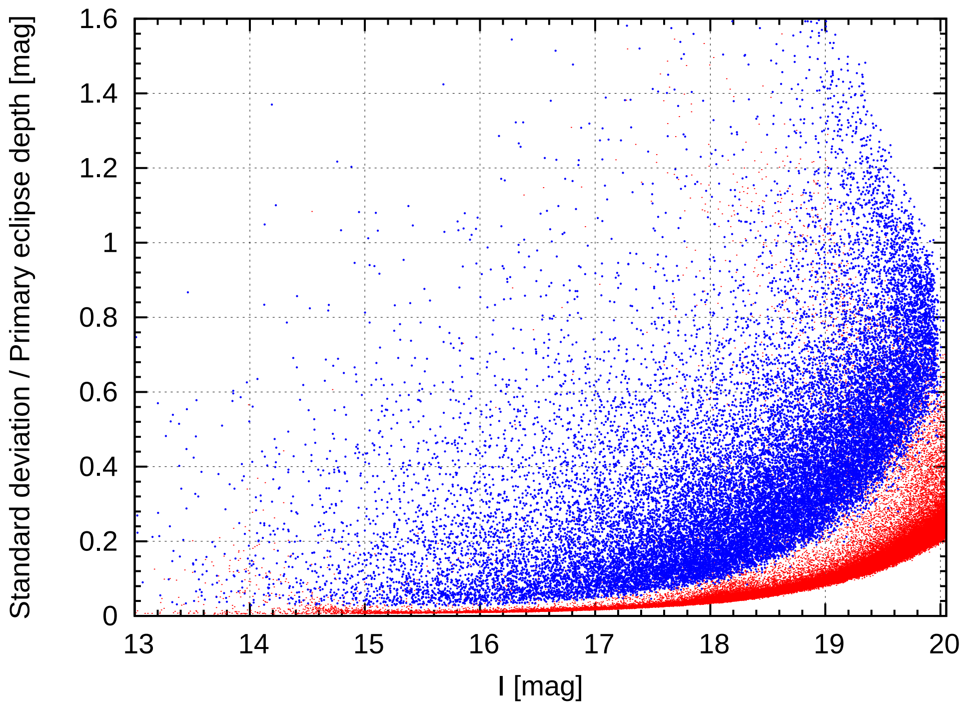

Fig. 3. Standard deviation (σ) *vs.* I-band magnitude for all stars from LMC100.1 field (red dots) with superimposed primary eclipse depths from our catalog (blue dots). We can interpret the bottom of the σ distribution as a noise limit for a given magnitude. On the average we could detect eclipses having depth 2.5 times larger than the noise limit.

We believe that the conclusions given in Prša *et al.* (2011) paper on the low detection rate of detached binaries in previous catalogs "stresses selection effects of ground based surveys" and that "Kepler's sensitivity to detached binaries is superior because of the continuous data coverage" are somewhat controversial. In our opinion, sensitivity for detached binaries is conditioned mostly by the use of the proper finding algorithm as we demonstrate in this paper and if the time baseline and the number of measurements of the ground based survey are large enough the selection effects are of minor importance. Selection effects of previous catalogs were caused mainly by the use of Fourier based period finding methods (poorly suited for detached EBs in the case of not uniformly spaced data) and/or the lack of the efficient filtering out of non-eclipsing stars at early stages of the catalog preparation. We use such filtering based on the light curve statistical moments which was proposed by Graczyk and Eyer (2010). The only real selection effect here is that because of the observational noise (caused, for example, by weather conditions) we are constrained to those EBs which were showing relatively deep minima and lack of strong additional variability that smears out the presence of eclipses. For stars fainter than $I = 19$ mag the photometric noise in OGLE-III is larger than 0.1 mag rendering the detection of EBs with eclipses having depth smaller than 0.2 mag impossible (see Fig. 3). For the brightest stars we could detect eclipses as shallow as ~ 0.03 mag down to a limiting magnitude of $I = 16.5$.

There are, however, some differences between the distribution of EBs from our catalog and the Kepler one. The relative number of semidetached systems is much larger in our catalog. Part of this disagreement may come from a different classification scheme. However, we believe that there is another reason behind it. In the LMC we probe the upper part of the main sequence (O, B and early A type stars) where numerous algol type semidetached systems exist. They can be easily identified in our photometry because they have, usually, short orbital periods and deep primary minima. On the contrary the relative number of contact systems is much larger in the Kepler catalog. However, most of them are short period main sequence binaries having absolute luminosities well below the OGLE-III detection limit in the LMC.

Fig. 4 presents the distribution of orbital periods. There is one distinctive peak of the distribution of all the stars from the catalog at ≈ 2.5 days and it slightly differs from the MACHO LMC peak distribution which is at ≈ 2.0 days (Derekas *et al.* 2007) and from the ASAS Milky Way peak distribution (≈ 1.5 days, Paczyński *et al.* 2006). However, for stars brighter than $I = 18$ mag the distribution is somewhat more complex having additionally two smaller peaks at around 15 days and 100 days.

