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

Sunay Ibryamov$^1$, Gabriela Zidarova$^1$, Evgeni Semkov$^2$ and Stoyanka Peneva$^2$

$^1$ Department of Physics and Astronomy, University of Shumen, 115, Universitetska Str., 9700 Shumen, Bulgaria; sibryamov@shu.bg

$^2$ Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, 72, Tsarigradsko Shose Blvd., 1784 Sofia, Bulgaria

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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$^h$44$^m$ to 23$^h$08$^m$ and Dec. +61$^\circ$ to +64$^\circ$ (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 are their photometric variability. Both main classes of PMS stars – the low-mass ($M \leq 2 M_\odot$) T Tauri stars (TTs) 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, TTs are separated into two subgroups: classical T Tauri stars (CTTs) and weak-line T Tauri stars (WTTs). 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 WTTs (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 WTTs 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/).
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in order
that all stars exhibit brightness variations with
that 10 of the monitored stars
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of the University of Crete (Greece), and we
features an
sequence in the field around V733 Cep reported in
from 10 to 13 arcsec.
applying the same aperture, which was chosen to have a
technical parameters and specifications are given in
ANDOR DZ436-BV on the 1.3-m RC telescope. Their
data were reduced by an
FLI PL09000 on the 60-cm Cassegrain telescope and
and FLI PL16803 on the 50/70-cm Schmidt telescope,
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 in 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 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.

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.

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, 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 ($\Delta I_c=2.60$ 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.
Evidenve 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 \textit{Gaia} distances to them.

| Nr. | 2MASS ID$^1$ | RA$^{2000.0}$ | Dec$^{2000.0}$ | 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 | 867 |
| 7   | J22545815+6241327 | 22:54:58.15 | +62:41:32.7 | II | 2624 |
| 8   | J22550095+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); $^3$\textit{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) | \(V_{\text{min}}\) | \(V_{\text{max}}\) | \(R_{\text{c, min}}\) | \(R_{\text{c, max}}\) | \(I_{\text{c, min}}\) | \(I_{\text{c, max}}\) | \(\Delta V\) | \(\Delta R_{\text{c}}\) | \(\Delta I_{\text{c}}\) |
|-----|----------------|-------------------|-------------------|-----------------|-----------------|-----------------|-----------------|--------------|----------------|-----------------|
| 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 | 19.73 | 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 | 18.49 | 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   | J22550095+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 | 19.78 | 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.
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...
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.
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3.4 2MASS J22541742+6236221

During our observations, this star manifested photometric variability with the highest amplitude (ΔI\textsubscript{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\textsuperscript{-1} for the I\textsubscript{c} band, 29×10^{-2} mag yr\textsuperscript{-1} for the R\textsubscript{c} band and 29×10^{-2} mag yr\textsuperscript{-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+6234485, 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.
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