DOUBLE MODE CEPHEIDS IN M31
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ABSTRACT

Until now, double mode Cepheids (or beat Cepheids) were known only in the Galaxy, the Magellanic Clouds, and M33. Curiously, none of the more than 2000 Cepheids in M31 was claimed to show two pulsation modes. We conducted a systematic search for double mode Cepheids in the archival data of M31 and discovered four such objects. We identify one of the stars as a first and second overtone pulsator even though its secondary period is subject to strong aliasing. Two stars pulsate in the fundamental mode and the first overtone. Their fundamental periods are 9.392 days and 9.163 days. This makes them the first candidates for fundamental mode and first overtone Cepheids, of which double mode pulsations are caused by the 2:1 resonance of the fundamental mode and the second overtone.

Key words: galaxies: individual (M31) – stars: oscillations – stars: variables: Cepheids

Online-only material: color figure

1. INTRODUCTION

Among many different types of pulsating stars, arguably the most important group is the classical (or type I) Cepheid variables. They obey a power-law period-luminosity relation, which allows measurement of distances to external galaxies. However, the details of this relation are the subject of an active debate. The slope of the relation changes around a period of ≈10 days at some wavelengths (e.g., Ngeow et al. 2009; Tammann et al. 2011). Also the zero point of the relation is affected by metallicity. Different star formation histories in different galaxies result in different histograms of Cepheid periods, which impacts the distance estimates if the period-luminosity relation is not a pure power-law. The other effects that affect the observed brightness of Cepheids are: extinction, infrared emission of circumstellar dust, and blending. The above problems cannot be tackled without a deep understanding of the Cepheid internal structure. Only recently has the discrepancy in Cepheid masses derived from stellar evolution and pulsation theories been solved (Pietrzyński et al. 2010).

Among the Cepheid variables, an important group constitute multimode radial pulsators. The identification of two modes with the expected period ratio clearly shows that the object is a classical Cepheid, not a different type of variable star. It also yields an additional constraint on stellar parameters as the two modes probe different parts of the star. In this context, triple mode pulsators are even more important (Moskalik & Dziembowski 2005) of which we know a dozen or so.

The highest number of Cepheids is known in the Magellanic Clouds. Altogether these galaxies contain more than 8000 known Cepheids (Soszyński et al. 2008, 2010, 2012; Marquette et al. 2009). Among them, 6% show at least two radial modes in the Small Magellanic Cloud (SMC). For the more metal-rich Large Magellanic Cloud (LMC), the corresponding value is 10%. Except for these stars, double mode Cepheids are known only in the Milky Way and M33 (Beaulieu et al. 2006). There are also more than 2000 known Cepheids in the Andromeda galaxy (M31; Fliri & Valls-Gabaud 2012; Kodric et al. 2013) and until now none of them has been claimed as a double mode pulsator.1 If the same single mode to double mode ratio of Cepheids is in M31 as in the Magellanic Clouds, one would expect more than a hundred double mode Cepheids to be detected by a deep enough survey. The number should be smaller because of more severe blending, which lowers the observed amplitudes of Cepheids and most affects the smaller amplitude mode. Even accounting for this, one would expect at least a few longest period (i.e., brightest) double mode Cepheids to be found in M31. We note that three double mode RR Lyr variables were found in the Hubble Space Telescope photometry by Reyner et al. (2010) and they are fainter than Cepheids.

Here we present a search for double mode Cepheids in archival photometry for known variable stars in M31. The next section briefly presents data used in the analysis. We present the search method and its results in Sections 3 and 4. Finally, we discuss our findings. During our research, we found misclassifications for a few Cepheids, which are presented in the Appendix.

2. DATA AND METHOD DESCRIPTION

Our analysis is based on two sets of publicly available light curves for the Cepheids in M31. In their search for Cepheids in M31 Vilardell et al. (2007) used data collected between 1999 and 2003 for stars in the NE part of this galaxy. One field of 0.3 deg2 was observed with the 2.5 m Isaac Newton Telescope. The pixel scale was 0″.33 and median seeing was 1″.2 in the B band and 1″.3 in the V band. The analysis, based on 265 epochs in the B band and 259 in the V band led to a discovery of 416 Cepheids. For more details, see Vilardell et al. (2006, 2007).

