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LETTER TO THE EDITOR

The outburst of an embedded low-mass YSO in L1641★

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ABSTRACT

Context. Strong outbursts in very young and embedded protostars are rare and not yet fully understood. They are believed to originate from an increase in the mass accretion rate ($\dot{M}_{acc}$) onto the source.

Aims. We report the discovery of a strong outburst in a low-mass embedded young stellar object (YSO), namely 2MASS-J05424848-0816347 or [CTF93]216-2, as well as its photometric and spectroscopic follow-up.

Methods. Using near- to mid-IR photometry and NIR low-resolution spectroscopy, we monitor the outburst, deriving its magnitude, duration, as well as the enhanced accretion luminosity and mass accretion rate.

Results. [CTF93]216-2 increased in brightness by ~4.6, 4.0, 3.8, and 1.9 mag in the J, H, K_s bands and at 24 μm, respectively, corresponding to an L_{bol} increase of ~20 $L_\odot$. Its early spectrum, probably taken soon after the outburst, displays a steep almost featureless continuum, with strong CO band heads and H_2O broad-band absorption features, and Brγ line in emission. A later spectrum reveals more absorption features, allowing us to estimate $T_{eff} \sim 3200$ K, $M_* \sim 0.25\ M_\odot$, and $\dot{M}_{acc} \sim 1.2 \times 10^{-6}\ M_\odot\,yr^{-1}$. This makes it one of the lowest mass YSOs with a strong outburst so far discovered.

Key words. accretion, accretion disks – stars: formation – ISM: jets and outflows – infrared: ISM

1. Introduction

Most of the stellar mass in low-mass YSOs is assembled within the first 10^5 yr of their evolution (i.e. class 0, 10^4 yr, and Class I, 10^5 yr: see e.g., Lada & Wilking 1984; Andre et al. 1993). During this stage, the YSO luminosity is thus expected to be dominated by accretion. However, several studies, including the latest *Spitzer* Space Telescope surveys (e.g., Enoch et al. 2009; Evans et al. 2009), have found that more than 50% of the embedded YSOs have L_{bol} and $\dot{M}_{acc}$ values considerably lower than those theoretically predicted (i.e. ~$2 \times 10^{-6}\ M_\odot\,yr^{-1}$ for solar-mass YSOs; Shu 1977; Terebey et al. 1984) and roughly of the same order of magnitude as the classical T Tauri stars (CTTs; i.e. $10^{-8} \le \dot{M}_{acc} \le 10^{-6}\ M_\odot\,yr^{-1}$; e.g., White & Hillenbrand 2004). Among several hypotheses, a likely explanation is that the mass accretion is *episodic*, and the protostars with the lowest luminosities are those observed in quiescent accretion states (Enoch et al. 2009; Evans et al. 2009; Vorobyov 2009). Non-steady mass accretion is often observed in CTTs, such as EXors and FUors (lasting from a few months to several decades), in which $\dot{M}_{acc}$ increases by several orders of magnitude up to $\dot{M}_{acc} \sim 10^{-4}\ M_\odot\,yr^{-1}$ (Hartmann & Kenyon 1996). It is thus reasonable to believe that a similar mechanism also exists in earlier and more embedded YSOs. Unfortunately, there is little direct observational evidence of outbursts in Class I YSOs, and so far, only a few clear cases have been detected (e.g. V 1647 Ori outbursts in 2003 and 2008, or OO Ser in 1995; see e.g. Fedele et al. 2007; Kóspál et al. 2007). To reconcile theory with observations and improve the quality of the statistics, it is mandatory to detect and study these rare events.

With this aim, we started a long-term project to monitor the NIR flux and spectroscopic variability of embedded YSOs (mostly Class I and Flat sources) in nearby, young, and active star-forming regions (namely L 1641, CrA, and the Serpens Molecular Cloud). This letter reports the outburst of an embedded YSO in L 1641, namely 2MASS-J05424848-0816347, hereafter [CTF93]216-2 (α_{2000} = $05^h42^m48.48^s$, δ_{2000} = $-08°16'34''.7$). This object was identified by our group as a low-mass embedded YSO (spectral type M, circumstellar $A_V \sim$ 18 mag) with a flat spectral index (α = 0.25, derived by fitting all the photometric data points from 2.2 to 24 μm) and a bolometric luminosity of ~1.9 $L_\odot$ (Caratti o Garatti et al. in prep., hereafter CoG). It has been named [CTF93]216-2, because it is relatively close to [CTF93]216 (Chen et al. 1993; Chen & Tokunaga 1994), located about 38''.5 SW. Our *Spitzer*/IRAC images indicate that both YSOs have precessing jets, thus they could be part of a wide binary system (~17 300 AU, assuming a distance d = 450 pc). During our recent survey in October 2010 with the robotic telescope REM (see Sect. 2), we detected for [CTF93]216-2 a brightness increase of several magnitudes with respect to the 2MASS images. We then compared our new

