Type II Cepheids Pulsating in the First Overtone from the OGLE Survey

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Abstract

We report the discovery of the first type II Cepheids (BL Herculis stars) pulsating solely in the first overtone. We found two such objects among tens of millions of stars regularly observed by the Optical Gravitational Lensing Experiment survey in the Large Magellanic Cloud. Our classification and the pulsation mode identification is based on the position of these stars on the period–luminosity and color–magnitude diagrams and on the light-curve analysis. We discuss why single-mode first-overtone BL Her pulsators must be very rare. For the two discovered stars we present nonlinear models that successfully reproduce their light variation. These models indicate that both first-overtone pulsators should be more massive than is typically assumed for BL Her stars, i.e., their masses should be above 0.75 $M_\odot$. However, the higher mass requires higher luminosity to match the observed periods of the stars, which is inconsistent with observations.

Key words: Magellanic Clouds – stars: oscillations – stars: Population II – stars: variables: Cepheids

1. Introduction

The standard model of stellar pulsations (Eddington 1926) predicted that stars may pulsate not only in the fundamental mode but also in the overtone modes. Edgar (1933) was the first who theoretically studied this idea in detail, while Schwarzschild (1940) first suggested that RR Lyrae stars of type c (Bailey 1902) are the first-overtone pulsators. The physical nature of the so-called sinusoidal or s-Cepheids has been a matter of debate for years (e.g., Arp 1960; Ivanov & Nikolov 1976; Connolly 1980; Antonello et al. 1990; Gieren et al. 1990) until large-scale microlensing surveys: EROS (Beaulieu et al. 1995), MACHO (Alcock et al. 1995), and Optical Gravitational Lensing Experiment (OGLE) (Udalski et al. 1999) presented large samples of classical Cepheids in the Magellanic Clouds and unambiguously proved that s-Cepheids are the first-overtone pulsators. Modern catalogs of classical Cepheids contain single- and multimode variables with the first, second, and even the third overtone excited (e.g., Soszyński et al. 2015).

In the virtually complete collection of Cepheids and RR Lyr stars (collectively referred to as classical pulsators) in the Magellanic Clouds published by the OGLE survey (Soszyński et al. 2015, 2017a), the overtone pulsators constitute a significant fraction of the total population. About 28% of all RR Lyr stars, 31% of anomalous Cepheids, and 46% of classical Cepheids have the overtone modes excited (including multimode pulsators). Type II Cepheids are an exception in the family of classical pulsators—until recently all known variables of this class were pure fundamental-mode pulsators.

The first two double-mode type II Cepheids pulsating simultaneously in the fundamental and first-overtone modes were discovered by Smolec et al. (2018), who identified them among nearly 1000 type II Cepheids detected by the OGLE survey in the Galactic bulge (Soszyński et al. 2017b). These two unique objects have (fundamental-mode) periods equal to 1.04 days and 1.18 days, so they belong to the shortest-period subclass of type II Cepheids—BL Herculis stars—just above the conventional borderline (1 day) between RR Lyr stars and type II Cepheids. The ratios of the first-overtone to the fundamental-mode periods for these two stars are almost identical and are equal to about 0.705. Recently, Udalski et al. (2018) reported the discovery of two other double-mode BL Her stars in the Galactic bulge and disk.

Inspired by these discoveries, we decided to search the OGLE photometric databases for single-mode first-overtone BL Her stars. The best environment to perform such a search is the Magellanic System, particularly the Large Magellanic Cloud (LMC), because it contains rich populations of spatially resolvable stars at approximately the same distance from us. This allows us to precisely locate pulsating stars on the period–luminosity (PL) diagram to find out in which mode they pulsate. The long-term OGLE photometry is useful for studying the light-curve morphology, which is also an invaluable discriminator between fundamental and overtone pulsators.

