THE CoRoT DISCOVERY OF A UNIQUE TRIPLE-MODE CEPHEID IN THE GALAXY

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ABSTRACT

The exploitation of the CoRoT treasure of stars observed in the exoplanetary field allowed the detection of a unusual triple-mode Cepheid in the Milky Way, CoRoT 0223989566. The two modes with the largest amplitudes and a period ratio of 0.80 are identified with the first (P₁ = 1.29 days) and second (P₂ = 1.03 days) radial overtones. The third period, which has the smallest amplitude but is able to produce combination terms with the other two, is the longest one (P₃ = 1.89 days). The ratio of 0.68 between the first-overtone period and the third period is the unusual feature. Its identification with the fundamental radial or a nonradial mode is discussed with respect to similar cases in the Magellanic Clouds. In both cases, the period triplet and the respective ratios make the star unique in our Galaxy. The distance derived from the period–luminosity relation and the galactic coordinates put CoRoT 0223989566 in the metal-rich environment of the “outer arm” of the Milky Way.

Key words: stars: individual (CoRoT 0223989566) – stars: interiors – stars: oscillations – stars: variables: Cepheids

1. INTRODUCTION

Double-mode Cepheids are a powerful tool to test the stellar models of supergiants since the simultaneous excitation of two pulsation modes tightly constrains the physical parameters. In the 1990s, the introduction of the new OPAL opacities (Rogers & Iglesias 1994) solved the discrepancy between the beat and pulsation masses (Moskalik et al. 1992), also reconciling the evolutionary ones (Christensen-Dalsgaard & Petersen 1995). Nowadays, the period ratio is used to investigate the metallic content of stellar systems hosting double-mode Cepheids. Sziládi et al. (2007) obtained observational evidence of the relic content of stellar systems hosting double-mode Cepheids. Nowadays, the period ratio is used to investigate the metallicity of hundreds of double-mode Cepheids in the framework of Cepheids. The metallicity of the Large (LMC) and Small (SMC) Magellanic Clouds has been investigated by using the period ratios of hundreds of double-mode Cepheids in the framework of large-scale surveys: MACHO (e.g., Alcock et al. 1999), EROS-2 (e.g., Marquette et al. 2009), OGLE-III (e.g., Soszyński et al. 2008a, 2008b).

The involved radial modes are the fundamental (F) and the first (1O), second (2O), and third (3O) overtones. Typical period ratios are 1O/F = 0.71, 2O/1O = 0.80, 3O/1O = 0.68. However, the large-scale surveys revealed other particular subclasses (for a review, see Moskalik 2014): stars with a nonradial mode in close proximity to the dominant 1O mode and double-mode pulsators with a period ratio of 0.60–0.64.

On the other hand, triple-mode Cepheids are extremely rare. The current statistics (Moskalik 2014) report six cases of 1O/2O/3O stars (three in the LMC, one in the SMC, and two in the galactic bulge) and four cases of F/1O/2O stars (two in the LMC, two in the SMC). The two triple-mode Cepheids in the galactic bulge have extremely short periods: the 1O periods are 0.295 day and 0.230 day, corresponding to F periods shorter than 0.4 day. The modeling of these periods and the evolutionary calculations are expected to place strong constraints both on Cepheid mass–luminosity relations and on the internal physics.

The variability of GSC 0746-01186 was discovered in the ASAS survey (ASAS 064135+0756.6; Pojmanski 2002). The star was classified as a Cepheid with \( \pi = 1.28859 \) days, with an amplitude of 0.41 mag and \( \langle V \rangle = 12.48 \). Later, Khruslov (2009) identified it as a double-mode Cepheid with periods \( P₁ = 1.28861 \) days and \( P₂ = 1.03153 \) days. These periods were confirmed by the analysis of the NSVS data (Woźniak et al. 2004). The ratio of 0.8005 suggested a pulsation in the 1O and 2O modes. GSC 0746-01186 \( \equiv \) ASAS 064135+0756.6 \( \equiv \) SRa01b.16229 was re-observed during the BEST II survey (Berliner Exoplanet Search Telescope; Klugkist et al. 2013). The double-mode pulsation and the period ratio were both confirmed. The space mission CoRoT (Baglin et al. 2006) monitored the star in a serendipitous mode since it is located in a field contiguous to that of the open cluster NGC 2264, the main target of the first short run in the anticenter direction (SRa01). We definitely cross-identify CoRoT 0223989566 \( \equiv \) GSC 0746-01186 \( \equiv \) ASAS 064135+0756.6 \( \equiv \) 2MASS 06413457+0756396 when searching for Cepheids in the CoRoT database (E. Poretti et al., in preparation).

