Long-term $V(RI)_c$ CCD photometry of pre-main-sequence stars in the association Cepheus OB3[⋆]

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Abstract Results from optical CCD photometric observations of 13 pre-main-sequence stars collected during the period from February 2007 to November 2020 are presented. These stars are located in the association Cepheus OB3, in the field of the young star V733 Cephei. Photometric observations, especially concerning the long-term variability of the stars, are missing in the literature. We present the first long-term $V(RI)_c$ monitoring for them, that cover 13 years. Results from our study indicate that all of the investigated stars manifest strong photometric variability. The presented paper is a part of our program for the photometric study of pre-main-sequence stars located in active star-forming regions.

Key words: stars: pre-main sequence — stars: variables: T Tauri, Herbig Ae/Be — techniques: photometric — methods: observational, data analysis — stars: individual

1 INTRODUCTION

Pre-main-sequence (PMS) stars are frequently found in associations with dense molecular clouds. One such association is Cepheus OB3 (Cep OB3), which is located in the region between R.A. 22^h44^m to 23^h08^m and Dec. $+61°$ to $+64°$ (Blaauw et al. 1959).

The distance to this association was determined as 725 pc by Blaauw et al. (1959) and as 900 ± 100 pc by Moreno-Corral et al. (1993). The star-formation process in Cep OB3 was studied in detail by many authors (e.g., see Sargent 1979; Moreno-Corral et al. 1993; Naylor & Fabian 1999; Mikami & Ogura 2001; Pozzo et al. 2003; Allen et al. 2012; Huang et al. 2014).

One of the most important features of PMS stars is their photometric variability. Both main classes of PMS stars − the low-mass ($M \leq 2\,M_\odot$) T Tauri stars (TTSs) and the more massive ($2\,M_\odot \leq M \leq 8\,M_\odot$) Herbig Ae/Be stars (HAEBES) exhibit various types of light variations. Generally, TTSs are separated into two subgroups: classical T Tauri stars (CTTSs) and weak-line T Tauri stars (WTTSs). Most of the features that characterize each subgroup suggest that spacious

circumstellar accretion disks surround CTTSs, whereas they must have almost disappeared (or at least their inner parts) in WTTSs (Ménard & Bertout 1999).

CTTSs often show irregular variability (with photometric amplitudes up to 2–3 mag), associated with variable accretion rate from the circumstellar disk onto the stellar surface. The brightness variations of CTTSs also might be due to spots moving as the star rotates on the stellar surface (Herbst et al. 2007). A classification scheme for CTTSs based on the light curve shape was proposed by Ismailov (2005). The photometric variability of WTTSs is due to cool spots or groups of spots on the stellar surface. Amplitudes of this variability are about 0.03–0.3 mag, but in extreme cases can reach 0.8 mag in the V-band.

In some PMS stars, large amplitude dips in the brightness (reaching up to 3 mag in the V band) are observed. These dips last from days to some weeks or months, which presumably result from circumstellar dust or cloud obscuration (see Voshchinnikov 1989; Grinin et al. 1991; Herbst et al. 2007). The prototype of this group of PMS objects, named UXors, is UX Orionis (Grinin et al. 1991).

The stars included in the present study were selected from the International Variable Star Index (VSX) database of the American Association of Variable Star Observers (AAVSO, *https://www.aavso.org/*

`vsx/`; checked in June 2020) by exact object type (young stellar object, YSO) and with the first condition that their location is within 25 arcmin of the typical FU Ori star V733 Cep (see Reipurth et al. 2007; Semkov & Peneva 2008; Peneva et al. 2010), because our observations were carried out in the field centered on this star. The second condition was the stars are bright enough for the telescopes and cameras used.

Photometric observations, especially concerning the long-term variability of the monitored stars, are missing in the literature. We present the first long-term $V(RI)_c$ photometry for these stars that cover 13 years. The long-term observations are important for the exact classification and clarifying the nature of the young stars. Some recent studies of PMS stars based on such observations were made by Rigon et al. (2017), Hambálek et al. (2019), Siwak et al. (2019), Semkov et al. (2019), Evitts et al. (2020), Froebrich et al. (2020), Ibryamov et al. (2020), etc.

Section 2 in the present paper gives information about the telescopes and cameras employed. Section 3 describes the obtained results and their analysis. Section 4 provides the conclusion.

