LONG-TERM OPTICAL PHOTOMETRIC MONITORING OF THE FUOR STAR V900 MON

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SUMMARY: We present results from photometric monitoring of V900 Mon, one of the newly discovered and still under-studied object from the FU Orionis type. The FUor phenomenon is very rarely observed, but it is essential for stellar evolution. Since we only know about twenty stars of this type, the study of each new object is very important for our knowledge. Our data were obtained in optical spectral region with the BVRI Johnson-Cousins set of filters during the period from September 2011 to April 2021. In order to follow the photometric history of the object, we measured its stellar magnitudes on available plates from the Mikulski Archive for Space Telescopes. The collected archival data suggest that the rise in brightness of V900 Mon began after January 1989 and the outburst goes on so far. In November 2009, when the outburst was registered, the star had already reached the level of brightness close to the current one. Our observations indicate that during the period 2011-2017 the stellar magnitude increased gradually in each pass band. The observed amplitude of the outburst is about 4 magnitudes (R). During the last three years, the increase in brightness has stopped and there has even been a slight decline. The comparison of light curves of the known FUor objects shows that they are very diverse and are rarely repeated. However, the photometric data we have so far show that V900 Mon’s light curve is somewhat similar to those of V1515 Cyg and V733 Cep.

Key words. Stars: pre-main sequence – Stars: variables: T Tauri, Herbig Ae/Be – Stars: individual: V900 Mon

1. INTRODUCTION

One of the main characteristics of the young stellar objects is their photometric variability. In fact, most of the pre-main sequence (PMS) stars show variations in brightness that are associated with the evolutionary processes. The PMS stars that undergo episodic outbursts with large amplitudes can be divided into two types: FUors and EXors (Herbig 1989). The common factor between the two types of eruptive phenomena is that they are observed on T Tauri stars.

The outburst of FU Orionis occurs in 1936, and for several decades this star remained the only object of this type. Ambartsumian (1971) was first to
draw attention to this object by linking it to the evolution of the PMS stars and he proposed the abbreviation FUor. After the discovery of two new FUor objects - V1057 Cyg and V1515 Cyg, Herbig (1997) defined them as a new class of young eruptive stars. Another dozen FUor objects were assigned to this class of young variables over the next four decades (Reipurth and Aspin 2010, Audard et al. 2014, Connelley and Reipurth 2018). These objects have been classified in terms of a large range of available photometric and spectral properties, but their outbursts are thought to have the same cause: an enhanced accretion rate from the circumstellar disk onto the central star (Hartmann and Kenyon 1996, Herbig 2007). During the outbursts, FUor objects undergo significant increase in their accretion rate from $\sim 10^{-3} M_\odot/yr$ up to $\sim 10^{-4} M_\odot/yr$.

Several reasons are suggested to explain the enhanced accretion rate. The most popular is that the increase is caused by thermal or gravitational instability in the circumstellar disk (Hartmann and Kenyon 1996, Zhu et al. 2009). Another possible triggering mechanisms could be the interactions of the circumstellar disk with a planet or nearby stellar companion on an eccentric orbit (Lodato and Clarke 2004, Reipurth and Aspin 2004, Pfalzner 2008) and in fall of clumps of material formed by the disk fragmentation onto the central star (Vorobyov and Basu 2005, Vorobyov et al. 2021).

Our experience in studying FUor objects shows that the outbursts can last for several decades or even a century. As a rule, it is considered that the time to increase the brightness is much shorter than the time to decrease it. All known FUors share the same defining characteristics: location in star-forming regions, association with reflection nebulae, a 4-6 mag. outburst amplitude, an F-G supergiant spectrum during the outbursts, a strong Li I 6707 Å line in absorption, and CO bands in near-infrared spectra (Herbig 1997, Reipurth and Aspin 2010). An important feature of FUors is the massive supersonic wind observed as a P Cyg profile, most commonly for both the H and Na I D lines.

The first three, also called classical FUor objects (FU Ori, V1515 Cyg and V1057 Cyg) are well-studied and their light curves are published in the literature (Clarke et al. 2005, Kopatskaya et al. 2013). Due to the large-scale optical and infrared monitoring programs carried out in several observatories and the contributions of amateur astronomers, some new objects have been observed to undergo outbursts with large amplitude: V733 Cep (Reipurth et al. 2007, Peneva et al. 2010), V2493 Cyg (Semkov et al. 2010, 2012, Miller et al. 2011), V2492 Cyg (Aspin 2011, Hillenbrand et al. 2013, Kóspál et al. 2013), V2494 Cyg (Aspin et al. 2009), V2495 Cyg (Mohssenian et al. 2006), V582 Aur (Semkov et al. 2013, Ábrahám et al. 2018), V2775 Ori (Fischer et al. 2012), V900 Mon (Reipurth et al. 2012), V900 Mon (Hillenbrand et al. 2013, Kóspál et al. 2015), Gaia 18bpy (Hillenbrand et al. 2018), Gaia 18bvy (Szegedi-Elek et al. 2020). Due to the very small number of known FUor objects, each newly discovered attracts significant attention.

