Long-term $BVRI$ photometric light curves of 15 PMS stars in the star-forming region IC 5070 *

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Abstract This paper reports results from the multicolor photometric observations of 15 pre-main sequence stars collected in the period September 2010 – October 2017. The stars from our study are located in the star-forming HII region IC 5070. These objects were previously detected as either emission line stars, flare stars, T Tauri variables or Herbig Ae/Be stars. Photometric observations, especially concerning the long-term behavior of the objects, are missing in the literature. We present the first photometric monitoring for all stars from our study. The analysis of the obtained $BVRI$ photometric data allows us to draw the conclusion that all investigated objects are variable stars. In the case of LkHα 146, we identified previously unknown periodicity in its photometric variability.

Key words: stars: pre-main sequence — stars: variables: T Tauri, Herbig Ae/Be — stars: individual (LkHα 137, 2MASS J20504608+4419100, V1956 Cyg, LkHα 141, V1490 Cyg, V1532 Cyg, V1597 Cyg, LkHα 146, LkHα 147, V1598 Cyg, V1492 Cyg, LkHα 161, LkHα 168, LkHα 172, LkHα 173)

1 INTRODUCTION

The North America and Pelican Nebulae (NGC 7000/IC 5070) represent one of the most notable and well-studied active star-forming complexes, where a large number of young pre-main sequence (PMS) stars, cometary nebulae, collimated jets and Herbig-Haro objects can be found (Herbig 1958; Guieu et al. 2009; Rebull et al. 2011 and Bally et al. 2014). Recent major studies of the NGC 7000/IC 5070 complex were made by Rebull et al. (2011), Armond et al. (2011), Zhang et al. (2014), Bally et al. (2014) and Damiani et al. (2017).

One of the most important features of PMS stars is their photometric and spectroscopic variability discovered at the beginning of their study. PMS stars are separated into two types: the low-mass T Tauri stars (TTSs) and the more massive Herbig Ae/Be stars (HAEBESs).

The TTSs exhibit strong irregular photometric variability and emission spectra. TTSs are divided into two subclasses: classical T Tauri stars (CTTSs), still actively accreting from their circumstellar disks, and weak-line T Tauri stars (WTTSs) which show no signs of disk accretion (Ménard & Bertout 1999).

The superpositions of cool and hot spots on the stellar surface, flare-like events, variable mass accretion rate from the circumstellar disk onto the stellar surface, as well as circumstellar dust or cloud obscuration events are possible causes for the observed variability of TTSs (Grinin et al. 1991; Herbst et al. 1994; Ismailov 2005 and Herbst et al. 2007). A review of various classification schemes for photometric variability of young stars can be found in the work of Cody et al. (2014). Ismailov (2005) proposed a classification scheme based on the light curve shape especially for CTTTs.

Unlike TTSs, HAEBESs are less photometrically active and less studied. Detailed descriptions of the ob-
served features of HAEBESs are given in Hillenbrand et al. (1992), Perez & Grady (1997) and Waters & Waelkens (1998). Evidence for stellar winds, jets and mass accretion in HAEBESs was not found (Waters & Waelkens 1998). The variability (if any) of these stars derives from cool spots and/or from the transit of disc clumps. The obscuration events are very likely to be present in most HAEBESs but they can be only registered when the circumstellar disks are located at a small angle with respect to the line of sight (Grinin et al. 1991 and Natta & Whitney 2000). When PMS stars approach the main sequence, they lose their distinctive features and at this stage they are hardly different from main sequence stars.

The stars from our study were selected from the SIMBAD database by exact object types (variable star of Orion type, emission line star, flare star and HAEBES) and with the condition that their location is within 20 arcmin of the well-studied young stellar object (YSO) V2492 Cyg (see Covey et al. 2011; Aspin 2011; Kós pál et al. 2013; Hillenbrand et al. 2013; Giannini et al. 2018 and Ibryamov et al. 2018). Photometric observations, especially concerning the long-term behavior of stars from our study, are missing in the literature. Long-term photometric observations are important for the exact classification of PMS stars. Such observations are directed at the active star-formation fields with the goal of finding and classifying the variability of YSOs embedded in them.