2 OBSERVATIONS AND DATA REDUCTION

We obtained photometric observations of the field centered on V733 Cep within the association Cep OB3. The $V(RI)_c$ data presented in this paper were collected in the period from February 2007 to November 2020 with the 50/70-cm Schmidt and the 60-cm Cassegrain telescopes administered by the Rozhen National Astronomical Observatory (Bulgaria). Only one of the stars (2MASS J22533430+6236307) is also visible in the field of view of the 1.3-m Ritchey-Chrétien (RC) telescope of the Skinakas Observatory[1] of the University of Crete (Greece), and we have B data for this star.

The observations were performed with five different types of CCD cameras − SBIG ST-8, SBIG STL-11000M and FLI PL16803 on the 50/70-cm Schmidt telescope, FLI PL09000 on the 60-cm Cassegrain telescope and ANDOR DZ436-BV on the 1.3-m RC telescope. Their technical parameters and specifications are given in Ibryamov et al. (2015). All frames were taken through a standard Johnson−Cousins set of filters. The photometric data were reduced by an IDL software package (standard DAOPHOT subroutine). As a reference, the comparison sequence in the field around V733 Cep reported in Peneva et al. (2010) was used. All data were analyzed applying the same aperture, which was chosen to have a 3 arcsec radius, while the background annulus was taken from 10 to 13 arcsec.

3 RESULTS AND DISCUSSION

The stars from our study are listed in Table 1 in order of increasing right ascension. The table contains the Two Micron All Sky Survey (2MASS) designations, equatorial coordinates, classes and *Gaia* distances of the stars. It can be seen from Table 1 that 10 of the monitored stars are most probably members of the association Cep OB3. There are no *Gaia* distances to two of the stars (2MASS J22515547+6218170 and 2MASS J22543612+6243047), and 2MASS J22545815+6241327 likely is a field star projected beyond the association because the distance to it seriously exceeds the one determined to Cep OB3. Roughly all stars (11) are included in the list of YSOs: class II (PMS star with disk) published by Allen et al. (2012).

Figure 1 features an I_c band image of the vicinity of V733 Cep, where the positions of the stars from our study are marked. The image was obtained with the 50/70-cm Schmidt telescope.

The registered minimal and maximal magnitudes, and the amplitudes of variability in the $V(RI)_c$ bands of the stars are given in Table 2. It is important to mention that our observations were obtained mainly in the R_c and I_c bands. That is why we have fewer V observational points and the registered amplitudes for some stars in the V band are smaller than those in R_c and I_c bands. It can be seen from Table 2 that all stars exhibit brightness variations with large amplitudes. The largest amplitude star is 2MASS J22541742+6236221 (ΔI_c=2.60 mag).

For all stars we constructed color-magnitude ($R_c - I_c/R_c$) diagrams, which are depicted in Figure 2. We utilized the software package PERIOD04 (Lenz & Breger 2005) to search for periodicity in the light variations of the monitored stars. In the following subsections, we discuss the stars in groups that exhibit close photometric behavior.

3.1 2MASS J22515547+6218170 and 2MASS J22545815+6241327

During our monitoring, these stars exhibited rapid brightness variation, whose amplitude is almost the same in different years. Their light curves constructed on the basis of our observations are displayed in Figure 3. The registered photometric amplitudes of the stars are given in Table 2. Usually, variability with such amplitudes is observed in CTTSs and it can be explained by rotational modulation of a spot or group of spots on the stellar surface, as well as by variable accretion rate. Evidence of periodicity in the variability of 2MASS J22515547+6218170 and 2MASS J22545815+6241327 is not detected.

Table 1 Designations, equatorial coordinates and classes of the stars from our study, and the *Gaia* distances to them.

Nr.	2MASS ID[1]	RA$^1_{J2000.0}$	Dec$^1_{J2000.0}$	Class[2]	d (pc)[3]
1	J22515547+6218170	22:51:55.47	+62:18:17.0	-	-
2	J22533129+6237114	22:53:31.30	+62:37:11.4	II	807
3	J22533430+6236307	22:53:34.30	+62:36:30.7	II	819
4	J22534450+6238305	22:53:44.51	+62:38:30.5	II	884
5	J22541742+6236221	22:54:17.43	+62:36:22.1	II	898
6	J22543612+6243047	22:54:36.13	+62:43:04.7	II	-
7	J22545815+6241327	22:54:58.15	+62:41:32.7	II	2624
8	J22550051+6233485	22:55:00.52	+62:33:48.6	II	843
9	J22550590+6234504	22:55:05.90	+62:34:50.5	II	947
10	J22551206+6228169	22:55:12.06	+62:28:16.9	II	897
11	J22551996+6218162	22:55:19.96	+62:18:16.3	-	867
12	J22552178+6237535	22:55:21.79	+62:37:53.6	II	833
13	J22552445+6239137	22:55:24.46	+62:39:13.8	II	953

[1] 2MASS (Skrutskie et al. 2006); [2] Allen et al. (2012); [3] *Gaia* mean distance (Bailer-Jones et al. 2018).