The number of detected EBs as a function of their brightness is presented in Fig. 5. Systems brighter than 18 mag with periods of 6 days or longer constitute 40% of all stars. However, for fainter stars this ratio is much lower: 25% for $I = 19$ mag and just 13% for $I = 19.5$ mag. This clearly shows how the detection of long period EBs is biased for faint stars. Fig. 6 shows the period–magnitude diagram for all detected EBs. One can note the presence of narrow zone of “avoidance” close to a period of 2 days. This is caused by the finding algorithm which has strong filters to remove spurious candidates having periods of 1 day or its multiples.

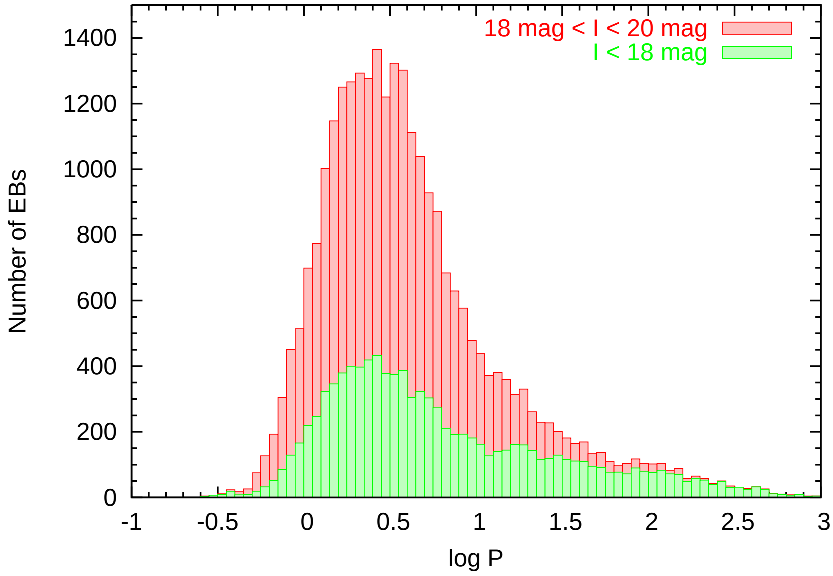

Fig. 4. Histogram of the EBs distribution as a function of period logarithm. It peaks for a period of ≈ 2.5 day. For stars brighter than $I = 18$ mag the distribution is much more flat what indicates that the probability of finding an eclipsing binary of a given period depends on its brightness. Detected eclipsing binaries fainter than 18 mag are, in the vast majority, relatively short period binaries ($P < 10$ days), and at same time detected EBs with periods longer than 200 days are almost exclusively systems brighter than 18 mag. Note the cut-off for systems with orbital period shorter than 0.25 day and a power law decrease for systems having period longer than 4 days with some excess visible around 100 days.

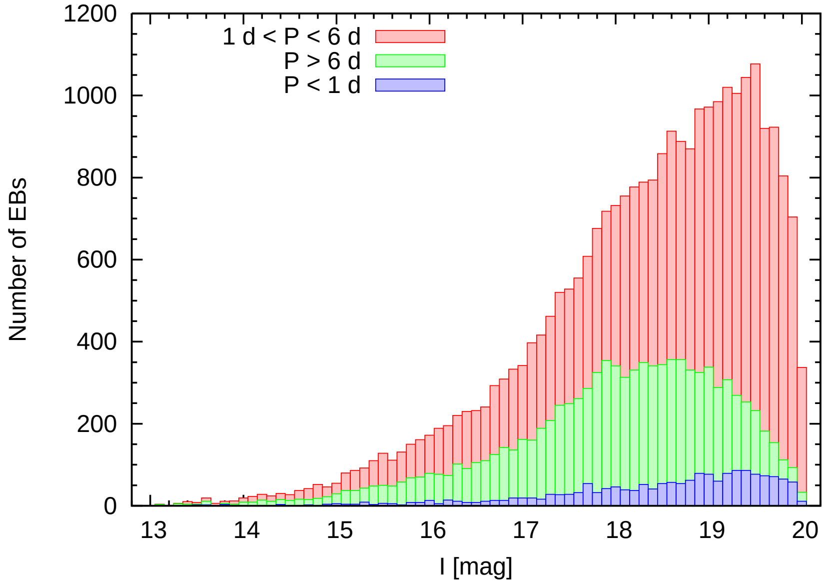

Fig. 5. Histogram of the number of detected EB in the I-band magnitude bins. Note power law growth until around 18 mag and the peak at ≈ 19.4 mag again suggesting relatively good completeness of the catalog for stars brighter than 18 mag. The distribution for very short period systems ($P <$ 1 day) reflects that for all eclipsing binaries. However, for longer period systems ($P > 6$ days) the distribution is different and after the power law rise it peaks already at 17.8 mag.

