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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. VI. Delta Scuti Stars in the Large Magellanic Cloud [1]

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ABSTRACT

The sixth part of the OGLE-III catalog of Variable Stars presents δ Sct pulsators in the Large Magellanic Cloud. Altogether 2786 variable stars were found and amongst them 92 are multi-mode objects, including 67 stars pulsating in the fundamental mode and the first overtone (F/1O), nine double-mode pulsators with various combinations of the first three overtones excited (1O/2O, 2O/3O and 1O/3O pulsators), and two triple mode (F/1O/2O) δ Sct stars. In total 1490 of stars are marked as uncertain, due to scattered photometry and small amplitudes. For single-mode objects it was not possible to unambiguously identify pulsation mode, however we suggest the most of the single-mode variable stars pulsate in the first overtone.

Key words: *Catalogs – δ Scuti – Stars: oscillations – Magellanic Clouds*

1. Introduction

δ Scuti stars are main sequence (MS) or early post-MS pulsators occupying lower part of the classical instability strip. It is much harder to discover these stars at the same distance as other pulsators lying in the classical instability strip,

[1]Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington.

Cepheids and RR Lyr stars, because generally they are fainter and their light variations have smaller amplitudes. Until now only very few pulsators of this type were known in the galaxies other than the Milky Way.

Mateo *et al.* (1998) detected 20 δ Sct stars in the Carina dwarf spheroidal galaxy and those were the first extragalactic stars of this type. Their short periods and position in the color–magnitude diagram (CMD) suggest they belong to a subgroup of δ Sct variable stars – SX Phe stars. Members of this subgroup are Population II objects and are frequently identified as blue stragglers in the globular clusters. Kaluzny and Rucinski (2003) searched for short-period variable stars in the field of the Large Magellanic Cloud (LMC) open cluster LW 55 and revealed eight objects. Soszyński *et al.* (2003) searched for RR Lyr stars in the LMC using data obtained by the second phase of the Optical Gravitational Lensing Experiment (OGLE). As a by-product a list of 37 short-period variable stars was presented. McNamara *et al.* (2007) classified 24 of these stars as LMC δ Sct stars. Di Fabrizio *et al.* (2005) found one δ Sct star in the LMC. Huber *et al.* (2005) announced a discovery of a large number of δ Sct stars in the LMC by the SuperMACHO project, but no further details were published. Kaluzny *et al.* (2006) found one δ Sct pulsator in the LMC disk field. Around 100 other δ Sct or SX Phe stars were found in NGC 6822 irregular galaxy and also Fornax, Coma and Leo IV dwarf spheroidal galaxies (Baldacci *et al.* 2005, Poretti *et al.* 2008, Greco *et al.* 2009, Musella *et al.* 2009, Moretti *et al.* 2009).

The OGLE-III project collected photometric data for about 32 million stars in the LMC for eight years. Typically 500 *I*-band and 50 *V*-band images of each field were taken during that time. Although the original purpose of the project was to find the gravitational microlensing events the resulting data base allows discoveries of unprecedented number of variable stars. This paper is the sixth part of the OGLE-III catalog of Variable Stars (OIII-CVS) and presents 2786 δ Sct stars observed in the direction of the LMC. Out of them 67 objects pulsate simultaneously in the fundamental mode and the first overtone. The distance to the LMC is known with an uncertainty of $\approx 3\%$ (Pietrzyński *et al.* 2009) and gives additional constrain on absolute luminosity for modeling of multi-mode pulsators presented in this paper.

Current observational works on δ Sct stars are rather focused on multi-site campaigns investigating individual field objects. They allow discoveries of many pulsation modes in observed stars. Good example is the campaign carried out by Breger *et al.* (2005) on FG Vir. The catalog prepared on the basis of the OGLE data gives less detailed information about individual stars but covers much larger number of objects.

Section 2 describes observational data and their reduction. Section 3 gives detail information on our selection procedure. The catalog itself is described in Section 4. The discussion of discovered variable stars is given in Section 5. We end with conclusions in Section 6.

2. Observations and Data Reduction

The OGLE-III photometric data had been collected between 2001 and 2009 with the 1.3-m Warsaw telescope situated at Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institution of Washington. The telescope was equipped with the "second generation" camera containing eight SITe 2048×4096 CCD detectors. Pixel size of 15 μm corresponds to 0.26 arcsec/pixel scale. Total field of view was around 35×35.5 arcmin. The readout noise varied between different detectors from 6 e^- to 9 e^- and gain was set to about 1.3 e^-/ADU. Details of the instrumental setup were described by Udalski (2003).

The photometry was obtained using the Difference Image Analysis (DIA) method (Alard and Lupton 1998, Alard 2000, Woźniak 2000). The final data reduction procedure was described in detail by Udalski *et al.* (2008a). The 116 OGLE-III fields in the LMC cover an area of almost 40 square degrees and around 32 million of stars. For central 4.5 square degrees of the LMC the OGLE-II photometry is available (Szymański 2005). Whenever it was possible we connected the OGLE-III photometric data with the OGLE-II ones. To assure these additional data are in the same photometric system we added to the OGLE-II magnitudes the difference between mean brightnesses in OGLE-III and OGLE-II data. The objects lying near the edges of the CCD chips are in some cases present in two or even three fields because the OGLE-III fields slightly overlap. We combined the photometry from the adjacent fields. For the particular objects, especially very faint ones, either cross identification or brightness transformation may be defective. No interstellar extinction corrections were applied.

