Non-radial Modes and Modulation in Galactic Cepheids from OGLE-IV Survey

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This work involves a detailed search for additional low-amplitude variability phenomena such as presence of a non-radial mode or a periodic modulation, in Galactic Cepheids. We perform frequency analysis of ∼2000 Cepheids from Galactic disk and bulge sample using the OGLE-IV survey photometry. In our study, we identify 16 candidate detections for radial multi-mode pulsations, 12 first overtone (1O) Cepheids with associated non-radial mode signature, and 3 Cepheids with periodic modulation of pulsation. These findings extend their respective samples in the Galactic fields and overall provide a basis to compare their properties with samples in the Magellanic Clouds.

1 Introduction

Cepheids are variable stars which were earlier known to be pulsating only in single radial modes. With progress in studies of the Magellanic Clouds, the above-mentioned radial mode notion was recently extended and later established that Cepheids not only have the presence of non-radial modes, but in some cases also show periodic modulation similar to Blazhko effect in the RR Lyrae stars (e.g., Moskalik & Kołaczkowski, 2009; Smolec, 2017). Are similar phenomena present also in the Galactic Cepheids, and if so, do their properties depend on the metallicity?

Previous studies of low-amplitude variability in classical Cepheids have been mostly conducted in the Magellanic Clouds, leaving Galactic fields fairly unexplored, which forms the basis of our investigation. Therefore, our work involves a detailed search for additional low-amplitude variability phenomena in the Galactic Cepheids. We perform frequency analysis of ∼2000 Cepheids using the OGLE-IV I-band photometry (Soszyński et al., 2020, and references therein). The database has high-quality photometry (error of a few mmag on the mean weighted magnitude), long temporal baseline (∼ 8 seasons), and high sampling rate (cadence of 19–60 min for the inner Galactic bulge and 1–3 days for remaining bulge fields and the Galactic disk). We perform a semi-automatic frequency analysis procedure which follows standard consecutive prewhitening technique. First, discrete Fourier transform is computed to identify the dominant radial frequencies. Then, Fourier series is fitted to the data. Significant outliers and trends are removed from the data, the latter using low order polynomials. Finally, we investigate the residuals for low-amplitude signals.

2 Results

Galactic Cepheids with additional low-amplitude radial modes. Our analysis reports additional periodicity that can be attributed to a radial mode, based

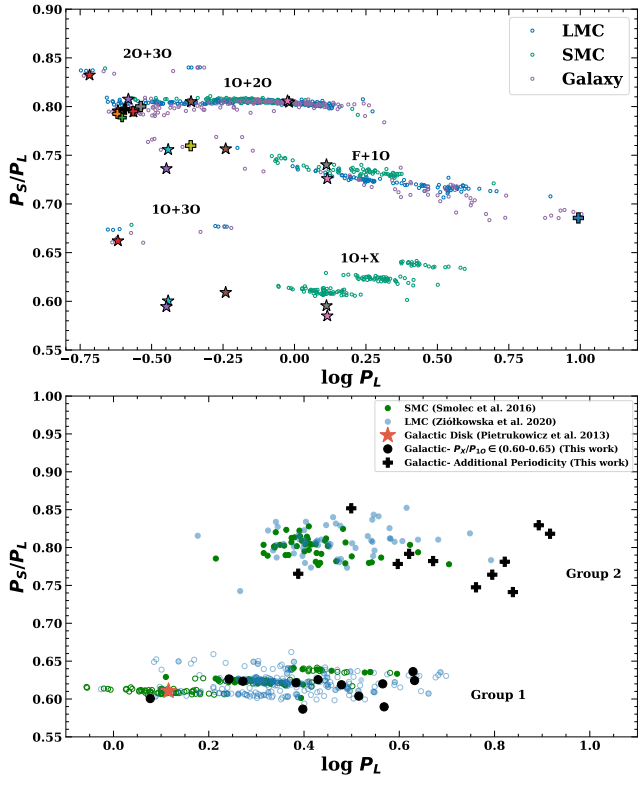

Fig. 1: *Top*: Petersen diagram showing new detections of double-mode (plus symbol) and triple mode (star symbol) candidates (same colour denotes different modes for the same star). Empty circles are the OGLE-IV Cepheids from the LMC (blue), the SMC (green), and the Galaxy (purple). *Bottom*: Petersen diagram showing Galactic sample candidates with period ratios in the $0.60 - 0.65$ range ('Group 1'; black filled circles) and possibly, detection of sub-harmonic signal ('Group 2', black plus symbols).