The present paper is a part of our program for the photometric study of PMS stars located in the NGC 7000/IC 5070 star-forming complex. The results from our recent studies have been published in Ibryamov et al. (2015), Ibryamov & Semkov (2016), Semkov et al. (2017) and Ibryamov et al. (2018). Section 2 in the present paper gives information about the process of acquiring photometric observations and data reduction. Section 3 describes the obtained results and their analysis. A conclusion is provided in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

The CCD observations reported in the paper were collected during the time period from September 2010 to October 2017. All CCD observations were obtained with two telescopes — the 50/70-cm Schmidt and the 60-cm Cassegrain — administered by Rozhen National Astronomical Observatory (NAO) in Bulgaria. The number of observational nights used to estimate the brightness of each object is 119.

The observations were performed with two different types of CCD cameras: FLI PL16803 (4096 × 4096 pixels and 9×9 μm pixel−1 size) on the 50/70-cm Schmidt telescope and FLI PL09000 (3056 × 3056 pixels and 12×12 μm pixel−1 size) on the 60-cm Cassegrain telescope. All frames were taken through a standard Johnson–Cousins (BVRI) set of filters. The frames were dark frame subtracted and flat field corrected. The photometric data were reduced using an IDL based DAPHT subroutine. As a reference, the BVRI comparision sequence of 11 stars in the field around V2492 Cyg reported in Ibryamov et al. (2018) was used. All data were analyzed using the same aperture, which was chosen to have a 4 arcsec radius, while the background annulus was taken from 9 to 14 arcsec. The mean value of errors in the reported magnitudes is 0.01–0.02 mag for the I- and R-band data and 0.01–0.03 mag for the V- and B-band data.

3 RESULTS AND DISCUSSION

The stars from our study are listed in Table 1 in order of increasing right ascension. Star identifiers used in this paper are marked in boldface.

Figure 1 shows an image of the field around V2492 Cyg, where the positions of the objects are marked. The minimal and maximal magnitudes and the amplitudes of variability in the BVRI-bands of the stars registered during our photometric monitoring are given in Table 2.

The V magnitude range versus average brightness in the V-band of the investigated objects is shown in Figure 2 (left). The used object designations are the same as in Table 1. It is seen from the figure that there is no apparent correlation between range and average brightness among the objects. The histogram of V magnitude ranges for the objects is shown in Figure 2 (right). Roughly all objects (12) exhibit long-term amplitude variability in the range 0.1 to 0.8 mag. The lowest amplitude star is LkHα 168 (∆V = 0.16 mag). Only three stars have an amplitude of variability larger than 1 mag. They are LkHα 137, V1490 Cyg and V1492 Cyg. The largest amplitude star is V1492 Cyg (∆V = 1.62 mag).

We used the 2MASS (JHKs) magnitudes of the stars from our study to construct a two-color diagram (J − H/H − Ks) to identify stars with infrared excess, indicating the presence of disks around them.
Fig. 1 An image of the field around V2492 Cyg obtained on 2013 September 5 in $R$-band with the 50/70-cm Schmidt telescope at Rozhen NAO. The stars from our study and V2492 Cyg are marked.

Fig. 2 Left: Range in $V$ versus average $V$ mag for stars from our study; Right: Histogram of $V$ mag ranges for stars from our study.

Figure 3 shows the location of the main sequence (the black line) and giant stars (the green line) from Bessell & Brett (1988), and the CTTS locations (the orange line) from Meyer et al. (1997). A correction to the 2MASS photometric system was performed following the prescription of Carpenter (2001). The three parallel dotted lines indicate the direction of interstellar reddening vectors determined for the NGC 7000/IC 5070 star-forming complex by Straižys et al. (2008). In Figure 3, the objects are designated using their numbers given in Table 1.