Table 2 The registered minimal and maximal magnitudes, and the amplitudes of variability in the $V(RI)_c$ bands of the stars from our study.

Nr	Star (2MASS ID)	$V_{\min}$	$V_{\max}$	$R_{c_{\min}}$	$R_{c_{\max}}$	$I_{c_{\min}}$	$I_{c_{\max}}$	ΔV	ΔR_c	ΔI_c
1	J22515547+6218170	18.82	17.72	17.39	16.32	15.83	14.95	1.10	1.07	0.88
2	J22533129+6237114	19.66	18.51	18.69	17.11	16.87	15.64	1.15	1.58	1.23
3	J22533430+6236307	20.17	17.93	18.62	16.51	16.82	15.12	2.24	2.11	1.70
4	J22534450+6238305	17.38	15.09	16.01	13.76	14.71	12.85	2.29	2.25	1.86
5	J22541742+6236221	19.38	18.82	19.48	16.89	18.26	15.66	0.56	2.59	2.60
6	J22543612+6243047	19.01	18.14	18.89	16.77	17.01	15.28	0.87	2.12	1.73
7	J22545815+6241327	19.18	18.22	18.22	17.08	16.49	15.67	0.96	1.14	0.82
8	J22550051+6233485	17.12	15.45	16.14	14.15	14.74	13.06	1.67	1.99	1.68
