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Letter to the Editor

Light curves of the latest FUor: Indication of a close binary★

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ABSTRACT

We monitored the recent FUor 2MASS J06593158-0405277 (V960 Mon) since November 2009 at various observatories and multiple wavelengths. After the outburst by nearly 2.9 mag in r around September 2014 the brightness gently fades until April 2015 by nearly 1 mag in U and 0.5 mag in z. Thereafter the brightness at $\lambda > 5000$ Å was constant until June 2015 while the shortest wavelengths (U, B) indicate a new rise, similar to that seen for the FUor V2493 Cyg (HBC722). Our near-infrared (NIR) monitoring between December 2014 and April 2015 shows a smaller outburst amplitude (∼2 mag) and a smaller (0.2–0.3 mag) post-outburst brightness decline. Optical and NIR color–magnitude diagrams indicate that the brightness decline is caused by growing extinction. The post-outburst light curves are modulated by an oscillating color-neutral pattern with a period of about 17 days and an amplitude declining from ∼0.08 mag in October 2014 to ∼0.04 mag in May 2015. The properties of the oscillating pattern lead us to suggest the presence of a close binary with eccentric orbit.

Key words. stars: variables: T Tauri, Herbig Ae/Be – binaries: close – stars: individual: 2MASS J06593158-0405277

1. Introduction

Recently Maehara et al. (2014) detected a FUor-type brightness outburst in 2MASS J06593158-0405277, henceforth denoted V960 Mon (Semkov 2015).

Hillenbrand (2014) confirmed the optical spectroscopic results on the P-Cygni line profiles and determined the temperature and gravity. Subsequent near-infrared (NIR) spectra by Reipurth & Connelley (2015) and Pyo et al. (2015) corroborated the FUor nature. These spectra and X-ray spectra by Pooley et al. (2015) indicated low extinction towards the FUor. Hackstein et al. (2014) presented the first multiband monitoring results, revealing that the outburst was about 1 mag brighter than reported by Maehara et al. (2014). Varricatt et al. (2015) reported on the NIR monitoring during December 2014.

After the flood of initial Astronomical Telegrams, Kóspál et al. (2015) presented an almost complete picture of the FUor progenitor. It is likely a young Class II source associated with a group of several other young stellar objets. The FUor progenitor star has a temperature of $T_{\rm eff}$ = 4000 K, a mass of 0.75 $M_\odot$ and an age of about 6×10^5 yr.

Caratti o Garatti et al. (2015) reported on NIR adaptive optics imaging and spectroscopy using VLT/SINFONI. An extended 90 AU disk-like structure was resolved, as were two companions with projected distances of 11 and 100 AU from V960 Mon. Both companions display accretion signatures.

Here we present the first results from multifilter monitoring of V960 Mon. We focus on the full outburst amplitude, the nature of the subsequent brightness decline, and the superimposed color-neutral brightness oscillations.

2. Observations and data

Optical monitoring was carried out at three observatories:

Universitätssternwarte Bochum (USB), Chile: between November 2009 and May 2015 we used the robotic 15 cm Twin Telescope RoBoTT near Cerro Armazones[1]. The observations were obtained in the course of the Bochum Galactic Disk Survey, described in detail by Haas et al. (2012) and Hackstein et al. (2015). V960 Mon was monitored in the Sloan r and i filters, and since October 2014 additionally in the Johnson UBV and Sloan z filters with median sampling of 1 day. The light curves are created using several hundred non-variable stars located in the same field and of similar brightness to V960 Mon. The absolute photometric calibration is based on several standard star fields measured each night.

Konkoly Observatory, Hungary: between December 2014 and March 2015, we monitored V960 Mon in the Johnson-Cousins $BVRI$ filters using the 60/90/180 cm (aperture diameter/primary mirror diameter/focal length) Schmidt telescope. Details about the instrument and the steps of data reduction and photometry are described in Kóspál et al. (2011). We used 110 stars within 10′ of the source as comparison stars.