The second set of light curves was presented by Kodric et al. (2013). They analyzed data collected by the 1.8 m Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) with the 1.4 × 10⁶ pixel camera. The pixel scale is 0″.258 and the total field of view is 7 deg², i.e., it covers the whole of M31 in a single image. The 183 epochs in the rp1 and lp1 bands (Tonry...
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Figure 1. Prewhitening of J00450019+4129313 photometry. The top panel presents the periodogram of the original data. The second panel shows the data phased with the period of highest peak of the periodogram. After subtracting the Fourier fit we recalculated the periodogram (third panel) and phased the data according to the highest peak (bottom panel). The insets in the first and the third panels magnify the parts of the periodogram close to the highest peak.

et al. 2012) collected in 2010 and 2011 were used to search for Cepheids. The median seeing of the 30 best seeing images was 0′.86. Altogether 2009 Cepheids were found including type II objects and variables that could not be definitely assigned to type I or type II. A more detailed description of the observation and their analysis was presented by Lee et al. (2012) and Kodric et al. (2013). Both Vilardell et al. (2007) and Kodric et al. (2013) used difference image analysis to perform photometric measurements.

The light curves of Cepheids were prewhitened with the period given in the original papers as well as periods independently found by us. The two periods differed only in questionable cases. The prewhitened light curves were searched for periods using both a discrete Fourier transform and a multiharmonic analysis of variance (Schwarzenberg-Czerny 1996). The final period estimates were taken using results from the latter method. All the secondary periods found in a wide range around known structures in the Petersen diagram (period ratio versus longer period) were visually verified. During our analysis we found a few stars that were incorrectly classified. We present these in the Appendix in order to help purify the M31 Cepheid sample used in future studies.

3. RESULTS

In this section we present each double mode pulsator separately. Comparison to the Cepheids found in other environments and a discussion of pulsation properties will be presented in the following section. We denote fundamental mode and first overtone pulsators by F/1O and first and second mode pulsators by 1O/2O. The star identifiers are from Vilardell et al. (2007) and Kodric et al. (2013). Periods and Fourier parameters (phase differences $\phi_{21} = \phi_2 - 2\phi_1$ and amplitude ratios $R_{21} = A_2/A_1$; Simon & Lee 1981) are presented in Table 1 for each mode separately.

3.1. J00450019+4129313 – 1O/2O Type Pulsator

The photometry presented by Vilardell et al. (2007) reveals the primary period of this star to be 1.694919(16) days. We found a strong signal for a secondary period but its value cannot be found unambiguously because of the strong aliases in the power spectrum. The prewhitening of the light curve is illustrated in Figure 1. The four possible values are (starting from the most probable): 1.361279(27), 1.356241(44), 1.366328(47),
or 1.351260(51). They give period ratios of 0.8032, 0.8002, 0.8061, and 0.7972, respectively. All of these values fall in the range typical for $1\Omega/2\Omega$ pulsators.

### 3.2. PSO J010.6063+40.8608 – $F/1\Omega$ Type Pulsator

An et al. (2004) found the period of this star to be 9.42 days. The photometry presented by Kodric et al. (2013) results in a primary period of 9.3918(85) days and a secondary period of 6.5551(49) days. The prewhitening of the light curve is presented in Figure 2. The period ratio of 0.698 is slightly lower than the period ratio for known $F/1\Omega$ pulsators but all of them have shorter periods. It lies on the extension of the $F/1\Omega$ sequence on the Petersen diagram. Thus we classify it as $F/1\Omega$ Cepheid.

### 3.3. PSO J010.9364+41.2504 – $F/1\Omega$ Type Pulsator

This object was already announced by Kaluzny et al. (1999) and Joshi et al. (2003) with periods of 9.173 days and 9.160 days, respectively. Using Kodric et al. (2013) photometry we found periods of 9.1633(80) days and 6.3618(61) days (Figure 3). This object turns out to have periods similar to PSO J010.6063+40.8608 discussed above, with a slightly smaller period ratio of 0.694. We conclude that this is a $F/1\Omega$ pulsator.

