Nonradial Modes in Classical Cepheids

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Abstract

Systematic search for multiperiodicity in the LMC Cepheids (Moskalik, Kołaczkowski & Mizerski 2004) has led to discovery of low amplitude nonradial modes in a substantial fraction of overtone pulsators. We present detailed discussion of this new type of multimode Cepheid pulsators and compare them to similar nonradial pulsators discovered among RR Lyrae stars. Finally, we show first detections of secondary nonradial modes in FU/FO double-mode Cepheids.

LMC Cepheids: Data and Analysis

Our search for multiperiodic variations in the LMC Cepheids was performed with I-band DIA-reduced OGLE-II photometry (Zebruń et al. 2001). It spans 1000-1200 days, with 250-500 flux measurement per star. The data was analyzed with a standard consecutive prewhitening technique. First, we fitted the data with a Fourier sum representing variations with the dominant frequency:

\[
I(t) = I_i + \sum_k A_k \sin(2\pi k f t + \phi_k) \tag{1}
\]

The frequency of the mode, f, was also optimized. For double mode Cepheids, a double frequency Fourier sum was fitted. The residuals of the fit were then searched for secondary frequencies. This was done with the Fourier transform, calculated over the range of 0 to 5 days. In the next step, a new Fourier fit with all frequencies identified so far was performed and the fit residuals were searched for additional frequencies again. The process was stopped when no new frequencies were detected.

We have analyzed all fundamental (FU), first overtone (FO) and double mode (FU/FO and FO/SO) Cepheids listed in the OGLE-II catalogs (Udalski et al. 1999; Soszyński et al. 2000), nearly 1300 stars in total. Results for the FO/SO double mode Cepheids have been presented elsewhere (Moskalik, Kołaczkowski & Mizerski 2006; Moskalik & Kołaczkowski 2008). Here we discuss in details our findings for single mode and for FU/FO double mode pulsators.

First Overtone Cepheids

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First Overtone Cepheids

The OGLE-II catalog list 462 first overtone (FO) Cepheids. We have detected residual power in 64 of them. In 42 variables, which constitute 9% of the entire LMC sample, we were able to resolve this power into individual frequencies. We consider two frequencies to be resolved if \( |\Delta f| < 600 \) days.
For one object frequency resolution was achieved with the MACHO data (Allsman & Axelrod 2001), which is more than twice longer. The complete inventory of resolved FO Cepheids is presented in Table1. Following notation originally introduced for RR Lyrae variables (Alcock et al. 2000), we call these stars FO-ν Cepheids. Consecutive columns of Table1 give OGLE number of the star, primary and secondary periods $P_1$ and $P_ν$, frequency difference $Δf = f_ν − f_1$, period ratio $P_ν/P_1$ and amplitude ratio $A_ν/A_1$. All parameters are determined from the least square fits to the data.