★ The light curve Table is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/582/L12

[1] http://www.astro.ruhr-uni-bochum.de/astro/oca/

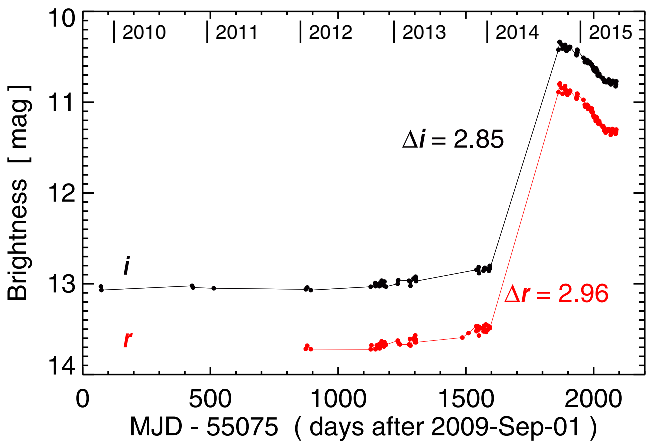

Fig. 1. Sloan r and i light curves of V960 Mon obtained at USB Bochum (USB).

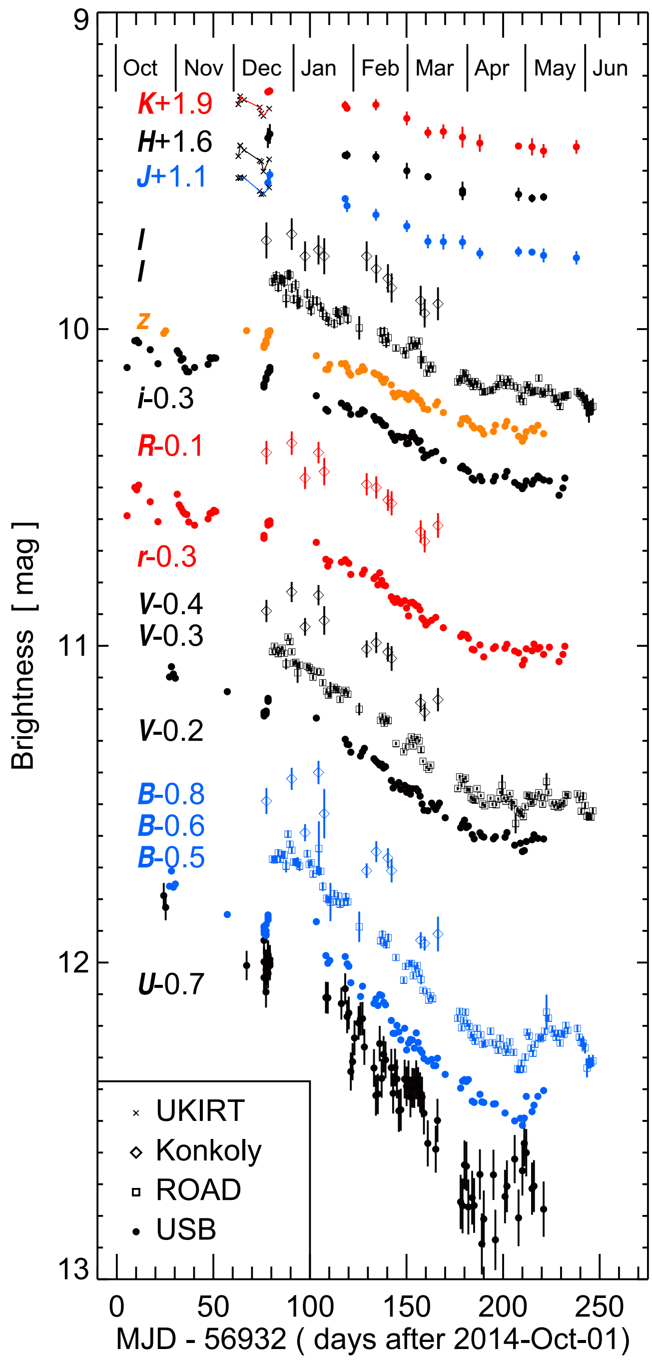

Fig. 2. Post-outburst light curves of V960 Mon.

Photometric calibration was done using the UCAC4 catalog magnitudes of the comparison stars (Zacharias et al. 2013), where we first converted the Sloan r and i magnitudes to Johnson-Cousins R and I magnitudes using the formulae of Jordi et al. (2006).

The Remote Observatory Atacama Desert (ROAD): we performed extensive monitoring using the robotic 40 cm telescope near San Pedro de Atacama (Hambsch 2012). V960 Mon was observed in the Johnson-Cousins *BVI* filters between December 2014 and June 2015 twice per night with median sampling of 1 day. Photometry was obtained relative to two non-variable AAVSO stars located in the same field and which have a similar brightness to V960 Mon.

