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V371 Per — A thick-disk, 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 disk or the Halo, while all other Galactic beat Cepheids belong to the thin disk. There are indications from historical data that both the fundamental and first overtone periods have lengthened.

Keywords: stars — individual — V371 Per, Cepheids

1 Introduction

The variability of V371 Per was diskovered 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 reanalyzed (the latter with revised values for the comparison stars), and data from the Northern Sky Variability Survey (NSVS; Woźniak et al. 2004) are analyzed 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 BVR_CI_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 color 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 AIP4WIN (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 color 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. Figure 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, from two separate pulsators within the same resolu-

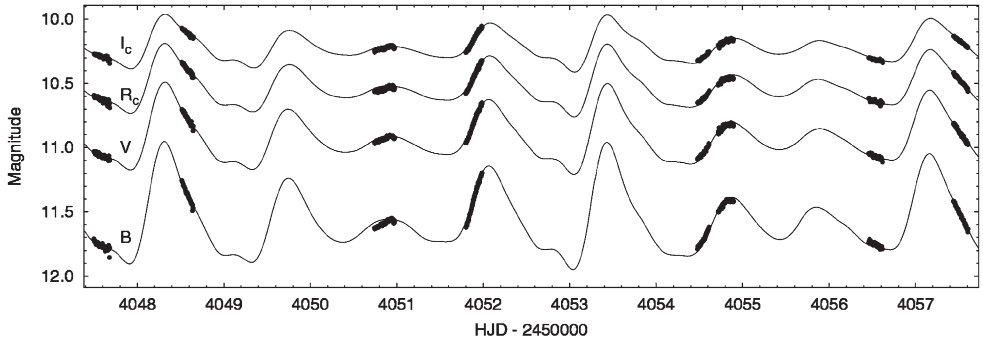

Figure 1. Part of the light curves and model curves in BVR_CI_C for V371 Per.

Table 1. Observation log for V371 Per.

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

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

GSC ID	RA (J2000) Dec.		V	σ_V	$B-V$	σ_{B-V}	$V-R_C$	σ_{V-R}	R_C-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	02:55:05.88	+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	+42:33:24.2	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	0.709	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	0.095	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	0.479	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	0.787 329(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	0.575 678(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	1.363 007	85.8(11)	189(1)	23.9	60.0(7)	189(1)	29.0	48.4(7)	186(1)	18.9	37.3(4)	186(1)	22.9
$2f_1$	1.574 658	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	0.211 651	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
$2f_0$	1.151 355	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
$2f_0+f_1$	1.938 684	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	2.150 336	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
$3f_1$	2.361 987	14.1(9)	173(4)	4.4	11.7(6)	160(4)	6.0	10.6(6)	167(4)	4.9	9.1(5)	162(4)	5.6
$3f_0$	1.727 033	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

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

tion 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 colors 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 Figure 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.

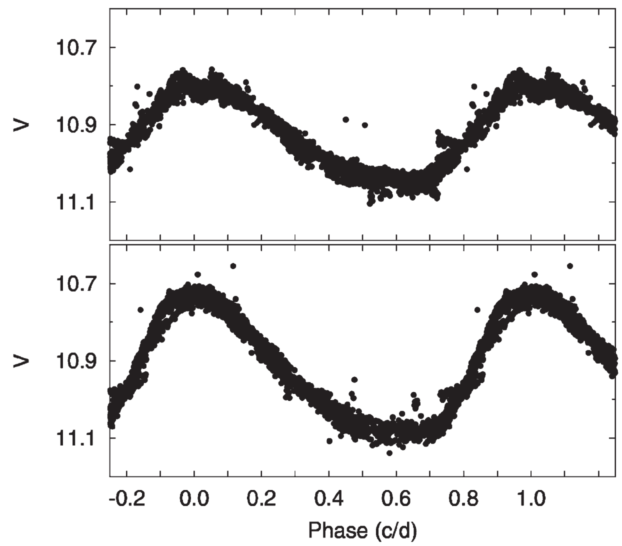

Figure 2. Phase plot of V data from SRO and Zagori Observatory. The top panel shows the data pre-whitened for the first overtone mode and all combination frequencies as given in Table 3. The bottom panel shows the data pre-whitened for the fundamental mode and all combination frequencies.