Table 1: FO-ν Cepheids in OGLE-II LMC Sample

| OGLE ID   | $P_1$[day] | $P_ν$[day] | $Δf$[c/d] | $P_ν/P_1$ | $A_ν/A_1$ |
|-----------|------------|------------|-----------|-----------|-----------|
| SC1–201683| 2.319211   | 2.340033   | -0.00384  | 1.00898   | 0.048     |
|           | 3.069683   | -0.10542   |           | 1.32359   | 0.022     |
| SC1–229541| 1.216360   | 1.359217   | -0.08641  | 1.11745   | 0.043     |
| SC2–158672| 2.313334   | 1.477135   | 0.24471   | 0.63853   | 0.032     |
| SC2–208897| 2.417847   | 2.346886   | 0.01251   | 0.97065   | 0.074     |
| SC2–283723| 1.308907   | 1.425531   | -0.06250  | 1.08910   | 0.070     |
| SC3–274410| 2.446161   | 2.981644   | -0.07342  | 1.21891   | 0.043     |
|           | 3.099460   | -0.08617   |           | 1.26707   | 0.033     |
| SC3–421512| 3.186057   | 4.652311   | -0.09892  | 1.46020   | 0.055     |
| SC4–36200 | 3.476962   | 3.912773   | -0.03203  | 1.12534   | 0.054     |
|           | 4.057330   | -0.04114   |           | 1.16692   | 0.038     |
| SC4–131738| 3.122245   | 3.780949   | -0.05580  | 1.21097   | 0.032     |
| SC4–295932| 4.166232   | 2.633729   | 0.13967   | 0.63216   | 0.023     |
| SC5–75989 | 2.238255   | 2.949657   | -0.10775  | 1.31784   | 0.091     |
| SC5–138031| 2.681369   | 3.249411   | -0.06520  | 1.21185   | 0.029     |
| SC6–135695| 1.864922   | 1.949614   | -0.02329  | 1.04541   | 0.037     |
| SC6–135716| 2.838799   | 2.780248   | 0.00742   | 0.97938   | 0.064     |
| SC6–267289| 1.845746   | 1.906899   | -0.01738  | 1.03313   | 0.039     |
| SC6–363194| 2.797085   | 3.727012   | -0.08920  | 1.33246   | 0.043     |
| SC7–344559| 2.062992   | 2.140660   | -0.01759  | 1.03765   | 0.068     |
| SC8–205108| 3.515988   | 3.905659   | -0.02884  | 1.11083   | 0.026     |
| SC8–224964| 2.866473   | 3.189296   | -0.03531  | 1.11262   | 0.041     |
| SC9–216934| 4.001017   | 4.997407   | -0.04983  | 1.24903   | 0.031     |
| SC9–230584| 4.395271   | 5.672324   | -0.05122  | 1.29055   | 0.059     |
|           | 5.860579   | -0.05689   |           | 1.33338   | 0.028     |
| SC10–95827| 1.974513   | 2.070361   | -0.02345  | 1.04854   | 0.076     |
| SC10–132645| 1.576676  | 1.594462   | -0.00708  | 1.01128   | 0.053     |
| SC10–259946| 5.075153  | 6.183343   | -0.03531  | 1.21836   | 0.039     |
| SC13–165223| 2.043172  | 2.039852   | 0.00080   | 0.99838   | 0.040     |
|           | 1.230847   | 0.32301    |          | 0.60242   | 0.041     |
| SC13–242700| 3.452472  | 3.262793   | 0.01684   | 0.94506   | 0.060     |
|           | 3.363016   | 0.00771    |          | 0.97409   | 0.077     |
In most of the FO-ν Cepheids only one secondary peak was detected, but in several variables two peaks were found. In all cases they have extremely small amplitudes. With the exception of a single star (SC18–208875), the amplitude ratio \(A_ν/A_1\) is always below 0.1, with the average value of 0.048. We note, that secondary peaks detected in the first overtone RR Lyrae stars are typically an order of magnitude stronger, with \(A_ν/A_1 = 0.45\) on average (Alcock et al. 2000).

It is easy to check, that period ratios measured in FO-ν Cepheids are not compatible with those of the radial modes. This implies, that the secondary frequencies detected in these pulsators must correspond to nonradial modes of oscillations.

The secondary frequencies in FO-ν Cepheids come in two different flavours. In 37 variables they are located close to the primary pulsation frequency \(f_1\). Several examples of such behaviour are displayed in Fig.1. In 84% of cases, secondary frequencies are lower than the primary one (\(Δf < 0\)). When two secondary peaks are detected, they always appear on the same side of the primary peak. In 7 FO Cepheids a different type of secondary periodicity was found: a high frequency mode, with the period ratio of \(P_ν/P_1 = 0.60 \div 0.64\). The two types of secondary nonradial modes are not mutually exclusive. In two objects (SC13–165223 and SC17–39517) both a high frequency secondary peak and a secondary peak close to the primary frequency are present.

**Table 1: - continued**

| OGLE ID    | \(P_1\) [day] | \(P_ν\) [day] | \(Δf\) [c/d] | \(P_ν/P_1\) | \(A_ν/A_1\) |
|------------|----------------|----------------|---------------|-------------|-------------|
| SC14–46315 | 2.315774       | 1.442102       | 0.26161       | 0.62273     | 0.023       |
| SC15–170744| 4.992984       | 3.148984       | 0.11728       | 0.63068     | 0.055       |
| SC16–37119 | 2.795951       | 3.520911       | -0.07364      | 1.25929     | 0.051       |
| SC16–177823| 1.918044       | 1.892260       | 0.00710       | 0.98656     | 0.046       |
| SC16–194279| 2.065767       | 2.146254       | -0.01815      | 1.03896     | 0.059       |
| SC16–230207| 3.418163       | 4.416698       | -0.06614      | 1.29213     | 0.039       |
| SC17–39484 | 3.541888       | 4.063954       | -0.03627      | 1.14740     | 0.055       |
| SC17–39517 | 2.113535       | 2.149961       | -0.00802      | 1.01725     | 0.065       |
| SC17–80220 | 2.258854       | 2.829748       | -0.08931      | 1.25274     | 0.058       |
| SC17–146711| 1.883131       | 1.137820       | 0.34784       | 0.60422     | 0.049       |
| SC17–171481| 2.537651       | 3.707561       | -0.12435      | 1.46102     | 0.066       |
| SC17–211310| 2.023579       | 2.087774       | -0.01519      | 1.03172     | 0.054       |
| SC18–144653| 4.158193       | 5.222752       | -0.04902      | 1.25602     | 0.049       |
| SC18–208875| 3.928946       | 3.508220       | 0.03052       | 0.89292     | 0.202       |
| SC19–74265 | 2.364944       | 2.790232       | -0.06445      | 1.17983     | 0.046       |
| SC20–83423 | 2.068067       | 2.108720       | -0.00932      | 1.01966     | 0.053       |
Figure 1: Prewhitened power spectra of FO-ν Cepheids. Frequencies of removed radial modes indicated by dashed lines.

