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Research Note

Time series analysis of V 368 Cephei photometry*

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Abstract. Our time series analysis of V 368 Cep photometry ascertains the rotation period of $2.^{\rm d}74$ uniquely. The manifestations of starspot induced luminosity variations in this chromospherically active star include rapid light curve changes and differential rotation of about 3%. We conclude that the single rapidly rotating variable V 368 Cep is a high inclination K1V post T Tauri star.

Key words: stars: variables: general – stars: individual: V 368 Cep – techniques: photometric

1. Introduction

The most recent estimates for the variable star V 368 Cep are K2V, $v \sin i = 16.1 \text{ km s}^{-1}$, $v_{\rm rad} = -15.6 \text{ km s}^{-1}$ (constant) and $P_{\rm phot} = 2.^{\rm d}75$ (Our Table 1: Bianchi et al. 1991; Chugainov et al. 1991, 1993; Bossi & La Franceschina 1995). EXOSAT imaging by Pravdo et al. (1985) revealed that V 368 Cep (HD220140) is the optical counterpart of the bright X-ray source H2311+77 detected with the HEAO1 satellite (Nugent et al. 1983). Subsequent IUE–, EUVE– and ROSAT–satellite detections include chromospheric, transition region and coronal emission at shorter wavelengths (Bianchi et al. 1991; Bowyer et al. 1994; Malina et al. 1994; Pye et al. 1995). The first evidence for magnetic activity, strong CaII H&K emission, was already detected by Joy & Wilson (1949). Indications of magnetic activity have been observed in 11 groups of late–type stars (Hall 1991). Earlier studies by Pravdo et al. (1985), Nations et al. (1990), Bianchi et al. (1991) and Chugainov et al. (1991, 1993) have implied that the RS CVn (Hall 1976), BY Draconis (Bopp & Fekel 1977) or naked T Tauri (Walter 1986) group definitions might be relevant for V 368 Cep. Regardless of uncertainties in spectral-type or luminosity class, several activity–rotation–relations (e.g. Strassmeier et al. 1990) would predict high level of magnetic activity in V 368 Cep, all available $v \sin i$ estimates exceeding those of a typical late–type star (see Gray 1982, 1989; Gray & Nagar 1985). Halliwell (1979) included this object among stars *maybe* within 25 pc, and later estimates ranged between 21 and 70 pc (Pravdo et al. 1985; Chugainov et al. 1991, 1993). The Hipparcos satellite confirmed the distance of 20 pc (ESA 1997).

Table 1. [1]Boss (1937), [2]Joy & Wilson (1949), [3]Wilson & Joy (1950), [4]Moore & Paddock (1950), [5]Wilson (1953), [6]Poretti et al. (1985), [7]Heckert et al. (1990), [8]Nations et al. (1990), [9]Bianchi et al. (1991), [10]Chugainov et al. (1991, 1993), [11]Mantegazza et al. (1992), [12]Bossi & La Franceschina (1995), [13]Fekel (1997)

$P_{\rm phot}$[d]	$v_{\rm rad}$[km s^{-1}]	Sp–type	$v \sin i$ [km s^{-1}]
0.58[6]	-15.1 ± 1.3[3]	G5[1]	13[9]
2.75[7]	-19 ± 0.9[4]	K0V[2]	25[10]
2.73[8]	-16.8[5]	G9V[4]	16.1[13]
2.76[9]	-15.6[10]	K2V[9]	
2.75 or 1.57[10]			
2.77[11]			
2.75[12]			

2. Observations

The *earlier* V 368 Cep photometry consists of that in Poretti et al. (1985), Nations et al. (1990), Bianchi et al. (1991), Heckert et al. (1990), Chugainov et al. (1991, 1993), and Mantegazza et al. (1992). Of these, only Bianchi et al. (1991) and Mantegazza et al. (1992) published their numerical values. The first part of the data in Mantegazza et al. (1992) is from Poretti et al. (1985), while the Chugainov et al. (1993) photometry is from Chugainov et al. (1991). HD 219522 and HD 219285 were used as the comparison (C_1) and check star (C_2) of the differential photometry by Bianchi et al. (1991) and Mantegazza et al. (1992). The $\rm V = 8.22$ and $\rm B = 8.80$ of C_1, which have been measured only once (Mantegazza et al. 1992), were added to the differential

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* Table 5 is only available in electronic form at CDS via anonymous ftp to edarc.u-strasbg.fr (130.79.1285) or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 2. The collected V 368 Cep photometry: The observing time interval, the subset (SET), the observatory, the primary comparison star (C_1), the secondary comparison star (C_2), the reference and the number of observing nights (nts)