2. Observational Data and Candidate Selection

The OGLE database contains light curves of over 75 million stars in the Magellanic Clouds. These data have been collected with the 1.3 m Warsaw Telescope located at Las Campanas Observatory in Chile. The observatory is operated by the Carnegie Institution for Science. Since 2010, the Warsaw Telescope has been equipped with the 256 Megapixel mosaic CCD camera with a field of view of 1.4 square degrees at a scale of 0.26/pixel. OGLE uses the $V$- and $I$-band filters from the Johnson-Cousins photometric system, but most of the observations (typically 700 points per star) have been carried out with the $I$ passband. Details of the OGLE instrumental setup, data reduction, and calibration can be found in Udalski et al. (2015).

Candidates for the first-overtone BL Her stars have been sought among sources observed since 2010 by the OGLE-IV survey. First, we used the FNPEAKS code\(^3\) to compute the Fourier amplitude spectra for all $I$-band light curves obtained by OGLE in the Magellanic System to determine periods with corresponding amplitudes and signal-to-noise ratios.

\( ^3 \) http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks
Second, we defined PL relations obeyed by hypothetical first-overtone type II Cepheids, separately for the LMC and Small Magellanic Cloud (SMC). We used the $\log P$ versus $W_I$ and $\log P$ versus $I$-band luminosity planes, where $W_I$ is the reddening-independent Wesenheit index, defined as $W_I = I - 1.55(V - I)$, and $I$ and $V$ are the intensity-averaged mean magnitudes in these filters. In Figure 1, we present the period-Wesenheit (PW) and PL diagrams for classical pulsators in the LMC (Soszyński et al. 2017a, 2018): classical Cepheids (blue points), anomalous Cepheids (green points), type II Cepheids (pink points), and RR Lyr stars (orange points). Lighter and darker colors indicate fundamental-mode and overtone-mode pulsators, respectively. The dashed red lines show the expected PW and PL relations for the first-overtone BL Her stars. These lines have the same slopes as the relations for the fundamental-mode type II Cepheids (plotted with the solid red lines) and are shifted toward the shorter periods, corresponding to the period ratio of 0.7 between both modes.

Third, we visually inspected all light curves in both Magellanic Clouds meeting the following criteria: (i) the primary period in the range 0.7–3 days (corresponding to 0.7 of the period range of fundamental-mode BL Her stars 1–4 days), (ii) $I$-band luminosity and $W_I$ Wesenheit index that placed the star up to 0.3 mag above or below the red dashed lines shown in Figure 1 (which is comparable to maximum dispersions of the PL relations obeyed by other types of classical pulsators), (iii) $I$-band peak-to-peak amplitude larger than 0.15 mag (to avoid low-amplitude nonradial pulsators and other types of variable stars). Using these criteria we selected several thousand variable stars in both Magellanic Clouds and carefully examined their light curves.
Figure 2. $I$-band light curves of the BL Her stars pulsating in the first-overtone. Solid red lines shifted by 0.2 mag correspond to the best-matching nonlinear pulsation models for OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 (see Section 3.4). Physical parameters of the models—mass, metallicity, and $T_{\text{eff}}$—are given in each panel.

![Scope](image-url)
A wide range of pulsation periods. The morphology of the light curves varies from star to star, but one feature is common for all stars with the overtone modes excited—they have round minima of their light curves. This is a very strong argument that OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 belong to the same (first-overtone) class of pulsating stars.

