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$BV(RI)_c$ photometric study of three variable PMS stars in the field of V733 Cephei

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Abstract This paper reports results from the first long-term $BV(RI)_c$ photometric CCD observations of three variable pre-main-sequence stars collected during the period from February 2007 to January 2020. The investigated stars are located in the field of the PMS star V733 Cep within the Cepheus OB3 association. All stars from our study show rapid photometric variability in all-optical passbands. In this paper, we describe and discuss the photometric behavior of these stars and the possible reasons for their variability. In the light variation of two of the stars, we found periodicity.

Key words: stars: pre-main sequence — stars: variables: T Tauri, Herbig Ae/Be — techniques: photometric — methods: observational, data analysis — stars: individual (2MASS J22534654+6234582, 2MASS J22533629+6231446, 2MASS J22531578+6235262)

1 INTRODUCTION

Pre-main-sequence (PMS) stars are important in the study of star formation. They are divided into two main types – low mass ($M \leq 2\,M_\odot$) T Tauri stars (TTS) and more massive ($2\,M_\odot \leq M \leq 8\,M_\odot$) Herbig Ae/Be stars (HAEBES). The first systematic study of TTS as a separate class of variable was made by Joy (1945), and their characteristics were reviewed by Petrov (2003) and Cram et al. (1989). TTS are dwarf stars with photospheric spectra ranging from late F to M (Petrov 2003). These stars exhibit rapid irregular light variations and emission spectra, and they are associated with molecular clouds, and dark and bright nebulae.

TTS are separated into two subgroups – classical T Tauri stars (CTTS), surrounded by a massive accreting circumstellar disk, and weak-line T Tauri stars (WTTSs), which display no signs of disk accretion (Ménard & Bertout 1999). Variable mass accretion rate and the presence of hot and cool spots on the stellar surface are possible reasons for the variability of CTTS. The variability of WTTSs is often associated with the presence of cool spots or groups of spots on the stellar surface and flare-like events (Herbst et al. 2007).

Some PMS stars undergo obscuration in which their brightness decreases with an amplitude of up to 2–3 mag. Such decreases in the brightness are observed in both CTTS and WTTSs, and its clearest form is observed in young stars in an earlier spectral class (HAEBES) (Petrov 2003). These PMS stars are called UXors, named after their prototype UX Orionis. The observed deep Algol-type minima in the light curves of UXors probably are caused by obscuration of the star from circumstellar dust clouds with different densities or edge-on circumstellar disks. These ideas were discussed by Grinin (1988), Voshchinnikov (1989), Grinin et al. (1991), Dullemond et al. (2003) and other authors. In the deep minima, the color indices of UXors often become bluer. This specific color variability is known as the blueing effect (see Bibo & Thé 1990). The star's color initially becomes redder (when its light is covered by dust clumps or filaments), but with a large extinction, the scattered light from the dust clouds begins to dominate, and the star becomes bluer. Illustrative figures for the blueing effect in UXors can be seen in the works of Herbst & Shevchenko (1999) (figs. 6-8 therein) and Semkov et al. (2015) (fig. 3 therein).

The stars included in the present study are located near the well-studied PMS star V733 Cep (see Reipurth et al.

2007, Semkov & Peneva 2008, Peneva et al. 2010) within the Cepheus (Cep) OB3 association. During their photometric study of V733 Cep, Semkov & Peneva (2008) discovered the variability of three nearby stars. For short, these stars were named Var. 1, Var. 2 and Var. 3, corresponding to 2MASS J22534654+6234582, 2MASS J22533629+6231446 and 2MASS J22531578+6235262, respectively. Munari (2009) estimated their brightness on 40 plates from the archive of the Asiago 67/92-cm Schmidt telescope distributed over the period from August 1971 to November 1978.

In this paper, we present results from the multicolor observations of these stars that cover 13 years. We aim to describe and discuss the optical photometric behavior of the investigated stars and the possible reasons for their variability. This paper is organized as follows. In Section 2, we give information about the telescopes and cameras used to perform the observations. In Section 3, we describe the results obtained for the investigated stars and their interpretation. In Section4, we briefly present the main results of our study.

2 OBSERVATIONS AND DATA REDUCTION

We obtained $BV(RI)_c$ photometric CCD observations of the field of V733 Cep in the period from February 2007 to January 2020. The observations were performed with four telescopes: the 2-m Ritchey-Chrétien-Coudé (RCC), the 50/70-cm Schmidt and the 60-cm Cassegrain telescopes administered by the Rozhen National Astronomical Observatory in Bulgaria, and the 1.3-m Ritchey-Chrétien (RC) telescope administered by the Skinakas Observatory[1] of the University of Crete in Greece.