The photometric uncertainties of the DIA photometry are known to be underestimated. To make them more reliable we have corrected them using formula $\sigma_{\rm new} = \sqrt{(\gamma\sigma_{\rm old})^2 + \varepsilon^2}$. The coefficients γ and ε differ for the different fields and chips and were calculated by J. Skowron (private communication). The details are described by Wyrzykowski *et al.* (2009).

3. Selection Criteria

We expected most of the δ Sct stars in the LMC would have *I*-band magnitudes in the range between 19 mag and 21 mag. It is close to the detection limit of the OGLE-III photometry and the standard deviation of magnitudes rises in this interval from 0.05 mag to 0.3 mag (see Udalski *et al.* 2008, Fig. 2 and 6). Thus, selection of candidates was performed in a few steps during which we tried to remove interfering variable stars, such as short period Cepheids, RR Lyr stars, β Cep stars and eclipsing variables, as well as photometric artifacts which are more of a problem for fainter stars, but not to remove the most sound δ Sct stars.

3.1. Selection of Single-Mode Pulsators

At the beginning of the investigation of the OIII-CVS we performed a massive period search. For each star observed in the LMC the frequency range from 0 1/d to 24 1/d with a step of 0.00005 1/d was inspected using the FNPEAKS code (Z. Kołaczkowski, private communication). To search for δ Sct stars we selected only the stars with the most prominent peak in the periodogram corresponding to the period shorter than 0.249 d and with the signal to noise ratio higher than 5 (if not stated otherwise signal to noise ratio – S/N – mentioned below corresponds to a value from these periodograms). We note here 0.24 d period was taken as a boundary between first overtone Cepheids and δ Sct stars by Soszyński *et al.* (2008). In the present study we did not find any good candidate for the single-mode pulsator with period longer than 0.24 d.

The period distribution of the stars selected in such a way contained two prominent peaks near 1/5 d and 1/6 d, thus almost all the stars with periods close to these values were left out. Visual inspection of the light curves ensured us that the majority of these stars were indeed artifacts. The DIA photometry is influenced by variability of nearby stars thus from the groups of objects lying close to each other on the sky and possessing similar periods only one object was selected and all the remaining were removed. Using the first two parts of the OIII-CVS (Soszyński *et al.* 2008, 2009) we have also removed stars lying near the previously found Cepheids and RR Lyr type stars.

For further selection and analysis, outlying photometric points as well as ones with the highest values of the magnitude uncertainties were removed. For all objects we tried to correct the period found during the massive period search using the method described by Schwarzenberg-Czerny (1996). For most of the stars the difference between two period estimations was very small. Some periods were changed to their $\pm 1/\mathrm{d}$ harmonics and for a group of objects we could not confirm initially derived periods and these objects were left out.

The next step of the selection was the visual inspection of the remaining candidates. Stars with large amplitudes were marked as eclipsing binaries, if folded with period twice longer than estimated above they showed different depths of minimum light or different shapes of two halves of the light curve. In this stage some objects were classified as artifacts.

For more sophisticated elimination of the eclipsing systems we have fitted all the *I*-band light curves with the Fourier series (Simon and Lee 1981) consisting of two to five terms depending on the quality of the light curve. The number of the *V*-band measurements in the OGLE-III photometry is much smaller than in the *I*-band. Instead of fitting the Fourier series to the *V*-band data we decided to transform the fitted *I*-band light curves. Using the Levenberg-Marquardt algorithm (Press *et al.* 1992) for each star we have found three coefficients – phase difference, difference in the mean brightness and amplitude ratio – that minimize the χ^2 between *V*-band data and the transformed fitted *I*-band light curve. We found for most of the obvious eclipsing systems that the amplitudes in each of the pass bands are nearly equal. This should be true for contact systems as temperatures of components are similar. For pulsating stars the effective temperature changes during each cycle and thus amplitude is different in different pass bands. In many cases our candidates had very noisy light curves thus the comparison of amplitudes was performed only for objects with $\mathrm{S/N} > 7.5$. Fig. 1 shows a plot of the ratio of amplitude of the first Fourier terms in V ($A_1(V)$) and I ($A_1(I)$). One can see that points in Fig. 1 tend to group around two regions. This is more evident if higher S/N limit is assumed. For the first group (eclipsing systems) $A_1(V) \approx A_1(I)$ and for the second (pulsating stars) $A_1(V) \approx 1.5A_1(I)$. The line which best separates the two groups is in our opinion $A_1(V) = 1.316A_1(I)$ and it was adopted as a border line between two groups. In obvious examples (detached eclipsing binaries and double mode pulsators) we did not take into account the amplitude ratio.