The detection of a new eruptive star in Monoceros (LDN 1656 cloud) has been reported by the amateur astronomer Jim Thommes (Thommes et al. 2011). According to the General Catalog of Variable Stars, the new variable is defined by designation – V900 Mon (Fig. 1). Reipurth et al. (2012) performed detailed multi-wavelength study of V900 Mon and find significant similarities with objects from the group of FUors. According to the authors, the outburst of V900 Mon occurred between 1953 and 2009 and its luminosity is $106 L_\odot$ at distance of 1100 pc. Reipurth et al. (2012) also suggest that V900 Mon is a Class I source and the spectrum of the object is very similar to those of the classical prototype FU Orionis. The spectrum of V900 Mon in the infrared region is much later than in the optical. Also, the characteristic deep infrared CO bandhead absorption and the lithium Li I 6707 Å line, which is typical of young stars, are observed in case of V900 Mon.

Fig. 1: Color image of V900 Mon obtained with the 2 m RCC telescope in NAO Rozhen. The cometary nebula arising from the star is clearly visible.

Gramajo et al. (2014) model the SED curve of V900 Mon in the 1–200 µm spectral range and estimate the basic parameters of the disk and the envelope of the star. The authors confirm that V900 Mon appears as a Class I source with disk mass 0.1 $M_\odot$ and disk mass accretion rate $2.0 \times 10^{-6} M_\odot$ yr$^{-1}$. They found considerable similarity to those of another eruptive star V1647 Ori after its outburst. In order to study the mass and physical parameters of the envelope around V900 Mon, Kóspál et al. (2017) measured the $^{12}$CO and $^{13}$CO lines using the FLASH$^+$ receiver at the APEX telescope. The results indicate that the mass of the envelope is low compared to other FUor objects and V900 Mon is at the end of the Class I evolutionary stage.

Varricatt et al. (2015) observed V900 Mon using the 3.8-m United Kingdom Infrared Telescope with the $L'$ and $M'$ MKO filters. The observations were
made in April and September 2015 and show a slight increase in brightness in the infrared region. In our first paper concerning V900 Mon, we draw attention to the observed increase in brightness in the optical range during the period 2011-2016 (Semkov et al. 2017b). No other optical photometric data have been published since the outburst of V900 Mon was detected in 2009 and the object joined the FUors group.

Recently, data from observations of V900 Mon using ALMA array were published in two papers (Takami et al. 2019, Hales et al. 2020). The presence of an extended molecular bipolar outflow and a rotating envelope is detected. The disk around V900 Mon is resolved and its radius is set to ~ 50 au. (Kóspál et al. 2020) note the presence of the 10 µm silicate feature in emission that is rather characteristic of Class II sources, but define it as a geometric effect from the high viewing angle.

2. OBSERVATIONS AND DATA REDUCTION

2.1. CCD photometry

The photometric observations of V900 Mon were performed with the 2 m RCC and 50/70 cm Schmidt telescopes of the National Astronomical Observatory Rozhen (Bulgaria) and with the 1.3 m RC telescope of the Skinakas Observatory\(^1\) of the Institute of Astronomy, University of Crete (Greece). Observations were performed with four types of the CCD camera – Vers Array 1300B (1340 × 1300 pixels, 20 × 20 µm/pixel size, scale 0.26 arcmin/pixel) and ANDOR iKon-L BEX2-DD (2048 × 2048 pixels, 13.5 × 13.5 µ m/pixel size, scale 0.17 arcmin/pixel) at the 2-m RCC telescope, ANDOR DZ436-BV (2048 × 2048 pixels, 13.5 × 13.5 µ m/pixel size, scale 0.33 arcmin/pixel) at the 1.3 m RC telescope, and FLI PL16803 (4096 × 4096 pixels, 9 × 9 µ m/pixel size, scale 1.08 arcmin/pixel) at the 50/70 cm Schmidt telescope.\(^2\)

Due to negative Declination, V900 Mon can be observed from southern Europe only in the period September-April. All frames were exposed through a set of standard Johnson-Cousins filters. All the data were analyzed using the same aperture, which was chosen as 2 arcsec in radius, while the background annulus was taken from 9 arcsec to 14 arcsec in order to minimize the light from the surrounding nebulosity. In order to facilitate the process of photometric measurement of the star, we calibrated twelve standard stars in close proximity to it. Standard stars have a wide range of stellar magnitudes (from 13.689 to 17.286 mag in \(I\)-band). In this way, we made it possible to compare the current CCD observations with those from archival photographic plates. Calibration was made during five clear nights in 2011 and 2012 with the 1.3 m RC telescope of the Skinakas Observatory and one night in 2011 with the 2-m RCC telescope of the Rozhen Observatory. Standard stars from Landolt (1992) were used as a reference.