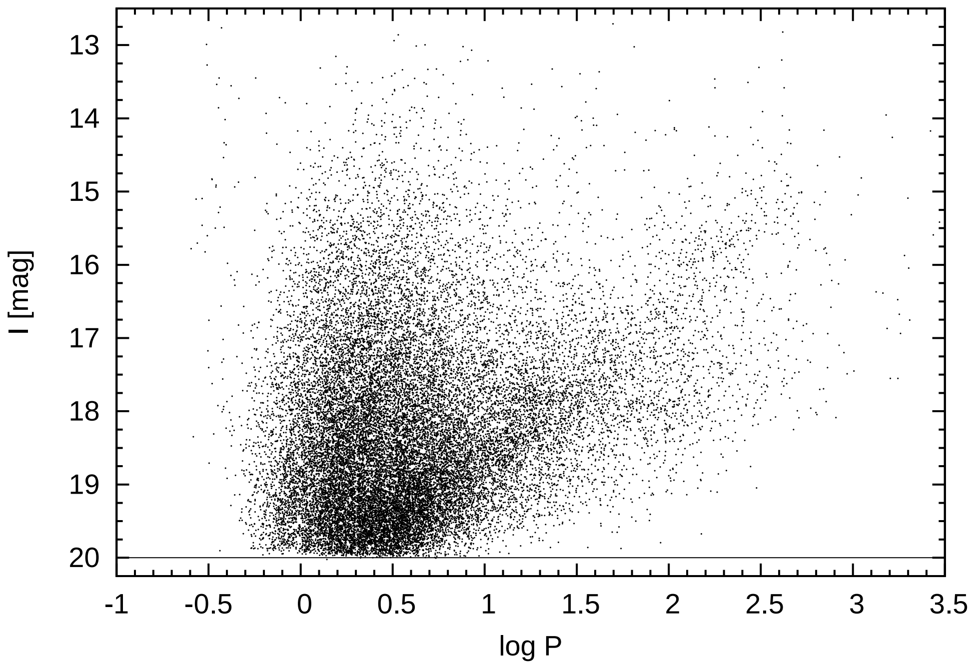

Fig. 6. I-band magnitude *vs.* logarithm of period diagram for all detected EBs. The vertical line at $I = 20$ mag denotes the limiting magnitude of the catalog.

The color–magnitude diagram (CMD) is presented in Fig. 7. No de-reddening was applied. Fig. 8 presents the color–period diagram. The brightest stars clump in three separate regions: the LMC blue main sequence, the LMC red giant branch and the Milky Way red, short period close binaries.

Fig. 8 also reveals a striking feature – a lack of bright ($I < 16$ mag), blue, long period EBs with periods $P \gtrsim 150$ days. At the first glance it seems that almost all long period progenitors containing bright ($M_V < -2.0$ mag) and massive ($M \gtrsim 7.5$ $M_\odot$) components have already evolved into red giant phase, but their shorter period counterparts still remain on the main sequence. A question arises if this is merely an observational bias as we could detect even fainter ($I > 16$ mag), blue, long period EBs.

The number of stars detected by OGLE-III in the LMC in the range of $16 < I < 18$ mag is six times larger than a number of the brightest stars with $I < 16$ mag. On the other hand, counting blue, long period systems in Fig. 8 we obtain this ratio equal to eleven, *i.e.*, almost two times larger than if in the case of a simple selection effect.

We can also count main sequence blue, bright systems (defined as $V - I < 0.2$ mag) and, separately red giant, bright ones ($1.2 < V - I < 1.6$) and compare these numbers with stellar evolution expectations. We have 1 and 96 systems, respectively. This ratio for massive stars depends on relative size between main sequence and red giant branch star, a duration of these evolutionary phases, a mass

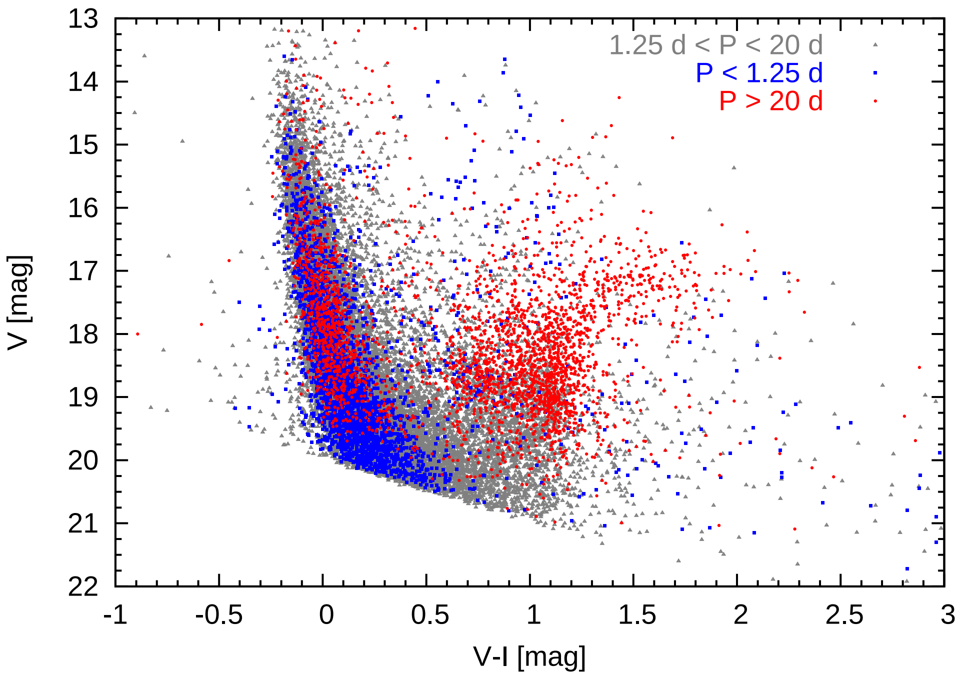

Fig. 7. Color–magnitude diagram for EBs from the catalog. Note the bimodality of color distribution for systems with periods longer than 20 days: they clump around red giant branch and along the main sequence.