Near-IR monitoring was performed in J, H, and K_s between December 2014 and April 2015 using the 0.8 m Infrared Imaging System (IRIS, Hodapp et al. 2010) at USB. Images were obtained and reduced in the standard manner. Photometry was obtained relative to 20 non-variable high-quality flag (AAA) 2MASS stars located in the same field.

All light curves are listed in the table at the CDS with the following columns: telescope, date, filter, mag, err. For Sloan filters we use the AB system, for all other filters the Vega mag system. Photometric errors are smaller than 0.015 mag for RoBoTT and ROAD, about 0.02 mag for IRIS, about 0.03–0.04 mag for Konkoly, and about 0.05–0.1 mag for the RoBoTT U-band data.

3. Results and discussion

3.1. Optical and infrared light curves

Figure 1 shows the r and i light curves. Between 11 November 2009 and 17 April 2012, the sparse light curves did not catch any variations larger than 0.05 mag. Thereafter, the denser sampled light curves (median <2 days) show a scatter of up to 0.2 mag amplitude on the time scale of days and a gradual brightness increase until 11 January 2014 to $i = 12.77$ mag and $r = 13.42$ mag. When the target became visible again, on 6 October 2014 the brightness had drastically increased by about 2.6 mag to i = 10.2 mag and $r = 10.75$ mag. The color before the outburst $r - i = 0.65 \pm 0.04$ mag became slightly bluer during and after the outburst $r - i = 0.55 \pm 0.03$ mag.

The observations confirm the outburst of V960 Mon, where a brightening of $I_c = 1.5$ mag was reported in the discovery telegram by Maehara et al. (2014). In contrast to that relatively modest brightening, we find a much stronger brightness outburst by about 2.6 mag between 11 January and 6 October 2014, and in total about 2.9 mag between 2009–2011 and October 2014. This is still below the typical 5 mag brightening of known FUors.

Figure 2 shows the light curves in various bands after the outburst. The main features are as follows:

Between October 2014 and April 2015 the brightness faded by nearly 1 mag in U and 0.5 mag in z. Thereafter the brightness was constant at wavelengths longer than V, while U and B show a turn-over between April and May 2015; this indicates the transition to a brightness rise similar to that seen for V2493 Cyg (Semkov et al. 2014). Until 4 September 2015, however, when V960 Mon became visible again, no strong rise in *BVRI* has been found (B = 13.14, V = 11.87, R = 11.04, I = 10.14, Semkov 2015).

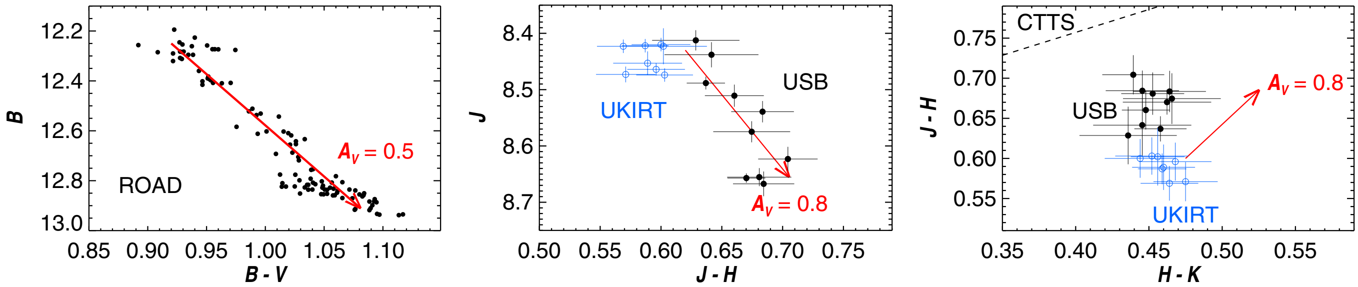

Fig. 3. Post-outburst color–magnitude diagrams at optical and NIR wavelengths. The UKIRT data are from Varricatt et al. (2015). The red arrow shows A_V as labeled (using standard interstellar reddening, Rieke & Lebofsky 1985), the dashed line indicates the domain of classical T Tauri stars.

Our NIR monitoring between December 2014 and April 2015 shows a smaller outburst amplitude (about 2 mag compared to 2MASS, see Kóspál et al. 2015) and a smaller (0.2–0.3 mag) post-outburst brightness decline compared to the optical.

The FUor becomes redder when fading (Sect. 3.2).

The post-outburst light curves are superposed by an oscillating pattern with a period of about 17 days (Sect. 3.3).

