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On the nature of V1647 Ori

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Abstract. V1647 Ori is a young eruptive star which brightened by ≈ 5 mag in the I_C passband during its outburst, started in November 2003. We present our $(RI)_C$ CCD photometric observations of V1647 Ori spanning from October 28, 2004, till October 31, 2005, which cover the light curve during the outburst at a prolonged brightness maximum of ~ 14.5 mag and a rapid decline for about 3.5 mag. The regions B and C in McNeil's nebula reflect the radiation from V1647 Ori (region A) with the time delay of 59 and 85 days, respectively. 2-year duration and 37-year recurrence allow us to classify the outburst of V1647 Ori as intermediate between FU Orionis (FUor) and EX Lupi (EXor) type events. Distinct IR spectroscopic behaviour suggests that V1647 Ori can be the prototype of a new class of objects.

Key words: techniques: photometric – stars: pre-main sequence – stars: variables – stars: individual: V1647 Ori

1. Introduction

At the end of January 2004, a new bright fan-shaped nebula was discovered serendipitously (McNeil, 2004) in the vicinity of the NGC 2068 star-forming region, in the northern part of the Orion B giant molecular cloud. Subsequent studies showed that the appearance of this reflection nebula (named McNeil's nebula) originated in an optical/IR outburst suffered by the young stellar object (YSO) IRAS 05436-0007 = 2 MASS JO 5461313-0006048 (Clark, 1991), which lies at the apex of this nebula. Briceño et al. (2004) constrained the start of this outburst to November 2003, and obtained a light curve in the I_C-band of V1647 Ori (designation of the variable star illuminating McNeil's nebula), showing a ≈ 5 mag brightening in about 4 months. Another outburst of V1647 Ori may have occurred about 37 years before the present one (Mallas & Kreimer, 1978).

The morphology of the nebula is consistent with a cavity in the envelope of a protostar scattering light from the highly reddened central star (Briceño et al., 2004; Reipurth & Aspin, 2004; Kun et al., 2004).

The optical spectrum of V1647 Ori shows a red, heavily veiled continuum with H_α strongly in emission with a pronounced P Cyg type profile, indicating a significant mass loss in a powerful wind (Reipurth & Aspin, 2004). The blue portion of the optical spectrum is consistent with an early B spectral type (Briceño et al., 2004). The IR spectrum of V1647 Ori shows strong CO band head emission, and Br_γ in emission (Reipurth & Aspin, 2004). No clear evidence for the presence of a molecular outflow in the submillimeter CO spectral line maps (Lis et al., 1999; Andrews et al., 2004) was found.

The pre-outburst spectral energy distribution (SED) of V1647 Ori from IR to millimetre shows a flat-spectrum source (Ábrahám et al., 2004). Andrews et al. (2004) proposed that V1647 Ori is a transition object between Class I protostars (with a circumstellar disk and extended remnant envelope) and Class II T Tau stars (with a circumstellar disk). Muzerolle et al. (2005), analysing Spitzer observations of V1647 Ori secured in early March 2004, found an increase in brightness across the spectrum from the optical to 70 μm, leading to a bolometric luminosity of 44 $L_\odot$ ($\sim$ 15 times higher luminosity than in the pre-outburst stage). They explained the event by an increase in the accretion luminosity of the central source driven by an instability in the accretion disk and classified the outburst as intermediate between FUor and EXor type events.

X-ray imaging spectroscopy obtained with Chandra by Kastner et al. (2004) revealed a factor ~ 50 increase in the X-ray count rate from V1647 Ori during its outburst compared to the pre-outburst level. The data suggest that the probable cause of the outburst is sudden infall of gas onto the surface of the star from an accretion disk. Furthermore, the X-ray observation of V1647 Ori in outburst, obtained with XMM-Newton by Grosso et al. (2005), showed an enhanced X-ray variability with the period of 0.72 days caused by the Keplerian rotation of the inner part of the accretion disk.

The aim of our paper is to present our $(RI)_C$ CCD photometry of V1647 Ori during its 2004-5 outburst, discuss its variability and nature.

2. Observations and results

Our $(RI)_C$ CCD photometric observations of V1647 Ori were obtained with the 0.5 m telescope of the Astronomical Institute of the Slovak Academy of Sciences at Stará Lesná Observatory from October 28, 2004, till October 31, 2005. The SBIG ST10-MXE CCD camera with the chip 2184x1472 pixels was used. The size of the pixel is 6.8 μm and the scale 0.56"/pixel. All frames were taken through the standard Cousins R_C, I_C set of filters. Integration time 60 s in R_C and 90 s in I_C was used. Every observing run 4 - 21 frames were taken with each filter.