Table 1 contains the \(IRVB\) photometric data for the comparison sequence. The corresponding mean errors in the mean are also listed in the table. The measured stellar magnitudes of standard stars in the \(B\)-band are still uncertain and subject to improvement. The stars are labeled from A to L in order of their \(I\)-band magnitude. In regions of star formation, a great percentage of stars can be photometric variables. Therefore, there is a possibility that some of our standard stars are low amplitude variables, and we advise observers to use our photometric sequence with care.

The finding chart of the comparison sequence is presented in Fig. 2. The field is 8 × 8 arcmin, north is at the top and east is to the left. The chart is retrieved from the STScI Digitized Sky Survey Second Generation Red.

2.2. Data from photographic plates from the Mikulski Archive for Space Telescopes

In order to investigate the photometric history of V900 Mon and to search for the beginning of the outburst, we searched the photographic plate archive of Mikulski Archive for Space Telescopes\(^2\). As a result, we found scanned copies from a total of six photographic plates obtained with the Palomar Schmidt and the UK Schmidt telescopes. The object was identified and measured on four of them. On the other two plates, the object is below the plate limit (XO661) and it is outside the field of the plate (S772). Aperture photometry of the scanned plate copies was performed with DAOPHOT routines using the same aperture radius and the background annulus as for

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\(^1\)Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology - Hellas, and the Max-Planck-Institut für Extraterrestrische Physik.

\(^2\)https://archive.stsci.edu/cgi-bin/dss/plate_finder
3. RESULTS AND DISCUSSION

The results of our photometric CCD observations of V900 Mon are summarized in Table 3. The columns provide the Julian Date of observation, $I R V B$ magnitudes of V900 Mon, the telescope and CCD camera used. The typical instrumental errors in the reported magnitudes are 0.01-0.02 for the $I, R$ and $V$-band, and 0.03 - 0.05 for the $B$-band.

The $B V R I$ light curves of V900 Cyg during the period of our observations are plotted in Fig. 3. The filled diamonds represent the CCD observations from the 50/70 cm Schmidt telescope, the filled squares CCD observations from the 2 m RCC telescope, and the filled triangles the CCD observations from the 1.3 m RC telescope.

The historical $V R I$ light curves of V900 Mon from all available observations are plotted in Fig. 3. Our CCD observations are indicated by the same symbols as in Fig. 3. The filled circles in Fig. 3 represent data from Mikulski Archive for Space Telescopes, listed in this paper. The empty circles represent data from DSS reported in Table 1 of the paper of Reipurth et al. (2012).

Archival data show that before the outburst V900 Mon was variable, which is especially noticeable in the $R$-light. The amplitude of variability is about 1 magnitude, which is a typical variability of T Tauri stars. There are several FUor objects for which the data for photometric variability before the outburst are available (FU Ori, V1057 Cyg, V2493 Cyg, V582 Aur, Gaia 18dvy). They all show non-periodic changes in brightness that proves the affiliation of the prototypes of FUors with the class of T Tauri stars.

The exact time of the beginning of the outburst of V900 Mon cannot be determined now. But it can certainly be concluded that the outburst occurred after January 1989. Due to the lack of data for the period 1989-2011, we cannot determine the rate of increase in brightness and the nature of the light curve before reaching the maximum brightness. The first photometric data for V900 Mon from 2009 and 2010 reported by Thommes et al. (2011) and Reipurth et al. (2012) were obtained in the $g′r′i′z′$ system and are not compatible with our results. Also, these data were obtained with a smaller aperture (1 arcsec), and as noted by Reipurth et al. (2012), the aperture radius is of great importance for the measured value of the stellar magnitudes.

Since the beginning of our observations in 2011, we have been recording a gradual rise in brightness. But during the last three observation seasons (from the end of 2018 to the beginning of 2021), the increase in brightness has stopped and there has even been a slight decline. The increase in brightness is noticeable in all filters, as for the $R$-band it is about 0.5 mag for the eight-year period from 2011 to 2017. Therefore, V900 Mon has reached its maximum brightness during the observation season 2017–2018 and we should expect a decrease in brightness in the coming years. But occasionally it is possible to observe two peaks at maximum brightness, as is the case of V2493 Cyg outburst (Semkov et al. 2012). Whether we have really registered the maximum of the FUor type outburst should be confirmed by subsequent observations.