The coefficients derived from the Fourier decomposition of light curves provide a quantitative description of their morphology. We fitted the cosine Fourier series to the I-band light curves of our variables and derived the $f_{21}$, $f_{31}$, $R_{21}$, and $R_{31}$ coefficients (Simon & Lee 1981). Figure 5 compares these parameters for first-overtone classical pulsators in the LMC. The light curves of our candidates seem to be the most similar to the first-overtone classical Cepheids, although at the considered period range, Fourier parameters for anomalous Cepheids and classical Cepheids partially overlap. This similarity confirms that OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 are the first overtone pulsating stars, although they do not fit perfectly in each diagram which is expected because they are members of a different class of pulsators than classical and anomalous Cepheids. Our candidates have smaller Fourier phases $\phi_{21}$ and $\phi_{31}$ (upper panels of Figure 5) than typical anomalous Cepheids with the same periods and slightly larger amplitude ratios $R_{21}$ and $R_{31}$ (lower panels of Figure 5) than most of classical Cepheids. The Fourier parameter diagrams nicely confirm the first-overtone pulsation of OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 and, together with the PL and PW diagrams, discriminate between variability classes.

### 3.2. Position in the Color–Magnitude Diagram

Another indicator of the pulsation mode is the position of a star in the color–magnitude diagram. It is known that the overtone pulsators occupy the blue side of the instability strip. Their $(V - I)$ colors are on average 0.10–0.15 mag smaller than for the fundamental-mode Cepheids and RR Lyr stars, although there is an overlap between different pulsation modes. Additionally, the apparent color indices of individual objects may be strongly affected by the interstellar reddening or blending by an unresolved companion, which limits the applicability of the color criterion for determining the pulsation modes.

In the upper panel of Figure 6, we present the $(V - I)$ versus $I$ color–magnitude diagram for classical pulsators in the LMC. As in Figure 1, darker colors indicate overtone variables. OGLE-LMC-T2CEP-291 has an apparent color index $(V - I) = 0.51$ mag, which agrees with typical colors of other overtone classical pulsators and is bluer than most of the fundamental-mode BL Her stars. This is another direct proof that OGLE-LMC-T2CEP-291 pulsates in the first-overtone mode.

However, the color index of OGLE-LMC-T2CEP-290 (0.65 mag) places this star closer to the fundamental-mode
pulsators. This fact can be explained by a high interstellar reddening toward this object. Lower panels of Figure 6 present color-magnitude diagrams for all stars (included in the OGLE-IV database) within a radius of 10 arcmin (for OGLE-LMC-T2CEP-291) and 5 arcmin (for OGLE-LMC-T2CEP-290) around both candidates for the overtone type II Cepheids. The surroundings of OGLE-LMC-T2CEP-291 (lower left panel of Figure 6) are characterized by a well-defined red clump with the mean apparent color index of \((V-I) = 0.97\) mag. On the other hand, in the vicinity of OGLE-LMC-T2CEP-290 (lower right panel), the red clump is significantly elongated toward redder and fainter stars, which indicates high and differential reddening toward these regions. The mean apparent \((V-I)\) color index of the red clump stars in this area cannot be precisely determined—we can only specify that it is included in the range from 1.01 to 1.22 mag. It translates into a range from 0.04 to 0.25 mag of higher reddening toward OGLE-LMC-T2CEP-290 than to OGLE-LMC-T2CEP-291, which fully explains the redder color of the former object.

Figure 4. Example I-band light curves of first-overtone classical pulsators in the LMC: classical Cepheids (upper panels), anomalous Cepheids (middle panels), and RR Lyr stars (lower panels). Note the round minima in all these light curves, just like in the first-overtone BL Her stars (Figure 2).
3.3. Spatial Location

Figure 7 displays the sky map of the LMC with classical pulsators marked with the same symbols as in Figure 1. OGLE-LMC-T2CEP-290 is located closer to the LMC center, on the western edge of the LMC bar, while OGLE-LMC-T2CEP-291 is located in the northern outskirts of the LMC, where classical Cepheids are absent, but the old stellar population (RR Lyr stars) is still common. This confirms that at least OGLE-LMC-T2CEP-291 belongs to the old population.

