V371 Per – A thick-disc, short-period F/1O Cepheid

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ABSTRACT

V371 Per was found to be a double-mode Cepheid with a fundamental mode period of 1.738 days, the shortest among Galactic beat Cepheids, and an unusually high period ratio of 0.731, while the other Galactic beat Cepheids have period ratios between 0.697 and 0.713. The latter suggests that the star has a metallicity [Fe/H] between −1 and −0.7. The derived distance from the Galactic plane places it in the thick disc or the Halo, while all other Galactic beat Cepheids belong to the thin disc. There are indications from historical data that both the fundamental and first overtone periods have lengthened.

Key words: stars: individual: V371 Per – Cepheids.

1 INTRODUCTION

The variability of V371 Per was discovered by Weber (1964). From photographic studies, Satyvaldiev (1966) and Meinunger (1980) did not find any periodicity, and the star was therefore assumed to be an irregular variable. Schmidt, Chab & Reiswig (1995) found a period of 1.2697 days from CCD data and suspected it to be a beat Cepheid because of its changing light curve. This interpretation agrees with the spectral type G0 given by Bond (1978). As a consequence, the star was observed for a number of years at the Behlen Observatory at the University of Nebraska, the United States Naval Observatory Flagstaff Station (NOFS), the Sonoita Research Observatory (SRO; Sonoita, Arizona) and the Zagori Observatory (Athens, Greece). The resulting data will be presented in this paper. In addition to the new data, the data sets from Satyvaldiev (1966) and Schmidt et al. (1995) are reanalysed (the latter with revised values for the comparison stars), and data from the Northern Sky Variability Survey (NSVS; Woźniak et al. 2004) are analysed as well.

2 OBSERVATIONS

Table 1 contains a summary of the new observations. All data will be made available at the Centre de Données astronomiques de Strasbourg. A comparison star sequence in the Johnson–Cousins system, derived from observations at SRO, is given in Table 2. Observations on each photometric night included following an extinction star from low-to-high airmass, along with $BVRCI_c$ exposures of Landolt standard fields. Further details on the procedure are outlined in Templeton & Henden (2007). A similar procedure was used to obtain the data from the NOFS. The comparison star sequence was chosen to have a large colour range in the vicinity of the variable. GSC 3854–1439 is a close double of about 1 arcsec separation of which both components need to be included in any aperture.

The method described in Schmidt et al. (2004) was used to reduce the data from the Behlen Observatory. Data from the Zagori Observatory were reduced with the photometry package ab4win (Berry & Burnell 2000) and were transformed to the standard system with transformation coefficients obtained by measuring several of the comparison stars from Table 2. While the colour terms for $V$ and $I_c$ were found to be almost negligible, those for $B$ and $R_c$ involved corrections of up to 0.05 mag. Fig. 1 contains a section of the data superposed on a model plot as derived in the following section.

3 PERIOD ANALYSIS

A Fourier analysis of the data was done using PERIOD04 (Lenz & Breger 2005). For all available data sets, two independent frequencies were found: a first one, hereafter referred to as $f_1$, near 0.787 c/d or 1.270 d, corresponding to the period found by Schmidt et al. (1995), and a second one, further referred to as $f_0$, near 0.576 c/d or 1.737 d. The ratio $f_0/f_1 = 0.7312$ also proves that the suggestion of a beat Cepheid was correct and that $f_0$ and $f_1$ should be interpreted, respectively, as the frequency of the fundamental and the first overtone mode.

The two most extensive data sets also reveal a number of combination modes of these two frequencies, demonstrating that the variations observed are from a single star and not, for example,
Table 1. Observation log for V371 Per.

| Observatory | Instruments                  | Filters | JD - 240 0000 | Nights | Points |
|-------------|------------------------------|---------|----------------|--------|--------|
| Behlen      | 76-cm Cassegrain + TI4849   | V, R, c | 47872-53967    | 51     | 157    |
| NOFS        | 1.0-m Ritchey-Chrétien + Tektronix | VR, R, c | 50033-51528    | 32     | 47     |
| SRO         | 35-cm C-14 + SBIG ST-1001E  | VR, R, c | 53629-54054    | 23     | 1341   |
| Zagori      | 30-cm LX200 + SBIG ST-7XMEI | VR, R, c | 53726-54135    | 38     | 1331   |

Table 2. Comparison star data from the Sonota Research Observatory.