Eight different CCD cameras were operated to obtain the observations as follows: VersArray 1300B and Andor iKon-L on the 2-m RCC telescope; Photometrics CH360 and Andor DZ436-BV on the 1.3-m RC telescope; SBIG ST-8, SBIG STL-11000M and FLI PL16803 on the 50/70-cm Schmidt telescope; and FLI PL09000 on the 60-cm Cassegrain telescope. The technical parameters and chip specifications for the cameras used are given in Ibryamov et al. (2015). Because the Andor iKon-L camera at the 2-m RCC telescope was installed in 2018, its specifications are reported in Ibryamov & Semkov (2020).

All frames were taken through a standard Johnson-Cousins (BVR_cI_c) set of filters. The data were reduced applying an IDL based DAOPHOT subroutine. All data were analyzed using the same aperture, which was chosen to have a 3 arcsec radius (the background annulus was taken from 10 arcsec to 13 arcsec). As a reference, the improved $BV(RI)_c$ comparison sequence in the field around V733 Cep reported in Peneva et al. (2010) was applied. The calibrations of the comparison stars were made with the 1.3-m RC telescope during six clear nights (four in 2007 and two in 2009), as the standard stars from Landolt (1992) were utilized as a reference. The finding chart of the comparison sequence and the coordinates of the stars can be found in Semkov & Peneva (2008).

3 RESULTS AND DISCUSSION

Figure 1 features a three-color image of the field around V733 Cep, where the positions of the investigated stars are marked. These stars are probable members of the Cep OB3 association. The *Gaia* mean distances (Bailer-Jones et al. 2018) to the three stars are as follows: 817 pc to Var. 1, 725 pc to Var. 2 and 826 pc to Var. 3. The distance to the Cep OB3 association was determined as 725 pc by Blaauw et al. (1959) and as 900±100 pc by Moreno-Corral et al. (1993).

The results from our long-term observations of the stars are summarized in Table A.1, Table A.2 and Table A.3 in the Appendix[2]. The columns contain Date (dd.mm.yyyy format) and Julian date (JD) of the observations, the measured magnitudes of the star, and the telescopes and CCD cameras employed. The average value of the errors in the reported magnitudes is 0.01-0.02 mag for the data in I_c and R_c bands, and 0.02-0.05 mag for the data in V and B bands. Table 1 shows the mean magnitudes of the investigated stars from Munari (2009) and the present study.

3.1 2MASS J22534654+6234582 (Var. 1 hereafter)

Semkov & Peneva (2008) reported the observed values of the brightness of Var. 1 for the period from February 2007 to February 2008. According to the authors, the star manifests a very high amplitude of brightness variation, and it is probably a long-period variable of Mira-type. Munari (2009) measured the star's brightness for the period 1971 - 1978 and reported that its variability at I_c is much less pronounced than what is listed in Semkov & Peneva (2008). The author discussed the characteristics that a Mira-type star should exhibit, which lies within the Galaxy in that direction with $\overline{V}$=16.9 mag. Munari (2009) concluded that ΔI_c=2.36 mag reported by Semkov & Peneva (2008), but not confirmed by their data, would be far too large for such a Mira case. The star was included in the list of young stellar objects: class II published by Allen et al. (2012).

[1] Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology, Greece, and the Max-Planck-Institut für Extraterrestrische Physik, Germany.

[2] The tables with the photometric data will be available also via CDS VizieR Online Data Catalogue.