9	J22550590+6234504	16.76	15.92	15.94	14.62	14.50	13.25	0.84	1.32	1.25
10	J22551206+6228169	19.46	17.98	18.11	16.92	16.45	15.70	1.48	1.19	0.75
11	J22551996+6218162	14.93	14.20	14.39	13.47	13.51	12.75	0.73	0.92	0.76
12	J22552178+6237535	18.49	17.03	17.45	15.85	16.19	14.68	1.46	1.60	1.51
13	J22552445+6239137	19.29	18.39	19.36	17.18	17.54	15.77	0.90	2.18	1.77
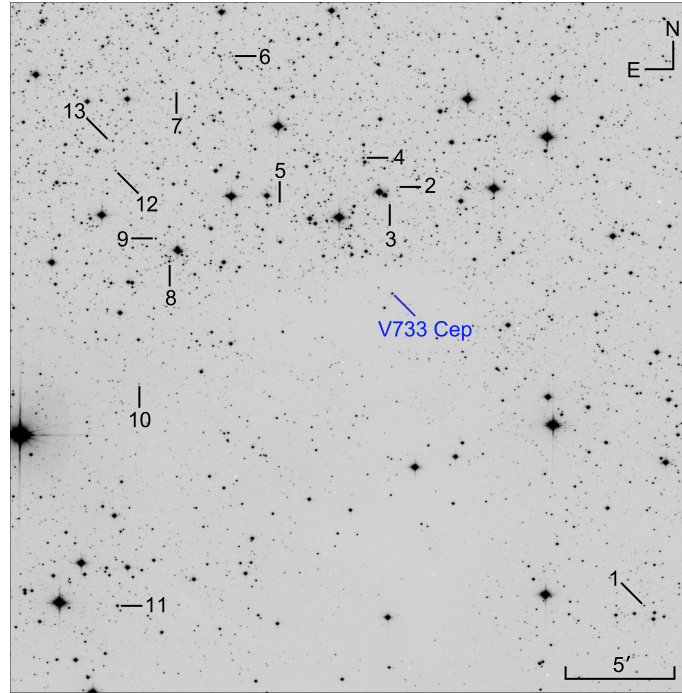
Fig. 1 An I_c band image of the vicinity of V33 Cep obtained with the 50/70-cm Schmidt telescope. The positions of the stars from our study and V733 Cep are marked. The stars are designated using their numbers given in Table 1.
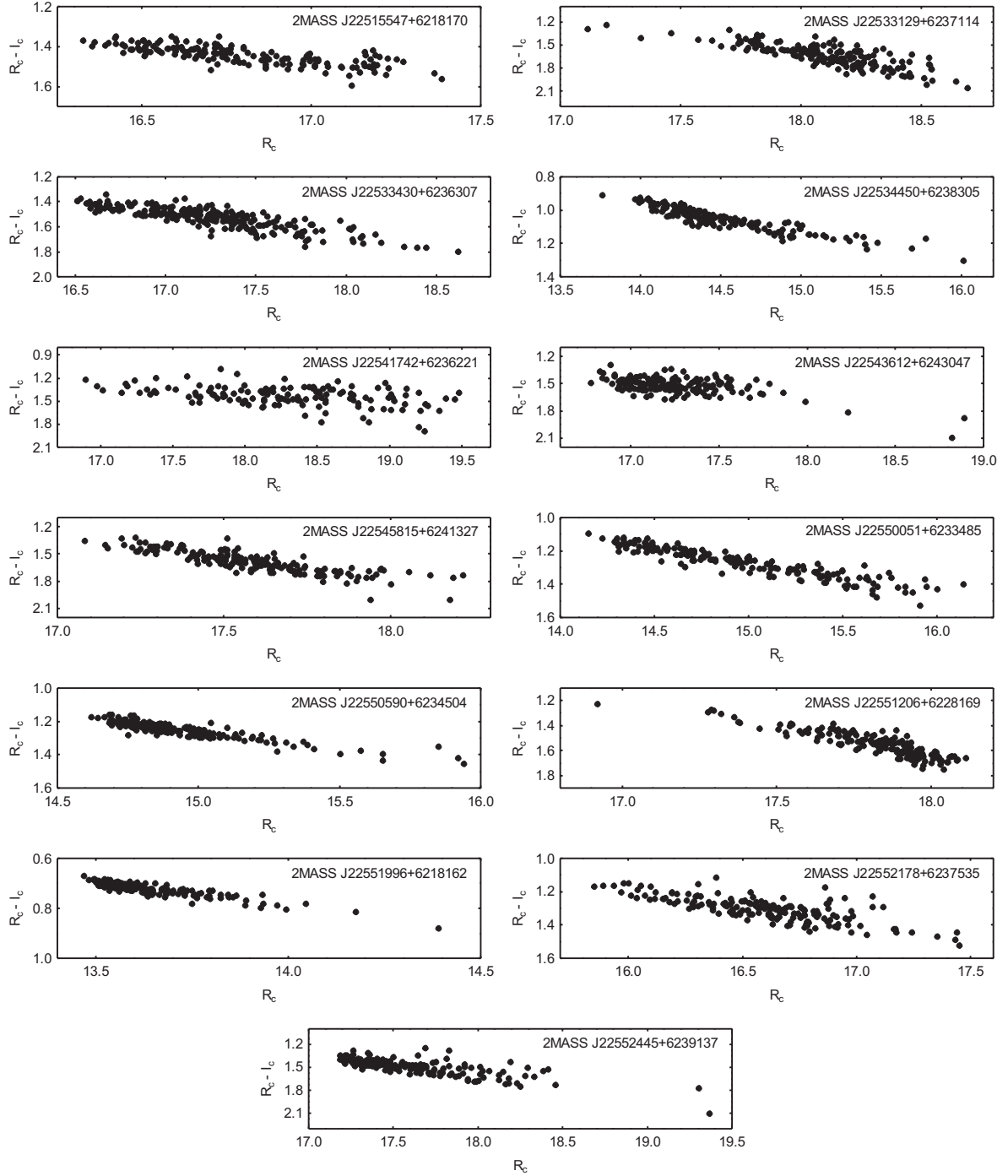
Fig. 2 Color index $R_c - I_c$ versus the stellar R_c magnitude of the stars from our study.