| GSC ID      | RA (J2000) Dec. | V | σ_V | B - V | σ_{B-V} | V - R | σ_{V-R} | R - I_c | σ_{R-I} |
|-------------|-----------------|---|-----|-----|--------|-----|--------|-------|--------|
| 2854-0440   | 02:54:43.43     | +42:27:07.8 | 11.700 | 0.016 | 0.634 | 0.026 | 0.373 | 0.013 | 0.289 | 0.013 |
| 2854-0492   | 02:55:05.14     | +42:38:07.7 | 12.262 | 0.013 | 0.741 | 0.023 | 0.427 | 0.018 | 0.340 | 0.016 |
| 2854-0965   | 02:55:08.88     | +42:39:10.9 | 11.704 | 0.010 | 0.471 | 0.017 | 0.275 | 0.020 | 0.202 | 0.022 |
| 2854-1439   | 02:55:14.45     | +43:23:24.2 | 13.145 | 0.003 | 0.596 | 0.007 | 0.354 | 0.005 | 0.377 | 0.007 |
| 2854-1056   | 02:55:15.05     | +42:32:35.6 | 12.793 | 0.004 | 0.952 | 0.006 | 0.529 | 0.006 | 0.493 | 0.008 |
| 2854-0637   | 02:55:23.95     | +42:45:05.3 | 12.339 | 0.013 | 0.706 | 0.031 | 0.406 | 0.021 | 0.339 | 0.022 |
| 2854-1058   | 02:55:37.11     | +42:30:36.8 | 11.570 | 0.020 | 1.453 | 0.021 | 0.799 | 0.011 | 0.713 | 0.021 |
| 2854-0696   | 02:55:37.35     | +42:44:21.6 | 11.922 | 0.012 | 0.673 | 0.032 | 0.387 | 0.021 | 0.301 | 0.021 |
| 2854-0713   | 02:55:45.27     | +42:31:16.5 | 9.609 | 0.036 | 0.185 | 0.041 | 0.995 | 0.035 | 0.127 | 0.035 |
| 2854-0768   | 02:56:03.32     | +42:43:01.7 | 10.728 | 0.013 | 0.511 | 0.029 | 0.307 | 0.023 | 0.224 | 0.011 |
| 2854-1013   | 02:56:09.96     | +42:39:52.4 | 11.658 | 0.007 | 0.470 | 0.020 | 0.289 | 0.012 | 0.210 | 0.012 |

Table 3. Frequencies for V371 Per and their semi-amplitudes (in millimag) and phases (in degrees) derived from the SRO and Zagori data sets.

| Frequency (c/d) | A_B | φ_B | S/N_B | A_V | φ_V | S/N_V | A_R | φ_R | S/N_R | A_I | φ_I | S/N_I |
|----------------|-----|-----|-------|-----|-----|-------|-----|-----|-------|-----|-----|-------|
| f_1           | 0.787329(3) | 244.5(10) | 314(1) | 51.1 | 173.5(6) | 311(1) | 68.1 | 136.2(6) | 309(1) | 45.5 | 105.4(5) | 305(1) | 56.0 |
| f_0           | 0.575678(4) | 175.2(10) | 109(1) | 60.7 | 124.8(7) | 106(1) | 63.5 | 99.2(6) | 102(1) | 50.7 | 77.2(4) | 97(1) | 44.8 |
| f_0 + f_1     | 1.363007     | 85.8(11)  | 189(1) | 23.9 | 60.6(7)  | 189(1) | 29.0 | 48.4(7)  | 186(1) | 18.9 | 37.3(4) | 186(1) | 22.9 |
| 2f_1          | 1.574658     | 53.3(11)  | 44(2)  | 14.6 | 38.6(6)  | 40(1)  | 17.0 | 30.0(6)  | 41(2)  | 12.5 | 23.2(5) | 41(2)  | 12.8 |
| f_1 - f_0     | 0.211651     | 41.7(9)   | 152(2) | 9.8  | 27.5(6)  | 154(2) | 11.5 | 24.1(6)  | 148(2) | 7.5  | 19.4(5) | 154(2) | 8.5  |
| 2f_0          | 1.151355     | 25.2(8)   | 11(3)  | 4.8  | 18.3(7)  | 356(2) | 5.8  | 13.6(7)  | 360(3) | 3.7  | 11.4(4) | 360(3) | 4.5  |
| 2f_0 + f_1    | 1.938684     | 23.1(9)   | 115(3) | 4.2  | 17.9(7)  | 110(2) | 7.2  | 14.9(6)  | 117(3) | 4.3  | 12.8(4) | 122(3) | 5.9  |
| f_0 + 2f_1    | 2.150336     | 34.0(10)  | 303(2) | 7.2  | 24.9(7)  | 306(2) | 10.0 | 19.0(6)  | 306(2) | 5.9  | 15.3(5) | 307(2) | 7.4  |
| 3f_1          | 2.361987     | 14.1(9)   | 173(4) | 4.4  | 117.6(7) | 160(4) | 6.0  | 10.6(6)  | 167(4) | 4.9  | 9.1(5)  | 162(4) | 5.6  |
| 3f_0          | 1.727033     | 16.3(8)   | 298(4) | 3.8  | 7.4(7)   | 302(5) | 4.2  | 9.9(5)   | 304(4) | 3.7  | 7.6(5)  | 312(4) | 4.0  |