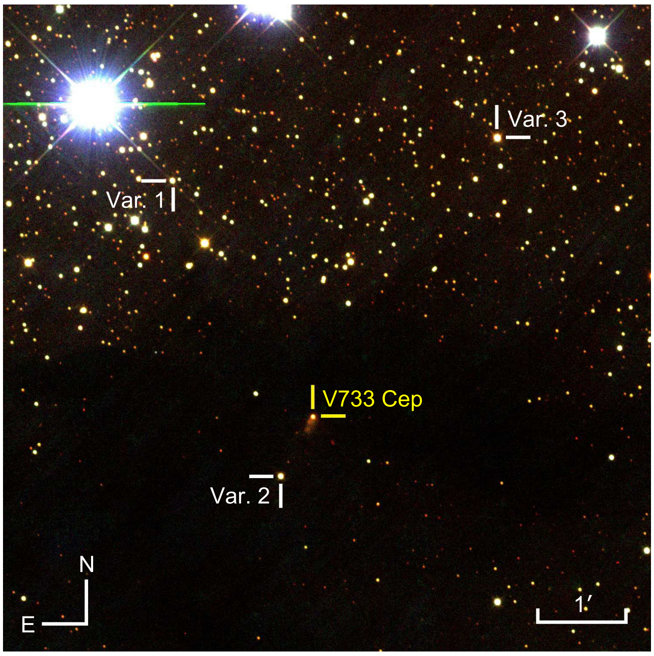

Fig. 1 A three-color image of the field around V733 Cep obtained on 2015 August 12 with the 1.3-m RC telescope at the Skinakas Observatory. The stars from our study and V733 Cep are marked.

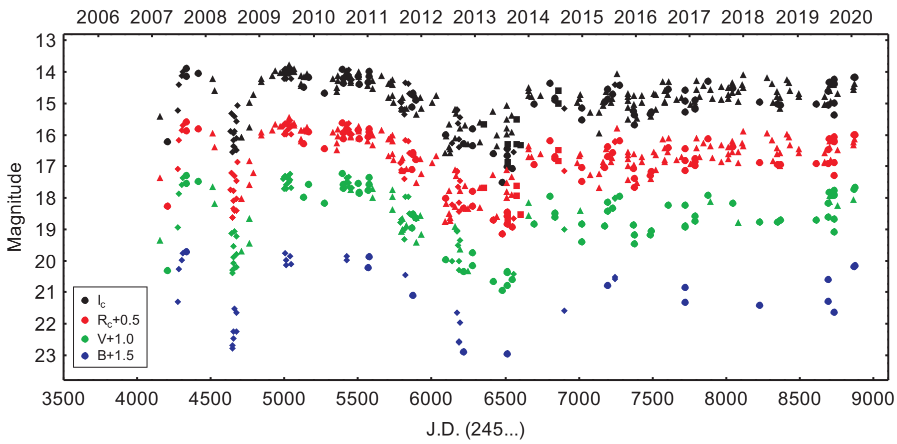

Fig. 2 $BV(RI)_c$ light curves of Var. 1 for the period February 2007 - January 2020. The circles signify photometric data from the 2-m RCC telescope, the diamonds represent photometric data from the 1.3-m RC telescope, the triangles mark photometric data from the 50/70-cm Schmidt telescope and the squares correspond to photometric data from the 60-cm Cassegrain telescope. In very low light, the brightness of the star, especially in the V and B bands, is under the photometric limit of the telescopes used.

The $BV(RI)_c$ light curves of Var. 1 from our observations are depicted in Figure 2. During our monitoring, the star exhibits rapid variability and fading events in the light curves. As can be seen in Figure 2, the star's brightness varies in wide ranges: 13.77–17.49 mag in the I_c band, 14.93–18.62 mag in the R_c band, 16.20–19.92 mag in the V band and 18.19–21.45 mag in the B band.

In the period February 2007 - January 2020, several well defined deep minima in the light curves of Var. 1 are registered in all-bands. They have different amplitudes, shapes and durations. The first minimum is registered in April 2007, at the beginning of our photometric monitoring of the star. The second well defined minimum is registered in June - July 2008. The third minimum is longer than the others, and it is registered in the period June 2012 - November 2013. During this minimum, two deeper drops in the brightness of the star are also observed. The deepest dip (ΔI_c=3.72 mag) we registered is in the second half of 2013. Out of deep minima, the star shows significant rapid brightness variation on the time scale of days and weeks.

An important result from our study of Var. 1 is the registered change in its color at the deep minima. We

Table 1 Comparisons of the Mean Magnitudes of Var. 1, Var. 2 and Var. 3

Star	$\overline{I_c}$	$\overline{R_c}$	$\overline{V}$	$\overline{B}$	$\overline{I_c}$	$\overline{R_c}$	$\overline{V}$	$\overline{B}$
	(Munari 2009)				(our study)			
Var. 1	14.49	-	16.93	18.80	14.91	16.26	17.58	19.56
Var. 2	13.83	-	16.40	17.68	13.97	15.26	16.51	18.48
Var. 3	13.01	-	15.03	16.95	13.25	14.37	15.50	17.36