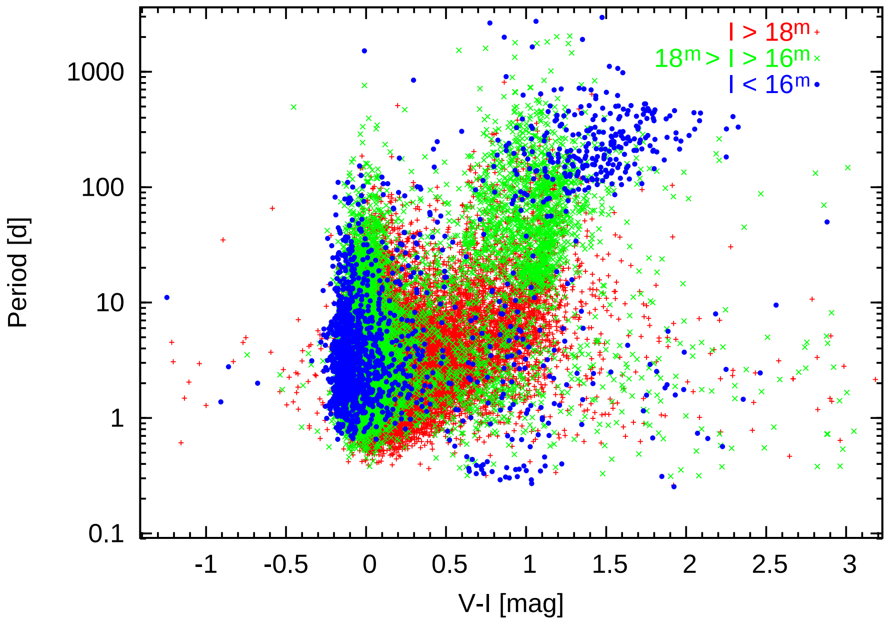

Fig. 8. Orbital period *vs.* $V-I$ color diagram. Note numerous blue EBs with periods longer than 20 days. A comparison with the bottom panels of Fig. 30 from Faccioli *et al.* (2007) demonstrates how the selection effects are important in the detection of long period well detached binaries.

loss rate shifting shorter period systems into $P \gtrsim 150$ days region and a change in spectral energy distribution during evolution shifting fainter (less massive) stars into bright ($I < 16$ mag) region during RGB phase. All the above mentioned factors are somehow uncertain (especially the mass loss rate) but assuming reasonable limits we obtain the expected ratio between 1/50 and 1/20, again suggesting the lack of blue, long period systems.

We propose two purely phenomenological explanations of this finding: 1) the rate of stellar evolutionary processes in massive detached EBs depends on the separation of binary components and systems which are closer evolve in general slower; 2) the LMC long period systems, with a large separation of their components, were, in general, formed before their short period counterparts. However, we still cannot exclude an existence of some hidden selection effects.

7. Interesting Eclipsing Binaries in the Catalog

While inspecting the EBs from the catalog we found 17 systems showing the presence of a fast orbital precession. All of them are well detached binaries and most of them are eccentric systems. They have blue colors consistent with possessing late B-type or early A-type components. In the most cases we see a gradual change of the depth of both eclipses: at some moment of time the eclipses becoming visible, and then – little by little, deeper. Eventually, the eclipses become gradually shallower and completely disappear. In two cases we observed the appearance of eclipses and their disappearance during the time span of the OGLE-III survey – see Fig. 9. The apsidal movement as an explanation of such a behavior can be ruled out because we observed two eclipses simultaneously. We call such EBs "Transient Eclipsing Binaries" (TEB). They are virtually non-variable systems, but for some limited amount of time we observe them as eclipsing binary stars when due the precession of its orbital plane, or "regression of the nodes" (Soderhjelm 1975), the inclination of their orbits to the line of the sight become close to 90 degrees. As a result we observe cycles during which the eclipses show up and then gradually disappear for some period of time.

The prototypes of such TEBs in the Galaxy are SS Lac (discovery: Zakirov and Azimov 1990, analysis: Milone *et al.* 2000, Torres and Stefanik 2000, Torres 2001, Eggleton and Kiseleva-Eggleton 2001) and V907 Sco (discovery: Rahe and Schoffel 1976, analysis: Lacy *et al.* 1999). The cause of the orbital precession or changes of the orbital orientation is the presence of a third, outer star being on inclined orbit to the inner binary. The fast change of the eclipses depth in the LMC TEBs suggests that the likely cause is "regression of the nodes" where the angular momentum vector of the inner binary precesses around the total (constant) angular momentum vector of the system. In the case of V907 Sco the nodal period of the cycle is just ≈ 70 years (Lacy *et al.* 1999) and for most of the identified TEBs from the LMC it should be of comparable length. It is worth noting that an eclipsing binary KID 5897826 found by the Kepler mission and having tertiary eclipses also shows the presence of orbital precession caused by a third, outer component (Carter *et al.* 2011).