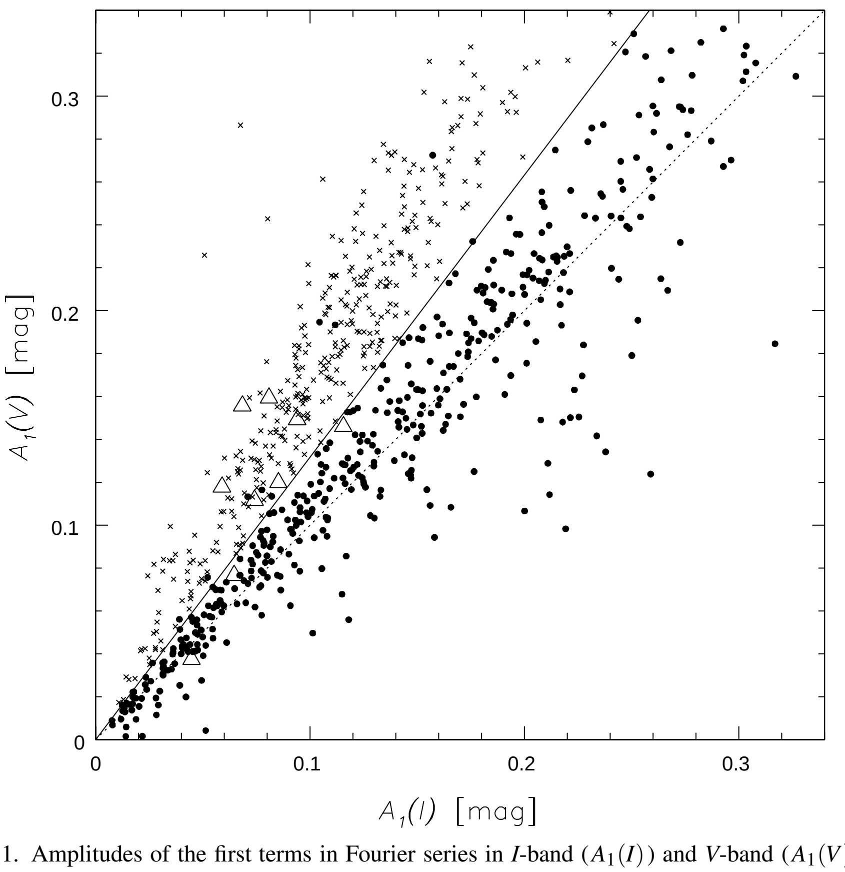

Fig. 1. Amplitudes of the first terms in Fourier series in I-band ($A_1(I)$) and V-band ($A_1(V)$) data. Stars classified as eclipsing binaries are marked by filled circles. Crosses mark single mode δ Sct stars and open triangles – F/1O ones. Solid line represents the adopted boundary between eclipsing binaries and pulsating stars. Dashed line represents $A_1(V) = A_1(I)$ relation.

We classified 84 stars from our list as candidates for β Cep. First such stars in the LMC were discovered by Pigulski and Kołaczkowski (2002). The more detailed search, probably with a smaller limit on the S/N, and the analysis of these pulsators will be done in one of the next parts of the OIII-CVS.

Many candidates for short-period pulsating stars were found among the red clump and red giant stars. Some of these objects may be δ Sct pulsators blended with other star but most of these stars were spurious candidates. In order to clean candidate list from artifacts situated in this region of the CMD we have removed objects with the $\mathrm{S/N} < 6.2$ and with $\phi_{21} = \phi_2 - 2\phi_1$ smaller than 3 or greater than 5. It is shown in Section 4 that most of the δ Sct stars have light curves described by $3 < \phi_{21} < 5$. After applying this procedure the red giant branch and the red clump are barely seen on the CMD of candidates.

The next step of our cleaning procedure was removing numerous eclipsing systems amongst stars with $\mathrm{S/N} < 7.5$. These stars had periods near our selection limit (*i.e.*, half of the orbital period was close to 0.24 d), were typically 1.5 mag fainter in the *I*-band than the δ Sct stars with similar periods and had ϕ_{21} values close to 0, contrary to $\phi_{21} \approx 4$ for the δ Sct stars. All the objects lying inside the selected region on $\log P$–I magnitude diagram were removed from the list of candidates.

In order to identify galactic objects in the foreground of the LMC we estimated for each candidate the proper motion using profile photometry of the OGLE-III data (Udalski *et al.* 2008a) which also gives astrometric position of a star for each observation. Since we only wanted to select high proper motion objects in our candidate list we did not correct measured positions for parallax or differential refraction effects. We left out a few dozens of mostly red high proper motion stars. These objects are nearby stars for which observed light variations are most probably caused by rotation.

Finally, we added to the list of δ Sct stars altogether eleven stars with periods longer than adopted limit (0.249 d). One of them (OGLE-LMC-DSCT-0765 = LMC_SC11_241461) came from Soszyński *et al.* (2003) and all other stars were found during the earlier searches for variable stars in the LMC (Soszyński *et al.* 2008, 2009). The catalog contains also five stars for which the mean luminosities vary in our data.

Finding the clear cut between variable stars and artifacts is especially difficult task for the noisy light curves like the ones analyzed in the present study. We decided to remove single-mode candidates with $\mathrm{S/N} < 5.2$ and assign objects with $5.2 < \mathrm{S/N} < 6$ as uncertain in our catalog. Fig. 2 presents sample light curves of stars with $\mathrm{S/N} < 6$ (left panels) and $\mathrm{S/N} > 6$ (right panels). We note that even though our classification may be wrong for individual stars, the catalog contains mostly true pulsating variable stars and may be used for statistical investigations.