### 3.4. PSO J011.3583+42.0404 – Candidate Non-radial Pulsator

The analysis of photometry presented by Kodric et al. (2013) revealed two periods in this object: 10.4672(74) days and...
6.1610(52) days. The prewhitening shown in Figure 4 reveals a sound detection of a secondary period. The period ratio of 0.589 is not typical for any known combination of radial modes. This object can be either a non-radial pulsator or a blend of two stars. Non-radial modes are observed in other Cepheids (Moskalik & Kołaczkowski 2009). We note that Dziembowski (2012) tried to reproduce the $\approx 0.6$ period ratio observed in some of the LMC and SMC first overtone Cepheids. Their findings are not applicable to PSO_J011.3583+42.0404 because neither the analyzed sample nor the models extended to long enough primary periods.

4. DISCUSSION

We show the Petersen diagram for known classical double mode F/1O and 1O/2O Cepheids in Figure 5. Separate symbols are used to present objects from the Milky Way (Soszyński et al. 2011; Smolec & Moskalik 2010, and reference therein), LMC (Soszyński et al. 2008, 2012; Marquette et al. 2009), SMC (Soszyński et al. 2010), M33 (Beaulieu et al. 2006), and M31. There are four different positions shown for J00450019+4129313, which correspond to the different aliases of the secondary period. All are consistent with a 1O/2O pulsator. One can see that positions of PSO_J010.6063+40.8608 and PSO_J010.9364+41.2504 are consistent with extrapolation of the relation seen for F/1O pulsators. The fact that fundamental mode periods of these objects are close to 10 days makes them unusual. The light curves of the fundamental mode Cepheids with similar periods show two maxima in each period. The appearance of the second maximum is caused by a 2:1 resonance of the second overtone and the fundamental mode. We note that the calculations of Buchler (2009), which were presented only in conference proceedings, suggest that F/1O pulsations with fundamental mode periods of around 10 days are caused by the resonance mentioned above. The range of luminosities and effective temperatures in which this mechanism operates is very small. This should allow very detailed modeling of these stars. Also the preliminary models for these stars indicate $P_{1O}/P_{2O}$ close to 2 and masses from 6 to 7 $M_\odot$ (W. A. Dziembowski & R. Smolec, in preparation). Based on the Petersen diagram presented in Figure 5 we suggest that the longest period F/1O Cepheids in the LMC (OGLE-LMC-CEP-1082, $P_{1O} = 7.86343$ days and $P_{2O} = 5.56518$ days) and SMC (OGLE-SMC-CEP-1497, $P_{1O} = 4.9780$ days and $P_{2O} = 3.588329$ days) may also display double mode pulsations because of the 2:1 resonance of 2O and F modes. Both these objects are separated from the rest of the F/1O Cepheids in a given galaxy by at least 2.3 days in $P_{1O}$. 

Figure 3. Same as Figure 1 for PSO_J010.9364+41.2504.
Figure 4. Same as Figure 1 for PSO_J011.3583+42.0404.

Figure 5. Petersen diagram for known F/10 and 10/20 Cepheids. $P_L$ and $P_S$ are the longer and shorter period, respectively. The number of Cepheids plotted is 355, 281, 49, 5, and 3 for the LMC, SMC, Milky Way, M33, and M31, respectively. Four possible positions of the M31 10/20 Cepheid J00450019+4129313 are presented with larger symbols corresponding to the more probable positions.

The double mode Cepheids with periods as long as presented here might have been overlooked in previous analyses of the existing time-series photometry for variable stars in other galaxies. The double mode pulsators presented here fall outside not only the previously published Petersen diagrams constructed for known pulsators but also outside the period range studied in many theoretical investigations.

The M31 Cepheids, for which double mode pulsations were found, were also observed by Kaluzny et al. (1999), Joshi et al. (2003), An et al. (2004), and possibly by Fliri & Valls-Gabaud (2012). Unfortunately, we were unable to access useful time-series photometry from any of these papers.

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**APPENDIX**

**MISCLASSIFIED OBJECTS**

$J00451769+4136367$. Vilardell et al. (2007) give a period of 7.862587 days. The true period is two times shorter.