Interval	SET	Observatory	C_1	C_2	Reference	nts
14.8.–25.9.1985	1	Merate Observatory	HD219522	HD219285	Mantegazza et al. 1992	21
7.10.–14.11.1985	2	Merate Observatory	HD219522	HD219285	Mantegazza et al. 1992	10
21.9.–17.10.1989	3	Konkoly Observatory	HD219522	HD219285	Bianchi et al. 1991	2
11.11.–10.12.1989	4	Konkoly Observatory	HD219522	HD219285	Bianchi et al. 1991	9
28.12.1989–6.2.1990	5	Konkoly Observatory	HD219522	HD219285	Bianchi et al. 1991	10
22.6.–29.7.1991	6	Tashkent Observatory	Absolute	Absolute	This paper	17
8.8.–7.9.1991	7	Tashkent Observatory	Absolute	Absolute	This paper	19
8.9.–7.10.1991	8	Tashkent Observatory	Absolute	Absolute	This paper	15
11.10.–6.11.1991	9	Tashkent Observatory	Absolute	Absolute	This paper	17

Table 3. The estimates for the photometric rotation period (P), and the epochs of the primary and secondary minima in HJD–2440000 ($t_{\mathrm{min},1}, t_{\mathrm{min},2}$) for $\mathrm{nts} \geq 7$ subsets. Note that some estimates are rejected with the rules $\mathrm{R_I}$, $\mathrm{R_{II}}$ and $\mathrm{R_{III}}$ (see the end of Sect. 3)

SET	P	$t_{\mathrm{min},1}$	$t_{\mathrm{min},2}$
1	2.7534 ± 0.0052	6293.180 ± 0.058	6291.618 ± 0.053
2	$2.701\pm.011^{\mathrm{R_I}}$	$6346.743\pm.066^{\mathrm{R_I}}$	
4	$2.784\pm.012^{\mathrm{R_{II}}}$	$7842.752\pm.030^{\mathrm{R_{II}}}$	$7843.895\pm.050^{\mathrm{R_{II}}}$
5	$2.748\pm.012^{\mathrm{R_I}}$	$7890.07\pm.15^{\mathrm{R_I}}$	
6	$2.753\pm.039^{\mathrm{R_I}}$	$8432.23\pm.28^{\mathrm{R_I}}$	$8430.73\pm.29^{\mathrm{R_I}}$
7	$2.746\pm.013$	$8480.04\pm.10$	
8	$2.751\pm.011$	$8510.58\pm.10$	$8510.11\pm.11^{\mathrm{R_{III}}}$
9	$2.7137\pm.0093$	$8542.400\pm.057$	

magnitudes from Bianchi et al. (1991). Finally, two possibly erroneous V magnitudes on $\mathrm{HJD} - 2446000 = 359.347$ and 367.248 were removed from Mantegazza et al. (1992).

Our *new* UBVR photometry was made with the 60 cm telescope at Tashkent Observatory during 68 nights between June, 1991 and November, 1991. The nightly extinction coefficients and transformations into the standard Johnson UBVR system were determined by standard star measurements. Every observation is the mean of 3–5 integrations in each filter. The external accuracy is about $0\overset{\mathrm{m}}{.}015$ in BVR and $0\overset{\mathrm{m}}{.}030$ in U.

Table 2 summarizes the combined earlier and new photometry, and specifies the separately analysed subsets. The whole UBVRI photometry is published *only* in electronic form (hereafter Table 5). Given the accuracy in Bianchi et al. (1991), the BV precision for $C_1(\lesssim 0\overset{\mathrm{m}}{.}01)$, and the unknown error for each individual measurement, reasonable error estimates for the *whole* data in Table 5 are $0\overset{\mathrm{m}}{.}015$ in BVRI and $0\overset{\mathrm{m}}{.}030$ in U. Note that the U and $\mathrm{(RI)_C}$ in Table 5 during SET=3, 4 and 5 are magnitude differences between V 368 Cep and HD219522.

The detection procedure by Jetsu et al. (1993) revealed two probable photometric flares on $\mathrm{HJD} - 2448000 = 445.4566$ (SET=6: Flare) and 482.4540 (SET=7: Flare?), i.e. no U–band measurement was available for the latter event. These two events may also represent observational errors, since an indisputable identification would require more than one flare measurement in UBV, like in Jetsu et al. (1993: Figs. 1–3). Optical flares have been detected in several late–type main sequence stars (Haisch et al. 1991), but rarely in late–type subgiants or giants (Henry & Newsom 1996).

