NO EVIDENCE FOR CLASSICAL CEPHEIDS AND A NEW DWARF GALAXY BEHIND THE GALACTIC DISK

P. Pietrukowicz1, A. Udalski1, M. K. Szymański1, I. Soszyński1, G. Pietrzyński1,2, Ł. Wyrzykowski1, R. Poleski1,3, K. Ulaczyk1,4, J. Skowron1, P. Mróz1, M. Pawlak1, and S. Kozłowski1

1 Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
2 Departamento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Chile
3 Department of Astronomy, Ohio State University, 140 W. 18th Avenue, Columbus, OH 43210, USA
4 Department of Physics, University of Warwick, Coventry CV4 7AL, UK

Received 2015 June 30; accepted 2015 October 24; published 2015 November 9

ABSTRACT

Based on data from the ongoing OGLE Galaxy Variability Survey (OGLE GVS), we have verified observed properties of stars detected by the near-infrared VVV survey in a direction near the Galactic plane at longitude $l \approx -27^\circ$ and recently tentatively classified as classical Cepheids belonging to, hence claimed, a dwarf galaxy at a distance of about 90 kpc from the Galactic Center. Three of four stars are detected in the OGLE GVS $I$-band images. We show that two of the objects are not variable at all, and the third one with a period of 5.695 days and an amplitude of 0.5 mag cannot be a classical Cepheid and is very likely a spotted object. These results together with a very unusual shape of the $K_s$-band light curve of the fourth star indicate that it is very likely that none of them is a Cepheid and, thus there is no evidence for a background dwarf galaxy. Our observations show that great care must be taken when classifying objects by their low-amplitude close-to-sinusoidal near-infrared light curves, especially with a small number of measurements. We also provide a sample of high-amplitude spotted stars with periods of a few days that can mimic pulsations and even eclipses.

Key words: galaxies: dwarf – Galaxy: disk – stars: variables: Cepheids

Supporting material: data behind figures

1. THE TARGET OBJECTS

Recently, Chakrabarti et al. (2015) reported on the detection of four classical Cepheids clustered in angle (within one degree) and distance (on average 90 kpc from the Galactic Center) in a direction near the Galactic plane at longitude $l \approx -27^\circ$. They used near-infrared data from the ESO public survey VISTA Variables in the Via Lactea (VVV; Minniti et al. 2010). Their search for periodic variables was based on timeseries photometry in the $K_s$ band with only 32 epochs per star across the VVV disk area. For each of the stars classified by them as a Cepheid, they provide single-epoch VVV photometry in the $JHK_s$ bands and extinction values derived from the color excess assuming the Cardelli et al. (1989) extinction law. Finally, they calculate distances to the objects using a formula given in Feast et al. (2014). The obtained a mean distance of 90 kpc, and a clumped location in the sky led them to the conclusion that the stars are associated with a previously unknown dwarf galaxy. In our work, we show that to reach a conclusion on the presence of such a galaxy one has to be absolutely sure that the observed stars are of particular type and are indeed located at a similar distance behind the Galactic disk.

2. ANALYSIS OF THE OGLE DATA

The OGLE project in its fourth phase of operation (OGLE-IV; Udalski et al. 2015) conducts, among others, a survey of the Galactic disk area visible from Las Campanas Observatory, Chile—the OGLE Galaxy Variability Survey (OGLE GVS). It covers 2/3 of the Galactic plane with longitudes from $-170^\circ$ to $+60^\circ$ and latitudes of $-3^\circ \lesssim b \lesssim +3^\circ$. Regular monitoring with a cadence of 1–2 days, called the shallow OGLE GVS, started in 2013. It spans a magnitude range of $10 < I < 19$. A complementary, deeper survey started in 2010 and maps the Galactic plane area down to $I \approx 22$ mag. The data will be extremely useful for studying the Milky Way structure and properties of many variable objects (cf. Pietrukowicz et al. 2013a, 2013b). However, at the moment of writing (2015 June), a sufficient amount of data has been collected to find information on selected Galactic plane objects, such as the candidate Cepheids reported in Chakrabarti et al. (2015).