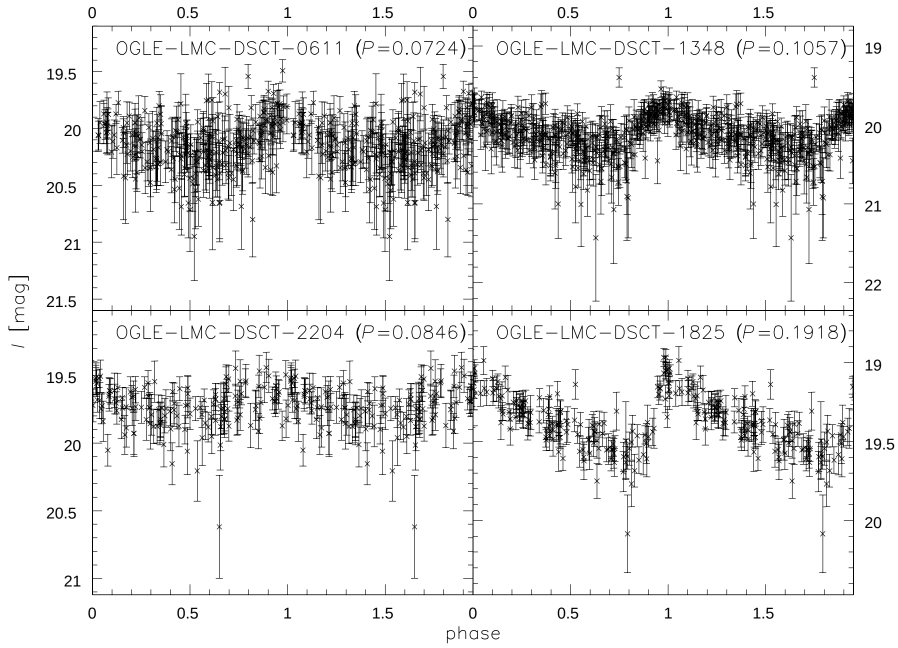

Fig. 2. Sample light curves of δ Sct stars marked as uncertain (*left panels*) and not marked (*right panels*). In each panel OGLE designation and period are given. For clarity randomly chosen 1/3 of points is shown.

3.2. Selection of Multi-Mode Pulsators

The selection of candidates for multi-mode pulsators was performed in two ways. In the first one the periodograms from the massive period search were inspected for prominent secondary peaks with $S/N > 5$ and not caused by the daily aliases. The second method was the prewhitening of all previously selected δ Sct candidates for which we derived the periods with the Schwarzenberg-Czerny (1996) method. After the prewhitening, the periodograms were calculated once more using the FNPEAKS software and searched for peaks with $S/N > 5$ (for combination frequencies the limit was lowered to 4). In both methods we also checked several stars with the peaks $S/N < 5$ but closer examination revealed that all of these peaks (except one with $S/N = 4.92$) were spurious results.

The Petersen diagram (*i.e.*, the plot of logarithm of the longer period P_L *vs.* ratio of the shorter to the longer period P_S/P_L) revealed that most of the double mode pulsators oscillate in the fundamental mode (F) and the first overtone (1O). For δ Sct stars the period ratios of these stars lie in the range 0.75–0.79 what is predicted by models (Petersen and Christensen-Dalsgaard 1996) and confirmed by observations (Alcock *et al.* 2000, Pigulski *et al.* 2006). We used the PERIOD04 software (Lenz and Breger 2005) for the closer examination of all multi-mode candidates. Finally, we found 92 multi-mode pulsators. The identification of 1O/2O, 2O/3O and 1O/2O period ratios are based on Olech *et al.* (2005, their Fig. 6). Fig. 3 presents the Petersen diagram for our multi-mode δ Sct stars.

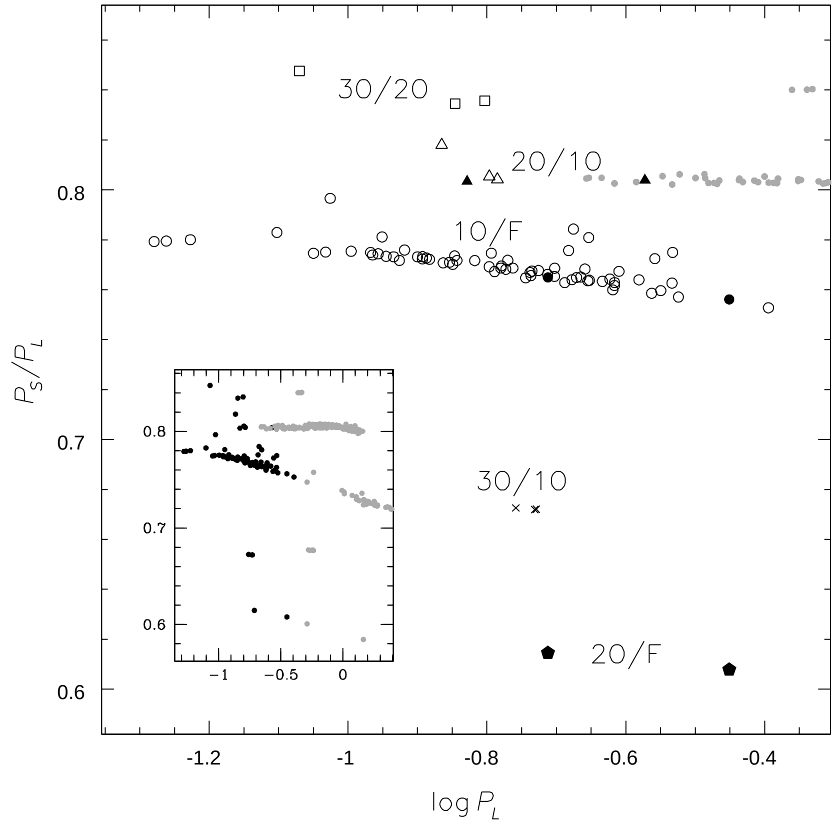

Fig. 3. Petersen diagram for multi-mode pulsators with mode identified. Open symbols correspond to the objects with two modes identified and filled black ones – to objects with three modes identified (three symbols per star). Circles represent F/1O modes, triangles – 1O/2O, squares – 2O/3O, pentagons – F/2O and crosses – 1O/3O (three double mode objects, two of them the very near each other). Gray dots show OGLE-III Cepheids (Soszyński 2008). The insert shows δ Sct stars (black dots) and Cepheids (gray dots).

We did not find any candidates for δ Sct stars in eclipsing binary systems.