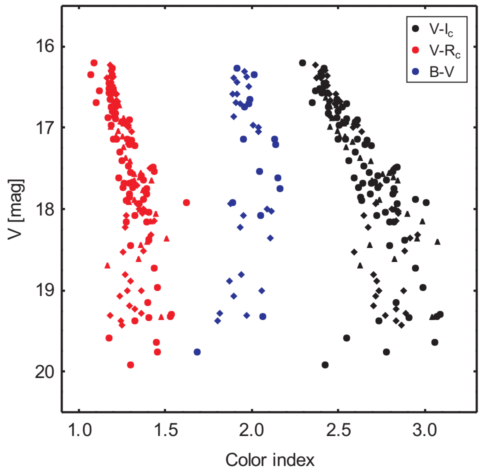

Fig. 3 Color indices versus the V magnitude of Var. 1. The symbols featured are the same as those in Fig. 2.

constructed three diagrams of color - magnitude, which are displayed in Figure 3. It is seen that the star becomes redder as it fades, and during the deep minima real blueing effect is observed on all diagrams. Most probably, the observed color reverse is caused by the scattered light from small dust grains. In this case, it can be assumed that the ratio of scattered light to direct light increases and the star's color turns bluer.

Our analysis of the collected photometric data of Var. 1 affirms that the observed large amplitude minima in the brightness and the blueing effect in the color-magnitude diagrams are independent evidence of its UXor-type variability. The different shapes and amplitudes of the minima in the star's light curves give grounds to predict a variety of obscuration reasons: massive dust clumps, the precession and inhomogeneous structures of the circumstellar disk, planetesimals at different stages of formation and clouds of protostellar material orbiting in the vicinity of the star.

Another important result from our study of Var. 1 is the identification of previously unknown periodicity in its light variation. We carried out a periodicity search in the photometric behavior of the star by PERIOD04 (Lenz & Breger 2005). Initially, we considered all our data to search for periodicity, but we did not find any reliable one. Using the data received after December 2013, when the star's brightness varies around some intermediate level in maximal light, our time-series analysis indicates

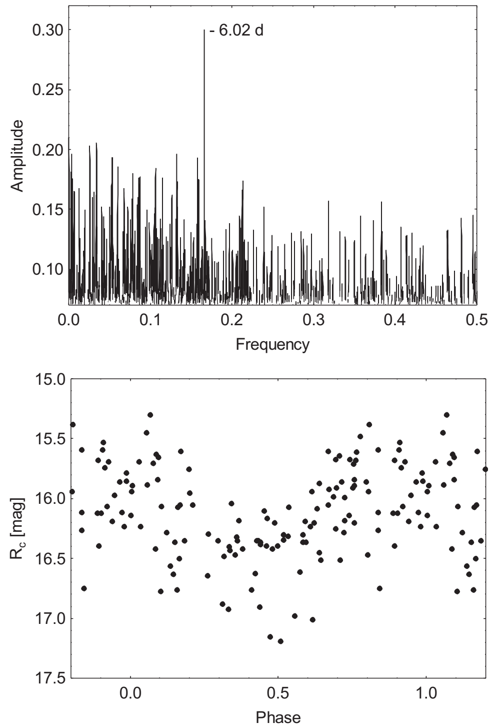

Fig. 4 *Top*: Periodogram analysis of the photometric data of Var. 1. *Bottom*: R_c band phased light curve of the star.

a 6.02^d period. The periodogram analysis of our data on the star and its R_c band phased light curve according to the identified period is plotted in Figure 4. The period remained stable during the time interval of six years and it is a typical rotational period for a young stellar object. Such periodicity could be caused by rotation modulation of cool spots on the stellar surface. According to Herbst et al. (1994), cool spots may last for hundreds or thousands of rotations of the young star, as in the case of Var. 1.

3.2 2MASS J22533629+6231446 (Var. 2 hereafter)

Var. 2 is located at 45 arcsec from V733 Cep and it is embedded in LDN 1216. According to Semkov & Peneva (2008), the star is probably a PMS object. Munari (2009) reported that Var. 2 does not vary on the 1971 - 1978 plates. The star was included in the list of young stellar objects: class II published by Allen et al. (2012).

