Recent Advances in Star Formation: Observations and Theory
ASI Conference Series, 2012, Vol. 4, pp 1 – 8
Edited by Annapurni Subramaniam & Sumedh Anathpindika

The outburst and nature of young eruptive low mass stars in dark clouds

J. P. Ninan[1], D. K. Ojha[1*], B. C. Bhatt[2], K. K. Mallick[1], A. Tej[3],
D. K. Sahu[2], S. K. Ghosh[1] and V. Mohan[4]

[1]*Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400 005, India*
[2]*CREST, Indian Institute of Astrophysics, Bengaluru 560 034, India*
[3]*Indian Institute of Space Science and Technology, Valiamala P.O., Thiruvananthapuram 695 547, India*
[4]*Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India*

Abstract. The FU Orionis (FUor) or EX Orionis (EXor) phenomenon has attracted increasing attention in recent years and is now accepted as a crucial element in the early evolution of low-mass stars. FUor and EXor eruptions of young stellar objects (YSOs) are caused by strongly enhanced accretion from the surrounding disk. FUors display optical outbursts of ~ 4 mag or more and last for several decades, whereas EXors show smaller outbursts ($\Delta m \sim 2$ - 3 mag) that last from a few months to a few years and may occur repeatedly. Therefore, FUor/EXor eruptions represent a rare but very important phenomenon in early stellar evolution, during which a young low-mass YSO brightens by up to several optical magnitudes. Hence, long-term observations of this class of eruptive variables are important to design theoretical models of low-mass star formation. In this paper, we present recent results from our long-term monitoring observations of three rare types of eruptive young variables with the 2-m Himalayan *Chandra* Telescope (HCT) and the 2-m IUCAA Girawali Observatory (IGO) telescope.

Keywords : stars: formation – stars: pre-main-sequence – stars: variables: other – ISM: clouds – (ISM:) reflection nebulae

*email: ojha@tifr.res.in

1. Introduction

There is now convincing evidence that EXor and FUor outburst phenomena are closely related to the earliest stages of stellar evolution (Herbig, Petrov & Duemmler 2003). Rarity and obscuration have resulted in a poor understanding of the eruption mechanism in spite of an established integral link to disk accretion (Reipurth & Aspin 2004; Hartmann, Hinkle & Calvet 2004). FUor and EXor, also referred to as sub-FUors, are among the most interesting and intriguing class of known pre-main-sequence (PMS) stars. They are likely to be near solar-mass protostars that are still accreting material from their circumstellar disks and are associated with collimated outflows (Sandell & Weintraub 2001). Only a handful of these objects are known to date (e.g., Vittone & Errico 2005). Hence, there is an urgent need for observations and studies to facilitate a deeper understanding of their nature and the effects of their associated eruptions. The morphology and nature of small compact reflection nebulae in the star-forming clouds possibly hint at these objects being in a transition phase between an embedded PMS star and a visible Herbig-Haro object (Reipurth & Bally 2001; Reipurth & Aspin 2004). A similar case was the emergence of McNeil's nebula, which was found to harbour a possible EXor event (Ojha et al. 2006 and references therein).

In this paper, we present optical observations of the post-outburst phases of McNeil's nebula (V1647 Ori), a new reflection nebula in LDN 1415, and a cometary reflection nebula associated with the infrared source IRAS 06068-0641. In Section 2, we present details of the observations and data reduction procedures and in Section 3 we present the results and discuss the short- and long-term variability of three eruptive low-mass young variables.

2. Observations and data reduction

Optical (V, R, I) photometric observations were carried out on several nights with the Hanle Faint Object Spectrograph Camera (HFOSC) and IUCAA Faint Object Spectrograph Camera (IFOSC) on the 2-m HCT, Hanle and the 2-m IGO telescope, Pune, respectively, during the period February 2004 - March 2011. The HFOSC instrument, equipped with a SITe 2K $\times$ 4K pixel CCD and the IFOSC instrument, equipped with an EEV 2K $\times$ 2K pixel thinned, back-illuminated CCD were used. The field-of-view (FOV) for HFOSC, where only the central 2K $\times$ 2K region is used for imaging, is $\sim 10 \times 10$ arcmin^2 with a pixel scale of 0.296 arcsec and that of IFOSC is $\sim 10.5 \times 10.5$ arcmin^2 with a pixel scale of 0.307 arcsec. Photometric standard stars (Landolt 1992) were observed on several nights to obtain the atmospheric extinction and transformation coefficients. For nights when the Landolt standard stars were not available, we calibrated the data using secondary standards present in the image frames. The average seeing (full width at half-maximum) in all bands was $\sim$ 1.8 arcsec and 1.3 arcsec during our HCT and IGO observations, respectively.

