On the Properties of Blue Large-Amplitude Pulsators. No BLAPs in the Magellanic Clouds

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We present the properties of the recently discovered class of variable stars, Blue Large-Amplitude Pulsators (BLAPs). These extremely rare, short-period pulsating objects were detected thanks to regular, high-cadence observations of hundreds of millions of Milky Way stars by the OGLE variability survey. The new variables closely resemble classical pulsators, Cepheids, and RR Lyrae-type stars, but at effective temperatures at which pulsations are due to the presence of iron-group elements. Theory shows that BLAPs are evolved low-mass stars with a giant-like structure, but their origin remains a mystery. In this contribution, we report the negative result of a search for BLAPs in the whole Magellanic System.

Detection of the first variable showing regular, Cepheid-like brightness variations with an exceptionally large $I$-band amplitude of $0.24\text{mag}$ at the very short period of 28.26 min was a serendipitous result of searches for periodic variables in Galactic disc fields monitored by the Optical Gravitational Lensing Experiment (Pietrukowicz et al., 2013, OGLE). OGLE is a long-term, wide-field variability survey conducted with the 1.3 m Warsaw telescope at Las Campanas Observatory, Chile. It started in 1992 with the original aim of detecting microlensing events towards the Galactic bulge (Udalski et al., 1992). Since then, OGLE has detected and classified about one million new variable stars (e.g., Soszyński et al., 2013, 2014, 2016; Mróz et al., 2015). In its current fourth phase, OGLE-IV monitors about one billion stars over 3500 deg$^2$ of the Galactic bulge, Galactic disc, and Magellanic System (Udalski et al., 2015).

The unusual short-period variable was tentatively classified as a $\delta$ Scuti-type pulsator despite the amplitude is several times higher than amplitudes observed among the shortest-period $\delta$ Sct stars. Definitive classification required follow-up observations. Low-resolution spectroscopy showed that this object is much hotter than $\delta$ Sct stars, and its surface gravity is higher than in main sequence stars (Pietrukowicz et al., 2015). The proof for the pulsation nature of this mysterious object was provided with moderate-resolution spectra taken at opposite phases of the variability cycle (Pietrukowicz et al., 2017). By fitting model atmospheres to the combined spectrum, the following parameters were obtained: effective temperature $T_{\text{eff}} = 30800 \pm 500\text{K}$, surface gravity $\log g = 4.61 \pm 0.07$, helium-to-hydrogen ratio $\log (N_{\text{He}}/N_{\text{H}}) = -0.55 \pm 0.05$. True mean values can be slightly different due to difficulties in observations of such rapidly varying and relatively faint object ($\langle V \rangle = 17.71\text{mag}$, $\langle I \rangle = 17.22\text{mag}$).
Another thirteen variables with very similar photometric behaviour were found in the OGLE-IV Galactic bulge fields. All variables have exceptionally large amplitudes of about 0.2 – 0.4 mag in V and I bands at very short periods of roughly 20 – 40 min. Colour-magnitude diagrams constructed for observed fields with the variables show that these stars are located far blueward of the main sequence. The variables have mean I-band brightness between 16.7 and 18.5 mag but one brighter object of $I \approx 15.1$ mag. The bulge variables are moderately reddened if one compares their observed colour $V - I$ between $+0.1$ and $+1.3$ mag with the expected intrinsic value of $(V - I)_0 = -0.29$ mag. Spectroscopic data for three of the bulge stars confirmed that their atmosphere parameters are practically identical to the ones obtained for the Galactic disc object. All variables seem to form a homogeneous class of stars. Based on the observed properties, the name Blue Large-Amplitude Pulsators (BLAPs) was proposed [Pietrukowicz et al., 2017]. The first detected pulsator, OGLE-BLAP-001, can be treated as the prototype of the whole class. Details on each star are provided in Table 1.

Such photometric variations are not seen in any other hot pulsators, i.e., stars in which pulsations are driven by the $\kappa$-mechanism due to the presence of a metal bump in the opacity curve. Envelope models presented in [Pietrukowicz et al., 2017] demonstrate that BLAPs have a giant-like structure. Due to their inflated envelopes, they cannot be treated as dwarfs or subdwarfs. At similar effective temperatures, BLAPs are at least by an order of magnitude more luminous than hot subdwarf B-type (sdB) stars [Heber, 2010]. Long-term OGLE observations show that light curves of BLAPs are very stable over time. Period change rates of the order of $10^{-7}$ yr$^{-1}$ indicate that these stars evolve on the nuclear time scale.