4. Catalog

Our catalog of δ Sct stars in the LMC includes 2786 variable stars, of which 1490 are flagged as uncertain. There are 92 objects with more than one mode detected. This catalog is much larger than the biggest catalog of δ Sct stars published so far (Rodríguez *et al.* 2000) which contained around 600 stars in the Galaxy.

This part of the OIII-CVS is available in the electronic form only from the OGLE Internet archive:

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

The FTP site contains a full list of the identified δ Sct stars in the ident.dat file. All the stars are sorted according to their right ascension and have identifiers in the form of OGLE-LMC-DSCT-NNNN, where NNNN is a consecutive four digit number. The columns contain: OIII-CVS identifier, the OGLE-III photometric map identifier (the subfield and the number from Udalski *et al.* 2008b), our classification (SINGLEMODE or MULTIMODE), RA and DEC coordinates for epoch 2000.0 and OGLE-II designation (Udalski *et al.* 2000) for stars in the central region of the LMC.

Basic parameters of the single-mode pulsators are stored in the file single-mode.dat which contains: OIII-CVS identifier, intensity mean I and V-band magnitudes, period and its uncertainty, the I-band amplitude peak-to-peak, and two Fourier coefficients of the light curve – ϕ_{21} and R_{21} ($R_{21} = A_2/A_1$ where A_1 and A_2 are the amplitudes of the first two Fourier series terms). File multimode.dat contains basic parameters for multi-mode δ Sct stars. The number of frequencies found (up to eight) forced us to arrange this file differently. For each star the number of rows is equal to the number of frequencies detected. The first column contains OIII-CVS identifier only in the first row for a given star. Other rows have "–" mark in that column. The rest of the row contains: period and its error, time of the maximum light, amplitude in magnitudes and remarks such as mode identification or combination frequency identification at the end.

The file remarks.dat contains additional information on our δ Sct stars. Most records show uncertain objects. For nineteen stars significant proper motion was found and its value is given in each case. Since we were able to determine proper motions for Galactic stars the objects with given proper motion are δ Sct stars belonging to the Milky Way.

5. Discussion

5.1. Multi-Mode Pulsators

We found two triple mode pulsators pulsating simultaneously in the fundamental mode and the first two overtones (F/1O/2O). Among stars with two radial modes identified there are 67 F/1O, three 1O/2O, three 2O/3O and three 1O/3O pulsators. Out of them we found combination frequencies for 19 objects. Fundamental mode periods are longer than assumed selection limit (0.249 d) for eight F/1O and one F/1O/2O pulsator.

In Fig. 3 there are a few F/1O pulsators with period ratios higher by 0.01–0.02 than for the remaining stars and no pulsators with evidently smaller ratios. We note that for previously discovered F/1O δ Sct stars there are only a couple of stars with the period ratio smaller than typical and several with period ratio higher than typical (Pigulski *et al.* 2006). In our sample there is also one 1O/2O object with P_S/P_L ratio higher by 0.012 than for the remaining 1O/2O objects. Its classification is less clear. Some of both the F/1O and 1O/2O objects mentioned above may be nonradial pulsators for which it is not possible to photometrically identify pulsation mode. The mode identification for the star shown in Fig. 3 with $\log P_L \approx -1$ and $P_S/P_L \approx 0.8$ is less clear and this may be either F/1O or 1O/2O pulsator.

The insert in Fig. 3 shows that the period ratios for double mode δ Sct stars and Cepheids, with the same modes excited, follow the same relations. As it was mentioned before, the observational boundaries between these two groups of stars are a convention. Theoretical discussion of evolutionary status of the short period Cepheids was done by Baraffe *et al.* (1998) and Dziembowski and Smolec (2009).

The highest number of frequencies found in one object is eight (OGLE-LMC-DSCT-0048). Except for the fundamental mode frequency ($f_{\rm F}$) and the first overtone one ($f_{\rm 1O}$) also six their combinations were found: $2f_{\rm F}$, $f_{\rm F}+f_{\rm 1O}$, $f_{\rm 1O}-f_{\rm F}$, $3f_{\rm F}$, $2f_{\rm F}+f_{\rm 1O}$ and $2f_{\rm F}-f_{\rm 1O}$.

The period–luminosity relations for radial modes identified in multi-mode objects are shown in Fig. 4 separately in the *V*- and *I*-bands as well as for the reddening free Wesenheit index ($W_I = I - 1.55(V-I)$). The linear fits were found by the least squares method with 3σ clipping. The following relations were derived for fundamental modes:

$$
\begin{aligned}
V &= -2.84(\pm0.26)\log P + 17.68(\pm0.20) \qquad \sigma = 0.30 \text{ mag}\\
I &= -3.20(\pm0.24)\log P + 16.88(\pm0.19) \qquad \sigma = 0.30 \text{ mag}\\
W_I &= -3.68(\pm0.17)\log P + 15.76(\pm0.13) \qquad \sigma = 0.20 \text{ mag}
\end{aligned}
$$

and for the first overtone modes:

$$
\begin{aligned}
V &= -3.17(\pm0.28)\log P + 17.03(\pm0.25) \qquad \sigma = 0.34 \text{ mag}\\
I &= -3.35(\pm0.25)\log P + 16.36(\pm0.22) \qquad \sigma = 0.30 \text{ mag}\\
W_I &= -3.74(\pm0.17)\log P + 15.28(\pm0.15) \qquad \sigma = 0.19 \text{ mag}
\end{aligned}
$$

The magnitudes were not corrected for interstellar extinction. These relations predict similar brightnesses as for classical Cepheids (Soszyński *et al.* 2008) in the period range of 0.22–0.249 d in which, according to assumed boundaries, δ Sct and Cepheids meet. Because of lower brightnesses and smaller number of objects the uncertainties of the fitted parameters are an order of magnitude higher than for Cepheids. Our $\log P$–V relation is consistent within the uncertainties with earlier studies (McNamara *et al.* 2007).