All frames were dark-subtracted, flat-fielded and corrected for cosmic rays. The images were aligned and co-added in R_C and I_C bands separately for every observing run and photometry was done in the summed single image. In order to minimize the light from the surrounding nebula we used a 6.72" (12 pixel) radius aperture. Due to the fact that our system is close to the standard Cousins system, we determined the magnitudes of V1647 Ori using the sequence of comparison stars given by Semkov (2006). The observational errors of magnitude determination do not exceed 0.1 mag. The largest source of errors is complicated centering of the nebular sources.

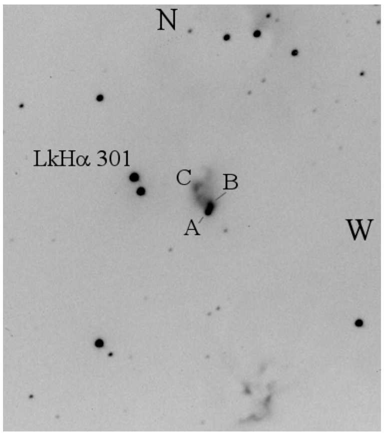

Figure 1. A CCD image of McNeil's nebula.

Fig. 1 displays the I_C passband summed image of McNeil's nebula taken on February 4, 2005. Following Briceño et al. (2004), we measured 3 different regions within the nebula: A, B and C. The point source A is centered on the nebula vertex and corresponds to V1647 Ori, the region B is centered on the nebulosity just north of the star and the region C is placed on the top of the object HH 22, which also brightened during the outburst. Briceño et al. (2004) compared the A, B, C light curves at the rise to outburst maximum (from October 25, 2003 till February 26, 2004) and found that the rise in brightness of the region B and C with respect to the source A is delayed by 18 days and $\gtrsim$ 50 days, respectively. The regions B and C reflect the radiation from the source A. The authors used the distance of 400 pc for HH 22 and angular separation of the A,B,C regions to determine the light-travel time 19 days between the regions A and B and 85 days between the regions A and C.

Our R_C and I_C magnitudes of the A,B,C regions of McNeil's nebula are presented in Table 1 and shown in Figs. 2 and 3, respectively. It is clearly seen that during the prolonged brightness maximum (from October 28, 2004 till March 22, 2005), the R_C and I_C brightness of the source A (V1647 Ori) varied with the amplitude of 0.8 mag on a time scale of weeks and months. Corresponding brightness variations of B and C regions with the amplitude of 0.6 - 0.9 mag were detected. Our A,B,C light curves indicate that the sources B and C trace the behaviour of the source A with the delay of 59 and 85

Table 1. CCD photometry of the A,B,C regions of McNeil nebula.

Date	HJD 2 400 000+	R_C^A	R_C^B	R_C^C	I_C^A	I_C^B	I_C^C	No.
Oct 28, 2004	53306.616	16.310	16.054	16.130	14.481	15.032	15.598	6
Nov 12, 2004	53321.501	16.212	16.003	17.003	14.118	14.639	15.864	12
Nov 30, 2004	53340.439	16.428	15.692	16.266	14.434	14.692	15.695	21
Dec 04, 2004	53344.496	16.480	15.726	16.188	14.494	14.676	15.691	21
Dec 09, 2004	53349.461	16.826	15.775	16.200	14.647	14.694	15.692	13
Dec 21, 2004	53361.447	16.703	15.638	16.268	14.240	14.725	15.761	10
Dec 22, 2004	53362.448	16.100	15.727	16.295	14.229	14.467	15.693	7
Jan 10, 2005	53381.386	16.567	15.557	16.288	14.301	14.548	15.810	10
Jan 12, 2005	53383.249	16.383	15.636	16.328	14.308	14.655	15.817	7
Jan 29, 2005	53400.254	16.134	15.982	16.152	14.671	15.109	15.616	5
Jan 30, 2005	53401.338	16.747	16.033	16.235	14.977	14.850	15.644	4
Feb 04, 2005	53406.321	16.528	16.217	16.252	14.699	14.233	15.669	5
Feb 06, 2005	53408.262	16.960	16.109	16.278	14.678	15.008	15.742	7
Mar 03, 2005	53433.300	16.332	15.891	16.682	14.427	14.754	16.198	6
Mar 22, 2005	53452.284	16.464	15.990	16.505	14.637	14.893	16.193	11
Sep 07, 2005	53621.588	17.384	16.319	17.172	15.107	15.274	16.658	9
Sep 08, 2005	53622.584	17.412	16.407	17.064	15.127	15.126	16.543	12
Oct 05, 2005	53649.599	17.771	16.891	17.058	15.767	15.812	16.561	10
Oct 06, 2005	53650.613	18.084	16.970	17.069	15.804	15.769	16.471	11
Oct 08, 2005	53652.617	17.590	16.887	17.069	16.006	15.983	16.501	10
Oct 31, 2005	53675.535	18.414	17.836	17.249	16.993	16.551	16.702	7