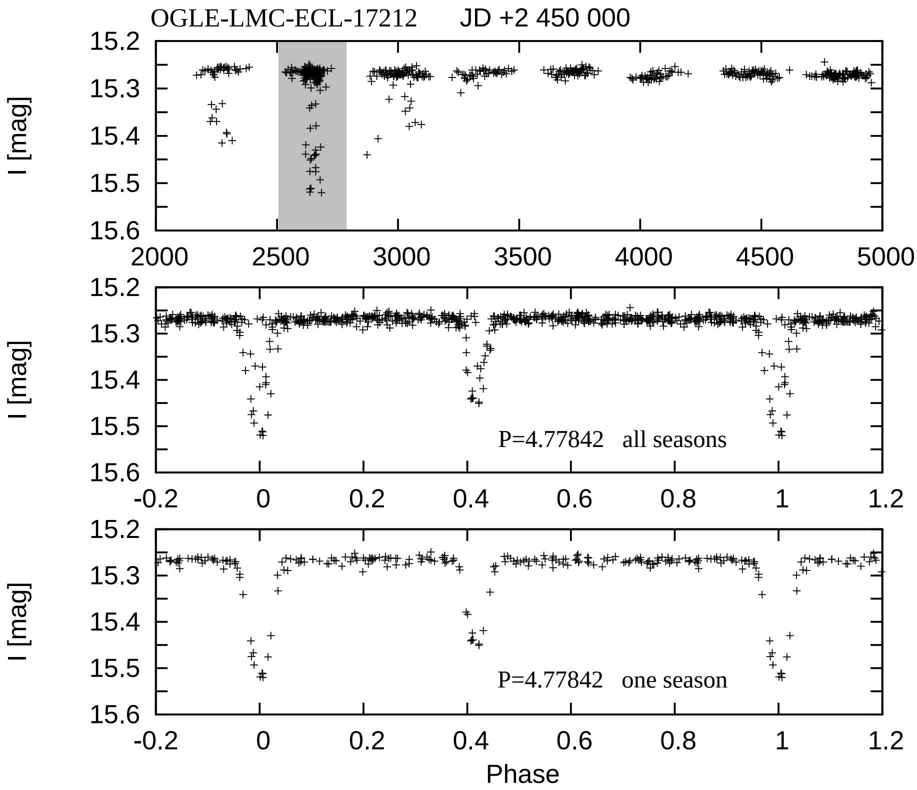

Fig. 9. *Upper panel:* an example of light curve of TEB system: OGLE-LMC-ECL-17212. The time range between JD 2 452 500 and JD 2 452 800 when the eclipses were deepest is marked by a shadow. Note the lack of eclipses after JD 2453400. *Middle panel:* light curve of OGLE-LMC-ECL-17212 folded with the period $P = 4.77842$ days. *Bottom panel:* light curve folded with the same period but with observations taken only from the shadowed region in the upper panel; note the clear presence of well defined eclipses in the eccentric system.

Another group of interesting eclipsing systems are EBs having other kind of variability superimposed and classified as ED/VAR. For example, OGLE-LMC-ECL-02594 is EB containing (or being blended with) a bumper – see Fig. 10. The astrometric position of the star during the brightening is the same as during the baseline. Furthermore, the system lies in one of a least crowded OGLE-III fields – LMC131.7 – strongly suggesting that the bumper is one of the components of the binary and not only a blend.

OGLE-LMC-ECL-16549 is a long period eclipsing binary showing a variability characteristic for a short period, contact eclipsing binary (Fig. 11). Small dispersion of points in the primary minimum suggests that the short period system is either a

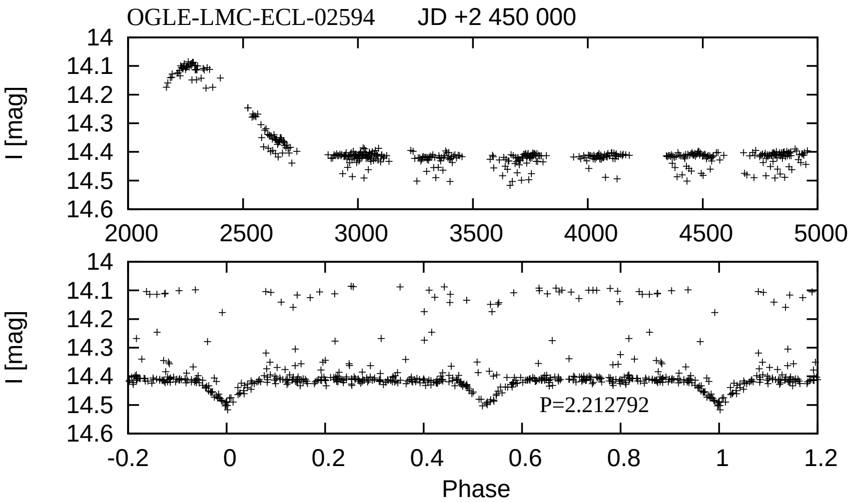

Fig. 10. *Upper panel:* light curve of OGLE-LMC-ECL-02594. Note the brightening during the first two OGLE-III observational seasons. This brightening is characteristic of a bumper variable. A blue $V-I$ color of OGLE-LMC-ECL-02594 supports such interpretation. *Bottom panel:* light curve of OGLE-LMC-ECL-02594 folded with the period P=2.21279 days showing well defined eclipses.