2. THE ANALYSIS OF CoRoT 0223989566 DATA

CoRoT 0223989566 was observed continuously for 23.4 days from 2008 March 7 to March 31. The EXODAT catalog (Deleuil et al. 2009) reports a spectral type of A5 III, an \( E_{B-V} = 1.1 \) mag (both from spectral energy distribution analysis) and a very low contamination level due to close stars, i.e., 0.004 in a range from 0 to 1. The “CoRoT Variability Classifier” (CVC) automated supervised method (Debosscher et al. 2009) correctly suggests a classical or a double-mode Cepheid. The measurements of CoRoT 0223989566 were performed in the 512 s mode from JD 2454533.4120 to 2454536.008 and then in the 32 s mode until the end of the observations at JD 2454556.795.

All the CoRoT measurements were taken into account for the initial frequency analysis. The outliers were removed by means of a cross-check between the flags provided by the reduction pipeline and a visual inspection of the light curve. Outliers are for most measurements that suffer from hot pixels during the passage through the South Atlantic Anomaly. The final time series is composed of 52,148 measurements: they
were obtained in the chromatic mode, but here we discuss the white measurements only since we are interested in a detailed frequency analysis requiring a high signal-to-noise ratio (S/N). The high-precision, high duty-cycle CoRoT photometry provides us with an excellent representation of the beating (light curve is a succession of two “bright” maxima followed by two “faint” ones. The four maxima span the short beating period of 5.16 days = 4P₁ = 5P₂.

The frequency analysis was performed by means of the iterative sine-wave, least-squares fitting method (Vanček 1971). It was applied to both the original CoRoT time series composed of 32 s and 512 s exposures and to a new data set obtained by grouping 16 consecutive 32 s measurements into a single 512 s point. The frequency values were refined by the MTRAP algorithm (Carpino et al. 1987), allowing us to search for the best fit by keeping the values of the harmonics and the combination terms locked to the independent frequencies. The analysis of the CoRoT data identified the two frequencies corresponding to the periods already known (Figure 1; top panel). The amplitudes of the peaks found were in the solutions of the light curves of double-mode Cepheids (Moskalik 2014). However, we cannot rule out the possibility of the main oscillations observed in some 1 O/Cepheids O/ of the main oscillations observed in some 1 O/Cepheids O/ of the main oscillations observed in some 1 O/Cepheids O/

The four terms f₁, f₂, f₁−f₂, and f₂−f₁ were detected after prewhitening the data with f₁ and its harmonics (panel (b)). The four terms f₁, f₂, f₁+f₂, and f₂−f₁ are the most common in the solutions of the light curves of double-mode Cepheids obtained from ground-based data (Pardo & Poretti 1996). We expected that the subsequent analysis of the CoRoT time series would disclose the rich ensemble of combination terms between the harmonics of f₁ and f₂. Therefore, it was a great surprise to detect a new independent term f₃ = 0.529 day⁻¹, at the next step (panel (c)). The presence of the f₁ + f₃ peak was particularly important since it immediately ruled out that f₁ was due to the variability of a close, unresolved star in the CoRoT mask or to a binary companion. After this, the combination terms between the harmonics of f₁, f₂, and f₃ were detected step-by-step, as shown in panel (d) for a subset of nine of them. The final solution of the CoRoT light curve was provided by the independent terms f₁ = 0.7176006 ± 0.0000002 day⁻¹, f₂ = 0.969787 ± 0.0000016 day⁻¹, and f₃ = 0.529632 ± 0.000143 day⁻¹, their harmonics (up to 7f₁, 2f₂, and 2f₃) and a set of 23 other combination terms, for a total of 34 components. Table 1 lists the ordered structure of the combination terms and the least-squares solution obtained from the time series composed of the 512 s and 32 s measurements, which leaves a residual rms of 0.0010 mag. The error bars on the amplitudes σ(A) = 6 × 10⁻⁶ mag and on the phases σ(φ) = σ(A)/A, can be immediately derived following Montgomery & O’Donoghue (1999).