For the following discussion we assume that the variations and features in the light curves are due to the FUor, and that the two nearby (11 and 100 AU) companion stars found by Caratti o Garatti et al. (2015) play a negligible role.

3.2. Nature of the brightness decline

Figure 3 shows the color–magnitude diagrams at optical and NIR wavelengths. Our NIR data obtained at USB after 19 December 2014 are supplemented by the eight data points observed with UKIRT between 2 December and 19 December 2014 by Varricatt et al. (2015). The $J-H$ color offset between our data and the Varricatt et al. data is not clear; it could be due to the presence of a reflection nebula or circumstellar dust, measured with different spatial resolution.

The FUor becomes redder when fading, and the orientation of the A_V vector agrees with the elongated distribution of the data points. This also holds for other filter combinations. The NIR data indicate $A_V \approx 1$. Thus, the radiation becomes optically thick at wavelengths shorter than V. In addition a reflection nebula might be present. Both effects could explain why at optical wavelengths the A_V values are smaller than in the NIR (Krügel 2009).

We suggest that the brightness decline between October 2014 and April 2015 is due to increasing extinction caused by dust swirled up by the outburst. Then after April 2015 the extinction growth stopped; one may speculate that during the further evolution of the system holes will be blown into the dust clouds leading to a subsequent re-brightening.

3.3. Nature of the brightness oscillations

The post-outburst light curves are superposed by an oscillating pattern, most visible in Fig. 2 in the r and i bands during the first 50 days. When zooming in, the oscillations are recognizable throughout the entire r, i, and z light curves.

Applying the Lomb-Scargle method (Lomb 1976; Scargle 1982) to the entire r, i, and z light curves reveals a local peak at about 17 days, alongside strong power from the long-term

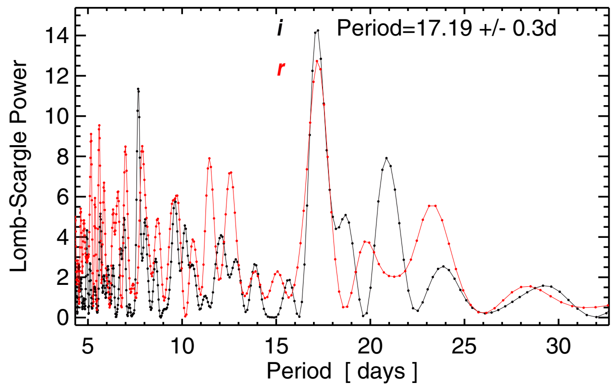

Fig. 4. Lomb-Scargle periodogram of the light curve oscillations in the i and r band after removal of the long-term trend via a third order polynomial. The peak at 17.19 days (determined from a Gaussian fit) has a width of $\sigma = 0.3$ days, and a false alarm probability of ~0.4%.

decline (in Fig. 2). To get rid of this power, we removed the long-term trend trying several fits: a sine function, a third-order polynomial, and a piece-wise linear function consisting of three parts: the high state, the decline, and the transition plateau. For all types of long trend removal, we find a period of about 17.2 days. This period agrees with the results using phase dispersion minimization (PDM, Stellingwerf 1978) and the technique to find minima in the phase-folded light curves by Lafler & Kinman (1965). We note that both Lomb-Scargle and Lafler-Kinman yield exactly the same resulting period (Fig. 4).

We did not find any significant change of the period with time. Likewise, the amplitude of the oscillations appears wavelength independent for r, i, z, the three bands where it could be measured reliably. To check whether this is also supported by the longer wavelength NIR data, the UKIRT data taken during eight nights in December 2014 by Varricatt et al. (2015) turn out to provide valuable clues. They are overplotted in Fig. 5 (top). Obviously, these NIR data fit the same model as the optical data do. Secondly, the UKIRT data points in the JHK color–color diagram show no elongation in the direction of the A_V vector (Fig. 3). These two findings argue in favor of a wavelength independence of the amplitude of the oscillations.

The amplitude of the oscillations declines from ~0.08 mag in October 2014 to ~0.04 mag in May 2015 (Fig. 5).

In search for explanations for the brightness oscillations we considered the following scenarios:

Pulsations of the accreting star: δ Cep and RR Lyr stars show strongly asymmetric saw-tooth light curve profiles, in contrast to V960 Mon, which shows rather symmetric profiles.