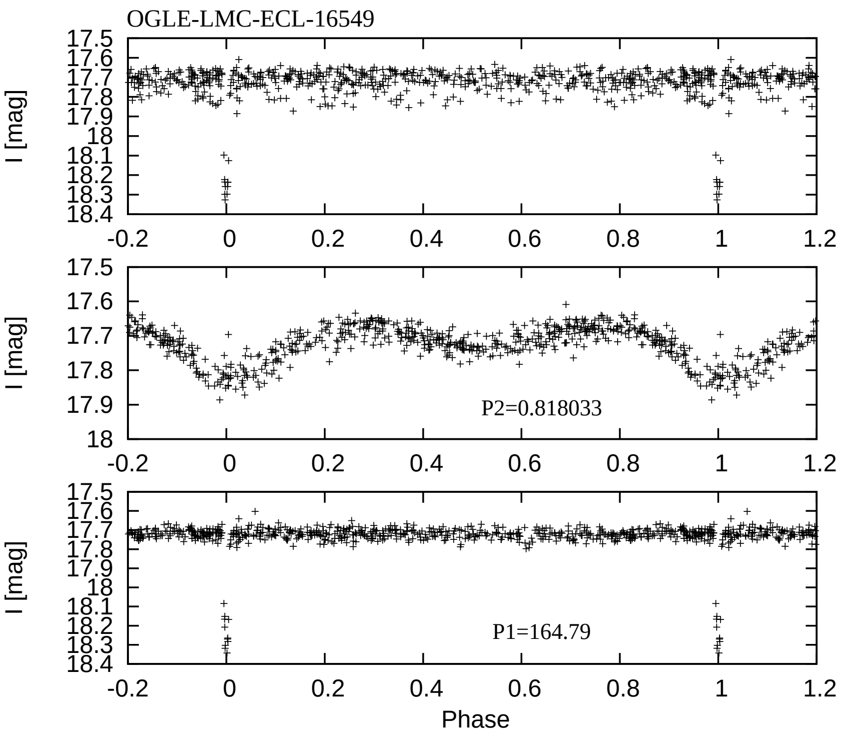

Fig. 11. *Upper panel:* light curve of OGLE-LMC-ECL-16549 folded with the orbital period $P_1 = 164.79$ days. Note the numerous downward outliers outside the deep, narrow primary eclipse. *Middle panel:* light curve of OGLE-LMC-ECL-16549 filtered out of deep eclipses and folded with the period $P_2 = 0.818033$ days. This reveals the presence of a contact binary. *Bottom panel:* light curve of OGLE-LMC-ECL-16549 filtered out of short period variability and folded with period P_1. Note the trace of a possible secondary minimum near the orbital phase 0.6.

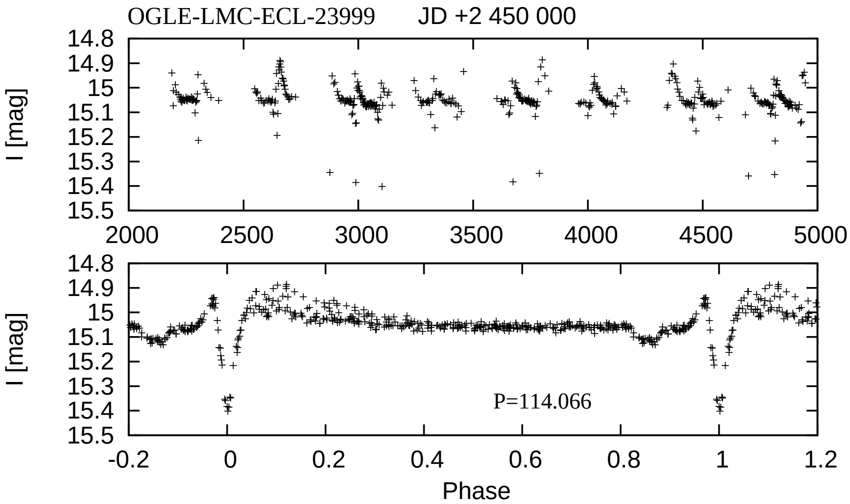

Fig. 12. *Upper panel:* light curve of a long period system OGLE-LMC-ECL-23999. *Bottom panel:* light curve of OGLE-LMC-ECL-23999 folded with the period $P = 114.066$ days showing an eccentric system with relatively wide eclipses and fairly large proximity effects.

part of a hierarchical, gravitationally bounded system of at least four stars: two components forming the long period system and two others in a contact system or a blend. However, we do not detected astrometric shifts during deep eclipses.

OGLE-LMC-ECL-23999 is another long period system having large and variable brightening visible after periastron passage (Fig. 12). Because of the position of eclipses and their similar time duration we expected that periastron passage was near the orbital phase 0.95, somewhere between secondary and primary minimum. However, the brightening, which could be interpreted as a result of intensive mutual reflection when stars are close each other near periastron, occurs later after primary minimum. Furthermore, the brightening is of considerably different strength during consecutive passages. We suppose that they are related to episodic mass exchange between components near periastron passage and soon afterwords. Indeed, it seems that a sum of the radii of both components is close to their smallest orbital separation.