The discovery of f₁ opened the possibility that other modes were excited and we performed an additional analysis to find them. The power spectra of the entire data set show some peaks close to f₁ and, much less relevant, to f₂. The highest one was at f = 0.728 day⁻¹ with an amplitude 0.008 times that of f₁. The nature of these peaks is ambiguous. They could have a stellar origin and be due to a long-term modulation or to detector aging. The analysis of the light curve of the residuals helped us to clarify this point. After the prewhitening with 34 components, the data show residual oscillations up to ±2 mmag (Figure 1, middle panel). The amplitudes of the peaks found in the frequency analysis of the residuals are smaller than 0.1 mmag. An erratic nature could be more plausible, but not fully convincing. Therefore, we calculated a new set of residuals by subdividing the 23.4 days time baseline into six contiguous subsets spanning 3.9 days each. The frequency values were kept fixed, but the amplitudes and phases were recalculated for each
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The 34 components from the six subsets (Figure 2, panel (e))
subset. Then, the residuals obtained from these subsets were
merged. The residual light curve thus obtained is almost flat and
the erratic oscillations have completely disappeared (Figure 1,
bottom panel). We can infer that the erratic oscillations are due
to instrumental effects that are affecting the CoRoT photometry
in such a way that the usual technique of prewhitening was not able
to clean (see also the case of CoRoT 101155310; Poretti et al.
2011). The frequency analysis of the residuals after subtracting
to clean (see also the case of CoRoT 101155310; Poretti et al.,
2011). We can infer that the erratic oscillations are due to
independent modes we were looking for.

Therefore, we can conclude that after $f_3$ no other independent
mode is detectable in the light curve of CoRoT 0223989566.
The noise level of the power spectrum of the residuals
(Figure 2, panel (e)) is around 0.004 mmag in the 0–3 day$^{-1}$
region and increases to 0.012 mmag in the 5.0–7.0 day$^{-1}$
region. Some of the peaks visible in the 5.0–7.0 day$^{-1}$ region are
close to combination terms (e.g., $6f_1 + f_3 = 5.18$ day$^{-1}$, $7f_1 = 5.43$ day$^{-1}$,
$7f_1 + f_3 = 6.40$ day$^{-1}$, $6f_1 + 2f_3 = 6.59$ day$^{-1}$), but their amplitudes
(0.028, 0.040, 0.028, and 0.030 mmag, respectively) are

![Figure 3. Petersen diagram of galactic double-mode Cepheids (open circles, $F$
and 10 stars; open squares, 10 and 20 pulsators). The triple-mode Cepheid
Corot0223989566 is indicated with filled symbols.](image)

below the heuristically accepted threshold of $S/N = 3.5$ (Breger et al. 1993).

For the sake of completeness, we successfully verified that the $f_3$ component was also detectable in the CoRoT data
before removing the outliers and that the solution of the time
series composed of the grouped 512 s points supplies the same
combination terms of the solution listed in Table 1.

3. DISCUSSION

The analysis of the data of CoRoT 0223989566 returned three
independent periods: $P_1 = 1.2886$ days, $P_2 = 1.03114$ days,
and $P_3 = 1.888538$ days. This triplet is completely new among
galactic Cepheids. The period ratios are $P_1/P_2 = 0.8002$,
$P_2/P_3 = 0.546$, and $P_1/P_3 = 0.682$.