3. Time series analysis

We performed the time series analysis of V 368 Cep photometry with the TSPA method from Jetsu & Pelt (1999: Paper I), where four detailed application examples are also given. A prolonged time series of V1794 Cyg photometry was recently analysed with this method in Jetsu et al. (1999: Paper II). The parameters of our second order ($K = 2$) light curve model

$$g(\bar{\beta}) = g(t, \bar{\beta}) = M + \sum_{\mathrm{k=1}}^{\mathrm{K}} B_{\mathrm{k}} \cos{(k 2\pi f t)} + C_{\mathrm{k}} \sin{(k 2\pi f t)}$$

were the mean (M), the amplitudes (B_1, B_2, C_1, C_2), and the frequency (f, i.e. the period $P = f^{-1}$). The free parameters were $\bar{\beta} = [M, B_1, B_2, C_1, C_2, f]$ or $\bar{\beta}_{\mathrm{f}} = [M, B_1, B_2, C_1, C_2]$ for fixed f. Excluding the two aforementioned probable flares, the normalized magnitudes y within every subset (Paper I: Eq. 17) were derived in those UBVRI passbands that contained measurements during at least seven nights (nts). Only subsets with $\mathrm{nts} \geq 7$ were modelled. The frequency f was a free parameter in the *nonlinear* modelling of y with the TSPA method. This gave the periods, and the primary and secondary minimum epochs (Table 3: P, $t_{\mathrm{min},1}$ and $t_{\mathrm{min},2}$). *Linear* modelling with these subset ephemerides $\mathrm{HJD_{min}} = (t_{\mathrm{min},1} + P)\mathrm{E}$ gave the mean and total amplitude of the UBVRI light curves (Table 4: $M_{\mathrm{U}}, ..., M_{\mathrm{I}}$ and $A_{\mathrm{U}}, ..., A_{\mathrm{I}}$). All error estimates were determined with bootstrap (Paper I: Sect. 4).

The observing window in photometry is usually one sidereal day (i.e. $P_0 = 0.9972$). If the real period is P, then spurious periods are induced at

$$P'(P_0 : k_1 : k_2) = [P^{-1} + k_1 (k_2 P_0)^{-1}]^{-1}, \qquad (1)$$

where $k_1 = \pm1, \pm2, ...$ and $k_2 = 1, 2, ...$ (Tanner 1948). Combining $P \approx 2.75$ with $P_0 \approx 0.9972$ predicts $P'(P_0 : 1 : 1) \approx 0.73$, $P'(P_0 : -1 : 1) \approx -1.56$, $P'(P_0 : 2 : 1) \approx 0.42$ and $P'(P_0 : -2 : 1) \approx -0.60$. These five alternatives explain the whole period finding history of V 368 Cep in our Table 1. The most recent study presented “unambiguous indications” for $P = 2.754$, and also mentioned some spurious periodicities (Bossi & La

Table 4. The light curve mean (M) and total amplitude (A) in UBVRI for $\mathrm{nts} \geq 7$ subsets. Note that the M estimates in SET=4 and 5 are magnitude differences between V 368 Cep and HD219522 in U and (RI)$_{\rm C}$. The errors in parenthesis are [mmag]

SET	Epoch	$M_{\rm U}$	$A_{\rm U}$	$M_{\rm B}$	$A_{\rm B}$	$M_{\rm V}$	$A_{\rm V}$	$M_{\rm R}$	$A_{\rm R}$	$M_{\rm I}$	$A_{\rm I}$
1	1985.68			8.321(1)	0.072(6)	7.474(2)	0.053(6)				
2	1985.80			8.348(2)	0.046(4)	7.502(4)	0.034(10)				
4	1989.88	-0.183(2)	0.057(6)	8.303(1)	0.044(4)	7.481(1)	0.035(4)				
5	1990.03	-0.189(3)	0.052(11)	8.303(3)	0.044(7)	7.481(2)	0.040(6)	-0.898(3)	0.046(14)	-1.047(4)	0.036(14)
6	1991.53			8.423(2)	0.019(6)	7.571(2)	0.027(8)	6.826(6)	0.026(19)		
7	1991.64	8.918(2)	0.053(8)	8.405(3)	0.057(7)	7.562(2)	0.047(5)	6.820(1)	0.041(4)		
8	1991.70			8.404(3)	0.051(7)	7.558(2)	0.047(8)	6.820(1)	0.037(5)		
9	1991.80	8.930(2)	0.073(8)	8.425(1)	0.065(4)	7.572(2)	0.047(5)	6.824(1)	0.036(4)		

Franceschina 1995). Unfortunately, Eq. 1 connecting the real and spurious periodicities does not identify the correct one, i.e. the probability of mistaking a spurious periodicity for a real one should never be underestimated, as reminded by Table 1 in Paper I. Thus we decided to perform the TSPA method analysis between $P_{\rm min} = 0.4$ and $P_{\rm max} = 3$, i.e. the above five alternative periodicities were tested against each other. The window periods P_0 within each subset were determined with the Deeming (1975) method.