Data reduction was done using the National Optical Astronomy Observatories'

(NOAO) IRAF[1] package tasks. Object frames were flat-fielded using the median combined normalized flat frames. Identification and aperture photometry of point sources were performed using the DAOFIND and DAOPHOT packages, respectively. Given the nebulosity around V1647 Ori and IRAS 06068-0641, photometry was obtained using the point-spread function algorithm ALLSTAR in the DAOPHOT package (Stetson 1987). The residuals to the photometric solution are ≤ 0.05 mag. Since the outburst source was too faint to be detected in the *VRI* bands, we used an aperture radius of 30 pixels (∼ 10 arcsec) for photometry of the L1415 nebula. This aperture radius was chosen to cover the entire nebular emission and enable direct comparison with the results of Stecklum, Melnikov & Meusinger (2007) who used the same aperture radius. The local sky was evaluated in an annulus with an inner radius of 128 pixels and a width of 20 pixels. The residuals of the photometric solution are ≤ 0.04 mag.

The color composite images of the central region of McNeil's nebula, the LDN 1415 nebula and the region around IRAS 06068-0641 were constructed from the HFOSC and IFOSC *V*, *R* and *I*-band images (*V* represented in blue, *R* in green, and *I* in red) and are shown in Fig.1.

Figure 1. *VRI* three-color composite images (*V*: blue, *R*: green, and *I*: red) of McNeil's nebula (*left*), the LDN 1415 nebula (*middle*) and the IRAS 06068-0641 region (*right*), obtained with HFOSC and IFOSC on 13 January 2011, 20 February 2011 and 2 January 2011, respectively. The outburst source of McNeil's nebula is located at the lower tip of the nebula.

3. Results and discussion

3.1 McNeil's nebula (V1647 Ori)

The compact source at the base of a variable nebula (McNeil's Nebula Object) in the Lynds 1630 dark cloud in Orion went into outburst in late 2003 (McNeil 2004). Later,

[1]IRAF is distributed by the NOAO, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

the McNeil's Nebula Object was identified as V1647 Ori (Samus 2004). V1647 Ori, a low-mass, deeply embedded, PMS star, has undergone two optical/near-infrared outbursts in the last decade, both of which gradually faded over several months to years. These eruptions are thought to have been the result of large-scale accretion events.

Ojha et al. (2006) presented a detailed study of the post-outburst phase of McNeil's nebula using optical (B, V, R, I) and near-infrared (J, H, K) photometric and low-resolution optical spectroscopic observations. The long-term optical and near-infrared observations showed a general decline in the brightness of the exciting source of McNeil's nebula, V1647 Ori. Our optical images taken in November 2005 showed that V1647 Ori had faded by more than 3 magnitudes since February 2004 (see Fig. 2, *top panel*). McNeil's nebula itself had also faded considerably. The optical spectra showed strong Hα emission with blue-shifted absorption and the Ca II IR triplet (8498 Å, 8542 Å and 8662 Å) in emission. The presence of the Ca II IR triplet in emission confirmed that V1647 Ori is a PMS star. Therefore, our long-term, post-outburst photometric and spectroscopic observations of V1647 Ori indicated an EXor rather than an FUor event.

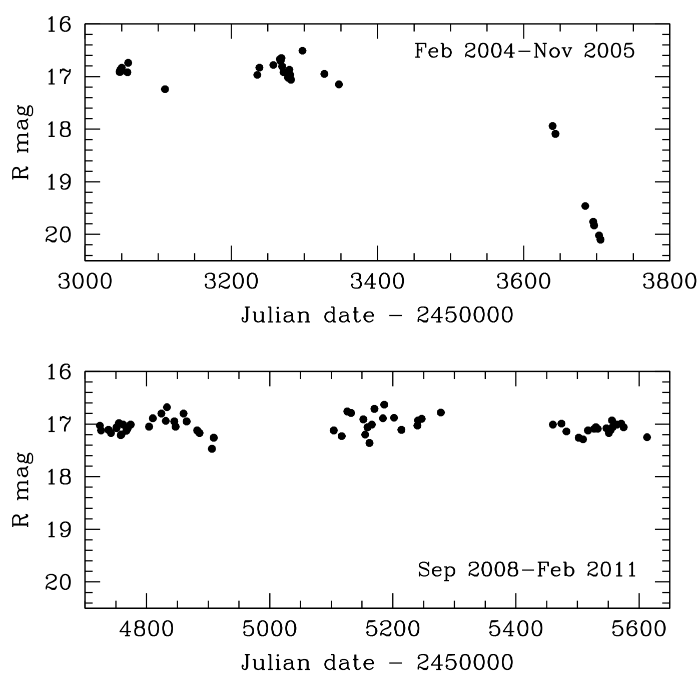

Figure 2. The optical light curve of V1647 Ori in *R* band. The filled circles show HFOSC and IFOSC measurements from February 2004 to February 2011.