There are, however, many fundamental questions related to the new stars: what is their exact mass and luminosity, what is their real metallicity, are they single objects, how did they form? Linking the envelope models developed for the prototype object with available stellar evolutionary models leads to two configurations of different masses. BLAPs are either $\sim 1.0$ M$_\odot$ stars with a helium-burning core or $\sim 0.3$ M$_\odot$ stars with a hydrogen-burning shell above a degenerate helium core. None of these configurations can be produced in the evolution of a single star. The fact that very few BLAPs are known points to a rare episode in stellar evolution. They can be remnants of stellar mergers. However, no signs of binarity in the obtained data supports this hypothesis.

The luminosity of the new pulsators was derived from envelope models. For the prototype object, depending on the configuration: $\log L/L_\odot = 2.3$ in the case of the $\sim 0.3$ M$_\odot$ star, $\log L/L_\odot = 2.6$ in the case of the $\sim 1.0$ M$_\odot$ star. These luminosities can be transformed to the following V and I-band absolute magnitudes: $M_V = +1.95$ and $M_I = +2.24$ in the less massive case, $M_V = +1.20$ and $M_I = +1.49$ in the more massive one.

Accurate determination of the mass and luminosity would be possible for a pulsator located at known distance. Discovery of such a star in the Large Magellanic Cloud (LMC) or Small Magellanic Cloud (SMC) would be very helpful. The expected brightness range of BLAPs at the LMC’s distance ($\approx 50.0$ kpc, Pietrzyński et al., 2013) is $19.20 < V < 20.45$ mag and $19.49 < I < 20.74$ mag, assuming negligible extinction. At the SMC’s distance ($\approx 62.1$ kpc, Graczyk et al., 2014), BLAPs would have $19.49 < V < 20.74$ mag and $19.94 < I < 21.19$ mag.

We have searched for BLAPs in the rich OGLE-IV data collected for the Mag-
ellanic System in years 2010 – 2015. The monitored area consists of 475 OGLE-IV fields covering a total of about 650 deg$^2$. The number of $I$-band measurements varies from field to field. There are $\sim$700 frames collected for the LMC, $\sim$600 frames for the SMC, and $\sim$400 frames for the Magellanic Bridge area. Standard OGLE observations, taken with exposure times of 150 s, reach $V \approx 22.5$ mag and $I \approx 22$ mag, but they are complete down to $V \approx 21$ mag and $I \approx 20.5$ mag.

We searched 77.9 million stellar detections for periodic signals in the frequency range of $30 - 100$ cycles per day or the period range of $14.4 - 48$ min, with the FNPEAKS code\[^1\]. Light curves of 46 830 stars with a signal-to-noise ratio $> 5$ were subject to visual inspection. Unfortunately, we did not find any BLAP. In the analyzed period range, we detected only one bona fide variable, a foreground SX Phoenicis-type (or population II $\delta$ Sct-type) star LMC512.02.16620 at equatorial coordinates (RA, Dec)$_{2000.0} = (05:10:25.55, -66:37:55.7)$, with mean brightness $I = 16.74$ mag, colour $V - I = 0.30$ mag, period of 31.02 min, and $I$-band amplitude of 0.013 mag. Our inspection led to the detection of four new short-period eclipsing binary stars, LMC527.10.3916, LMC556.21.1214, LMC570.22.45, and SMC732.19.320, with orbital periods between 1.68 and 3.36 h and three faint unknown $\delta$ Sct stars, LMC508.17.28064, SMC731.04.3587, and LMC570.26.6352, with pulsation periods of 81.25, 82.18, 91.69 min, mean $I$-band brightness of 20.09, 19.79, 20.57 mag, and amplitudes of 0.32, 0.35, 0.41 mag, respectively.

The result of our search for BLAPs in the Magellanic System is negative. However, we cannot exclude a possibility that some low-luminosity variables of this type reside in the Magellanic Clouds. In our calculations, we did not take interstellar extinction into account. Detection of stellar sources from the OGLE standard images is about 95% complete at $I = 20.7$ mag and about 80% at $I = 21.2$ mag. Completeness of our search for variables is likely lower, but the detection of faint $\delta$ Sct stars demonstrates that some large amplitude variables can be found. From the observational point of view, chances for BLAPs seem to be higher in the more distant SMC. On the other hand, the SMC is less metal-rich than the LMC and much less than the Milky Way. Recent theoretical models (Jeffery & Saio, 2016, A. Pamyatnykh, priv. comm.) show that pulsation instability in hydrogen-deficient atmospheres appears at high (solar) metallicity in the region occupied by BLAPs on the $T_{\text{eff}} - \log g$ plane. The lack of pulsations at low metallicity is consistent with the fact that BLAPs are not observed in the Galactic halo and globular clusters.