3.2 2MASS J22533129+6237114 and 2MASS J22551206+6228169

These stars manifest photometric variability with sudden increases in brightness. The light curves of the stars are displayed in Figure 4. During our monitoring, clearly distinguishable flare events in the brightness of 2MASS J22533129+6237114 were registered in November 2008, December 2014 and June 2018. Such events in the light

variation of 2MASS J22551206+6228169 were observed in August 2012 and May 2017. These non-periodic flares likely are caused by short-lived accretion-related events on the stellar surface. The time periods of increases in the brightness are relatively short; usually, we have only one photometric point during the flares.

It can be seen from the color-magnitude diagrams (Fig. 2) that the stars become bluer when they increase
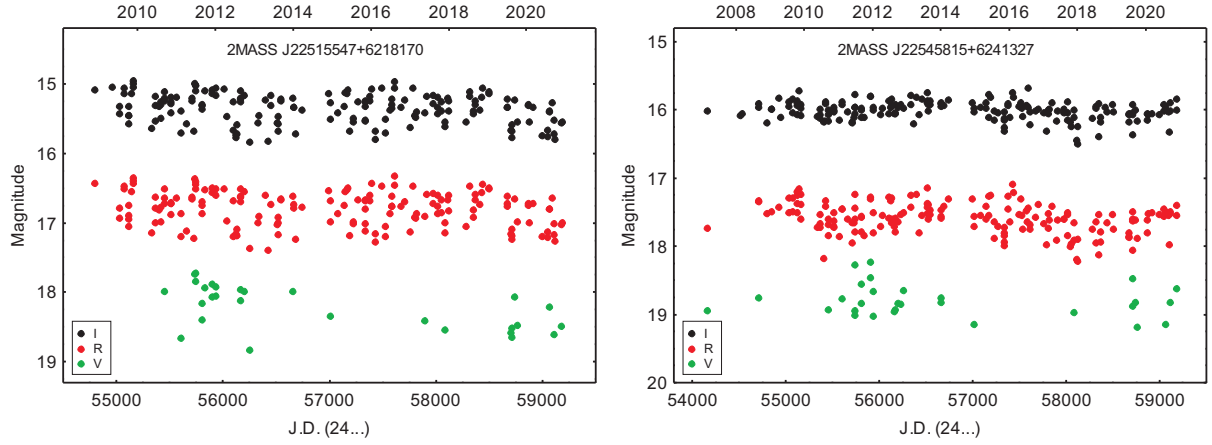
Fig. 3 $V(RI)_c$ light curves of 2MASS J22515547+6218170 and 2MASS J22545815+6241327.
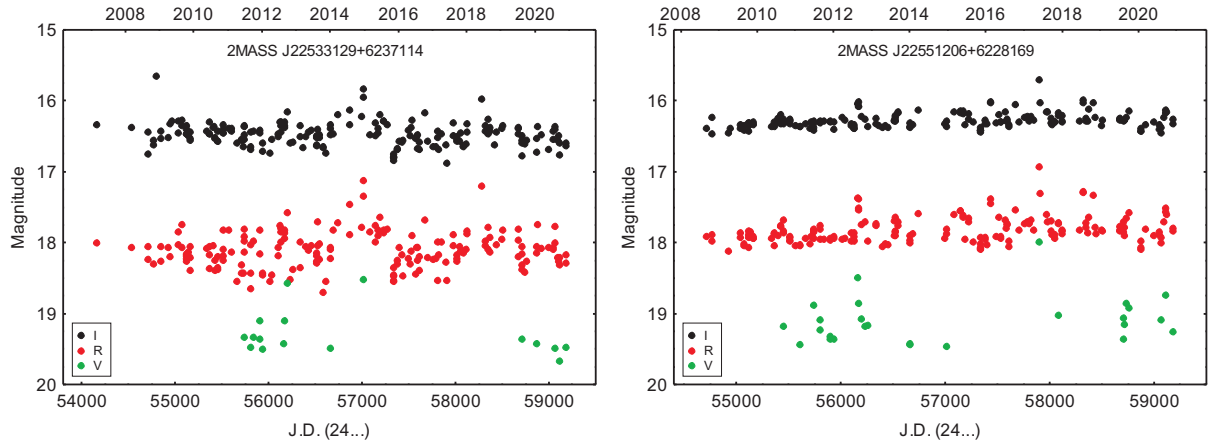

Fig. 4 $V(RI)_c$ light curves of 2MASS J22533129+6237114 and 2MASS J22551206+6228169.

their brightness. Such color variation is also an indication for flare events. Out of the flares, the variability of these stars is probably caused by rotating hot spots on the stellar surface and/or by variable accretion rate from the circumstellar disk. Evidence of periodicity in the variability of 2MASS J22533129+6237114 and 2MASS J22551206+6228169 is not detected.

3.3 2MASS J22533430+6236307, 2MASS J22534450+6238305, 2MASS J22543612+6243047, 2MASS J22550051+6233485, 2MASS J22550590+6234504, 2MASS J22551996+6218162 and 2MASS J22552445+6239137

The photometric behavior of these stars is characterized by strong variability and multiple brightness dips. The light curves of the stars are plotted in Figure 5. The registered amplitudes of the brightness variations of the stars during our monitoring are reported in Table 2. Usually, the large amplitude dips in brightness are an indication of UXor-type variability. In this case, it can be assumed that

one of the reasons for the variability of these stars is the obscuration by circumstellar material. On the other hand, the different shapes, amplitudes and durations of the observed dips provide grounds to predict a variety of reasons for the obscuration, e.g., clouds of proto-stellar material, massive dust clumps orbiting the central star, or planetesimals at different stages of formation.