The $BV(RI)_c$ light curves of Var. 2 from our monitoring are shown in Figure 5. The available data suggest that during our observations the star exhibits strong

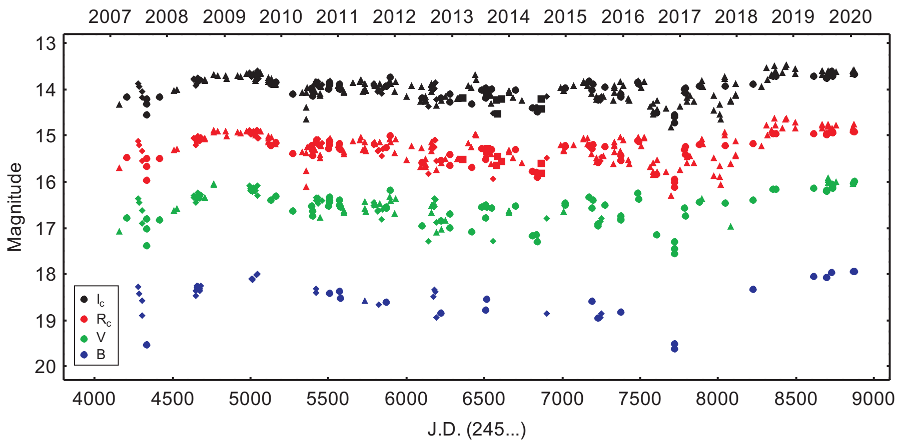

Fig. 5 $BV(RI)_c$ light curves of Var. 2 for the period February 2007 - January 2020. The symbols featured are the same as those in Fig. 2.

irregular variability in all bands. Short-term increases and decreases in the star's brightness are seen during the same period. The reasons for the observed variability of Var. 2 may be different: variable accretion rate, the presence of hot and cool spots on the stellar surface, and irregular obscuration by circumstellar material. Its brightness variation during the whole period of our observations is in the range 13.46-14.82 mag in the I_c band, 14.63–16.30 mag in the R_c band, 15.92-17.54 mag in the V band and 17.94–19.60 mag in the B band. By comparing our mean values of Var. 2 (Table 1) with those of Munari (2009), we get a good match for the I_c and V bands and difference of 0.8 mag for the B band.

The measured color indices versus the V magnitude of Var. 2 are plotted on Figure 6. As can be seen, the star becomes redder as it fades and the color reverse is not observed. Such color variation is typical for both CTTS and WTTSs with the presence of spots or groups of spots on the stellar surface. In case that the decreases in the brightness of Var. 2 are caused by obscuration, the registered amplitudes are too small to show indication of the color reverse. The direct light of the star is not suppressed enough to allow the scattered component to emerge. Evidence of periodicity in the brightness variability of Var. 2 is not detected.

3.3 2MASS J22531578+6235262 (Var. 3 hereafter)

Munari (2009) reported that Var. 3 does not vary in the 1971 - 1978 plates. The star was included in the list of young stellar objects: class III published by Allen et al. (2012).

The $BV(RI)_c$ light curves of the star from our observations are displayed in Figure 7. As can be seen during the period of our monitoring, Var. 3 shows a light variation with small amplitudes in all bands. The observed

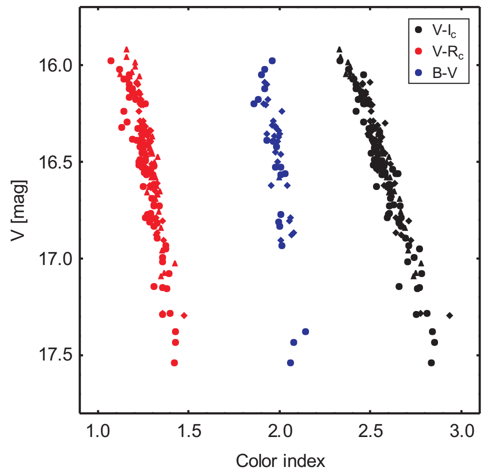

Fig. 6 Color indices versus the V magnitude of Var. 2. The symbols featured are the same as those in Fig. 2.

amplitudes of its variability are ΔI_c=0.57 mag, ΔR_c=0.67 mag and ΔV=0.70 mag. Usually, such low amplitude variability is typical for a low-mass WTTS and it is caused by spots on the stellar surface.

We found that the total brightness of Var. 3 gradually decreases during the whole period of our observations. Using a linear approximation for al- l our data, we calculated the following values for the rate of decreases: 0.92×10^{-2} mag yr^{-1} for the I_c band, 1.23×10^{-2} mag yr^{-1} for the R_c band and 1.13×10^{-2} mag yr^{-1} for the V band. By comparing our mean values of the star (Table 1) with those of Munari (2009), we get a significant difference in all bands. This is an expected result given that the star's total brightness decreases over time.