Fig. 13 presents observations of OGLE-LMC-ECL-17782 system. The light curve of the system possess a number of odd looking features. First note a strange, wide, flat-bottomed primary eclipse, reminiscent of ε Aurigae eclipses, with additional narrow, eclipse-like feature in the middle of the eclipse. There is also a considerable change in the primary eclipse shape. Second, note the numerous downward outliers which were not caused by worse weather conditions and we consider them to be real. Third, around the phase 0.5 there is a narrow secondary minimum, strikingly shorter than the primary minimum, but of a similar duration as the eclipse-like feature visible near the orbital phase 0. We interpret these features as the following: the circular, detached or semidetached system contains two stars,

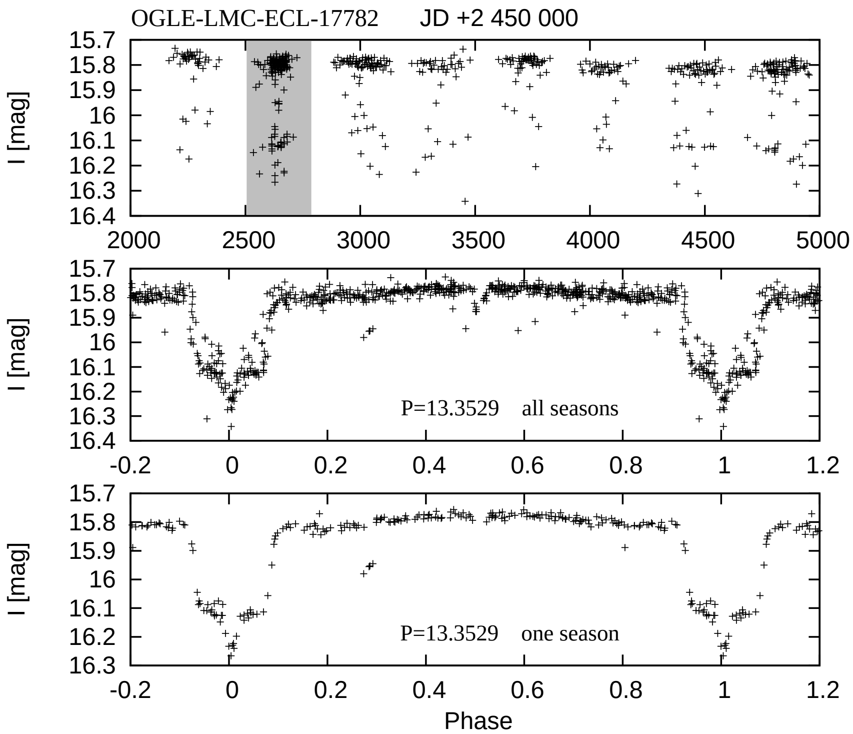

Fig. 13. *Upper panel:* light curve of OGLE-LMC-ECL-17782. *Middle panel:* observations of OGLE-LMC-ECL-17782 folded with the period $P = 13.3529$ days reveal a strange looking light curve of an eclipsing binary. The system configuration seems to be semidetached, but there are some serious oddities to be explained – see the text. *Bottom panel:* observations of OGLE-LMC-ECL-17782 from one OGLE-III observing season (shaded region in the *upper panel*) again folded with the period P. Note the well defined "boxed" primary minimum, suggesting that variations of the shape occur from one season to another. There is also startling, additional minimum of brightness visible near the phase 0.3, but not visible during other observing seasons – see the *middle panel*.

one of them being partially hidden within a semi-transparent, dark, elongated body or a disk. When the disk transits over the second star, "boxed" shaped minimum is produced and when the first star occults the second one, we can see additional fading near the phase 0. When the second star transits over the disk, we can detect only a narrow secondary eclipse which corresponds to an occultation of the first star (the disk itself does not contribute significantly to the total light, at least not in the *I*-band). The disk has probably time-varying dimensions and density producing different shapes of primary minimum during consecutive seasons. Furthermore there are transient structures in the system (disk debris?) responsible for additional minima at different orbital phases when one of the stars is hidden behind them. Probably this structure is somehow related to the non-uniform mass exchange between components. The real puzzle is how such a dark, semitransparent disk-like structure could be formed in such a short period system?

OGLE-LMC-ECL-17681 is the shortest period system ever detected in the di-

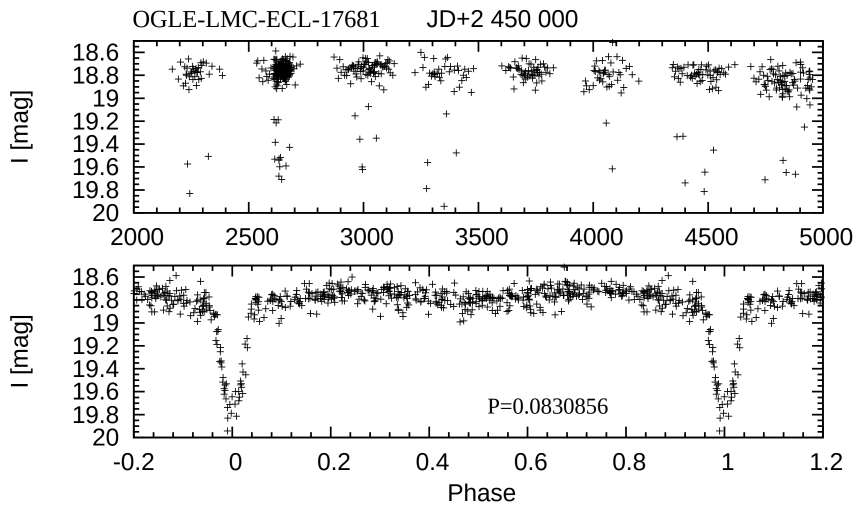

Fig. 14. *Upper panel:* light curve of OGLE-LMC-ECL-17681. *Bottom panel:* light curve of OGLE-LMC-ECL-17681 folded with the period 0.0830856 days. Note the deep primary minimum, the very shallow secondary minimum, small reflection effect and no presence of eruptive or nova-like activity.