In 2008, V1647 Ori again underwent a strong outburst (Aspin 2008), which is rarely seen in the early phases of low-mass young stellar objects. We monitored V1647 Ori with the HCT and IGO telescopes beginning with the second outburst. No significant variation in brightness of V1647 Ori was seen for about two months since the second outburst began (Ojha et al. 2008). In comparison with the last reported quiescent phase (Ojha et al. 2006), however, there was a brightening of about ~ 3 magnitudes in *R*, and the infrared colors suggested that circumstellar matter of $A_V \sim 7.5$ mag had probably been cleared during this outburst. Fig. 2 (*bottom panel*) shows the optical light curve (September 2008 - February 2011) of V1647 Ori in *R*-band. Comparison of the spatial flux distribution of the nebula with the first post-outburst phase in 2004 revealed a change in the dust distribution around the source during the second outburst. From our 2+ year long monitoring observations (September 2008 - February 2011), we see significant short-term variations in the brightness of V1647 Ori since the second outburst began. The source, however, has not faded away considerably as seen in 2004 - 2005. The source magnitude and 1-σ fluctuations in *V*, *R* & *I* during the period of our observations were 18.86±0.23, 17.04±0.16, 14.99±0.12, respectively.

The observed properties of the outburst of V1647 Ori are different in several respects from both the EXor and FUor type outbursts, and suggest that this star represents a new type of eruptive young star, one that is younger and more deeply embedded than EXor, and exhibits variations on shorter time scales than FUors.

3.2 LDN 1415 (IRAS 04376+5413)

The new reflection nebula in the not so well studied Lynds opacity class 3 dark cloud LDN 1415 (Lynds 1962) was first detected by Stecklum (2006) in early April 2006 in the vicinity of IRAS 04376+5413. Stecklum, Melnikov & Meusinge (2007) later reported the presence of a new compact arc-shaped nebula with a size of 20 arcsec in the CCD images of the dark cloud LDN 1415. The brightness peak of the nebula is within the positional error ellipse of IRAS 04376+5413. Optical spectra of the nebula taken by Stecklum, Melnikov & Meusinger on 21 September 2006 revealed the presence of a P-Cygni profile in the Hα line, indicating clear evidence for an FUor or EXor-type outburst due to temporarily enhanced accretion. Kastner et al. (2006) observed this eruptive source with the *Chandra* X-ray Observatory's Advanced CCD Imaging Spectrometer imaging array (ACIS-I). No X-ray sources were detected, which constrained the X-ray luminosity of the emergent source to be less than $\sim 2 \times 10^{28}$ erg s^{-1}, assuming the distance to the LDN 1415 cloud to be 170 pc.

To study the post-outburst phase of the embedded source in the LDN 1415 nebula, we have been carrying out optical observations of this source with HCT and IGO telescopes. We present in Fig. 3 variability measurements of the LDN 1415 nebula for a duration of about two and half years. In comparison with the available pre-outburst photometry from POSS II (epoch December 1996) and the KISO (January

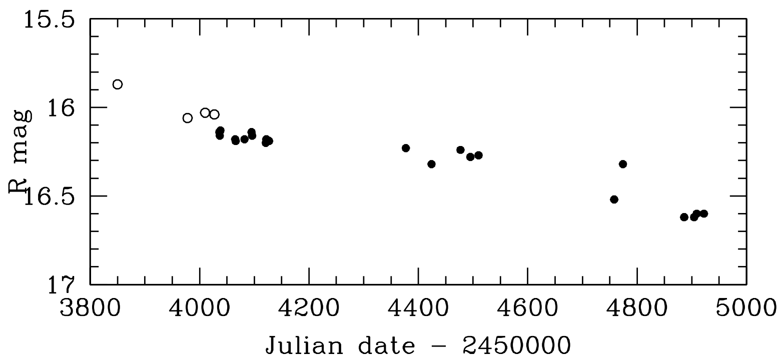

Figure 3. The optical light curve of L1415 nebula in *R* band. The filled circles show our HFOSC and IFOSC measurements (October 2006 - March 2009). The empty circles show the photometric measurements from Stecklum, Melnikov & Meusinger (2007).

2001) quoted in Stecklum, Melnikov & Meusinger (2007), our first post-outburst data point shows an enhancement of ~ 3.4 mags in the *I*-band. Following this observation, a general decline in the brightness is seen in all three (*VRI*) optical light curves (see Fig. 3). Superimposed on this decline, we see the presence of small-scale fluctuations of ~ 0.2 - 0.3 mags over short time scales of 3 - 8 months. This variation is consistent with the young and eruptive nature of this class of objects. Therefore, our long-term, post-outburst optical and NIR photometric and optical spectroscopic monitoring of the LDN 1415 nebula and its associated outburst source from October 2006 to March 2009 (Pawade et al. 2010) suggest an EXor or FUor event, possibly by the least luminous member of the known sample of FUor and EXor objects (Stecklum, Melnikov & Meusinger 2007).