★ Based on observations collected at the ESO/NTT (082.C-0264), at the REM telescope La Silla, Chile, and at the the Italian Telescopio Nazionale Galileo (TNG), operated on the island of La Palma by the Fundacion Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica).

images with the acquisition image in the K_s band and the NIR spectrum of this source acquired in February 2009, discovering that the outburst was already in progress.

2. Observations

NIR spectra were obtained at the ESO-NTT with SofI (Moorwood et al. 1998) (on the 13 Feb. 2009) and at the 3.5-m Italian telescope TNG (13 Oct. 2010) with NICS (Baffa et al. 2001), adopting the usual ABBA configuration. The SofI spectrum was taken with the red grism (1.51–2.5 μm), a 0.″6 slit $\mathcal{R}$ ~ 1000), and a total integration time of 1800 s. The full width half maximum (*FWHM*) in the dispersion direction, measured from Gaussian fits to the OH sky lines, was ~19 Å (~260 km s^{-1}) in the K band. The NICS low-resolution spectrum was acquired using a slit width of 1″ ($\mathcal{R}$ ~ 600) for the JH and HK grisms (1.15–1.75 μm and 1.4–2.5 μm, respectively) with a total integration time (*Int*) of 480 and 160 s for the JH and HK grisms, respectively. The measured *FWHM* in the dispersion direction was ~33 Å (~600 km s^{-1}) in the K band. Telluric and spectrophotometric standards were observed to correct for the atmospheric transmission and flux-calibrate the spectra. The wavelength calibrations were performed using a xenon lamp in the infrared.

Most of our J, H, and K_s images were collected between the 10 October and the 6 November 2010 at the 60-cm robotic telescope REM (Zerbi et al. 2001, ESO La Silla observatory) with the NIR camera REMIR (Conconi et al. 2004) and a 150 s total integration time per filter. An additional H band image was obtained with NICS (13 Oct. 2010) with a 18 s total integration time. Additional K_s photometry (5 Nov. 2003) with the near-IR instrument UIST (Ramsay Howat et al. 2004) was retrieved from the UKIRT data archive (*Int* = 15 s). Moreover, another photometric data point was derived from the K_s band of the SofI K_s acquisition image (*Int* = 6 s). Early epoch photometry was retrieved from the Two-Micron All Sky Survey (2MASS; Skrutskie et al. 2006, J, H, K_s band; November 1998) and from the DEep Near-Infrared southern sky Survey (DENIS; Epchtein et al. 1997, J and K_s bands; January 1997). All the raw data were reduced using *IRAF* packages, applying standard procedures for sky subtraction, dome flat-fielding, and bad pixel and cosmic ray removal. Photometric calibration was obtained by means of photometric standard stars, except for the SofI K_s acquisition image and the UIST image, where 2MASS photometry of field stars was used.

Finally, we also used additional *Spitzer*/IRAC photometric data (3.6, 4.5, 5.8, and 8 μm, obtained on the 8 Oct. 2004), MIPS-24 μm (taken on the 2 Apr. 2005 and 27 Nov. 2008), MIPS 70 and 160 μm (2 Apr. 2005), as well as *Spitzer*/IRS low-resolution spectroscopy (5.2–39 μm, obtained on the 12 Mar. 2007), presented in CoG. Additional SCUBA/JCMT photometry (at 450 and 850 μm) was taken from Di Francesco et al. (2008).