It is seen from the color−magnitude diagrams (Fig. 2) that the stars become redder as they fade. Such color variations are typical for PMS stars, whose variability is produced by irregular obscuration or the rotational modulation of one or more spots on the stellar surface.

An important result from our study of 2MASS J22533430+6236307 is the identification of previously unknown periodicity in its brightness variation. We found a significant peak in the star's periodogram corresponding to a 11.68 d period. This period remained stable during the whole time of our observations. The phase-folded R_c light curve of the star is displayed in Figure 6.
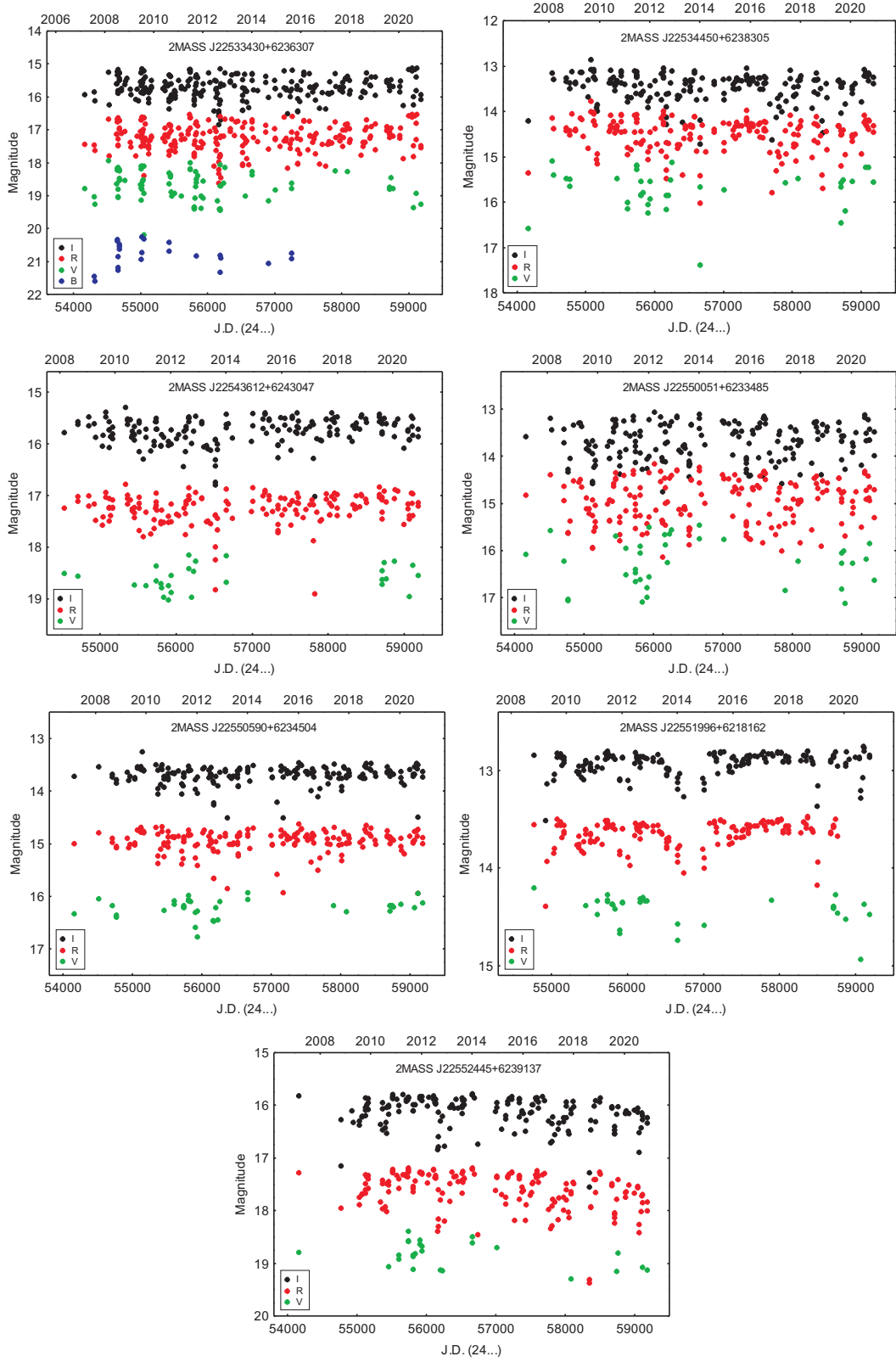
Fig. 5 $V(RI)_c$ light curves of 2MASS J22533430+6236307, 2MASS J22534450+6238305, 2MASS J22543612+6243047, 2MASS J22550051+6233485, 2MASS J22550590+6234504, 2MASS J22551996+6218162 and 2MASS J22552445+6239137.
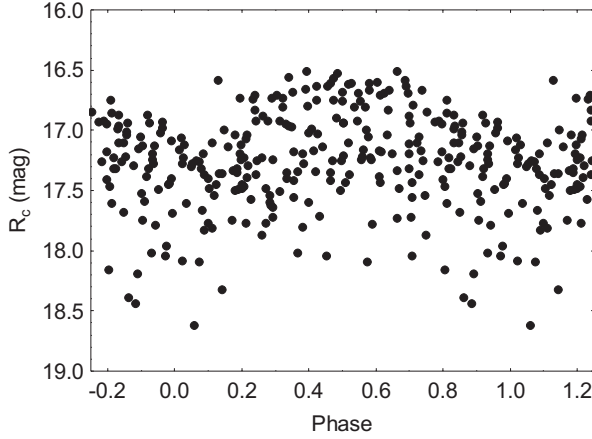
Fig. 6   Phase-folded R_c light curve of 2MASS J22533430+6236307 according to its 11.68 d period.
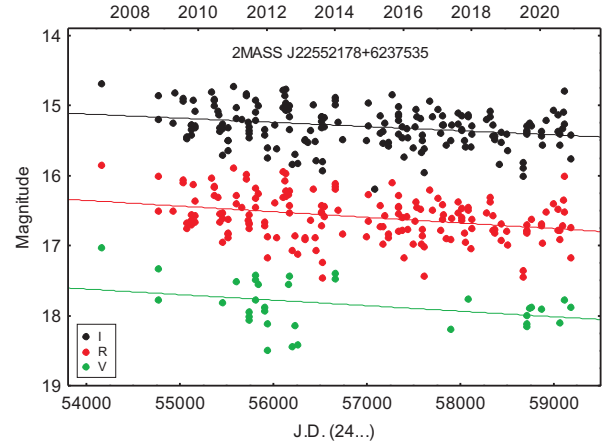