For clarity, it is very important to note that in their paper, Chakrabarti et al. (2015) made the following errors in IDs, coordinates, and finding charts for reported objects, later corrected in a private communication with us: (1) everywhere in their paper, the correct ID for the second reported star should be VVV J162231.35-512346.9 (not VVV J162328.18-513230.4) and thus the Galactic coordinates given in their Table 1 are also incorrect; (2) the finding chart for the second object is wrong, while the $K_s$-band light curve shown in their Figure 1 is correct; (3) in the same figure, they labeled the fourth object using the ID of the third one. Our Table 1 gives the correct positions of the investigated objects. Some minor things presented in Chakrabarti et al. (2015) in an unusual manner include the finding charts in Galactic coordinates instead of equatorial coordinates and an opposite direction of increasing Galactic longitude in their Figure 1.

Once we ascertained the positions of the reported objects, we found three of the four stars, hereafter denoted S1, S2, S3, and S4, in deep OGLE GVS $I$-band frames (see Figure 1). Only object S4, located about $0^\circ.77$ from the Galactic plane in a highly reddened area, is not visible. Star S1 is bright enough to be verified for variability in the shallow OGLE GVS images, but stars S2 and S3 required additional deep observations taken in 2015 May–June. The number of $I$-band measurements for

---

* Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution for Science.
The photometry was extracted using the Difference Image Analysis (DIA) method with an image subtraction algorithm implemented by Woźniak (2000) on the OGLE images of dense stellar fields. Udalski et al. (2015) give full details on the data reduction techniques. In Figure 2, we show light curves of the three detected stars, while in Figure 3, we present power spectra obtained with the ANOVA statistics (Schwarzenberg-Czerny 1996). Stars S1 and S2 look to be constant. There is no significant period in their power spectra. Light curves clearly do not phase with the periods given in Chakrabarti et al. (2015). If the two objects were indeed Cepheids with pulsation periods of 3–4 days as proposed based on the $K_s$-band observations, we would see them in the $I$-band as large-amplitude variables ($A_I \gtrsim 0.2$ mag). Objects S1 and S2 either are constant stars or have amplitudes of, at most, a few hundreds of magnitude.

Deep OGLE GVS observations confirm light variations in star S3 with a period of 5.695 days (or twice longer), but their shape is different than expected for fundamental-mode classical Cepheids. Observations from 2011 for this object are marked in red to show a likely amplitude change. The data used to create this figure are available.

### Table 1
Data on Individual Target Stars

| Star | VVV ID          | $l$ | $b$  | OGLE Field | OGLE ID | $P_{\text{OGLE}}$ (day) |
|------|----------------|-----|------|------------|---------|------------------------|
| S1   | J162559.36-522234.0 | −27.597 | −2.237 | GD1126.25  | 6394     | no                     |
| S2   | J162231.35-512346.9   | −27.273 | −1.168 | GD1133.28  | 15388    | no                     |
| S3   | J162119.39-520233.3   | −27.862 | −1.494 | GD1133.13  | 8832     | 5.6950(3) or $\times 2$ |
| S4   | J161542.47-494439.0   | −26.888 | +0.768 | GD1139.19  | ...      | ...                    |

S1, S2, and S3 is 61, 48, and 44, respectively. The photometry was extracted using the Difference Image Analysis (DIA) method with an image subtraction algorithm implemented by Woźniak (2000) on the OGLE images of dense stellar fields. Udalski et al. (2015) give full details on the data reduction techniques. In Figure 2, we show light curves of the three detected stars, while in Figure 3, we present power spectra obtained with the ANOVA statistics (Schwarzenberg-Czerny 1996). Stars S1 and S2 look to be constant. There is no significant period in their power spectra. Light curves clearly do not phase with the periods given in Chakrabarti et al. (2015). If the two objects were indeed Cepheids with pulsation periods of 3–4 days as proposed based on the $K_s$-band observations, we would see them in the $I$-band as large-amplitude variables ($A_I \gtrsim 0.2$ mag). Objects S1 and S2 either are constant stars or have amplitudes of, at most, a few hundreds of magnitude.