The χ^2 for y with the ~ 2.75 and ~ 0.73 periodicities were the smallest in 4 and 3 subsets out of eight, respectively. The ~ 0.60, ~ 1.56 and ~ 0.42 periodicities could be rejected with this χ^2–criterion. Nevertheless, this criterion could not separate ~ 2.75 from ~ 0.73. A unique solution was obtained from the linear correlation coefficients r between the phase residuals $\delta\bar{\phi}$ and $\delta\bar{\phi}'$ (Paper I: Sect. 5). The r for ~ 0.73 reached a significance higher than 0.001 in two subsets. No such cases occurred for ~ 2.75. Since the $\delta\bar{\phi}$ and $\delta\bar{\phi}'$ for spurious periods correlate, and those for real periodicity do not, we conclude that the real periodicity in V 368 Cep is ~ 2.75. The normalized magnitudes are displayed in Fig. 1 with such periodicities. Criteria for accepting or rejecting the TSPA method modelling results were also presented in Papers I & II. The rejection rules were

$\rm R_I$: *If* the distribution of the model residuals or that of the $M, P, A, t_{\rm min,1}$ or $t_{\rm min,2}$ bootstrap estimates is not gaussian, *then* the P, $t_{\rm min,1}$ and $t_{\rm min,2}$ estimates are rejected.
$\rm R_{II}$: P, $t_{\rm min,1}$ and $t_{\rm min,2}$ of $\mathrm{nts} < 10$ subsets are rejected.
$\rm R_{III}$: Those $t_{\rm min,2}$ not present in 95% of the bootstrap models are "unreal".

Comparison between Tables 3 and 4 confirmed that the $\rm R_I$ rejections occur for low amplitude light curves (SET=2, 5 and 6). The $t_{\rm min,2}$ rejection in SET=8 only implies that this secondary minimum may be "unreal", but the model itself is reliable. In conclusion, reliable periodicity detection in V 368 Cep succeeded for $A_{\rm V} \geq 0.^{\rm m}047$ with a subset length of about one month, and $\mathrm{nts} > 10$.

4. Discussion and conclusions

Photometric spectral classification of V 368 Cep with the new UBVR photometry gave K1V or G3III in UBV (FitzGerald 1970), and K1V or G5III in BVR (Johnson 1966). There is an excess of about $\sim 0.^{\rm m}05$ in V–R, which could be due to chromospheric activity (see Fekel et al. 1986). We could exclude the luminosity classes IV and III by combining the mean apparent visual magnitude of 7.53 (Table 5) to the the Hipparcos/Tycho Catologue distance of 20 pc, which yields an absolute magnitude of 6.1 in V, assuming no interstellar extinction. V 368 Cep lies in the galactic plane ($l = 118°$, $b = 17°$), but so close to the Sun that the interstellar extinction is negligible (e.g. Savage & Mathis 1979). Finally, it was already noted in the previous section that the ~ 0.78 periodicity is spurious. The relation $v \sin i = 50.6 R P^{-1} \sin i$ ($[P] = \mathrm{d}$, $[R] = R_\odot$, $[v] = \mathrm{km\,s^{-1}}$) provides additional evidence against this periodicity, because $P \sim 0.78$ for this K1V star would require an inclination so close to zero that no photometric variability could be detected. Hence all our results support the K1V spectral type for V 368 Cep, and the combination $P_{\rm phot} \approx 2.75$, $v \sin i = 16.1 \mathrm{km\,s^{-1}}$ (Fekel 1997) and $R = 0.85 \pm 0.17 R_\odot$ (Gray 1988) implies an inclination very close to $90°$.

Except for the slightly discrepant Moore & Paddock (1950) value, our Table 1 does not imply long–term $v_{\rm rad}$ changes, while Bianchi et al. (1991) and Chugainov et al. (1991, 1993) found no short–term variability. In absence of indications for a binary companion, V 368 Cep does not fulfill the RS CVn group definition by Hall (1976). V 368 Cep would meet all BY Draconis group classification criteria (Bopp & Fekel 1977: K–MV stars with CaII H&K emission and a low amplitude light curve with a few days), *but* the Li 6707Å line strength measurements imply it being a young object, i.e. a post T Tauri star (Nations et al. 1990; Chugainov et al. 1991, 1993). It remains uncertain whether V 368 Cep is a naked T Tauri star having dissipated its circumstellar envelope (Walter 1986), but we do note that such an envelope would offer an alternative explanation for the observed V–R excess.