Note. Uncertainties calculated from Monte Carlo simulations with Period04 [Lenz & Breger 2005] are given between parenthesis in units of the last decimal.

from two separate pulsators within the same resolution element on the sky, as those would not show these combination frequencies. The details of the frequencies found are given in Table 3. For each passband and detected frequency, the semi-amplitude, phase and signal-to-noise ratio are given. The values of the frequencies themselves were derived from the V data, and then used to calculate the amplitudes and phases for the other passbands. The small decrease in phase when going to redder colours for f_0 and f_1 indicate that these are radial modes. Phase plots of the fundamental mode variation and the first overtone variation in V (pre-whitened for the other mode and combination modes) are given in Fig. 2.

The amplitude of the first overtone mode is larger than that of the fundamental mode, which is not common among Galactic beat Cepheids. Only in AX Vel (with a fundamental period of 3.67 d) and
V458 Sct (4.84 d), the first overtone mode has a larger amplitude than the fundamental pulsation mode. There does not seem to be a relation of amplitude ratio with period.

The value of the generalized phase difference $G_{1,1}$ for the cross coupling term $f_0 + f_1$ for Galactic double-mode Cepheids. Besides V371 Per, the values are taken from Poretti & Pardo (1997) and Wils & Otero (2004) or calculated from ASAS-3 data (Pojmanski 2002) when not available otherwise.

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Figure 2. Phase plot of $V$ data from SRO and Zagori Observatory. The top panel shows the data pre-whitened for the first overtone mode and all combination frequencies as given in Table 3. The bottom panel shows the data pre-whitened for the fundamental mode and all combination frequencies.

Figure 3. Values (in degrees) of the generalized phase difference $G_{1,1}$ for the cross coupling term $f_0 + f_1$ for Galactic double-mode Cepheids. Besides V371 Per, the values are taken from Poretti & Pardo (1997) and Wils & Otero (2004) or calculated from ASAS-3 data (Pojmanski 2002) when not available otherwise.

The values and semi-amplitudes of the fundamental and first overtone frequencies and the frequency ratio calculated from the other data sets are given in Table 3. For reference, the corresponding values already given in Table 3 are repeated. The periods derived from the NSVS data are less reliable because of the short time-span of the data (less than a year).

Figure 4. $B$ data from SRO and Zagori Observatory plotted against colour $B - R_c$.

4 PERIOD EVOLUTION

The values and semi-amplitudes of the fundamental and first overtone frequencies and the frequency ratio calculated from the other data sets are given in Table 4. For reference, the corresponding values already given in Table 3 are repeated. The periods derived from the NSVS data are less reliable because of the short time-span of the data (less than a year).

The derived frequency values are plotted in Fig. 5. There are indications that both the fundamental mode and first overtone frequency have decreased, while the frequency ratio remained constant at 0.7312. This result highly depends on the photographic data set of Satyvaldiev (1966), and should therefore be treated with caution. However, there is also a significant difference between the frequencies derived from the Behlen data set and those from the newer SRO and Zagori data sets, in line with this conclusion.

There is no indication that the amplitude has changed over the years. Note that the Satyvaldiev (1966) data are photographic and the amplitude should therefore be compared to the $B$-band amplitudes. The NSVS data are unfiltered CCD data, so that amplitudes derived from them are to be compared with $R_c$-band amplitudes. The lesser number of data points in the NOFS data sets give less reliable amplitudes, and their uncertainties are likely underestimated.