days, respectively. The light-travel time 59 days between regions A and B is in disagreement with the value 18-19 days found by Briceño et al. (2004). One of the reasons for this discrepancy is possible presence of a short-term variability of the source A on a time-scale of hours, caused by the movements of inhomogenities in the central part of the accretion disk. Grosso et al. (2005) detected X-ray variability with the period 0.72 days.

During the outburst decline (September 7, 2005 - October 31, 2005), the brightness of the region A decreased by 1 mag and 1.9 mag in R_C and I_C passbands, respectively. In the same period, the brightness of the region B decreased by 1.5 mag and 1.4 mag in R_C and I_C passbands, respectively.

The I_C light curve of V1647 Ori, presented in Fig. 4, is based on our observations and published data. The shift of -0.6 mag was applied to the data of McGehee et al. (2004) and 0.4 mag for our data to be compatible with other data. Presence of the variable emission Ca II triplet at 0.8498, 0.8542 and 0.8662 μm (Gibb et al., 2006) and different transparency of the I_C filter at various sites can be the reason for discrepancy of photometry in I_C passband. The light curve clearly shows 2-year duration of the outburst. Our CCD image of McNeil's nebula taken on January 27, 2006 did not show the presence of A,B,C regions. Their magnitudes were under our detection treshold. Unfiltered CCD frames from Feb. 6, 2006 taken by Corelli (2006), did not show a nebula to a limiting stellar magnitude of 18. The JHK observations of Venkat & Anandarao (2006)

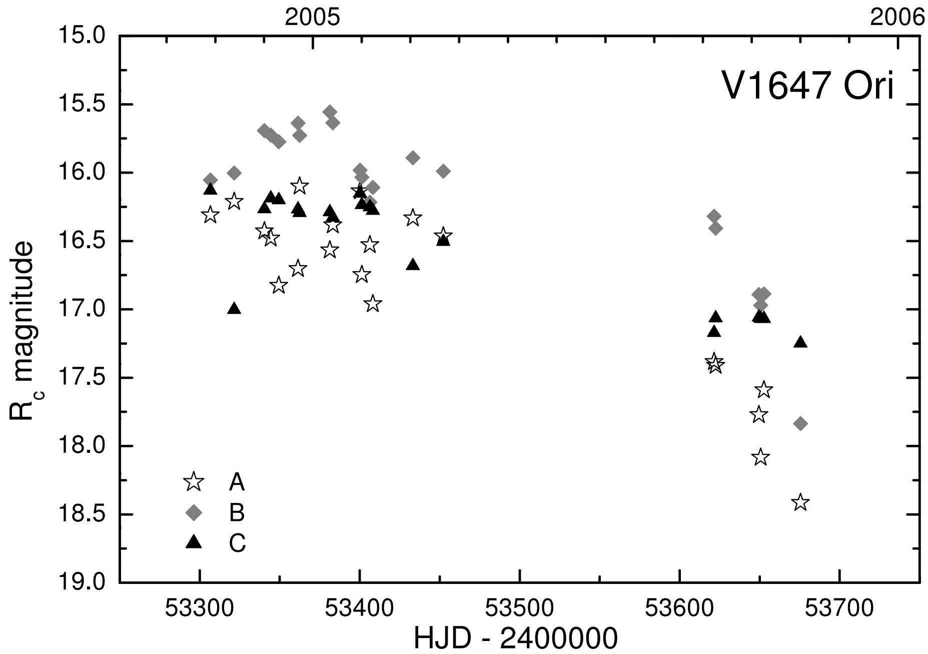

Figure 2. The light curves of A (V1647 Ori), B and C regions of McNeil's nebula in the R_C passband.

taken on February 27, 2006 showed that V1647 Ori was near its pre-eruptive state.

3. FUors and EXors overview

V1647 Ori offers a unique opportunity to study phenomena accompanying the strong brightening of a low-mass pre-main sequence star, taking into account that both types of outburst objects, FUors and EXors, are very rare.