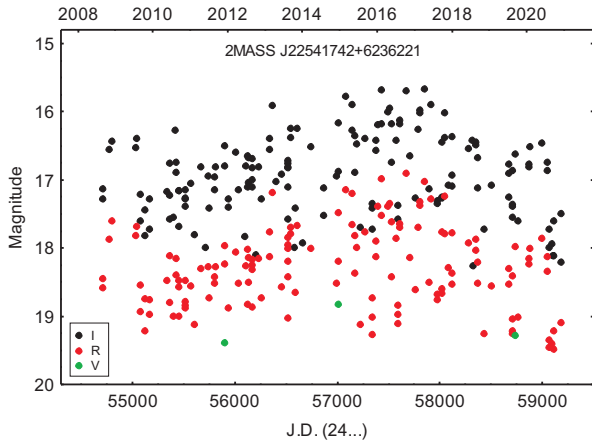**Fig. 8** $V(RI)_c$ light curves of 2MASS J22552178+6237535.

Fig. 7 $V(RI)_c$ light curves of 2MASS J22541742+6236221.

3.4 2MASS J22541742+6236221

During our observations, this star manifested photometric variability with the highest amplitude (ΔI_c=2.60 mag). In its light curves (Fig. 7), both rapid increases and drops are observed. Such strong variability could be caused by highly variable mass accretion from the circumstellar disk onto the stellar surface. Evidence of periodicity in the brightness variation of the star is not detected.

3.5 2MASS J22552178+6237535

This star exhibits irregular variability, whose amplitude is almost the same in different years. Its light curves are depicted in Figure 8. The registered amplitudes of the star's variability are listed in Table 2.

An important result from our study of 2MASS J22552178+6237535 is that the star's total brightness gradually decreases during the whole period of our observations. Using a linear approximation for all data on the star, we calculated the following values for the rates of decrease: 22×10^{-2} mag yr^{-1} for the I_c band, 29×10^{-2} mag yr^{-1} for the R_c band and 29×10^{-2} mag yr^{-1} for the V band. Evidence of reliable periodicity in the variability of 2MASS J22552178+6237535 is not detected.