on the period ratios on the Petersen diagram (see Fig. 1, top). Twelve new candidates for double-mode radial pulsation were identified consisting of F+1O, 1O+2O, and F+2O pulsation type (F: Fundametal; O: Overtone). Six triple-mode radial candidates were detected (five F+1O+2O and one 1O+2O+3O). These triple-mode candidates are rare and valuable as they are excellent laboratories for asteroseismology to test stellar evolution theory (e.g., Moskalik & Dziembowski, 2005).

Galactic Cepheids with non-radial modes. In twelve 1O Cepheids we detect additional low-amplitude periodicity of the shorter period, corresponding to the period ratios $P_{\rm x}/P_{\rm 1O} \in (0.60, 0.65)$ (see Fig. 1, bottom, 'Group 1'). Such double-periodic Cepheids are well known in the Magellanic Clouds (Moskalik & Kołaczkowski, 2009; Soszyński et al., 2008, 2010; Smolec & Śniegowska, 2016) and form three sequences in the Petersen diagram. Our detections significantly increase the Galactic sample, with only one candidate reported previously (Pietrukowicz et al., 2013). Comparing with the Magellanic Cloud Cepheids we note that the more metal rich field, the longer are the long periods ($P_{\rm L}$) of the double-periodic stars. According to a model proposed by Dziembowski (2016), these additional periodici-

ties are harmonics of non-radial modes of moderate degrees, $\ell = 7$, 8, and 9, which are easier to detect than non-radial modes themselves, as amplitudes of the latter are reduced by geometric cancellation. However, in two double-periodic stars with $P_x/P_{1O} \in (0.60, 0.65)$ we do detect significant signal at sub-harmonic frequency at $1/2\nu_x$, i.e., the non-radial modes directly. Moreover, in nine 1O Cepheids we detect additional variability that most likely corresponds to direct detection of the above mentioned non-radial modes, with no signature of signal at the harmonic frequency ('Group 2' in Fig. 1).

Galactic Cepheids with modulation. We report the discovery of three Cepheids with low-amplitude, periodic modulation of pulsation. Modulation was detected in the F-mode Cepheid OGLE-GD-CEP-1247 ($P_F = 3.61624(5)$ d; $P_m = 15.282(5)$ d), in the F+1O double-mode Cepheid, OGLE-BLG-CEP-095 ($P_F = 0.43329(2)$ d; $P_{1O} = 0.32924(3)$ d; $P_m = 28.5(4)$ d), and in the 1O-mode Cepheid, OGLE-BLG-CEP-196 ($P_{1O} = 0.2535572(1)$ d; $P_m = 28.27(1)$ d) (see Fig. 8, 10, and 11 from Rathour et al., 2021). With our sample, the number of known modulated Cepheids in the Galactic fields is significantly increased. Modulation in the F+1O double-mode Cepheid is the very first detection of modulation in such combination of double-mode Cepheid pulsation. In this star, we detect modulation of the fundamental mode only.

3 Conclusion

We successfully searched for non-radial and modulation candidates in the Galactic field, thus extending the sample, with bonus of discovering twelve radial multi-mode candidates. With non-radial mode candidates in our sample and literature candidates, we comprehensively show the systematic shift in the pulsation period coupled with metallicity environment. We report three Galactic candidates with periodic modulation detected, with OGLE-BLG-CEP-095 being the first of its kind. Knowledge on whether and how these phenomena, their incidence rate and characteristics, depend on metallicity, or on a host population, could be crucial for proposing and testing the models behind. Full results of this work are presented in Rathour et al. (2021).

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