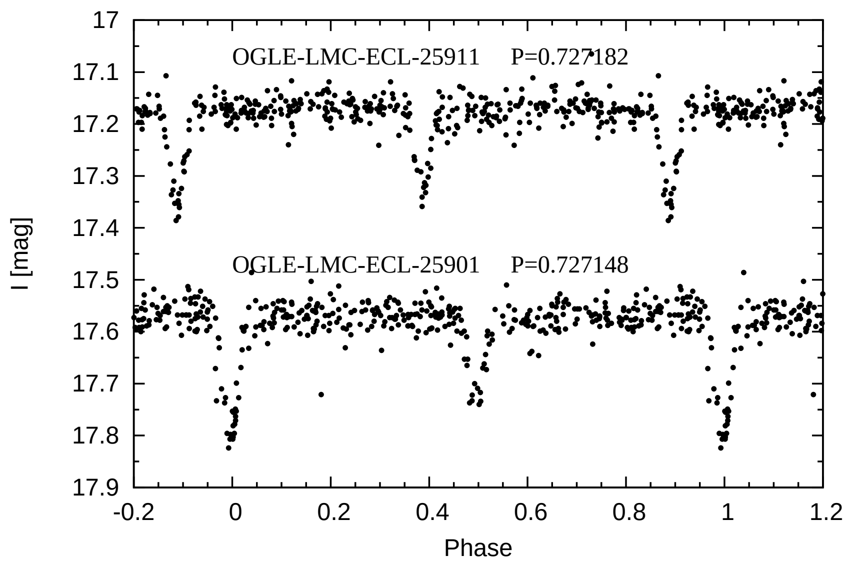

Fig. 15. Light curves of OGLE-LMC-ECL-25901 and OGLE-LMC-ECL-25911 folded with their orbital periods and the same epoch of primary minimum. The light curve of OGLE-LMC-ECL-25911 was shifted by ≈ -0.2 mag for clarity.

rection of the LMC (Fig. 14). The orbital period is just 2 hours. The system lies in the vicinity of the LMC bar, but its brightness ($V = 19.2$ mag), color ($V - I = 0.5$ mag), fast proper motion and very short period strongly suggest that it is a Galactic object. Probably the system contains a white dwarf and a red dwarf.

An interesting pair of short period, low mass EBs is presented in Fig. 15. The systems are separated in the sky by only 15 arcmins. Both have a very red color: $V-I=2.88$ mag, and their light curves are very similar. The relative difference of their periods is only $5\cdot 10^{-4}$. However, the epochs of the primary minimum are different indicating that they are not artifacts of the same eclipsing binary. Most likely, they are foreground Milky Way objects comprising a wide, hierarchical quadrupole system.

8. Final Remarks

Here we present the catalog of eclipsing binary stars in the LMC based on the OGLE-III photometric data, suitable for statistical analysis and for individual case studies. This is the largest catalog of eclipsing binaries published so far.

The catalog reveals a rich population of detached systems containing early type components. Detached systems constitute most of the stars in the catalog and their relative number is very similar to the relative number of detached systems detected in the direction of the Cygnus-Lyra region during the Kepler mission.

The work on this catalog demonstrates that at some point of the preparation a visual inspection of candidates was necessary. We feel, however, that such procedure is close to the limit of practical sense. During the verification of 79 000 candidate EBs we needed on average 13 seconds per star to make a reasonable evaluation (including the period verification). For bright stars the procedure of visual evaluation was quite fast, but for fainter stars, especially those close to the limiting magnitude, visual inspection proved to be tedious.

We think that the procedure of visual verification of candidates should be replaced at this stage by some advanced algorithm which could recognize the shape of the folded light curve, assign the proper period and evaluate if this is an eclipsing binary. A final visual inspection of "the best" sample (in our case: $\approx 30\,000$ stars) would be much more convenient.

A promising step in that direction is the use of an artificial neural network (ANN) like in Wyrzykowski *et al.* (2003, 2004). One of the important factors during the evaluation of light curves by an ANN is the use of a proper learning sample in order to teach an ANN how to recognize which light curves correspond to that of eclipsing binaries. We consider that our catalog can be regarded as a comprehensive learning sample for any ground based survey aimed at eclipsing binary detection.

The OGLE-III catalog of eclipsing binary stars in the LMC is available to the astronomical community from the OGLE Internet Archive:

http://ogle.astrouw.edu.pl
ftp://ftp.astrouw.edu.pl/ogle3/OIII-CVS/lmc/ecl/

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