The measured color indices versus the V magnitude of Var. 3 are plotted in Figure 8. The registered color variation is typical of WTTSs, stars with cool spots, whose

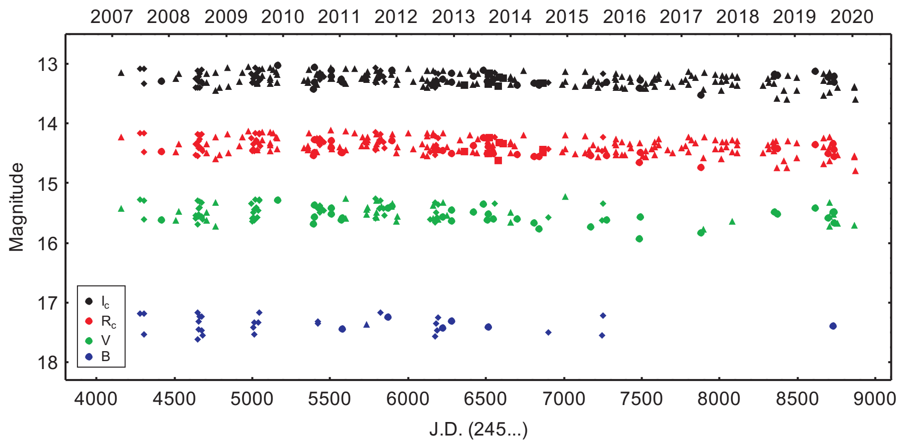

Fig. 7 $BV(RI)_c$ light curves of Var. 3 for the period February 2007 - January 2020. The symbols featured are the same as those in Fig. 2.

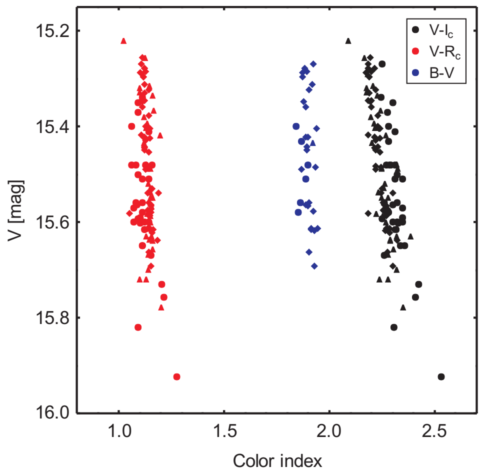

Fig. 8 Color indices versus the V magnitude of Var. 3. The symbols featured are the same as those in Fig. 2.

variability is produced by rotation of the spotted surface. Our time-series analysis of the data on the star indicated a period of 1.5568^d. This result confirms P=1.5565^d given in the ASAS-SN Variable Stars Database (Jayasinghe et al. 2018). The periodogram analysis of the data on Var. 3 and its R_c band phased light curve are plotted in Figure 9. The period remained stable during the whole period of our observations and it is a typical rotational period for a WTTS.

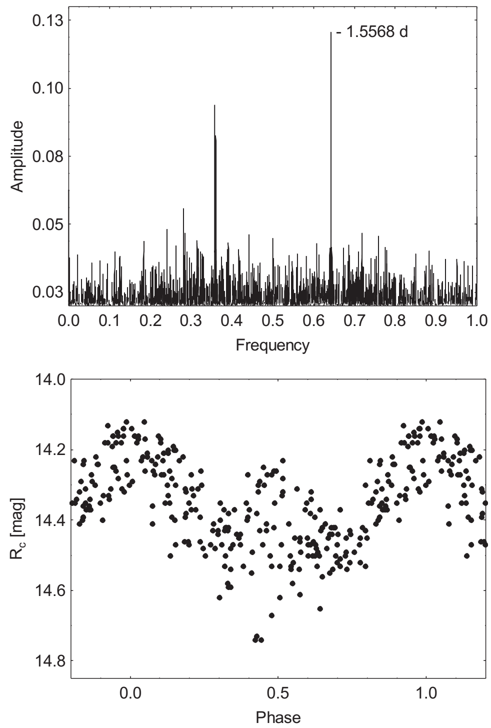

Fig. 9 *Top*: Periodogram analysis of the photometric data of Var. 3. *Bottom*: R_c band phased light curve of the star.