Using data from our multicolor photometry, we constructed three color–magnitude diagrams ($B - V/V$, $V - R/V$ and $V - I/V$) of the objects, which are dis-
Table 1 Designations and Coordinates of the Stars from Our Study

| Nr | GCVS¹ | HBC² | [KW97]³ | LkHo ⁴ | 2MASS ID⁵ | RA J2000.0 | Dec J2000.0 |
|----|-------|------|--------|--------|------------|------------|------------|
| 1  | 698   | 50–12|        | 137    | J20503703+4418247 | 20 50 37.03 | +44 18 24.7 |
| 2  |       |      |        |        | J20504608+4419100 | 20 50 46.08 | +44 19 10.1 |
| 3  | V1956 Cyg | 702 | 50–22 | 141 | J20505257+4416441 | 20 50 52.57 | +44 16 44.2 |
| 4  | V1490 Cyg | 703 | 50–29 | 146 | J20505378+4421185 | 20 50 53.78 | +44 21 18.5 |
| 5  | V1532 Cyg | 704 | 50–30 | 147 | J20505838+4414444 | 20 50 58.38 | +44 14 44.4 |
| 6  | V1597 Cyg | 705 | 50–30 | 148 | J20510157+4415420 | 20 51 01.57 | +44 15 42.1 |
| 7  | V1598 Cyg | 716 | 50–53 | 161 | J20510393+4411406 | 20 51 03.93 | +44 11 40.6 |
| 8  | V1492 Cyg | 717 | 51–4  | 168 | J20514191+4416082 | 20 51 41.91 | +44 16 08.2 |
| 9  |       | 298 | 51–15 | 172 | J20522676+4417066 | 20 52 26.76 | +44 17 06.6 |
| 10 |       | 316 | 51–16 | 173 | J20522740+4403259 | 20 52 27.40 | +44 03 25.9 |

Notes: Star identifiers used in this paper are marked in boldface. References: ¹ General Catalogue of Variable Stars (Samus' et al. 2017); ² Herbig & Bell (1988); ³ Kohoutek & Wehmeyer (1997); ⁴ Herbig (1958); ⁵ Two Micron All-Sky Survey (2MASS) (Skrutskie et al. 2006).

Table 2 The Registered Minimal and Maximal Magnitudes, and the Amplitudes of Variability in the BVRI-bands of the Stars from Our Study

| Nr  | Star      | Bmin | Bmax | Vmin | Vmax | Rmin | Rmax | Imin | Imax | ∆B  | ∆V  | ∆R  | ∆I  |
|-----|-----------|------|------|------|------|------|------|------|------|-----|-----|-----|-----|
| 1   | LkHo 137  | 18.53| 17.13| 16.64| 15.46| 15.26| 14.25| 13.65| 12.95| 1.40| 1.18| 1.01| 0.70|
| 2   | J2050+4419| 19.35| 18.86| 17.64| 15.45| 15.25| 14.47| 14.27| 14.04| 0.49| 0.40| 0.41| 0.35|
| 3   | V1956 Cyg | 17.46| 17.25| 16.26| 15.45| 15.25| 14.47| 14.27| 14.04| 0.49| 0.40| 0.41| 0.35|
| 4   | LkHo 141  | 17.34| 17.02| 15.79| 15.46| 14.90| 14.46| 13.93| 13.46| 0.32| 0.33| 0.44| 0.47|
| 5   | V1490 Cyg | 18.14| 16.99| 16.84| 15.69| 15.44| 14.91| 13.87| 13.51| 0.76| 0.66| 0.53| 0.36|
| 6   | V1532 Cyg | 18.56| 17.78| 16.80| 16.14| 15.44| 14.91| 13.87| 13.51| 0.76| 0.66| 0.53| 0.36|
| 7   | V1597 Cyg | 18.07| 17.71| 16.34| 15.99| 15.17| 14.76| 13.65| 13.29| 0.36| 0.35| 0.41| 0.36|
| 8   | LkHo 146  | 18.32| 17.58| 16.67| 15.91| 15.58| 14.78| 14.37| 13.68| 0.74| 0.76| 0.80| 0.69|
| 9   | LkHo 147  | 15.99| 15.84| 14.56| 13.45| 13.47| 13.29| 12.21| 12.04| 0.15| 0.21| 0.18| 0.17|
| 10  | V1598 Cyg | 15.27| 14.97| 14.28| 14.01| 13.69| 13.43| 13.13| 12.87| 0.30| 0.27| 0.26| 0.26|
| 11  | V1492 Cyg | 17.85| 16.90| 16.93| 15.31| 15.68| 14.16| 13.59| 13.14| 0.95| 1.62| 1.52| 1.45|
| 12  | LkHo 161  | 18.63| 17.96| 17.13| 16.58| 15.89| 15.39| 14.69| 14.29| 0.66| 0.65| 0.50| 0.40|
| 13  | LkHo 168  | 14.87| 14.75| 13.60| 13.44| 12.78| 12.57| 11.81| 11.68| 0.12| 0.16| 0.21| 0.13|
| 14  | LkHo 172  | 16.19| 16.02| 14.76| 14.54| 13.82| 13.59| 12.83| 12.69| 0.17| 0.22| 0.23| 0.14|
| 15  | LkHo 173  | –    | –    | 17.61| 17.19| 17.00| 16.62| 13.46| 13.30| –   | 0.42| 0.38| 0.16|