Long-term photometric data from observations of known FUor objects show a wide variety of light curves. Even the first three classical FUor objects show different rates of increase and decrease in brightness (Clarke et al. 2005). As the number of known FUor objects increases, the diversity of the light curves increases even more. Some objects show a very rapid rise in brightness within a few months or a year (FU Ori, V1057 Cyg, V2493 Cyg) (Clarke et al. 2005, Semkov et al. 2012). In others, the rise in brightness can take several years and even achieves to 20-30 years period (V1515 Cyg, V1735 Cyg, V733 Cep) (Clarke et al. 2005, Peneva et al. 2009, 2010).

Such diversity is observed for the periods of decline in brightness. Usually the decline in brightness

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**Table 1**: Photometric data for the $BVRI$ comparison sequence.

| Star | $I$   | $σ_I$ | $R$   | $σ_R$ | $V$   | $σ_V$ | $B$   | $σ_B$ |
|------|-------|-------|-------|-------|-------|-------|-------|-------|
| A    | 13.689| 0.019 | 14.099| 0.019 | 14.551| 0.014 | 15.3  | 0.1   |
| B    | 13.789| 0.025 | 14.183| 0.023 | 14.572| 0.014 | 15.2  | 0.1   |
| C    | 14.471| 0.024 | 15.084| 0.015 | 14.821| 0.014 | 16.8  | 0.1   |
| D    | 14.541| 0.021 | 15.951| 0.019 | 17.258| 0.029 | 19.4  | 0.3   |
| E    | 14.902| 0.026 | 15.525| 0.018 | 16.141| 0.018 | 17.1  | 0.2   |
| F    | 15.948| 0.022 | 16.575| 0.021 | 17.185| 0.046 | 18.1  | 0.2   |
| G    | 15.953| 0.040 | 16.480| 0.021 | 17.167| 0.034 | 18.7  | 0.2   |
| H    | 15.991| 0.077 | 16.764| 0.022 | 17.536| 0.015 | 18.3  | 0.3   |
| I    | 16.076| 0.077 | 16.996| 0.014 | 17.889| 0.042 | 19.4  | 0.3   |
| J    | 16.079| 0.025 | 16.989| 0.036 | 17.726| 0.036 | 18.7  | 0.2   |
| K    | 16.469| 0.055 | 17.465| 0.031 | 18.267| 0.028 | 19.8  | 0.3   |
| L    | 17.286| 0.084 | 18.485| 0.029 | 19.324| 0.105 | 20.0  | 0.4   |
There are also objects that for a period of several years (Takagi et al. 2020), and V582 Aur for which two deep decreases in brightness by about 3 mag are observed. This variety of photometric behavior strongly supports the idea that FUor objects are not a homogenous group and that the causes of this phenomenon can be different. 

### 4. CONCLUSIONS

During the last twenty years, we have undertaken intensive photometric monitoring of several unexplored FUor objects. This data can also be used to...
detect new FUor or EXor events and to determine the type of the outburst. FUors are the most noticeable young variable objects due to large amplitudes and eruptions lasting for years. Due to the small number of such objects, we do not know enough about their photometric history.

The data collected so far for V900 Mon show that it can be classified with confidence as a bona fide FUor. An outburst with an amplitude of 4 magnitudes was registered, which began after 1989. Maximum brightness was observed in the period 2017-2018 after which a decrease in brightness began.

Our results show the need for systematical photometric monitoring of objects of special interest. Collecting more data from observations as well as from astronomical archives can help clarify theories about the early stages of stellar evolution. We support the idea that the type of light curve of a FUor object can be the evidence of a specific cause of its outburst.
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Представљамо резултате фотометријског праћења V900 Mon, једног од новооткривених и још недовољно проучених објеката типа FU Orionis. Феномен FUor је веома ретко посматран али је кључан за еволуцију звезда. Будући да знаемо за само око двадесет звезда овог типа, проучавање сваког новог објекта је веома битно за наше сазнање. Наша посматрања су у оптичком делу спектра са BVRI Џонсон-Кузин филтерима током периода од септембра 2011. до априла 2021. године. Да бисмо пратили фотометријску историју објекта, измерили смо његову звездану магнитуду у доступним снимцима из архиве Микулски за свемирске телескопе. Сакупљени архивски подаци указују да је пораст сјаја V900 Mon почео након јануара 1989. а нагли скок се наставља и даље. У новемbru 2009. године, када је скок регистрован, звезда је већ достигла ниво сјаја близак тренутном. Наша посматрања указују да се током периода 2011-2017. године звездана магнитуда постојано у сваком од посматраних домена. Посматрана амплитуда скока је око 4 магнитуде (R). Током последње три године раст сјаја се зауставио, и чак је дошло до благог опадања. Поређења са познатим кривама сјаја FUor објеката показују велику разноврсност и ретко понављање. Ипак, фотометријски подаци које имамо за сада показују да је крива сјаја V900 Mon донекле слична кривама сјаја V1515 Cyg и V733 Cep.