Distance measurements to known BLAPs from the Gaia satellite should help us determine accurate luminosities and masses of these objects and to find out what their true structure is. Future high-resolution spectra should provide information on the exact iron content and presence of other elements in the atmospheres of BLAPs.

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\[^1\]http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks
Table 1: Parameters of known Blue Large-Amplitude Pulsators

| Variable name     | RA(2000.0)  | Dec(2000.0) | ⟨V⟩  | ⟨I⟩  | ampV | ampI | P  | r  \times 10^{-7} y^{-1} | T_{\text{eff}} | logg | log(N_{He}/N_{H}) |
|-------------------|-------------|-------------|-------|-------|------|------|----|-------------------------|---------------|------|------------------|
| OGLE-BLAP-001     | 10:41:48.77 | −61:25:08.5 | 17.71 | 17.22 | 0.41 | 0.24 | 28.255 | 2.69 ± 3.7 | 30800 ± 500 | 4.61 ± 0.07 | −0.55 ± 0.05 |
| OGLE-BLAP-002     | 17:43:58.02 | −19:16:54.1 | 18.89 | 17.95 | 0.32 | 0.36 | 23.286 |             |               |                  |                  |
| OGLE-BLAP-003     | 17:44:51.48 | −24:10:04.0 | 19.19 | 18.10 | 0.27 | 0.23 | 28.458 | +0.82 ± 0.32 |               |                  |                  |
| OGLE-BLAP-004     | 17:51:04.72 | −22:09:03.4 | 18.81 | 17.53 | 0.43 | 0.26 | 22.357 |             |               |                  |                  |
| OGLE-BLAP-005     | 17:52:18.73 | −31:56:35.0 | 19.99 | 18.77 | 0.33 | 0.30 | 27.253 | +0.63 ± 0.26 |               |                  |                  |
| OGLE-BLAP-006     | 17:55:02.88 | −29:50:37.5 | 18.35 | 17.38 | 0.28 | 0.23 | 38.015 | −2.85 ± 0.31 |               |                  |                  |
| OGLE-BLAP-007     | 17:55:57.52 | −28:52:11.0 | 19.27 | 18.46 | 0.33 | 0.28 | 35.182 | −2.40 ± 0.51 |               |                  |                  |
| OGLE-BLAP-008     | 17:56:48.26 | −32:21:35.6 | 18.73 | 17.59 | 0.28 | 0.19 | 34.481 | +2.11 ± 0.27 |               |                  |                  |
| OGLE-BLAP-009     | 17:58:48.20 | −27:16:53.7 | 15.65 | 15.07 | 0.29 | 0.24 | 31.935 | +1.63 ± 0.08 | 31800 ± 1400 | 4.40 ± 0.18 | −0.41 ± 0.13 |
| OGLE-BLAP-010     | 17:59:59.22 | −35:18:07.0 | 17.23 | 16.92 | 0.38 | 0.34 | 32.133 | +0.44 ± 0.21 |               |                  |                  |
| OGLE-BLAP-011     | 18:00:23.24 | −35:58:03.1 | 17.25 | 16.98 | 0.22 | 0.29 | 34.875 |               | 26200 ± 2900 | 4.20 ± 0.29 | −0.45 ± 0.11 |
| OGLE-BLAP-012     | 18:05:44.20 | −30:11:15.2 | 18.26 | 17.62 | 0.35 | 0.34 | 30.897 | +0.03 ± 0.15 |               |                  |                  |
| OGLE-BLAP-013     | 18:05:52.70 | −26:48:18.0 | 19.24 | 18.19 | 0.25 | 0.22 | 39.326 | +7.65 ± 0.67 |               |                  |                  |
| OGLE-BLAP-014     | 18:12:41.79 | −31:12:07.8 | 16.79 | 16.68 | 0.34 | 0.26 | 33.623 | +4.82 ± 0.39 | 30900 ± 2100 | 4.42 ± 0.26 | −0.54 ± 0.16 |
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