One can easily notice on the period-luminosity relations four F/1O objects with short periods which are evidently brighter than the remaining F/1O stars. Among these stars there are two for which we found significant proper motions: OGLE-LMC-DSCT-0048 and OGLE-LMC-DSCT-0972. These two stars are clearly located in the Galaxy.

The catalog also contains 14 multi-mode pulsators with no modes identified. For six (*i.e.*, 43%) of these stars we found more than two frequencies while 27% of

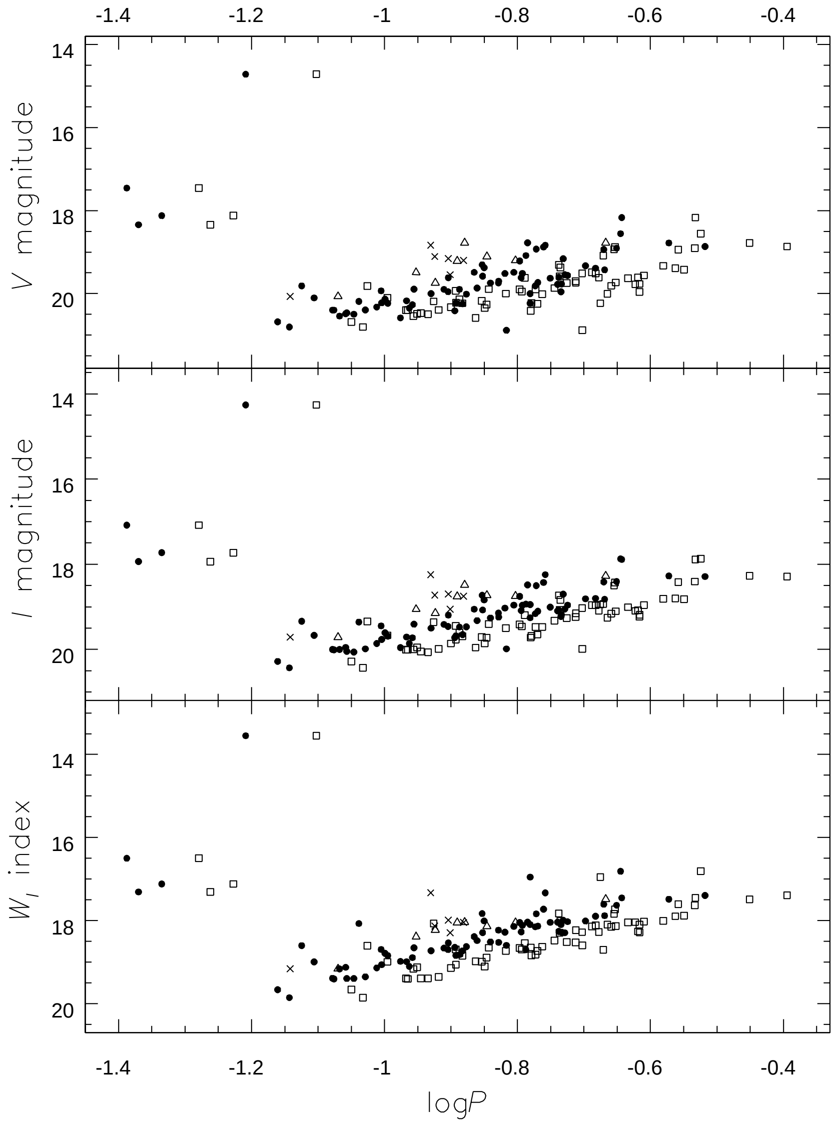

Fig. 4. Period–luminosity diagrams for multi-mode δ Sct stars with the radial modes identified. Open squares, filled circles, open triangles and crosses correspond to fundamental mode and first, second and third overtone, respectively.

objects with identified radial modes possess more than two frequencies. Only for two of these multi-mode pulsators we found combination frequencies. The ratios of periods are close to one. The exception is a star OGLE-LMC-DSCT-1684 for which we found period ratio equal to 0.309. If both periods correspond to radial modes then the shorter one is a very high order mode and this is an unusual object. For five multi-mode pulsators without mode identification we found significant proper motions what means that these objects are Galactic foreground δ Sct stars.

5.2. Single-Mode Pulsators

The period-luminosity relations for single-mode δ Sct stars are shown in Fig. 5.