3.1. The Petersen Diagram

Figure 3 shows the Petersen diagram of the galactic double-
mode Cepheids. There is little doubt that $P_1$ and $P_2$ can be
typed with the 10 and 20 modes, as is done in the galactic,
LMC, and SMC double-mode Cepheids. $P_3$ is giving us more
trouble. The ratio 0.68 has been observed in two double-mode
LMC Cepheids (Soszyński et al. 2008a) and in six triple-
mode Cepheids (10/20/30) in both the Magellanic Clouds
(Moskalik 2014). The related periods were identified with those
of the 30 and 10 modes. However, this is not the case for
CoRoT 0223989566: since $P_3$ is longer than $P_1$, it should be the
10 mode and $P_1$ the 30 mode, contradicting the previous robust
identification of $P_1$ as the 10 mode.

The fact that $P_3$ is much longer than $P_1$ and $P_2$ naturally
suggests its identification with the $F$ radial mode. However, the
corresponding ratio 10/$F = 0.682$ is lower than the usual one
(0.694–0.746; Moskalik 2014). Moreover, Figure 3 shows how the
10/$F$ ratio is expected to increase toward short $F$-periods,
thus making the 0.682 ratio of CoRoT 0223989566 still more
peculiar. There is only one example of a ratio of 0.68 typed as
a 10/$F$ one, i.e., J045917-691418 ($P_0 = 3.08$ days and

| ID | Frequency (day$^{-1}$) | Amplitude (mag) | Phase [0, 2$\pi$] |
|----|-----------------------|-----------------|-----------------|
| $f_1$ | 0.7760066 | 0.071792 | 0.6504 |
| $f_2$ | 0.99787 | 0.09816 | 3.8558 |
| $f_3$ | 0.529632 | 0.001181 | 1.5836 |
| $2f_1$ | 1.552012 | 0.015132 | 5.4488 |
| $3f_1$ | 2.328018 | 0.003827 | 3.8502 |
| $4f_1$ | 3.104024 | 0.000723 | 2.4672 |
| $5f_1$ | 3.880030 | 0.000198 | 0.1619 |
| $6f_1$ | 4.656036 | 0.000089 | 4.7833 |
| $2f_2$ | 1.93574 | 0.000137 | 0.8405 |
| $2f_3$ | 1.059264 | 0.000056 | 0.9304 |
| $f_2 - f_1$ | 0.193781 | 0.002828 | 1.0666 |
| $f_1 + f_2$ | 1.745793 | 0.003041 | 2.9196 |
| $2f_1 + f_2$ | 2.521799 | 0.001057 | 1.7247 |
| $3f_1 + f_2$ | 3.297805 | 0.000160 | 2.4153 |
| $4f_1 + f_2$ | 4.073811 | 0.000116 | 1.6367 |
| $5f_1 + f_2$ | 4.849817 | 0.000101 | 0.3820 |
| $6f_1 + f_2$ | 5.625823 | 0.000066 | 5.8167 |
| $2f_1 - f_3$ | 0.582225 | 0.000324 | 5.1539 |
| $3f_1 - f_3$ | 1.358231 | 0.000066 | 0.6502 |
| $4f_1 - f_3$ | 2.134237 | 0.000056 | 3.2205 |
| $f_1 + 2f_2$ | 2.715580 | 0.000162 | 6.0254 |
| $2f_1 + 2f_2$ | 3.491586 | 0.000104 | 5.5258 |
| $3f_1 + 2f_2$ | 4.267592 | 0.000104 | 4.8089 |
| $4f_1 + 2f_2$ | 5.043598 | 0.000080 | 3.8391 |
| $5f_1 + 2f_2$ | 5.819604 | 0.000055 | 2.5362 |
| $2f_2 - 2f_3$ | 0.387562 | 0.000056 | 1.5524 |
| $4f_1 + f_3$ | 3.633656 | 0.000061 | 0.9406 |
| $f_1 + f_3$ | 1.305638 | 0.000099 | 6.0973 |
| $2f_1 + f_3$ | 2.081644 | 0.000286 | 4.8419 |
| $3f_1 + f_3$ | 2.857650 | 0.000153 | 2.8912 |
| $f_1 - f_3$ | 0.246374 | 0.000271 | 4.3864 |
| $f_3$ | 1.499419 | 0.000192 | 2.9091 |
| $f_1 + 2f_3$ | 2.134237 | 0.000056 | 3.2205 |