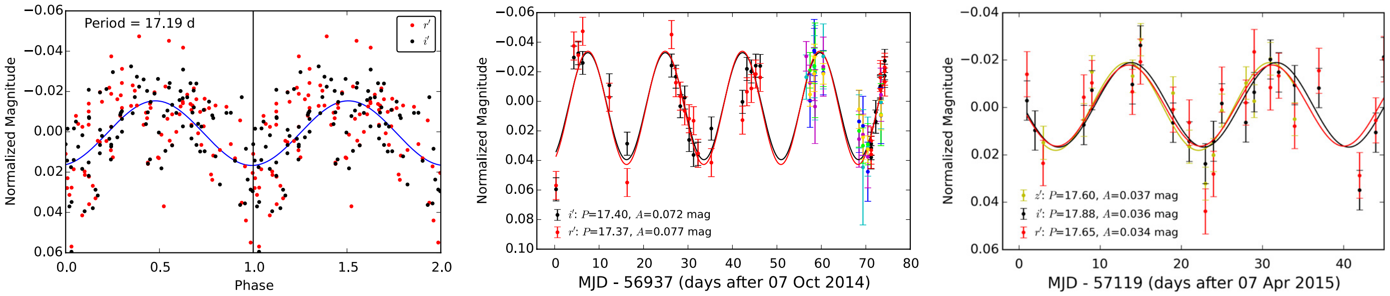

Fig. 5. *Left*: phase curves in *r* and *i* derived with the Lafler-Kinman algorithm after removal of the long-term trend via a piece-wise linear function. Overplotted is a least squares fitted sine function (blue); the χ^2 values are ~3.6 for the sine function and ~5.2 for a constant function at zero mag. *Middle and right*: light curves in the high state and the transition state after removal of the long-term trend via a piece-wise linear function. Overplotted on each light curve are fitted sine functions of period and amplitude as labeled. The χ^2 values are ~2.2 for the sine functions, and for a constant function at zero mag ~10 *(middle)* and ~4 *(right)*. The middle panel also shows the UKIRT data of Varricatt et al. (2015); *Z*, *Y*, *J*, *H*, and *K* in magenta, cyan, green, blue, and yellow, respectively.

Eclipsing events: Pooley et al. (2015) report on low X-ray absorption and Caratti o Garatti et al. (2015) inferred both a low extinction towards the FUor and a disk inclination of about 23°, i.e., more face-on than edge-on. This does not support eclipsing events, neither by a companion nor by dust clouds. In addition, the color-neutrality of the oscillations argues against eclipses by rotating dust clouds, such as proposed for V1647 Ori by Acosta-Pulido et al. (2007).

Rotating hot spots fed by magnetic tubes: In this case a bluer when brighter behavior is expected, in contrast to the color-neutrality of the oscillations (e.g., Herbst et al. 1994).

Flickering: The light curves should show a redder when brighter behavior as observed in FU Orionis itself (Kenyon et al. 2000; Siwak et al. 2013), in contrast to our observations, hence questioning this explanation.

An orbiting accreting hot Jupiter (Clarke & Armitage 2003): If the planet and disk planes are not perfectly aligned, there are geometries for which the "hot spot" signature would be more detectable when the planet is approaching the observer than on the opposite phase (Powell et al. 2012). However, such a scenario predicts a bluer when brighter behavior, in contrast to our observations.

Finally, the faint companion at 11 AU found by Caratti o Garatti et al. (2015) is too far off to exhibit an orbit of ~17 days.

Obviously, none of these scenarios provides a really satisfactory explanation for the brightness oscillations. Therefore, we now consider a different picture of a close binary surrounded by a circumbinary disk, as discussed and simulated by Artymowicz & Lubow (1996) and refined by, e.g., Günther & Kley (2002) and de Val-Borro et al. (2011). These simulations show that the rotating binary creates a gap in the circumbinary disk. The gap is not empty and matter flows in a confined stream from the circumbinary disk towards each star, feeding its small circumstellar accretion disk. Depending on the parameters of the system, the binary orbit can become eccentric. Then the interaction of the two circumstellar accretion disks and subsequent accretion rate onto the two stars may vary periodically, being stronger at periastron than at apoastron. This kind of model was successfully applied to several regularly accreting T Tauri binaries with circumbinary disks, such as DG Tau and GG Tau (Günther & Kley 2002; de Val-Borro et al. 2011).

To conclude, a close binary with eccentric orbit could naturally explain the observed brightness oscillations of the present FUor – a scenario we therefore strongly suggest.

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