What is the distance of our candidates for the first-overtone BL Her stars? So far we have assumed that both objects are located in the LMC and their position on the apparent PL diagram (Figure 1) reflects their position in the absolute PL plane. However, there is a possibility that we deal with first-overtone classical or anomalous Cepheids located behind the LMC. Taking into account the position of both stars in the extinction-free PW diagram, we may estimate that if they are the first-overtone classical Cepheids, they should be located about twice as far as the center of the LMC. It seems very unlikely that stars belonging to the young stellar population (classical Cepheids) exist in the intergalactic space. In turn, assuming that OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 are the first-overtone anomalous Cepheids, they should be located 50%–60% farther than the LMC. Taking into account that the light curves of our objects (quantified by the Fourier coefficients; Figure 5) are different than light curves of typical first-overtone anomalous Cepheids with the same periods, such a possibility also seems unlikely.

3.4. First-overtone BL Her Stars from the Theoretical Perspective

While single-periodic first-overtone pulsation is common among classical Cepheids and RR Lyrae stars, it has not been detected so far in any type II Cepheid. Here we explain why first-overtone pulsation for type II Cepheids must be very rare. In Figure 8, we show the pulsation and evolutionary scenarios for classical Cepheids (left panel) and for RR Lyrae stars and the shortest-period type II Cepheids—BL Her stars (right panel). Instability strips for the fundamental mode (F mode; solid blue and solid red lines) and for the first-overtone mode (1O mode;
gray-shaded area) were computed using linear convective
codes of Smolec & Moskalik (2008a). In all computations
presented in this paper parameters of the turbulent convection
model are the same as those we used in the successful modeling
of a period-doubled BL Her star (Smolec et al. 2012). For
classical Cepheids, the model grid was constructed assuming
the mass–luminosity relation inferred from evolutionary
models of Anderson et al. (2016) for [Fe/H] = −0.5. In the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{Apparent \((V - I)\) vs. \(I\) color–magnitude diagrams for stars in the LMC. Upper panel shows classical pulsators from the OGLE Collection of Variable Stars. Different symbols indicate the same types of stars as in Figure 1. Lighter and darker colors indicate fundamental-mode and overtone-mode pulsators, respectively. Lower panels show all stars in the vicinities of the two first-overtone BL Her stars: up to 10 arcmin from OGLE-LMC-T2CEP-291 (left panel), and up to 5 arcmin from OGLE-LMC-T2CEP-290 (right panel).}
\end{figure}
right-hand panel (RR Lyr and BL Her stars) we assumed a constant mass of 0.60 \( M_\odot \) and \([\text{Fe/H}] = -1.0\). Evolutionary tracks for classical Cepheids are from Bertelli et al. (2009) \((Z = 0.008)\) and evolutionary tracks for horizontal-branch stars are from Dotter et al. (2008) \(([\text{Fe/H}] = -1.0)\).

We note that model calculations are sensitive, e.g., to the physical parameters, treatment of the convection, or details of the evolutionary modeling. For example, different extent of overshooting during main-sequence evolution can shift the evolutionary tracks for Cepheids in luminosity and affect the extent of the blue loops. By adopting different parameters for turbulent convection model in pulsation calculations, the location of the instability strips may, e.g., slightly shift in effective temperature or in luminosity, but the overall shape and features of the instability strip, like the limited extent of the 1O instability strip in luminosity, will be the same. Here we just discuss the qualitative pulsation and evolutionary picture and these details are inessential for our discussion.