In Fig. 2 we show the distribution of frequency differences, Δf, for the LMC FO-ν Cepheids and, for comparison, for the LMC first overtone RR Lyrae stars (Alcock et al. 2000). The two distributions are not very different. FO-ν Cepheids show somewhat stronger preference for negative Δf, but otherwise, in both types of overtone pulsators nonradial modes are found in similar distances from the radial mode. The only difference between the two histograms is the presence of high frequency secondary peaks \( P_ν = P_1 : 0.62 \) in the Cepheids, but not in the RR Lyrae stars.

Although the population of FO Cepheids in the LMC extends down to periods as short as 0.4 day, nonradial modes were detected only in stars with \( P_1 > 1.2 \) day. In fact, the incidence rate of nonradial modes systematically increases with the primary pulsation period, reaching 19% for stars with \( P_1 > 3.0 \) day. This is illustrated in Fig. 3. We interpret this behaviour as a selection effect: the Cepheids with longer periods are brighter, consequently it is easier to detect very low amplitude secondary
periodicities in their lightcurves. If so, then the true incidence rate of nonradial modes in LMC overtone Cepheids can be significantly higher that 9% derived here for the entire OGLE-II sample.

Figure 2: Distribution of frequency differences $\Delta f = f_\nu - f_1$ for LMC FO-$\nu$ Cepheids and RRc-BL stars. High frequency nonradial modes shaded.

Figure 3: Incidence rate of LMC FO-$\nu$ Cepheids vs. primary period.

Fundamental Mode Cepheids

OGLE-II catalogs list 719 fundamental mode (FU) Cepheids. We have searched all of them for secondary periodicities. We have found no nonradial modes in the FU Cepheids of the LMC.
FU/FO Double-Mode Cepheids

In the course of systematic analysis of OGLE-II Cepheids, we have discovered 4 new FU/FO double mode pulsators. Together with stars listed in OGLE-II catalogs (Soszyński et al. 2000) this brings to 23 the total number of known FU/FO Cepheids in the LMC. We have found nonradial modes in 3 of them. These are the first detections of nonradial modes in the FU/FO double-mode Cepheids. In the following, we call these stars FU/FO-ν Cepheids. The prewhitened power spectra of the 3 stars are displayed in Fig.4. In the first two Cepheids, the secondary mode appears very close to the first overtone radial mode. The values of the frequency differences $\Delta f = f_2 - f_1$ are very similar to those observed in the FO-ν Cepheids. In the third star, the secondary mode has been found at high frequency, with the period ratio of $P_2/P_1 = 0.623$, i.e. with the same strange ratio which is frequently observed in the FO-ν Cepheids. Clearly, nonradial modes excited in the FU/FO-ν Cepheids are somehow connected with the first radial overtone. Their frequencies are drawn from the same distribution as in the single-mode FO-ν Cepheids.

![Figure 4: Prewhitened power spectra of FU/FO-ν Cepheids. Frequencies of removed radial modes indicated by dashed lines.](image-url)

Comparison with RR Lyrae Stars

In the last decade nonradial modes have been detected in many RR Lyrae stars belonging to various stellar systems, including both Magellanic Clouds and the Galactic Bulge. Since pulsations of Cepheids and of RR Lyrae stars are in many ways similar, it is instructive to compare the properties of nonradial modes in these two types of stars. Several obvious differences should be pointed out:

Amplitudes of nonradial modes in classical Cepheids are an order of magnitude smaller than in RR Lyrae stars.
In RR Lyrae stars, nonradial modes are detected both in fundamental mode pulsators (RRab) and in first overtone pulsators (RRc). In classical Cepheids nonradial modes are detected only in first overtone pulsators.

Nonradial modes are detected in 3 FU/FO double-mode Cepheids, which constitutes 13% of the LMC sample. This type of pulsators are extremely rare among RR Lyrae stars. In more than 200 FU/FO RR Lyrae variables known in various stellar systems, only one detection of nonradial mode has been reported (Alcock et al. 2000).

When two secondary frequencies are found in an RR Lyrae star, they usually form, together with the primary frequency, an equally spaced triplet. In sharp contrast, equidistant triplets are never observed in classical Cepheids.

Nonradial modes in Cepheids are usually detected very close to the primary pulsation mode, but in several stars a high frequency mode with $P_\nu = P_1 \approx 0.62$ was found. Such high frequency modes are not observed in RR Lyrae pulsators.

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