played in Figure 4. For all objects we conducted time-series analysis for a periodicity search with the software package PERIOD04 (Lenz & Breger 2005). In the present paper, we discuss the stars in groups with close photometric behaviors and features.

3.1 LkHo 137, V1490 Cyg, LkHo 146 and V1492 Cyg

Unlike the other stars studied in the paper, during our photometric monitoring LkHo 137, V1490 Cyg, LkHo 146 and V1492 Cyg exhibited bigger amplitudes of photometric variability. These objects are included in the list of candidates for YSOs published by Guieu et al. (2009).

The spectrogram of LkHo 137 taken by Herbig (1958) displays bright Hβ and Hγ on a continuous spectrum too weak for classification. According to the author who directly acquired the photographs, the image of LkHo 137 is diffuse, as if it were rather nebulous. Ogura et al. (2002) detected Hα emission in the spectrum of V1490 Cyg. The light curves of LkHo 137, V1490 Cyg,
LkHα 146 and V1492 Cyg constructed on the basis of our observations are plotted in Figure 5.

It can be seen from Figure 5 that LkHα 137 spends most of its time at high light. During our photometric monitoring, one decline in the star’s brightness is registered. The observed drop began in mid-2012 and it reached the biggest depth in April 2013 with amplitude 1.40 mag in the B-band, 1.18 mag in the V-band, 1.01 mag in the R-band and 0.70 mag in the I-band. In May 2013, the star’s brightness returned to the previous high level. The measured color indices (V − I, V − R and B − V) versus the star’s V magnitude are plotted in Figure 4. It can be seen from the figure that the stars become redder as they fade. Such color variations are typical for T Tauri variables, whose variability is produced by small irregular obscuration by the circumstellar material or by the rotational modulation of one or more spots on the stellar surface. Evidence of periodicity in the brightness variability of V1490 Cyg and V1492 Cyg is not detected.

LkHα 146 shows both active states with high amplitude and quiet states with lower amplitude, at the same brightness level. The registered amplitudes of brightness variations for the star during our photometric monitoring are given in Table 2. An important result from our study of LkHα 146 is the identification of previously unknown periodicity in its photometric behavior.

In Figure 6, we show the obtained periodogram using all data in the R-band of the star. We found a significant peak in the periodogram corresponding to a 7.365 d period. False Alarm Probability estimation was done by randomly deleting about 10% of the data approximately 20 times and then redetermining the period. The period remained stable during the whole time of our observations (2010–2017), even when a subsample with 20% of the data was removed. The phase-folded light curve of LkHα 146 in the R-band according to a 7.365 d period is also plotted in Figure 6. The period we found is a typical rotational period for a young low-mass star. The pe-
Fig. 4 Color indices ($V - I$, $V - R$ and $B - V$) versus stellar $V$-magnitude of stars from our study.
riodicity could be caused by rotation modulation of dark spots on the stellar surface. According to Herbst et al. (1994), dark spots may last for hundreds or thousands of rotations of the star, as in the case of LkHα 146.