FUors are characterized by a large-amplitude (ΔV $\sim$ 5-6 mag) brightening lasting several decades. The light curves of the three best studied FUors (i.e., FU Ori itself, V1515 Cyg and V1057 Cyg) show remarkable differences. The rise time-scale of FU Ori and V1057 Cyg is of the order of 1 yr, while that of V1515 Cyg is large ($t_{rise} \sim$ 20 yr). On the other hand, while FU Ori and V1515 Cyg have a very long decay time-scale ($t_{decay} \sim 20\div$ 100 yr), V1057 Cyg decays much faster ($t_{decay} \sim$ 10 yr).

The spectra of FUors are those of F or G supergiants, although near-IR characteristics of cooler K-type or M-type giants/supergiants, dominated by a deep CO overtone absorption, are present. FUors have very strong winds, as indicated by very broad, deep P Cyg absorption profiles seen in the Balmer

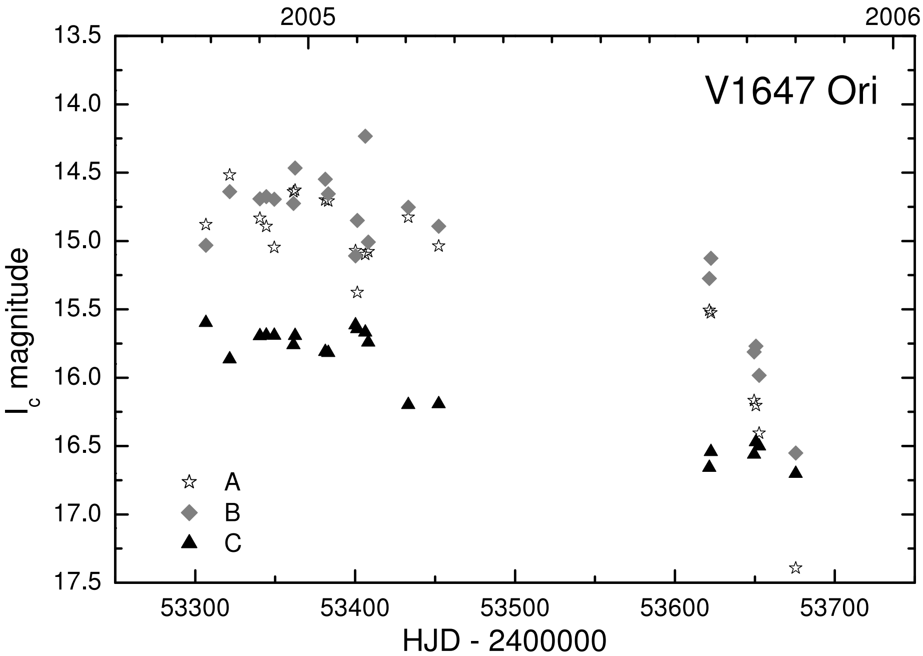

Figure 3. The light curves of A (V1647 Ori), B and C regions of McNeil's nebula in the I_C passband.

lines and the low-ionization Na I resonance lines. The embedded FUors ($A_V \geq$ 10 mag) drive large-scale molecular outflows and bipolar Herbig-Haro outflows.

EXors eruptions are recurrent, with amplitudes comparable to or smaller than in FUors. Their durations are shorter than in FUors - from a few weeks to a few months. EXors exhibit larger short-term photometric variability than FUors. During the outburst, EXors show the Balmer lines in emission, together with emission lines of He I and other lines characteristic of the most active T Tauri stars. Infrared spectra of EXors are very limited; one case is the eruption of SVS 13, for which the spectrum shows the CO band head strongly in emission as well as Br_γ in emission (Carr & Tokunaga, 1992). On the contrary, the spectrum of EX Lupi shows Br_γ in emission, but the CO band heads and Na I in absorption (Herbig et al., 2001).

According to Turner et al. (1997), outbursts of FUors are initiated by thermal instabilities in the inner part of the disk. The duration of the outburst is determined by viscosity within this hot, ionized area and terminated by its depletion due to the accretion onto the central star. The interval between the outbursts depends on the rate of the mass transfer in the inner portion of the disk. Similarly to FUors, the eruptions of EXors are attributed to the enhanced accretion rate from the disk to the surface of the central star. The most striking