Deep OGLE GVS observations confirm the variable nature of object S3 with a period around 5.69 days noted in Chakrabarti et al. (2015). The power spectrum based on the optical data shows a very strong signal at $P = 5.695$ days and also at $2P = 11.390$ days. The shape of the light curve is close to a sinusoid, but its stability is under question. It is likely that the $I$-band amplitude changed from about 0.35 mag in 2011 to 0.50 mag in 2015. The value for 2011 is, however, uncertain since only eight images were taken that year. In Figure 4, we show that the optimal Fourier fit to the $I$-band data is of a maximal order of $n = 2$, assuming $P = 5.695$ days and stability.
of the light curve. For \( n = 2 \), we obtain the following Fourier parameters: \( A_0 = 19.593 \pm 0.009 \), \( A_1 = 0.251 \pm 0.016 \), \( A_2 = 0.055 \pm 0.016 \), \( \phi_1 = 5.03 \pm 0.06 \), and \( \phi_2 = 3.49 \pm 0.29 \). From this, we find the following combinations: \( R_{21} = A_2 / A_1 = 0.219 \pm 0.065 \) and \( \phi_{21} = \phi_2 - 2\phi_1 = 5.99 \pm 0.31 \). In the case of \( n = 3 \), we would obtain: \( A_0 = 19.591 \pm 0.009 \), \( A_1 = 0.249 \pm 0.016 \), \( A_2 = 0.053 \pm 0.016 \), \( A_3 = 0.043 \pm 0.016 \), \( \phi_1 = 5.03 \pm 0.06 \), \( \phi_2 = 3.59 \pm 0.31 \), and \( \phi_3 = 5.09 \pm 0.36 \), and hence \( R_{31} = A_3 / A_1 = 0.213 \pm 0.066 \), \( \phi_{31} = \phi_3 - 2\phi_1 = 6.09 \pm 0.33 \), \( R_{31} = A_3 / A_1 = 0.173 \pm 0.065 \), and \( \phi_{31} = \phi_3 - 3\phi_1 = 2.56 \pm 0.41 \). All above uncertainties were calculated from the standard propagation formula for independent variables. The combination \( \phi_{21} \) is the best parameter to distinguish between the fundamental-mode and first-overtone pulsars with periods around 5.7 days \( (\log P \approx 0.76) \). The value of \( \phi_{21} \), here very similar for \( n = 2 \) and \( n = 3 \), is evidently too high for fundamental-mode Cepheids at this period \( (\text{see Figure 5}) \). The close-to-sinusoidal light curve shape of S3, or the \( \phi_{21} \) value of 6.0 \pm 0.3, could indicate a first-overtone Cepheid, but \( I \)-band amplitudes as high as 0.5 mag are not observed at long periods in this type of pulsator \( (\text{see Figure 7}) \). The observed abrupt phase difference at about 10 days is related to the effect of Hertzsprung progression. Star S3 with a nearly sinusoidal light curve is a clear outlier.
ones from the Small Magellanic Cloud, periods are not longer than 4.5 days (Soszyński et al. 2010). In none of the known environments, I-band amplitudes of the first-overtone Cepheids with periods $>2$ days exceed 0.35 mag. A dwarf galaxy is expected to host old and metal-poor stars, such as RR Lyrae–type variables and anomalous Cepheids, rather than classical ones.

On the other hand, amplitudes of 0.5 mag or higher are observed in numerous chromospherically active stars, such as of RS CVn type. In Figure 8, we show three examples of spotted stars with periods of a few days found in the OGLE database. Light curves of such stars change slowly over years and very often may mimic pulsations and eclipses if observed for a short period of time. Based on the observed properties of the light curve, we conclude that object S3 is very likely a spotted star with a period of 5.695 days, but the period of 11.390 days cannot be excluded. See the comparison of the Fourier combinations for S3 and spotted stars in Figure 9.