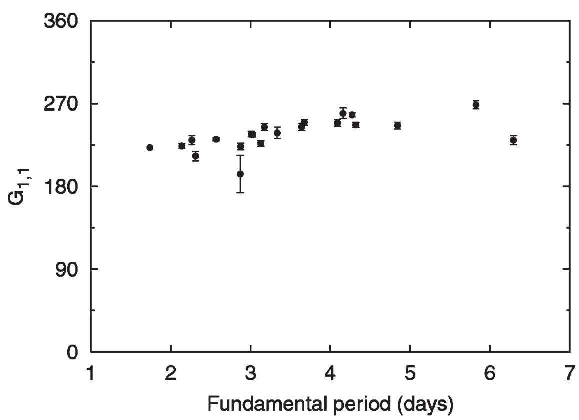

Figure 3. Values (in degrees) of the generalized phase difference $G_{1,1}$ for the cross coupling term f_0+f_1 for Galactic double-mode Cepheids. Besides V371 Per, the values are taken from Poretti & Pardo (1997) and Wils & Otero (2004) or calculated from ASAS-3 data (Pojmanski 2002) when not available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

The value of the generalized phase difference $G_{1,1}$= 3.88 ± 0.01 (expressed in radians) for the cross coupling term f_0+f_1 (Poretti & Pardo 1997) is in agreement with those of the other Galactic beat Cepheids (see Figure 3). Note that the definition of $G_{1,1}$ in Poretti & Pardo (1997) uses a cosine expansion for the Fourier series, while period04, and therefore also Table 3, uses a sine expansion, so that $\pi/2$ should be added to the result calculated from the data in Table 3. Only the star with the longest period, V367 Sct, does not follow the linear trend in $G_{1,1}$ with period.

There seems to be no indication for excess emission at any particular brightness or phase, as a plot of $B{-}R_C$ against B shows in Figure 4.

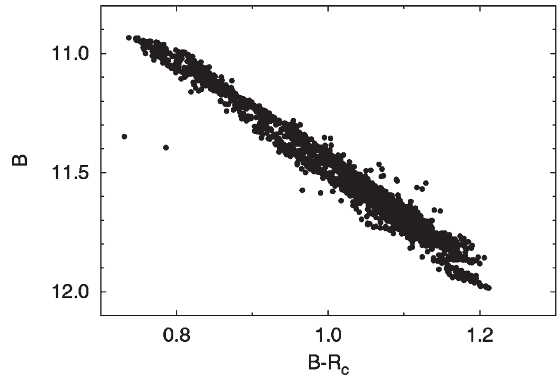

Figure 4. B data from SRO and Zagori Observatory plotted against color $B{-}R_C$.

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 Figure 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*-band amplitudes. The lesser number of data points in the NOFS data sets give less reliable amplitudes, and their uncertainties are likely underestimated.

5 Diskussion

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 Figure 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 indicate a low metallicity, uncommon for a Galactic Cepheid, as the values cited by Sziládi et al. (2007)

range from [Fe/H] = −0.20 ± 0.14 for VX Pup to [Fe/H] = 0.09 ± 0.18 for V458 Sct. This is also low compared to Galactic Cepheids pulsating in the fundamental mode only, as these have −0.5 < [Fe/H] < 0.4 (Luck, Kovtyukh & Andrievsky 2005; Lemasle et al. 2008; Pedicelli et al. 2009). Even taking into account a metallicity gradient with Galactocentric distance, this diskrepancy is not allowed for. An independent estimate for the metallicity of V371 Per can be deduced by following the procedure detailed by Caputo et al. (2001) for Cepheids pulsating in the fundamental mode. This gives a significantly larger value of $Z \approx 0.01$ or $[Fe/H] \approx -0.3$. Note, however, that the relations computed by Caputo et al. (2001) are based on Cepheid masses larger than $5\ M_\odot$, and periods longer than ≈3 days, so that strictly speaking they do not hold for V371 Per. For example, the quadratic relations in $\log P$ for the blue and red edge of the instability strip intersect at $Z \approx 0.011$ for the fundamental period of V371 Per, and the color–color relation results in a negative extinction value for $Z = 0.02$.

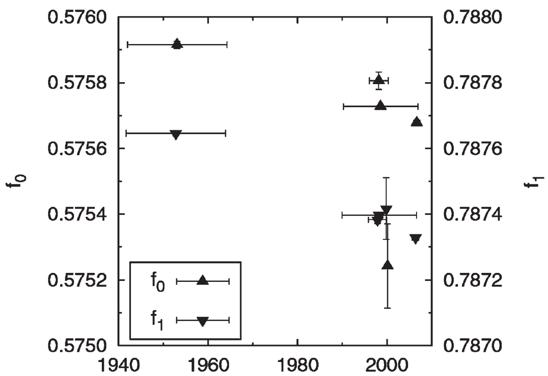

Figure 5. Frequency evolution of the fundamental and first overtone mode of V371 Per over the years from the data sets diskussed in this paper. The horizontal bars indicate the years in which the observations took place.