As for the unavailable earlier photometry, the light curve with $M_{\rm V} \approx 7.48$ and $A_{\rm V} \approx 0.05$ in Chugainov et al. (1993: Fig. 1), being nearly simultaneous with SET=4 and 5, fits our Table 3. The $0.06 \leq A_{\rm V} \leq 0.09$ during 1986, 1987 and 1990 in Nations et al. (1990) exceed all ours in Table 3. The overall short– and long–term changes of V 368 Cep light curves resemble those observed in numerous chromospherically active stars. For example, light curve changes within a few months occurred during the new photometry (SET=6–9), and our Table 4 reveals

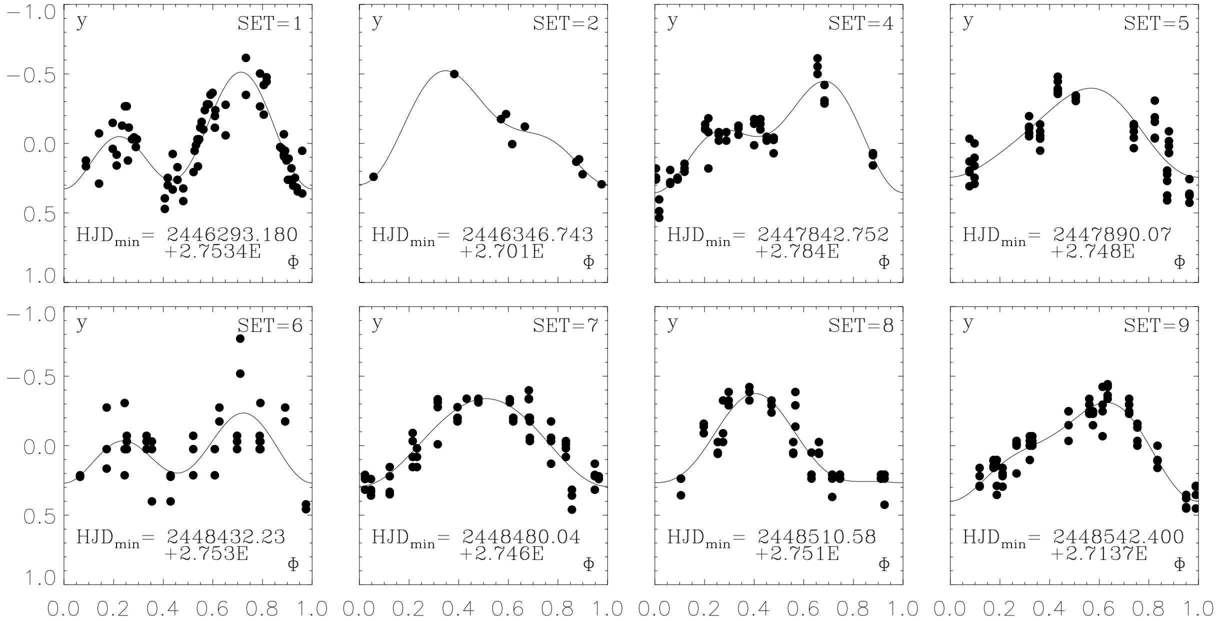

Fig. 1. The normalized magnitudes (y) with the ephemerides of Table 3

changes of about $0.^{\rm m}10$ in $M_{\rm V}$. All P in Table 3 have a weighted mean of $P_{\rm w} = 2.744{\pm}0.022$. Thus the $\pm 3\sigma$ upper limit for these P changes equals $Z = 4.8\%$. The hypothesis that the photometric period is constant (i.e. 2.744) gives $\chi^2 = 40.9$ with a critical level of $Q = 9{\rm x}10^{-7}$. The respective estimates for the four P not rejected with $\rm R_I$ or $\rm R_{II}$ are $P_{\rm w} = 2.745 \pm 0.015$, $Z = 3.3\%$ and $Q = 0.0026$. Hence it can be concluded that measurable differential rotation is present in V 368 Cep. Unfortunately, the available photometry does not allow us to perform a more thorough analysis similar to that in Paper II, where activity cycles, active longitudes and differential rotation were examined in the V1794 Cyg long–term photometry. New photometry would enable such an analysis for V 368 Cep.

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