4 CONCLUDING REMARKS

We presented and discussed the optical photometric behavior of three variable PMS stars in the field of the star V733 Cep. Our observations cover 13 years (2007 – 2020) and represent the first long-term CCD photometric monitoring of the investigated objects. The obtained results of our study can be summarized as follows: (i) 2MASS J22534654+6234582 (Var. 1) is a young stellar object and it exhibits light and color variations inherent to UXor-type variability. We found a 6.02^d rotational periodicity in its light variation. (ii) 2MASS J22533629+6231446 (Var. 2) manifests the photometric characteristics of both CTTS and WTTSs. For its exact classification, spectral observations are necessary. (iii) 2MASS J22531578+6235262 (Var. 3) is most probably a WTTS. We confirmed its periodicity given in the ASAS-SN Variable Stars Database.

Table A.1 Photometric CCD Observations of Var. 1

Date	JD (245...)	I_c	R_c	V	B	Tel	CCD
25.02.2007	4157.212	15.41	16.85	18.36	-	Sch	ST-8
10.04.2007	4200.581	16.20	17.75	19.29	-	2-m	VA
27.06.2007	4278.518	15.21	16.59	17.93	19.81	1.3-m	Phot
04.07.2007	4285.523	14.40	15.66	16.86	18.75	1.3-m	Phot
23.07.2007	4305.493	14.13	15.37	16.58	18.50	1.3-m	AND
25.07.2007	4306.511	13.98	15.19	16.38	18.28	1.3-m	AND
15.08.2007	4328.401	14.13	15.34	16.52	-	2-m	VA
17.08.2007	4330.459	13.86	15.08	16.27	18.19	2-m	VA
06.11.2007	4411.214	14.04	15.28	16.46	-	2-m	VA
12.02.2008	4509.229	14.21	15.45	16.64	-	Sch	STL-11
...	...	...	...	...	...	...	...

The three full tables A.1, A.2 and A.3 are available at *http://www.raa-journal.org/docs/Supp/ms4638_2020-0175TableA1A2A3.zip*.

Table A.2 Photometric CCD Observations of Var. 2

Date	JD (245...)	I_c	R_c	V	B	Tel	CCD
25.02.2007	4157.212	14.33	15.71	17.08	-	Sch	ST-8
10.04.2007	4200.581	14.16	15.47	16.77	-	2-m	VA
27.06.2007	4278.518	13.87	15.12	16.36	18.28	1.3-m	Phot
04.07.2007	4285.523	13.93	15.19	16.45	18.43	1.3-m	Phot
23.07.2007	4305.493	14.18	15.54	16.90	18.91	1.3-m	AND
25.07.2007	4306.511	14.05	15.34	16.62	18.58	1.3-m	AND
14.08.2007	4327.400	14.31	15.66	17.02	-	2-m	VA
15.08.2007	4328.401	14.19	15.49	16.79	-	2-m	VA
17.08.2007	4330.459	14.54	15.95	17.38	19.52	2-m	VA
06.11.2007	4411.214	14.16	15.49	16.82	-	2-m	VA
...	...	...	...	...	...	...	...

Table A.3 Photometric CCD observations of Var. 3

Date	JD (245...)	I_c	R_c	V	B	Tel	CCD
25.02.2007	4157.212	13.15	14.22	15.42	-	Sch	ST-8
27.06.2007	4278.518	13.08	14.16	15.27	17.19	1.3-m	Phot
23.07.2007	4305.493	13.34	14.48	15.61	17.53	1.3-m	AND
25.07.2007	4306.511	13.08	14.16	15.29	17.18	1.3-m	AND
06.11.2007	4411.214	13.28	14.46	15.60	-	2-m	VA
12.02.2008	4509.229	13.24	14.47	15.63	-	Sch	STL-11
29.02.2008	4526.300	13.16	14.35	15.48	-	Sch	STL-11
15.06.2008	4632.578	13.40	14.53	15.58	-	1.3-m	AND
20.06.2008	4638.418	13.24	14.35	15.54	-	1.3-m	AND
29.06.2008	4646.523	13.39	14.54	15.69	17.62	1.3-m	AND
...	...	...	...	...	...	...	...

Appendix A: $BV(RI)_C$ PHOTOMETRIC DATA OF VAR. 1, VAR. 2 AND VAR. 3

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