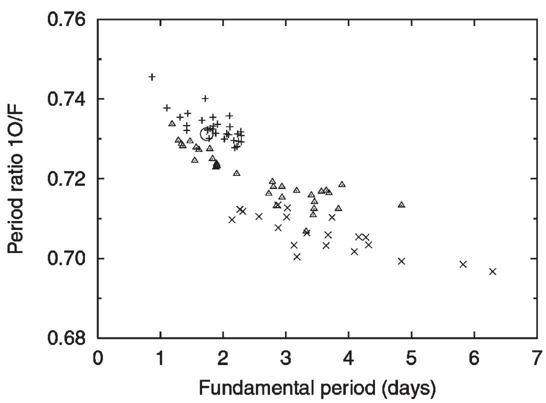

Figure 6. Period ratio P_1/P_0 plotted against fundamental period P_0 for Galactic Cepheids [shown as crosses; data from Welch (1998), Wils & Otero (2004) and Antipin (2006); the value for DZ CMa has been calculated from ASAS-3 data (Pojmanski 2002)], Small Magellanic Cloud Cepheids [triangles; data from Alcock et al. (1995) and Soszyński et al. (2000)) and SMC Cepheids (plusses, data from Beaulieu et al. (1997), Alcock et al. (1997) and Udalski et al. (1999)]. V371 Per is depicted with a large circle.

Furthermore, the Galactic latitude of V371 Per of −14.7° is rather high, higher than for the other double-mode Cepheids in the Galaxy. Apart from TU Cas (at latitude +11.4), all the others have latitudes between −8 and +5.5. η Aql, a bright and therefore relatively nearby Cepheid, has a Galactic latitude of −13.7°.

Although the metallicity of V371 Per is low and the height above the Galactic plane is large, it is likely not a low-mass Population II variable. The graphs of Buchler & Szabó (2007) suggest a mass for V371 Per just above $3\ M_\odot$, while BL Her stars have masses smaller than $1\ M_\odot$. The light curve of V371 Per does not resemble those 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 $B-V$ color 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 ± 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 ± 1.4, SW Tau 10.8 ± 1.4, RT TrA 14.1 ± 2.5, DU Ara 12.3 ± 5.1, UY Eri 25.7 ± 1.8). Of course, center-of-mass radial velocities, combined with the proper motion and distance, will only determine the kinematic group to which V371 Per belongs.

Table 4. Fundamental and first overtone mode calculated for all data sets.

Data set	Filter	f_0	A_0	f_1	A_1	f_0/f_1
Satyvaldiev	-	0.575 916(11)	211(35)	0.787 646(7)	295(37)	0.731 19(2)
Behlen	V	0.575 728(5)	116(8)	0.787 397(4)	171(6)	0.731 18(1)
Behlen	R_C		90(7)		132(6)	
NOFS	V	0.575 806(26)	90(5)	0.787 383(11)	148(5)	0.731 29(2)
NOFS	B		129(7)		220(8)	
NOFS	R_C		66(6)		114(6)	
NOFS	I_C		90(13)		162(14)	
NSVS	-	0.575 242(128)	103(5)	0.787 417(94)	140(5)	0.730 54(18)
SRO+Zagori	V	0.575 678(4)	125(7)	0.787 329(3)	174(6)	0.731 18(1)
SRO+Zagori	B		175(1)		245(1)	
SRO+Zagori	R_C		99(1)		136(1)	
SRO+Zagori	I_C		77(1)		105(1)	

Semi-amplitudes are given in millimag

Table 5. Mean apparent magnitude, extinction estimated from Schlegel et al. (1998) and absolute magnitude calculated from Fouqué et al. (2007) for V371 Per in the BVR_CI_C (our data) and 2MASS JHK_S passbands (Cutri et al. 2003).

Passband	Apparent mag. m_λ	Extinction A_λ	Absolute mag. m_λ
B	11.58	0.46	−1.48
V	10.93	0.35	−1.92
R_C	10.53	0.29	−2.22
I_C	10.22	0.21	−2.44
J	9.63	0.10	−2.83
H	9.35	0.06	−3.01
K_S	9.29	0.04	−3.09

With the extinction data from Table 5, the empirical BVR_CI_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 ± 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 disk, so that it is located in the Galactic thick disk or halo, while all of the previously known Galactic beat Cepheids lie within the Galactic thin disk. 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 Caputo 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_{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–color–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 disk 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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