4 CONCLUSIONS

All monitored objects in the present study show typical behavior for PMS stars in that they display strong photometric variability. The obtained main results for the investigated stars can be summarized as follows: (i) 2MASS J22515547+6218170 and 2MASS J22545815+6241327 exhibit brightness variations, whose amplitude is almost the same in different years; (ii) 2MASS J22533129+6237114 and 2MASS J22551206+6228169 manifest large amplitude flare events; (iii) the photometric behavior of 2MASS J22533430+6236307, 2MASS J22534450+6238305, 2MASS J22543612+6243047, 2MASS J22550051+6233485, 2MASS J22550590+6234504, 2MASS J22551996+6218162 and 2MASS J22552445+6239137 is characterized by strong variability and multiple brightness dips; (iv) 2MASS J22533430+6236307 is identified to have an 11.68 d periodicity in its light variation; (v) the variability of 2MASS J22541742+6236221 likely is caused by the highly variable mass accretion; (vi) the total brightness of 2MASS J22552178+6237535 decreases over time.

Our study adds 13 YSOs with long-term multicolor photometry to the family of known PMS stars. Further regular observations would offer clearer insight into the physical nature of the investigated stars. We plan to continue our photometric monitoring of the field of V733 Cep during the next years.

References

Allen, T. S., Gutermuth, R. A., Kryukova, E., et al. 2012, ApJ, 750, 125

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., et al. 2018, AJ, 156, 58

Blaauw, A., Hiltner, W. A., & Johnson, H. L., 1959, ApJ, 130, 69

Evitts, J. J., Froebrich, D., Scholz, A., et al. 2020, MNRAS, 493, 184

Froebrich, D., Scholz, A., Eislöffel, J., & Stecklum, B. 2020, MNRAS, 497, 4602

Grinin, V. P., Kiselev, N. N., Minikulov, N. Kh., Chernova, G. P., & Voshchinnikov, N. V. 1991, Ap&SS, 186, 283

Hambálek, L., Vaňko, M., Paunzen, E., & Smalley, B. 2019, MNRAS, 483, 1642

Herbst, W., Eislöffel, J., Mundt, R., & Scholz, A. 2007, The Rotation of Young Low-Mass Stars and Brown Dwarfs, in Protostars and Planets V, (eds.,) B. Reipurth, D. Jewitt & K. Keil, (Tucson: University of Arizona Press), 297

Huang, Y.-F., Li, J.-Z., Rector, T. A., & Fan, Z. 2014, RAA (Research in Astronomy and Astrophysics), 14, 1269

Ibryamov, S. I., Semkov, E. H., & Peneva, S. P. 2015, PASA, 32, e021

Ibryamov, S., Semkov, E., Peneva, S., & Gocheva, K. 2020, RAA (Research in Astronomy and Astrophysics), 20, 194

Ismailov, N. Z. 2005, Astronomy Reports, 49, 309

Lenz, P., & Breger, M. 2005, Communications in Asteroseismology, 146, 53

Ménard, F., & Bertout, C., 1999, The Nature of Young solar-Type Stars, in The Origin of Stars and Planetary Systems, eds. C. J. Lada, & N. D. Kylafis (Kluwer Academic Publishers), 341

Mikami, T., & Ogura, K. 2001, Ap&SS, 275, 441

Moreno-Corral, M. A., Chavarria-K., C., de Lara, E., & Wagner, S. 1993, A&A, 273, 619

Naylor, T., & Fabian, A. C. 1999, MNRAS, 302, 714

Ochsenbein, F., Bauer, P., & Marcout, J. 2000, A&AS, 143, 23

Peneva, S. P., Semkov, E. H., Munari, U., & Birkle, K. 2010, A&A, 515, A24

Pozzo, M., Naylor, T., Jeffries, R. D., & Drew, J. E. 2003, MNRAS, 341, 805

Reipurth, B., Aspin, C., Beck, T., et al. 2007, AJ, 133, 1000

Rigon, L., Scholz, A., Anderson, D., & West, R. 2017, MNRAS, 465, 3889

Sargent, A. I. 1979, ApJ, 233, 163

Semkov, E. H., Ibryamov, S. I., & Peneva, S. P. 2019, Serbian Astronomical Journal, 199, 39

Semkov, E. H., & Peneva, S. P. 2008, IBVS, 5831, 1

Siwak, M., Dróżdż, M., Gut, K., Winiarski, M., Ogłoza, W., & Stachowski, G. 2019, Acta Astronomica, 69, 227

Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163

Voshchinnikov, N. V. 1989, Astrofizika, 30, 509