For classical Cepheids (left panel of Figure 8) we can identify a domain in which only 1O is linearly unstable (dark-gray shaded area). If a star moves toward lower effective temperatures (first and third crossing of the instability strip) it first enters the domain in which only 1O is linearly unstable and single-periodic 1O pulsation is the only possibility. Then, it enters the domain in which both modes, F and 1O, are linearly unstable (light-gray shaded area), and finally a domain in which F mode pulsation is the only possibility. What happens in the domain in which both modes are linearly unstable is dictated by nonlinear mode selection (see, e.g., Smolec & Moskalik 2008b). The star that enters this domain from the hot side may continue the single-periodic 1O pulsation until it switches to F mode single-periodic pulsation somewhere within the domain. Similarly, the star that enters this domain from the cool side may continue the F mode pulsation, until it switches to 1O single-mode pulsation somewhere within the domain. In a part of the HR diagram within light-gray shaded area the so-called either-or scenario is possible: the star may pulsate either in 1O mode or in F mode depending on the direction of evolution. The other possible scenario is double-mode pulsation: simultaneous pulsation in both F and 1O modes. Only with nonlinear calculations this mode selection problem can be addressed. It is, however, clear that for a significant part of the HR diagram single-periodic 1O pulsation in classical Cepheids is possible. First-overtone classical Cepheids, as well as double-mode F+1O classical Cepheids are common.

For RR Lyr stars (right panel of Figure 8; stars with fundamental-mode periods below 1 day, i.e., below the thick long-dashed black line) the scenario is qualitatively the same as just outlined for classical Cepheids. We can identify the domain in which 1O pulsation is the only possibility (hottest pulsators; dark-gray shaded area) and a domain in which both 1O and F modes are linearly unstable (light-gray shaded area), in which either single-periodic 1O, or single-periodic F mode pulsation, as well as double-mode F+1O pulsation are possible. Indeed, both single-periodic 1O pulsators (RRc stars) and double-mode pulsators (RRd stars) are common (as well as single-periodic F mode pulsators, RRab stars).
At this point it is essential to point that there is a maximum period for 1O RR Lyr pulsators. Considering the most numerous OGLE collection of RR Lyr variables (Soszyński et al. 2014, 2016) the longest possible 1O periods are approximately 0.539, 0.495, and 0.487 days for RRc stars of the Galactic bulge, LMC, and SMC, respectively and 0.451, 0.521, and 0.524 days for RRd stars of the same stellar systems. These numbers are all quite similar; differences often rely on a single record-holder star. In 99% of the above considered stars from the OGLE collection, 1O period is shorter than 0.44 days—a value marked with a thick short-dashed line in Figure 8. Observations clearly indicate that above this line nearly all RR Lyr stars pulsate in F mode only, despite 1O can still be linearly unstable there. We note that above the discussed line, the 1O domain is essentially engulfed by the domain in which the F mode is unstable. Consequently, before entering the domain in which both F and 1O modes are linearly unstable, a star was necessarily single-periodic F mode pulsator.

The lack of long-period RRc/RRd stars indicates that nonlinear mode selection favors the F-mode-only pulsation also in the domain in which both modes are linearly unstable. A star that was pulsating in the F mode continues the F mode pulsation also after entering the domain in which 1O mode becomes linearly unstable. RR Lyr stars and BL Her variables are close siblings (e.g., Iwanek et al. 2018). BL Her stars are just slightly less massive, start the HB evolution at higher effective temperatures, and cross the instability strip at larger luminosities. The instability strip displayed in Figure 8 was computed for $M = 0.6 \ M_\odot$, however, for lower masses, the 1O instability strip shrinks and extends to lower luminosities (see Figure 9, bottom panels) so long-period single-periodic 1O pulsation is even more excluded for BL Her stars.

Still, as we determined on an observational basis, OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 with much longer periods are single-periodic 1O pulsators. To understand the nature of these two stars we have computed a small model survey covering a much larger range of masses than is typically considered for BL Her-type stars. Masses in the grid cover 0.5–0.9 $M_\odot$, range with 0.05 $M_\odot$ step. Their metallicities are in the $-2.5, -2.0, -1.5, -1.0, -0.5, 0.0, 0.5$ range with 0.5 dex step.

Instability strips for selected models are plotted in the HR diagrams in Figure 9, along with lines of constant period equal to the periods of OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291. In addition, a thick long-dashed line is placed at a constant fundamental-mode period equal to 1 day and thus separates the RR Lyr and BL Her domains. The thick short-dashed line is placed at constant first-overtone period of 0.44 day. Observations indicate that the majority of RRc and RRd stars have shorter periods. Two thin dotted lines are placed at constant first-overtone periods corresponding to pulsation periods of OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291.