Table 1

The Identification of the 34 Significant Frequencies
Detected in the Data of CoRoT 0223989566

Note. The amplitudes and phases obtained from the original 32 s and
512 s measurements are listed.
$P_1 = 2.10$ days) in the LMC (it is the apparently lowest outlier in Figure 3 of Marquette et al. 2009). The unusual ratio is explained in terms of an high-metallicity of $Z = 0.030$ (see also Figure 3 in Buchler & Szabó 2007), while the mean metallicity of LMC double-mode Cepheids is 0.004. The fundamental period of CoRoT 0223989566 is shorter than that of J045917-691418 and a still higher metallicity is necessary to include the ($\log P, P_1/P_0$) location of CoRoT0223989566 between the limits where $F$ and $1O$ are both unstable (Buchler & Szabó 2007).

Therefore, if $P_1$ is actually the $F$ mode, CoRoT 0223989566 is a very particular star: not only a unique $F/1O/2O$ Cepheid in the Galaxy but also one with an unusual $1O/F$ ratio. In any case, CoRoT 0223989566 is the triple-mode Cepheid showing the longest periods, both in the Galaxy and in the Magellanic Clouds. In the context of the galactic Cepheids, it should be noted that $P = 1.8$ days seems to be the shortest $F$ period among the $1O/F$ double-mode stars and the longest $1O$ period among the $2O/1O$ ones (Figure 3).

3.2. The Analysis of the Fourier Parameters

The Fourier decomposition could be used to disentangle the matter since the first harmonics were found for the three periods of CoRoT 0223989566. We calculated the Fourier parameters $R_{i,j} = A_i/A_j$ and $f_{i,j} = f_i - i f_j$ from the amplitude ($A_i$) and phase ($f_i$) coefficients of the $i$ and $j$ harmonics of the three independent frequencies $f_1$, $f_2$, and $f_3$.

The parameters $\phi_{21} = 4.1480 \pm 0.0006$ rad and $R_{21} = 0.2108 \pm 0.0001$ of $f_1$ are in excellent agreement with those of the $1O$ modes of the $1O/2O$ Cepheids. In a similar way, the Fourier parameters of $f_2$ ($\phi_{21} = 5.69 \pm 0.05$ rad, $R_{21} = 0.014 \pm 0.001$) are exactly located among those of the $2O$ modes (see Figures 2 and 3 in Alcock et al. 1999, for the LMC Cepheids). We conclude that CoRoT 0223989566 does not show any particularity as a $1O/2O$ double-mode pulsator.

The situation is slightly different when we consider $f_3$. The $\phi_{23} = 4.05 \pm 0.12$ rad value observed for $f_3$ is on the extension of the $F$-mode progression (see Figure 4 in Pardo & Poretti 1996), but $R_{31}$ = 0.047 $\pm$ 0.005 is a small value for the $F$-mode, usually greater than 0.20. V371 Per is another double-mode Cepheid where the $R_{31} = 0.15$ of the $F$-mode is below the 0.20 limit and smaller than the $R_{32} = 0.22$ of the $1O$-mode (Wils et al. 2010). We can suppose that the small amplitude of the $F$-mode oscillation reduces the $R_{21}$ value. It is also noteworthy that V371 Per shows an unusual high $1O/F$ period-ratio ($0.731$), explained in terms of a metal deficiency ($-1 < [Fe/H] < -0.7$). Therefore, it seems that given stars could deviate from the most common ratios.