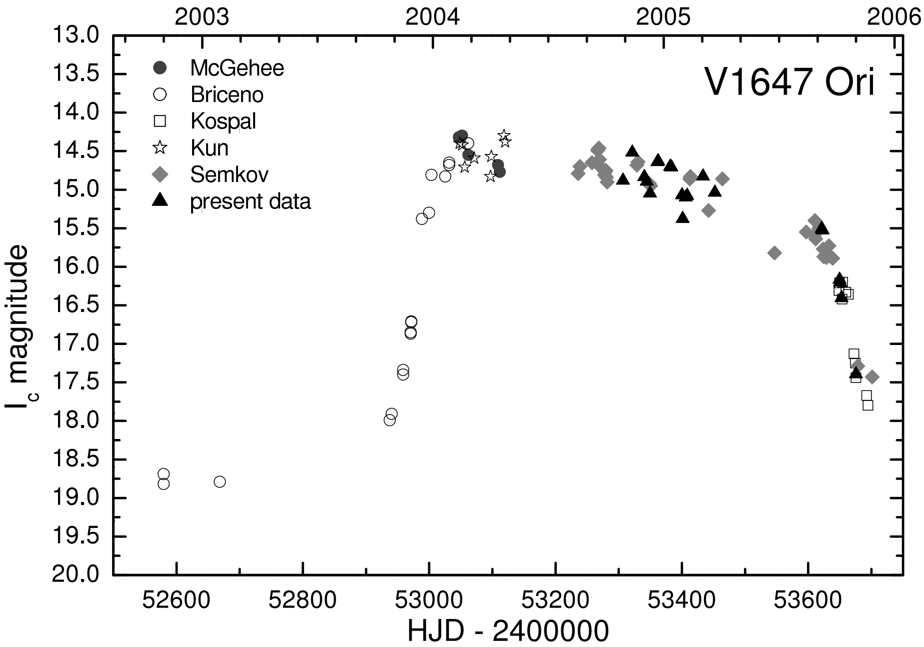

Figure 4. V1647 Ori light curve in the I_C passband. Our data and data from McGehee et al. (2004), Briceño et al. (2004), Kóspál et al. (2005), Kun et al. (2004) and Semkov (2004, 2006) were used.

differences between both types of objects are as follows: while FUors appear as rapidly rotating supergiant stars, exhibiting strong wind signatures during their outbursts lasting several decades, EXors appear extremely active, magnetospherically accreting T Tauri stars during their much shorter eruptions.

4. Nature of V1647 Ori

According to the photometric behaviour, the evidence for a previous outburst in 1966 allows us to classify the outburst of V1647 Ori as a recurrent EXor event. On the other hand, the total duration of the present outburst suggests that V1647 Ori is an intermediate event between FUors and EXors.

The spectroscopic behaviour of the object cannot discriminate between both cases, too. Vacca et al. (2004) reported that the near-IR spectrum of V1647 Ori does not appear similar to any known FUor or EXor object. The presence of CO bands in emission at 2.3-2.5 μm and lack of water absorption at 1.4 and 1.9 μm discriminates the object from other FUors (see also Gibb et al., 2006). The prominent H_α emission present in the spectrum of V1647 Ori does not suggest a FUor classification. On the other hand, Briceño et al. (2004) recalled that the FUor V1057 Cyg displayed a strong H_α emission immediately after its outburst which turned into the characteristic absorption with the P Cyg profile several years later (Herbig, 1977). Furthermore, the optical spectrum of V1647 Ori, detected in the light reflected from the nebula, obtained by Briceño et al. (2004), is consistent with an early B spectral type, incompatible with the EXors which exhibit T Tauri-type spectra during outburst. The SEDs of FUors indicate that, in addition to the accretion disks, the dusty envelopes are present around the stars. Both the pre- and post-outburst SED of V1647 Ori resembles those of known FUors. No clear evidence of magnetospheric accretion, characteristic of EXors, can be found in the published optical and infrared spectra of V1647 Ori. Finally V1647 Ori, similarly as FUors and EXors, has powerful mass loss.

We believe, based on the above arguments, that V1647 Ori outburst can be more likely associated to the FUor event, but with unusual observed features of the eruption, such as the unusual infrared emission spectrum, not found in other FUors. Shorter duration of the outburst in comparison with other FUors and 37-year recurrence of the outbursts allow us to classify the outburst of V1647 Ori as intermediate between FUor and EXor type events. Distinct IR spectroscopic behaviour suggests that V1647 Ori can be the prototype of a new class of objects. Kóspál et al. (2006) announced that the deeply embedded young star object OO Ser, which brightened by 5 mag in the K band between 1994 and 1995 and gradually faded afterwards, had already returned to the pre-outburst state in 2004. It seems that this object belongs to the same class as V1647 Ori.

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