Qualitative view on pulsation and evolutionary scenarios of classical Cepheids (left panel) and RR Lyr stars and BL Her variables (right panel). Solid blue and red lines show the blue and red edges of the classical instability strip. Instability strip for the first-overtone mode is gray shaded. In the dark-gray-shaded area only the first-overtone is linearly unstable, while in the light-gray-shaded area both first-overtone and fundamental modes are linearly unstable. Example evolutionary tracks are plotted in each panel with solid green lines and labeled with corresponding masses. In the right panel a thick long-dashed line is placed at the constant fundamental-mode period of 1 day and separates RR Lyr and BL Her domains. The thick short-dashed line is placed at constant first-overtone period of 0.44 day. Observations indicate that the majority of RRc and RRd stars have shorter periods. Two thin dotted lines are placed at constant first-overtone periods corresponding to pulsation periods of OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291.
temperature. These models were computed only across the domain in which the first-overtone is linearly unstable. As is clear from Figure 9, the fundamental mode is necessarily unstable as well then. The static models were perturbed with the first-overtone scaled velocity eigenfunction calculated for each model during linear analysis, and time integration was conducted for at least 6000 pulsation cycles.

During the model integration, after the initial transient phase in which first-overtone pulsation was present, the majority of models switched into single-mode fundamental-mode pulsation. It was the case for all models with masses below 0.75$ M_\odot$. It well agrees with the considerations presented above: with parameters expected for typical BL Her stars single-mode first-overtone pulsation is not possible. As mass is increased in the models we observe that the switching from the first-overtone pulsation to fundamental-mode pulsation occurs later during the integration. For models of OGLE-LMC-T2CEP-291 (with shorter pulsation period, $P \approx 0.818$ day), single-mode

Figure 9. HR diagrams with linear instability strips for selected models of 0.9$ M_\odot$ (top row), 0.7$ M_\odot$ (middle row), and 0.5$ M_\odot$ (bottom row). Metallicity is constant in each column: $-2.0$ (left column), $-1.0$ (middle column), and $+0.0$ (left column). Solid blue and red lines show the blue and red edges of the classical instability strip. Instability strip for the first-overtone mode is gray shaded. Thick long-dashed line is placed at constant fundamental-mode period of 1 day and separates RR Lyr and BL Her domains. Two thin dotted lines are placed at constant first-overtone periods corresponding to pulsation periods of OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291, as indicated in the top left panel.
first-overtone pulsation becomes possible for $M \geq 0.75 \, M_\odot$. For slightly more luminous and longer-period models of OGLE-LMC-T2CEP-290 ($P \approx 0.932$ day) first-overtone pulsation becomes possible only for $M \geq 0.85 \, M_\odot$. In Table 2 we provide the physical parameters of the models that converged for single-mode 1O pulsation. We find that 1O pulsation is not possible for the lowest considered metallicities, i.e., for $-2.5$ and $-2.0$. For $[\text{Fe/H}] = -1.5$ only a single model converged to 1O pulsation ($M = 0.85 \, M_\odot$). 1O pulsation is possible for $[\text{Fe/H}] \geq -1.0$. For the highest considered mass 1O models are present also for solar metallicity. The higher the mass, the wider the domain of 1O pulsation.

A rather large domain over which models converged to full amplitude 1O pulsation may indicate that such pulsation should be commonly observed. We recall, however, that the way we initialized model integration—low-amplitude perturbation with scaled velocity eigenvector of 1O mode—favors 1O pulsation. As is clear from Figure 9, the star that enters the domain in which 1O mode is linearly unstable is already a large amplitude F mode pulsator and may continue the F mode pulsation in the domain in which both F and 1O modes are unstable. In principle, using nonlinear calculation one can study the stability of full-amplitude F mode pulsation with respect to perturbation in 1O mode. This is, however, very time-consuming as it requires several integrations of the same model with different initial conditions (see, e.g., Smolec & Moskalik 2008b). Such an analysis is beyond the scope of the present paper, but it is planned.