3.2 2MASS J20504608+4419100, V1597 Cyg, V1598 Cyg and V1956 Cyg

In the literature, these objects were reported as flare stars. 2MASS J20504608+4419100 was discovered and classified as a flare star by Jankovics et al. (1980). The authors reported a flare event on 1979 August 28 when the brightness of the star increased with an amplitude of 3.2 mag in U-light. Erastova & Tsvetkov (1974) reported a flare event on 1973 August 24 in V1597 Cyg when the star’s brightness increased with an amplitude of 3.0 mag in U-light. Tsvetkov et al. (1974) registered a flare event on 1972 August 16 in the photometric behavior of V1598 Cyg with an amplitude of 1.7 mag in U-light. Rosino et al. (1987) also reported a flare event for V1598 Cyg on 1972 October 5 with an amplitude of 2.6 mag in U-light. Kőspál et al. (2011) used V1598 Cyg as one of the comparison stars in their study of VSX J205126.1+440523 (V2492 Cyg). V1956 Cyg was classified as a flare star by Tsvetkov & Tsvetkova (1990).

During our photometric monitoring, we did not register flare events in these stars. Our negative result does not mean that these objects do not show flares. Our mode of observation (about 100 estimations for ~2550 nights) did not allow for the detection of any flares. To detect flares, it is necessary to undertake continuous monitoring for several tens of nights with time resolution of a few seconds.

BVRI light curves of 2MASS J20504608+4419100, V1597 Cyg, V1598 Cyg and V1956 Cyg are plotted in Figure 7. The registered amplitudes of variability for these stars are given in Table 2. It can be seen that these objects exhibit no significant photometric variability. On the 2MASS diagram (Fig. 3), these objects are located in different areas – 2MASS J20504608+4419100 and V1597 Cyg lie above the CTTS line while V1598 Cyg and V1956 Cyg lie close to both the main sequence line...
and the giant star line. It is possible for V1598 Cyg and V1956 Cyg to be field stars projected in the front of the NGC 7000/IC 5070 complex. Using the data from our photometric observations, it is very difficult to classify these stars. Evidence of periodicity in their brightness variability is not detected.

3.3 LkH\(\alpha\) 141, V1532 Cyg, LkH\(\alpha\) 161, LkH\(\alpha\) 172 and LkH\(\alpha\) 173

These objects are included in the list of H\(\alpha\) emission-line stars published by Herbig (1958). Guieu et al. (2009) included these stars in their list of YSO candidates. The spectrogram of LkH\(\alpha\) 172 taken by Herbig (1958) shows an absorption spectrum of intermediate or late G type, with a rather strong emission at H\(\beta\). According to the author, emission may also be present at H\(\gamma\). Terranegra et al. (1994) determined the spectral type of LkH\(\alpha\) 172 as G3 III.

The results from our photometric monitoring indicate that LkH\(\alpha\) 141, V1532 Cyg, LkH\(\alpha\) 161, LkH\(\alpha\) 172 and LkH\(\alpha\) 173 show photometric variability with small amplitudes. The registered amplitudes of variability for the stars from the current selection are given in Table 2. \(BVRI\) light curves of LkH\(\alpha\) 141, V1532 Cyg, LkH\(\alpha\) 161, LkH\(\alpha\) 172 and LkH\(\alpha\) 173 are plotted on Figure 8. On the 2MASS color—color diagram (Fig. 3) the objects are located close to the CTTSs line. These stars have infrared excess indicating the presence of circumstellar disks around them. The brightness variability of the objects is probably caused by variations in the mass accretion rate and/or modulation of the stellar brightness in the presence of spot(s) on the stellar surface. The registered amplitudes of photometric variability also confirm this suspicion (see Herbst et al. 1994). Evidence of periodicity in the brightness variability of these stars is not detected.