Object S4, which is too faint to be detected in the deep OGLE GVS images according to Chakrabarti et al. (2015), has a period of 13.9 days and a skewed $K_s$-band light curve with the rising part about twice as long as the fading one. Such a shape is not observed in classical Cepheids. Soszyński et al. (2005) normalized near-IR photometry for 30 Galactic and 31 LMC fundamental-mode Cepheids with periods mostly longer than 10 days and showed that their $K$-band light curves are very homogeneous and nearly symmetric. Pejcha & Kochanek (2012) performed a global model for 287 classical Cepheids with $P > 10$ days based on thousands of multiband observations. According to their work, $K$-band light curves of stars with periods of 13–14 days have equal rising and falling timescales. $K$-band light curves of long-period classical Cepheids presented in Persson et al. (2004), Monson & Pierce (2011), and Macri et al. (2015) are practically symmetric, and none of them shows the rising branch twice as long as the fading one. Some of the presented light curves have a small number of points in $K$, and their scatter is comparable with the amplitude, like OGLE-LMC-CEP-2562 in Macri et al. (2015) and S4 here.
3. CONCLUSIONS

Our observations show that none of the three VISTA objects detected in the OGLE GVS data is a classical Cepheid. Objects S1 and S2 do not look to be variable at all. Object S3 is indeed variable, but it has a nearly sinusoidal light curve with a high amplitude of 0.5 mag in the $I$-band, likely not stable in time. This is not observed in classical Cepheids in any environment. S3 is very likely a spotted star of the RS CVn type. Although we are not able to detect star S4, its $K_s$-band light curve with $P = 13.9$ days and the rising part twice as long as the fading one would be very unusual for a fundamental-mode classical Cepheid. Based on the above findings, we conclude that there is no evidence for the presence of a dwarf galaxy behind the Galactic disk in the observed direction. Our results show that great care must be taken when classifying variable objects based on low-amplitude near-infrared light curves, especially when composed of a small number of data points.

The OGLE project has received funding from the National Science Centre, Poland, grant MAESTRO 2014/14/A/ST9/00121 to A.U. This work has been also supported by the Polish Ministry of Sciences and Higher Education grants No. IP2012 005672 under the Iuventus Plus program to P.P. and No. IdP2012 000162 under the Ideas Plus program to I.S.

REFERENCES

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chakrabarti, S., Saito, R., Quillen, A., et al. 2015, ApJL, 802, L4
Feast, M. W., Menzies, J. W., Matsunaga, N., & Whitelock, P. A. 2014, Natur, 509, 342
Macri, L. M., Ngeow, C.-C., Kanbur, S. M., Mahzooni, S., & Smitka, M. T. 2015, AJ, 149, 117
Minniti, D., Lucas, P. W., Emerson, J., et al. 2010, NewA, 15, 433
Monson, A. J., & Pierce, M. J. 2011, ApJS, 193, 12
Pejcha, O., & Kochanek, C. S. 2012, ApJ, 748, 107
Persson, S. E., Madore, B. F., Krzeminski, W., et al. 2004, AJ, 128, 2239
Pietrukowicz, P., Dziembowski, W. A., Mróz, P., et al. 2013a, AcA, 63, 379
Pietrukowicz, P., Mróz, P., Soszyński, I., et al. 2013b, AcA, 63, 115
Pojmański, G. 2002, AcA, 52, 397
Schwarzenberg-Czerny, A. 1996, ApJL, 460, L107
Sitek, M., & Pojmanski, G. 2014, AcA, 64, 115
Soszyński, I., Gieren, W., & Pietrzyński, G. 2005, PASP, 117, 823
Soszyński, I., Poleski, R., Udalski, A., et al. 2008, AcA, 58, 163
Soszyński, I., Poleski, R., Udalski, A., et al. 2010, AcA, 60, 17
Udalski, A., Szymański, M., & Szymański, G. 2015, AcA, 65, 1
Woźniak, P. R. 2000, AcA, 50, 421