The computed bolometric light curves were transformed to the $I$-band via static Castelli & Kurucz (2004) model atmospheres. In Figure 2, we compare the observed light curves with the best-matching model, i.e., the model in which relative differences of low-order Fourier coefficients between the model and observed light curve are the lowest. Physical parameters of these models are given in the panels. We note that the pulsation amplitude in the best model for OGLE-LMC-T2CEP-291 is nearly half of that observed. We comment on this difference more in the following. We note that the light curves of all computed first-overtone-models are all very similar to each other and that plotted in Figure 2 may be regarded as representative. The match between the model and observed light curves is reasonable. In the models, the change of inclination on the ascending branch, after the minimum brightness is quite pronounced, while in the observed light curves it is well visible only for OGLE-LMC-T2CEP-290. To compare the models and light curves in a more quantitative way, in Figure 5 we have also plotted the Fourier parameters of the best-matching models (large crosses). The match for OGLE-LMC-T2CEP-290 is remarkable. For OGLE-LMC-T2CEP-291 the match for Fourier phases is very good, while amplitude ratios are a bit lower, which is expected, as pulsation amplitude is also lower (Figure 2).

Although the light variation of OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 can be reproduced reasonably well, the first-overtone nonlinear models we have just discussed are inconsistent with observations regarding their luminosity. When the mass is increased, the luminosity must also be increased to match the periods of the two modeled stars (see Figure 9). Consequently, our models are both more massive and more luminous than expected for BL Her stars. In the PW plane (Figure 1), the models are placed at a position characteristic for fundamental-mode anomalous Cepheids, in between position typical for first-overtone anomalous Cepheids and position expected for first-overtone BL Her stars. The best-matching models for OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 are by 0.36 and 0.58 mag more luminous than observed, respectively.

Our initial model survey indicates that indeed the light-curve shape observed for OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 is characteristic for single-mode first-overtone pulsation. However, single-mode first-overtone pulsation becomes possible only when mass is significantly increased above the values expected for BL Her stars. It may indicate that our stars are a product of a specific mass transfer event during binary evolution. Binarity is often invoked as a plausible explanation for the properties of peculiar W Vir stars or of anomalous Cepheids (e.g., Soszyński et al. 2017b). In this scenario, however, the stars should be more luminous than observed. Pulsation modeling of OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 remains a puzzle at the moment.

We stress that our model’s survey is very limited; a thorough analysis that may help to resolve the raised issues, is planned. In particular, the following should be addressed in a more detailed model survey. (i) Full mode selection analysis should be done. It requires integration of each model with various initial conditions and analysis of the resulting hydrodynamic trajectories with amplitude equation formalism. (ii) Other sets of convective parameters should be investigated. In particular, models with decreased eddy-viscous dissipation. Such models should have larger pulsation amplitudes and hence should match the observations of OGLE-LMC-T2CEP-291 better. More importantly, the extent of the instability domains and mode selection strongly depend on eddy-viscous dissipation and other parameters that enter the convection model used in the code. By varying these parameters, we may hope for first-overtone pulsation at lower masses and hence at lower luminosities. (iii) Extension of the model survey to even higher masses, up to that considered for anomalous Cepheids ($\sim 1.5 \, M_\odot$), is desired.