Another possibility is to identify $f_3$ as a nonradial mode. Nonradial modes have been detected in $1O$ LMC Cepheids and $F/1O$ double-mode LMC Cepheids, always closely to the $1O$ mode ($\Delta f < 0.13$ day$^{-1}$; Moskalik 2014). If we suppose a canonical $F/1O$ frequency ratio of 0.72, we have $F = 1O \cdot 0.72 \cdot 0.559$ day$^{-1}$. The difference $0.559 - 0.529 = 0.030$ day$^{-1}$ is still in the range where we can think of a resonance. However, also under these assumptions CoRoT0223989566 remains a unique and challenging case since we have to model the excitation of a nonradial mode close to the expected—but not observed—$F$ radial mode.

3.3. The Location of CoRoT0223989566 in the Milky Way

The $P-L$ relation for galactic Cepheids $M_V = -2.999 (\pm 0.097) \log P - 0.995 (\pm 0.112)$ (Ngeow & Kanbur 2004) supplies similar $M_V$ values if we consider $f_3 = 0.529$ day$^{-1}$ or $0.776 \cdot 0.72 = 0.559$ day$^{-1}$ as the frequency of the $F$ radial mode, i.e., $M_V = -1.82 \pm 0.12$ and $M_V = -1.75 \pm 0.12$, respectively. The color excess $E_{B-V} = 1$ (EXODAT; Deleuil et al. 2009) yields $A_V = 3.2 E_{B-V} = 3.5$, $R = 3.2$ from Tammann et al. (2003). The distance modulus $V - M_V = 12.5 + 1.8 - 3.7 = 10.8$ and the galactic coordinates ($l = 204; 7407, b = +01:4386$) put CoRoT0223989566 at 1.4 kpc from the Sun, behind and farther than NGC 2264 (9.3; 202:936 +02:196). The large color excess seems confirmed by available photometry: $V = 12.50$ (Pojmanski 2002) and $B = 13.6$ (GSC 2.2 catalog). Smaller values close to $E_{B-V} = 0.4$ have been measured in that direction (Jenkins & Tripp 2011). Such a value would push CoRoT0223989566 at 4.0 kpc from the Sun. In any case, the resulting galactocentric distances $R_G = 9.8 kpc (E_{B-V} = 1.1)$ or $R_G = 12.2 kpc (E_{B-V} = 0.4)$ or any intermediate one obtained from $0.4 < E_{B-V} < 1.1$ mag place CoRoT0223989566 on the extreme “outer arm,” not far from the B0 II star HD 43818, i.e., in an environment known to be metal rich (Tripp & Song 2012).

Therefore, the very high metallicity could cause the $1O/F$ period ratio to decrease in the opposite sense of what the low metallicity probably does for V371 Per (Wils et al. 2010). The fact that the $2O/1O$ ratio is normal is not surprising since the metallicity affects mainly the $1O/F$ ratio (Beaulieu et al. 1997; Marquette et al. 2009). Other evolutionary effects linked with the particular galactic location as the first crossing of the instability strip of a young object or an anomalous mass with respect to other double-mode Cepheids can contribute to the unusual period ratio.

4. CONCLUSIONS

The intensive CoRoT monitoring of CoRoT0223989566 discovered a unique case among triple-mode galactic Cepheids. The $0.682$ ratio between the two longest periods is quite unusual. If interpreted as a $1O/F$ ratio, the fact that CoRoT0223989566 belongs to a metal-rich environment like the “outer arm” of the Milky Way could explain the value. We also note that the periods of CoRoT0223989566 are much longer than those of the triple-mode Cepheids detected in the galactic bulge. If not a radial mode, the excitation of an isolated nonradial mode with a period much longer than that of the $1O$ mode is also unusual for high-amplitude pulsators. As expected (e.g., Moskalik & Dziembowski 2005; Moskalik 2014), the discovery of a new member of the rare class of triple-mode Cepheids set new observational constraints on the stellar parameters of these variables and, in a wider context, on their evolutionary models.

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