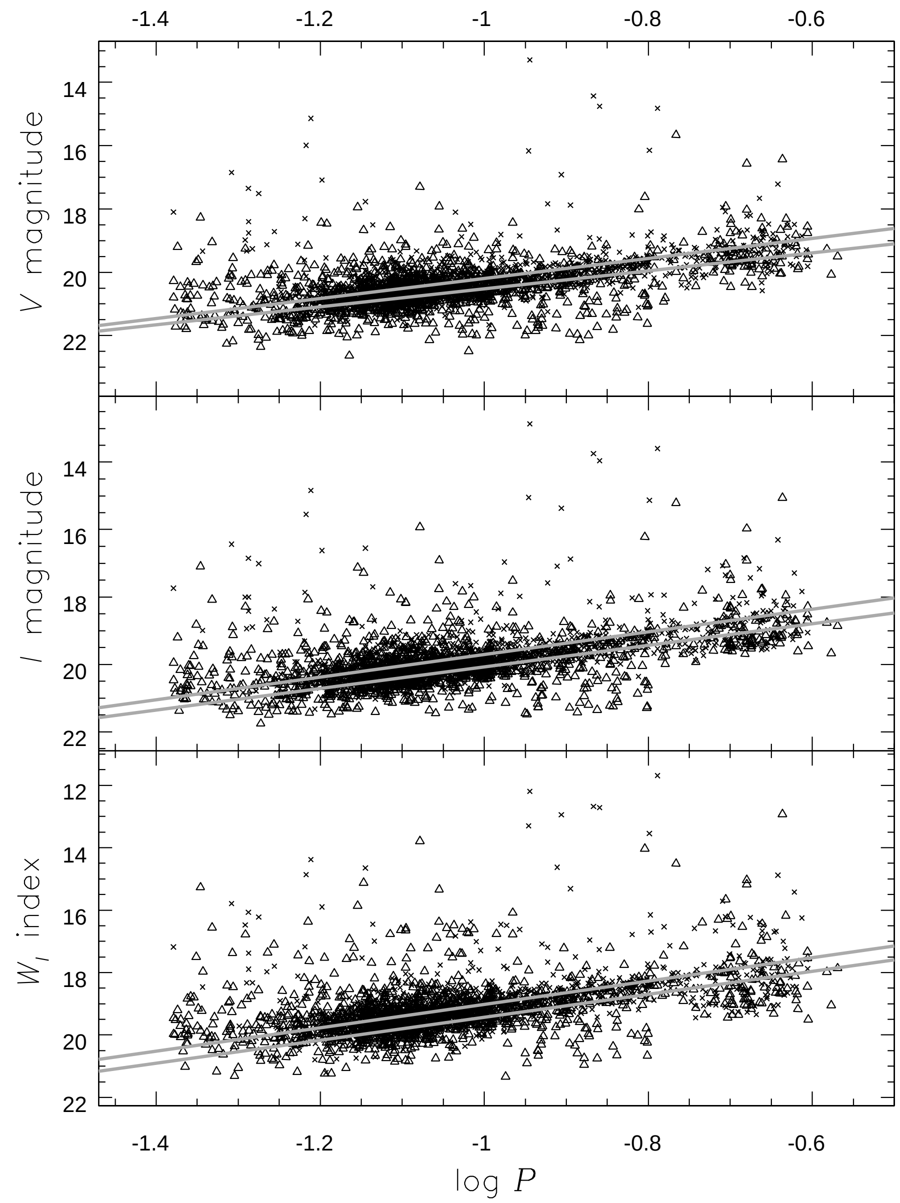

Fig. 5. Period-luminosity relations for single-mode δ Sct pulsators. Crosses correspond to the objects marked as uncertain while all the other single-mode δ Sct stars are represented by open triangles. The gray lines in each panel show linear fits for multi-mode objects. The bottom line in each panel corresponds to the fundamental mode pulsators and the top one – to the first overtone pulsators.

The gray lines show linear fits obtained in Section 4 for multi-mode pulsators. It is not possible to pinpoint pulsation mode for each individual object. As most of the stars are located symmetrically on the two sides of the line corresponding to the 1O modes we suspect most of the single-mode pulsators to be the 1O ones.

The group of δ Sct stars is typically divided into high and low amplitude objects (HADS and LADS respectively). The observational separation is not clear but typically *V*-band amplitude around 0.3 mag is a borderline. HADS are more frequently radial mode pulsators with a few modes observed and they are more evolved objects than LADS which have many nonradial modes observed. We did not find any differences between high and low amplitude objects. This may be a consequence of a low detection threshold.

Fig. 6 shows the CMD for δ Sct stars superimposed on the diagram showing one OGLE-III subfield. Most of the stars have $(V-I)$ color between 0.3 mag and