3.3 IRAS 06068-0641

A possible FUor-type eruption from the infrared source IRAS 06068-0641 was discovered by the Catalina Real-time Transient Survey (CRTS) on 10 November 2009 (Wils et al. 2009). The object lies inside a dark nebula to the south of the Monoceros R2 association, and is likely related to it. Fig. 4 shows the optical light curve (November 2009 - March 2011) of IRAS 06068-0641 in *R*-band. After a significant increase in the brightness from at least late November 2009 (*R* ~ 13.4 mag) to January 2010 (*R* ~ 12.2 mag), a general decline in the source brightness can be seen in recent observations.

The FUor class of eruptive low-mass YSOs display outbursts of ~ 4 mag or more that last for several decades. EXors show smaller outbursts (Δm ~ 2 - 3 mag) that

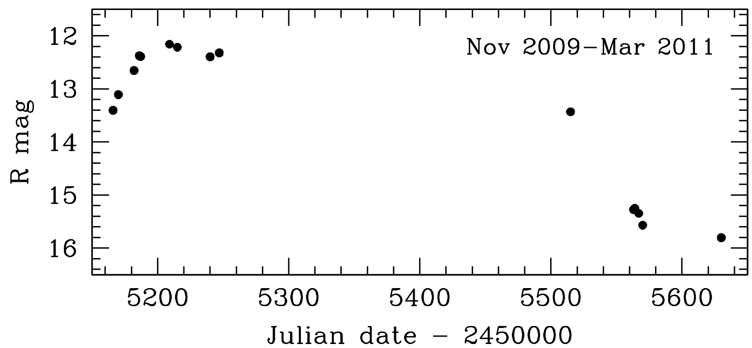

Figure 4. The optical light curve of IRAS 06068-0641 in *R* band.

last from a few months to a few years and may occur repeatedly (Herbig 1977; Bell et al. 1995; Hartmann 1998). For the more than a year that we followed the source IRAS 06068-0641 (January 2010 - March 2011), the brightness decreased by more than 3.5 mag in *R* band and it is probably returning to its pre-outburst state. It is therefore possible that we witnessed EXor behaviour, since the source variability had about the correct amplitude (Reipurth & Aspin 2004; Ojha et al. 2005, 2006). Further photometric observations of this object are required to understand and classify the outburst happening now in IRAS 06068-0641.

Acknowledgements

The authors thank the staff of HCT operated by Indian Institute of Astrophysics (Bangalore) and IGO operated by Inter-University Centre for Astronomy & Astrophysics (Pune) for their assistance and support during observations.

References

Aspin C., 2008, IAU Circ., 8969

Bell K. R., Lin D. N. C., Hartmann L. W., Kenyon S. J., 1995, ApJ, 444, 376

Hartmann L., 1998, in Accretion Processes in Star Formation. Cambridge Univ. Press, Cambridge

Hartmann L., Hinkle K., Calvet N., 2004, ApJ, 609, 906

Herbig G. H., 1977, ApJ, 217, 693

Herbig G. H., Petrov P. P., Duemmler R., 2003, ApJ, 595, 384

Kastner J., Richmond M., Simon T., Grosso N., Weintraub D., Hamaguchi K., 2006, CBET, 760, 1

Landolt A. U., 1992, AJ, 104, 340

Lynds B. T., 1962, ApJS, 7, L1
McNeil J. W., 2004, IAU Circ., 8284
Ojha D. K., et al., 2005, PASJ, 57, 203
Ojha D. K., et al., 2006, MNRAS, 368, 825
Ojha D. K., Ghosh S. K., Kaurav S. S., Bhatt B. C., Sahu D., Tej, A., 2008, IAU Circ., 9006
Pawade V. S., et al., 2010, ASInC, Vol. 1, pp 243-244, ed. D. K. Ojha
Reipurth B., Aspin C., 2004, ApJ, 606, L119
Reipurth B., Bally J., 2001, ARA&A, 39, 403
Samus N. N., 2004, IAU Circ., 8354
Sandell G., Weintraub D. A., 2001, ApJS, 134, 115
Stecklum B., 2006, CBET, 690, 1
Stecklum B., Melnikov S. Y., Meusinger H., 2007, A&A, 463, 621
Stetson P. B., 1987, PASP, 99, 191
Vittone A. A., Errico L., 2005, MmSAI, 76, 320
Wils P., Greaves J., Drake A. J., Catelan M., 2009, CBET, 2033, 1