$J00452829+4139547$. Photometry presented by Vilardell et al. (2007) indicates that this is an artifact produced by the
difference image analysis. The variations in measured flux are caused by the nearby brighter Cepheid J00452353+4140040. The periods of both objects agree.

PSO J009.9994+40.5558. Our analysis of photometry presented by Kodric et al. (2013) revealed that this object varies with periods of 13.084(14) days and 9.5589(80) days. The period ratio of 0.7306 is similar to F/1O pulsators. However, this object cannot be classified as a double mode pulsator. As noted by Baade & Swope (1965) there are two Cepheids of similar brightness separated by about 1.8. Baade & Swope (1965) identified them by the numbers 252 and 253. Their periods agree with those quoted above. We conclude that Kodric et al. (2013) presented the photometry of two blended stars.

PSO J010.5263+40.7724. Classification of this object by Kodric et al. (2013) as a Cepheid seems questionable as its light curve does not resemble that of typical Cepheids. The \(i_{P1}\)-band photometry does not show clear periodic variability.

REFERENCES

An, J. H., Evans, N. W., Hewett, P., et al. 2004, MNRAS, 351, 1071
Baade, W., & Swope, H. H. 1965, AJ, 70, 212
Beaulieu, J.-P., Buchler, J. R., Manque, J.-B., Hartman, J. D., & Schwarzenberg-Czerny, A. 2006, ApJ, 653, L101
Buchler, J. R. 2009, in AIP Conf. Ser. 1170, Stellar Pulsation: Challenges for Theory and Observation, ed. J. A. Guzik & P. A. Bradley (Melville, NY: AIP), 51
Dziembowski, W. A. 2012, AcA, 62, 323
Fliri, J., & Valls-Gabaud, D. 2012, Ap&SS, 341, 57
Joshi, Y. C., Pandey, A. K., Narasimha, D., Sagar, R., & Giraud-Héraud, Y. 2003, A&A, 402, 113
Kaluzyzny, J., Mochejska, B. J., Stanek, K. Z., et al. 1999, AJ, 118, 346
Kodric, M., Riffeser, A., Hopp, U., et al. 2013, AJ, 145, 106
Lee, C.-H., Kodric, M., Seitz, S., et al. 2013, ApJ, 777, 35
Lee, C.-H., Riffeser, A., Koppenhoefer, I., et al. 2012, AJ, 143, 89
Marquette, J. B., Beaulieu, J. P., Buchler, J. R., et al. 2009, A&A, 495, 249
Moskalik, P., & Dziembowski, W. A. 2005, A&A, 434, 1077
Moskalik, P., & Kołaczkowski, Z. 2009, MNRAS, 394, 1649
Ngeow, C.-C., Kanbur, S. M., Neilson, H. R., Nanthakumar, A., & Buonaccorsi, J. 2009, ApJ, 693, 691
Pietrzyński, G., Thompson, I. B., Gieren, W., et al. 2010, Natur, 468, 542
Reyner, S., Kanbur, S. M., Ngeow, C., & Morgan, C. 2010, MNRAS, 407, 1801
Schwarzenberg-Czerny, A. 1996, ApJ, 460, L107
Simon, N. R., & Lee, A. S. 1981, ApJ, 248, 291
Smolec, R., & Moskalik, P. 2010, A&A, 524, A40
Soszyński, I., Poleski, R., Udalski, A., et al. 2008, A&A, 58, 163
Soszyński, I., Poleski, R., Udalski, A., et al. 2010, A&A, 60, 17
Soszyński, I., Udalski, A., Pietrukowicz, P., et al. 2011, A&A, 61, 285
Soszyński, I., Udalski, A., Poleski, R., et al. 2012, A&A, 62, 219
Tamman, G. A., Reindl, B., & Sandage, A. 2011, A&A, 531, A134
Tonry, J. L., Stubbs, C. W., Lykke, K. R., et al. 2012, ApJ, 750, 99
Vilardell, F., Jordi, C., & Ribas, I. 2007, A&A, 473, 847
Vilardell, F., Ribas, I., & Jordi, C. 2006, A&A, 459, 321