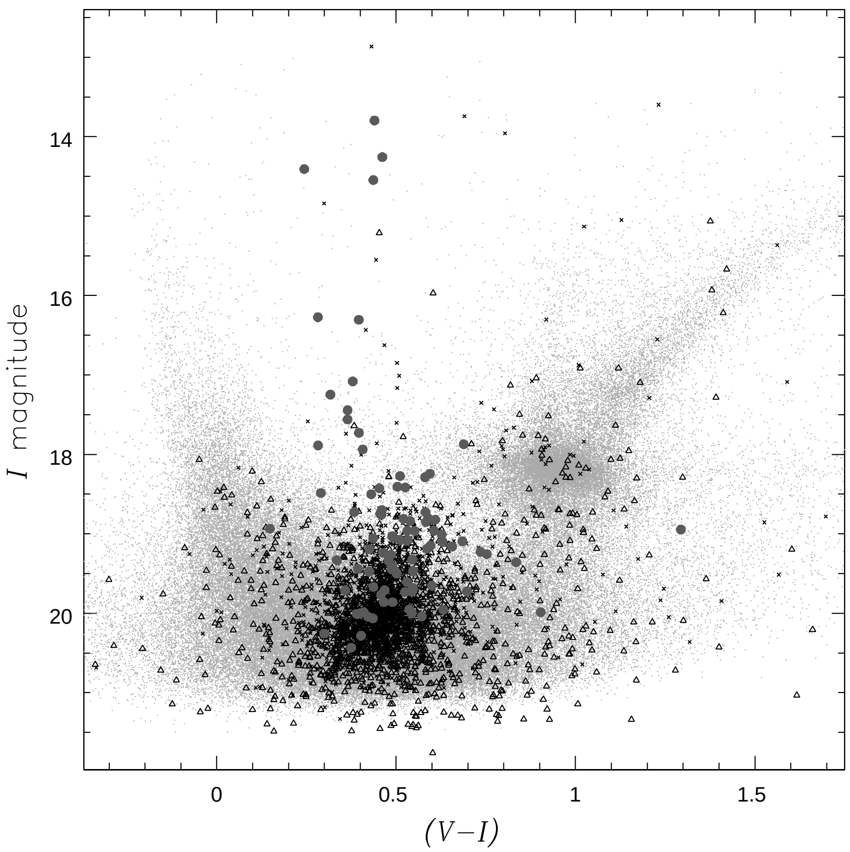

Fig. 6. Color–magnitude diagram for δ Sct stars superimposed on the CMD of the OGLE-III subfield LMC100.1. Gray circles, crosses and open triangles correspond respectively to multi-mode pulsators, uncertain single-mode pulsators and the remaining single-mode pulsators.

0.7 mag. As the stars are mostly faint ones ($I > 19$ mag), the blending affects their brightnesses and colors stronger than for *e.g.*, Cepheids.

The Fourier coefficients are frequently used parameters for describing the shape of the light curves of variable stars. We present calculated ϕ_{21} and R_{21} parameters in Fig. 7. The R_{21} coefficient is typically bigger than 0.1 and smaller than 0.6. For

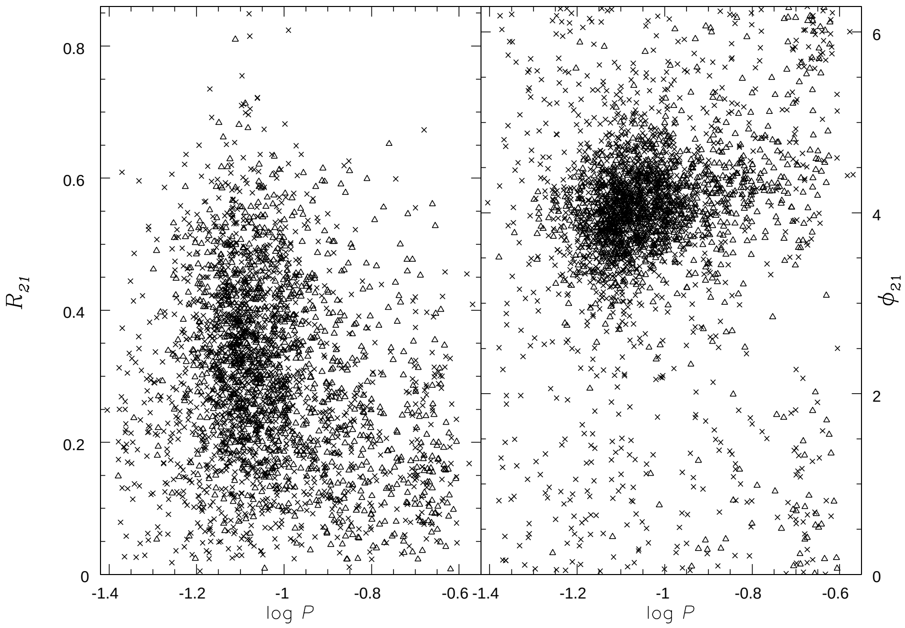

Fig. 7. Fourier coefficients R_{21} (*left panel*) and ϕ_{21} (*right panel*) as a function of the logarithm of period. Uncertain objects are marked with crosses and all the other as open triangles.

objects with period longer than around 0.12 days (*i.e.*, $\log P > -0.9$) the values of this coefficient decrease. Most of the δ Sct stars have ϕ_{21} close to 4. Objects with ϕ_{21} smaller than 3 or larger than 5 are mostly marked as uncertain (crosses in Fig. 7). Similar dependence of R_{21} and ϕ_{21} on $\log P$ was found by other authors (*e.g.*, Morgan *et al.* 1998, Poretti 2001). We did not find any dependence of higher order coefficients on $\log P$.

The shortest period for sound single-mode δ Sct star in our catalog is 0.041 d. It is much smaller than typical cadence of the OGLE-III measurements in the LMC which is usually about 3 d. Sometimes the observations of the given field are done more frequently but still very rarely the cadence is smaller than the shortest periods discovered. OGLE-III fields are overlapping, thus the observations of a star lying near the CCD edge occasionally are obtained one after another. We checked a few exemplary time-series using method described by Koen (2006). Although we did not find Nyquist frequency to be smaller than any of the variability frequencies of our objects we note the daily aliases are possible in some cases.

6. Conclusions

The most important result of the search for δ Sct stars in the LMC is a high number of multi-mode pulsators found. The distance to this galaxy is known rather accurately and together with measured luminosities gives additional constrain for pulsation models.

Also a few Milky Way multi-mode δ Sct stars discovered here are of interest. Up to eight frequencies were discovered and we can expect that much larger number of such objects can be found in the OGLE-III Galactic bulge data.

For the radial modes of the multi-mode objects we derived period-luminosity relations. The scatter of points does not allow mode identification for particular single-mode object. This scatter is also comparable to the differences in luminosity for the F and the 1O modes at the same period. Therefore, we conclude these relations cannot be used for mode identification of single-mode δ Sct stars, even if absolute luminosities are known.

Most of the multi-mode objects without the radial mode identification are most probably members of the LADS subgroup of δ Sct stars.

More than a half of the presented objects are marked as uncertain. Nevertheless, it is the biggest catalog of positively identified δ Sct pulsators published so far in any environment including our Galaxy.

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