3.4 LkH\(\alpha\) 147 and LkH\(\alpha\) 168

In the literature, LkH\(\alpha\) 147 and LkH\(\alpha\) 168 are classified as HAEBESs. The spectrogram of LkH\(\alpha\) 147 taken in 1957 by Herbig (1958) shows an essentially continuous spectrum with emission at H\(\beta\). According to the author, although no definite spectral type can be assigned, there is no doubt that this is an early-type star. Hernández et al. (2004) classified LkH\(\alpha\) 147 as an HAEBES and estimated its spectral type as B2. Herbst & Shevchenko (1999) included the star in their list of HAEBES and measured \(V = 14.45, B - V = 1.50\) and \(V - R = 1.61\) mag of the object during the time period 2450007–2450017 (JD).

According to Herbig (1958), the spectral type of LkH\(\alpha\) 168 is intermediate or late B, with no emission apparent in the photographic region on a 1954 plate. Chavarría-K. et al. (1989) concluded the spec-
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Fig. 7 Multicolor light curves of 2MASS J20504608+4419100, V1597 Cyg, V1598 Cyg and V1956 Cyg.

Central type of the star is F8-G0. According to the authors, LkHα 168 has a warm circumstellar dust envelope of ~1000 K and the star shows signs of photometric variability. Shevchenko et al. (1993) defined the spectral type of LkHα 168 as A8-F2e. Herbst & Shevchenko (1999) included the star in their list of HAEBES and measured \( V = 13.48, U-B = 1.05, B-V = 1.25 \) and \( V-R = 1.21 \) mag of the object during the time period 2446255–2450017 (JD).

\( BVRI \) light curves of LkHα 147 and LkHα 168 are plotted in Figure 9. During our photometric monitoring, these objects showed no significant photometric variability. We registered \( V = 14.44, U-B = 1.46, V-R = 1.06 \) and \( V-I = 2.31 \) mag for LkHα 147, and \( V = 13.54, B-V = 1.28, V-R = 0.84 \) and \( V-I = 1.79 \) mag for LkHα 168.

Our estimations of light and color indexes for LkHα 147 and LkHα 168 are very close to the estimations from the work of Herbst & Shevchenko (1999). There is only a significant difference in \( V-R \) values for the two stars.

Probably, the reason for this distinction is that the \( V-R \) color index is in the Johnson system in the work of Herbst & Shevchenko (1999), and in the Cousins system in the present paper. We used the transformation described in Fernie (1983) and we obtained, for \( V-R \) color index from the work of Herbst & Shevchenko (1999), the value 1.06 mag for LkHα 147 and 0.85 mag for LkHα 168. Apparently, the obtained values for \( V-R \) color index after the transformation coincide with the ones in the present paper.

On the 2MASS diagram (Fig. 3), LkHα 147 is located close to the main sequence line while LkHα 168 lies on the CTTS line. Evidence of periodicity in the brightness variability of these stars is not detected.

4 CONCLUDING REMARKS

We reported the \( BVRI \) photometric behavior of 15 PMS stars around V2492 Cyg in the star-forming region IC 5070. Our observations cover a 7-year time span (2010–2017) and represent the first long-term pho-
Fig. 8 Multicolor light curves of LkHα 141, V1532 Cyg, LkHα 161, LkHα 172 and LkHα 173.

Fig. 9 Multicolor light curves of LkHα 147 and LkHα 168.
photometric monitoring of the investigated objects. The obtained results can be summarized as follows: (i) LkHα 137, V1490 Cyg, LkHα 146 and V1492 Cyg show bigger amplitudes of photometric variability among the objects from our study. The results indicate that these stars are probably CTTSs; (ii) although 2MASS J20504608+4419100, V1597 Cyg, V1598 Cyg and V1956 Cyg were classified as flare stars in the literature, we did not register any such events. Our negative result does not mean that these objects do not exhibit flares; (iii) during our photometric monitoring, LkHα 141, V1532 Cyg, LkHα 147, LkHα 161, LkHα 168, LkHα 172 and LkHα 173 display no significant photometric variability; (iv) for LkHα 146 we identified a 7.365 d rotational periodicity in its photometric behavior.

Further photometric and spectral observations would offer clearer insight into the physical nature of the objects from our study.

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