5 DISCUSSION

The fundamental period of 1.737 days of V371 Per is short and outside the range of the periods of the other known Galactic beat Cepheids. Until now, those with the shortest fundamental periods known were TU Cas with a period of 2.139 days (Oosterhoff 1957) and DZ CMa with a period of 2.311 days (determined from ASAS-3 data; Pojmanski 2002). The beat Cepheid with the largest known period is V367 Sct (6.293 days; Efremov & Kholopov 1975). As can be seen in Fig. 6, the period and period ratio of V371 Per are more reminiscent of the Small Magellanic Cloud (SMC) double-mode Cepheids. From theoretical calculations, Buchler & Szabó (2007) have shown a relation between fundamental period, period ratio and metallicity. From the graphs of Buchler & Szabó (2007) and Buchler (2008), one can determine $Z$ to be approximately between $0.002$ and $0.004$ for V371 Per, depending on the particular mixture of elements chosen for $Z$, equivalent to [Fe/H] between $-1$ and $-0.7$. From the empirical formula (3) given by Sziládi et al. (2007), also relating fundamental period and period ratio to metallicity for Galactic beat Cepheids, a value [Fe/H] = $-0.92$ can be derived by extrapolation. Both values are in good agreement and indeed.
The light curve of V371 Per does not resemble those of BL Her stars of comparable apparent magnitude and period (in UCAC2 catalogue (Zacharias et al. 2004), much lower than some of BL Her stars (Population II Cepheids) with similar periods, as they have very steep rising branches. In addition, no double-mode Population II Cepheids are known. Furthermore, theoretical models from di Criscienzo et al. (2007) suggest that there are no stable first overtone pulsations in BL Her stars with the fairly cool temperature of V371 Per. With the extinction $E(B - V) = 0.11$ towards V371 Per estimated from Schlegel, Finkbeiner & Davis (1998) (see Table 5), its dereddened $B - V$ colour can be calculated as 0.54. The effective surface temperature should therefore be 6000 K or lower (depending on metallicity and surface gravity; VandenBerg & Clem 2003). All of the models in di Criscienzo et al. (2007) have the red edge of stable first overtone modes at temperatures above 6000 K.

The proper motion of V371 Per is $4.1 \pm 1.1$ mas yr$^{-1}$ from the UCAC2 catalogue (Zacharias et al. 2004), much lower than some BL Her stars of comparable apparent magnitude and period (in mas yr$^{-1}$: BL Her $13.2 \pm 1.4$, SW Tau $10.8 \pm 1.4$, RT Tra $14.1 \pm 2.5$, DU Ara $12.3 \pm 5.1$, UY Eri $25.7 \pm 1.8$). Of course, centre-of-mass radial velocities, combined with the proper motion and distance, will only determine the kinematic group to which V371 Per belongs.
With the extinction data from Table 5, the empirical $BVRi_c$ period–luminosity (PL) relations given by Fouqué et al. (2007) can be used to calculate the distance to V371 Per. The average distance modulus derived from these four passbands is $m - M = 12.51 \pm 0.07$, corresponding to a distance of $3.2 \pm 0.1$ kpc, and a Galactocentric distance of 10.6 kpc. Assuming the Sun is very near the Galactic plane (Reed 2005), a height of 0.8 kpc above the Galactic plane can then be calculated for V371 Per, much higher than all other Galactic Cepheids, which all lie within 300 pc from the Galactic plane. This would place V371 Per above the thin disc, so that it is located in the Galactic thick disc or halo, while all of the previously known Galactic beat Cepheids lie within the Galactic thin disc. Using the PL relations for the reddening-free Wesenheit magnitudes given in Fouqué et al. (2007), a somewhat smaller distance modulus $m - M = 12.34 \pm 0.03$ is obtained, bringing V371 Per about 50 pc closer to the Galactic Plane. The Two-Micron All-Sky Survey (2MASS) $JHK_s$ magnitudes (Cutri et al. 2003) give a similar distance modulus $m - M = 12.33 \pm 0.03$ (care should be taken here because the exact pulsation phase of the 2MASS measurements is difficult to determine.).

Using the calculated absolute magnitude from Table 5, an independent estimate can be made for the mass of V371 Per, using the relations for fundamental mode Cepheids established by Cutrò et al. (2005). In principle, these are only valid for stars with $Z = 0.02$ and $P > 3$ d. Depending on the passband, a pulsation mass between 2.3 and 3.1 $M_\odot$ is obtained. With the luminosity taken to be the canonical luminosity $L_{\text{can}}$ (Caputo et al. 2005), the deduced values for the evolutionary mass range between 3.3 and 3.8 $M_\odot$ from the mass–period–luminosity relation and between 3.6 and 3.7 $M_\odot$ from the mass–colour–luminosity relation. Although these estimates show a large range they do confirm V371 Per to be an intermediate-mass pulsator.

6 CONCLUSION

Extensive CCD photometry of V371 Per over a number of years has clearly shown it to be a Galactic beat Cepheid, with the shortest period known so far. The high value of the frequency ratio (0.731) suggests that its metallicity is much lower than that of the other Galactic beat Cepheids. Its distance derived from empirical PL relations places it in the Galactic thick disc or halo, 0.8 kpc above the Galactic plane. V371 Per is therefore a remarkable object and a spectroscopic study is warranted to confirm its low metallicity. It is very likely that V371 Per will help to refine the theoretical models for Cepheid pulsation. Further photometric observations may also confirm the period increase suspected for both modes. This will become evident within the next 5–10 years.

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