### 4. Conclusions

We reported here the discovery of two candidates for single-mode first-overtone type II Cepheids. OGLE-LMC-T2CEP-291 meets all observational criteria that can be checked using the

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**Table 2**

Physical Parameters of Nonlinear Models Computed for OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 that Converged to Full Amplitude Single-periodic First-overtone Pulsation

| ID                | Mass [$M_\odot$] | [Fe/H]  | $T_{\text{eff}}$ [K] |
|------------------|-----------------|---------|----------------------|
| OGLE-LMC-T2CEP-290 | 0.85            | -0.5    | 6450-6500            |
|                  |                 | -1.0    | 6500-6500            |
|                  |                 | -1.5    | 6400-6450            |
|                  | 0.90            | -0.5    | 6350-6550            |
|                  |                 | -1.0    | 6300-6500            |
| OGLE-LMC-T2CEP-291 | 0.75            | -0.5    | 6450-6550            |
|                  |                 | -1.0    | 6400-6600            |
|                  | 0.80            | -0.5    | 6350-6600            |
|                  |                 | -1.0    | 6350-6550            |
|                  | 0.85            | +0.0    | 6400-6550            |
|                  |                 | -0.5    | 6350-6600            |
|                  |                 | -1.0    | 6400-6500            |
|                  | 0.90            | +0.0    | 6350-6600            |
|                  |                 | -0.5    | 6350-6550            |
OGLE data: positions in the PL and PW diagrams, light-curve morphology, and \((V - I)\) color index. OGLE-LMC-T2CEP-290 meets the first two conditions, but it is too red as for the first-overtone pulsator; however, this fact can be explained by a higher interstellar reddening toward this star. We believe that our detection is very reliable, because the light curves of our two candidates definitely have different shapes than fundamental-mode pulsators located in this region of the PL diagram. Spectroscopic follow-up observations could bring new arguments for or against our classification.

To our knowledge, OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 are the first known type II Cepheids pulsating solely in the first-overtone. McCollum et al. (1997) suggested that a bright BL Her star VY Pyx is an overtone pulsator; however, a glance at the light curve of this objects (Sanwal & Sarma 1991) reveals sharp minima, which is a characteristic feature of the fundamental-mode pulsators. Also the Hipparcos parallax place VY Pyx on the PL relation obeyed by the fundamental-mode type II Cepheids (Feast et al. 2008).

With the help of pulsation models we explained why first-overtone pulsation of BL Her stars must be very rare, or is hardly possible, at least for masses typically assumed for these stars. For masses \(\sim 0.5 - 0.6 \, M_\odot\), the linear instability strip for the first-overtone mode does not extend to sufficiently high luminosities to secure first-overtone periods well above 0.7 day, in the range expected for BL Her variables. As mass is increased \((\sim 0.6 - 0.7 \, M_\odot)\), this restriction is no longer valid: linear first-overtone instability strip extends to sufficiently high luminosities, at least to warrant pulsation periods observed in OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291. However, the first-overtone instability strip is entirely engulfed within fundamental-mode instability strip then. As these are the masses expected also for RR Lyr stars, observations, namely the first-overtone periods observed in RRc and RRd stars (always below \(\approx 0.5\) day), point that nonlinear mode selection favors fundamental-mode pulsation in the high luminosity part of the joint instability strip of the two radial modes. This was fully confirmed with the help of nonlinear pulsation calculations. The model integration started with first-overtone perturbation always led to fundamental-mode finite amplitude pulsation. Only for \(M \geq 0.75 \, M_\odot\) the model integration finally ended in stable first-overtone pulsation. We stress that the best-matching model for OGLE-LMC-T2CEP-290 \((0.9 M_\odot)\) matches the observed light curve remarkably well. The best-matching model for OGLE-LMC-T2CEP-291 \((0.8 M_\odot)\) also well reproduces the observed light variation, only the amplitude is about twice as low as observed. The successful modeling of the light variation provides yet another strong argument that OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 are first-overtone pulsators.

The increased mass has its consequences, however. Evolution of single stars does not lead to such massive horizontal-branch stars. Although evolution in a binary system would provide a solution, higher mass implies higher luminosity, which is inconsistent with observations. More extensive modeling is planned to resolve this puzzle.

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