3. Results

3.1. Photometry

In Fig. 1, pre- and outburst images of [CTF93]216-2 in the K_s band (top panels) and the *Spitzer*/MIPS 24 μm band (bottom panels) are shown, clearly indicating an increase in the object brightness. Lightcurves in the J, H, K_s bands, and at 24 μm are shown in Fig. 2, and the corresponding photometric data points along with their uncertainties are reported in Table 1. We stress that the photometric data points at 24 μm (on the 12 Mar. 2007)

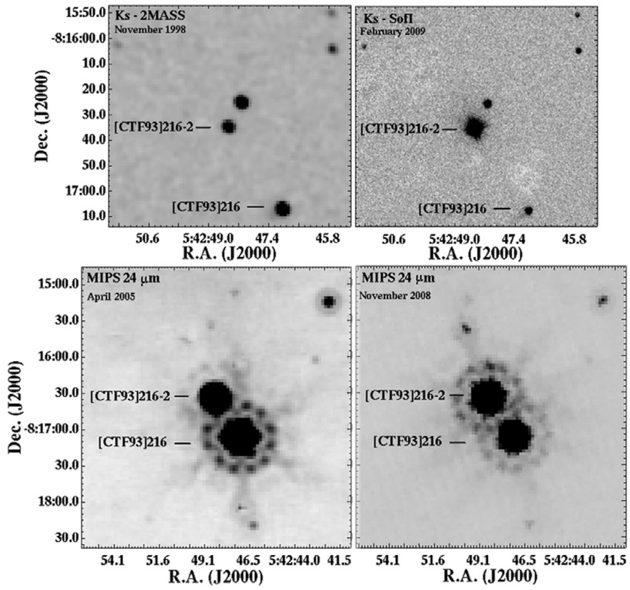

Fig. 1. K_s (*top panels*) and MIPS-24 μm (*bottom panels*) images of [CTF93]216-2 and its surroundings before (*left*) and after (*right*) the outburst. The position of the YSO [CTF93]216 is also indicated.

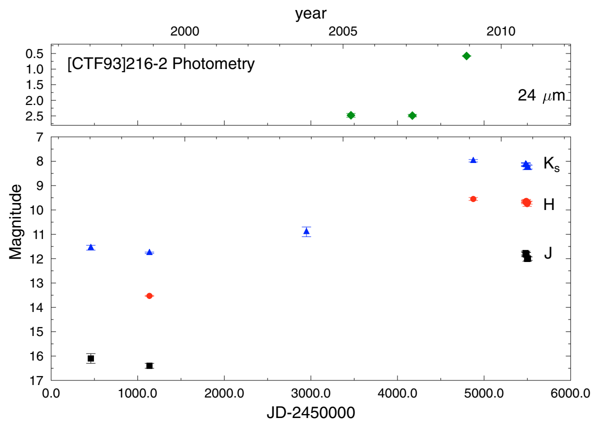

Fig. 2. [CTF93]216-2 lightcurves. J, H, K_s, and 24 μm data are represented as black squares, red dots, blue triangles, and green diamonds, respectively.

and in the H band (on the 13 Feb. 2009) were derived from the *Spitzer*/IRS and from the NTT/SofI flux-calibrated spectra, respectively. The 24 μm data points (Fig. 2, upper panel) give us some constraints on the date of the outburst, i.e. after March 2007 and before November 2008. Pre-outburst photometry from DENIS, 2MASS, and the UIST K_s images indicates that the object is variable (in both J and K_s bands, we have just one 2MASS data point for the H band), as is often the case for YSOs (Carpenter et al. 2001). Comparing 2MASS (November 1998) with our earliest outburst SofI photometry (February 2009), we measure the amplitudes ΔK_s ~ 3.8 mag, and ΔH ~ 4 mag, corresponding to a flux increase ΔF by a factor of ~33 and 40, respectively. Considering our earliest post-burst photometric point in the J band (October 2010), we derive ΔJ ~ 4.6 mag (or ΔF ~ 69), whereas the Δmag at 24 μm is ~1.9 mag (ΔF ~ 6). Our data do not allow us to determine the exact date of the peak, but it is clear that the NIR lightcurves are still close to the maximum, and that this plateau phase has lasted

Table 1. Photometry of [CTF93]216-2.

Date (d.m.y)	JD (2450000+)	*J* (mag)	*H* (mag)	Ks (mag)	24 μm (mag)
10.1.1997	0458.6	16.1 ± 0.2	···	11.55 ± 0.1	···
18.11.1998	1135.7	16.4 ± 0.1	13.53 ± 0.02	11.76 ± 0.03	···
5.11.2003	2948.8	···	···	10.9 ± 0.2	···
2.4.2005	3462.8	···	···	···	2.48 ± 0.1
12.3.2007	4172.0	···	···	···	2.49 ± 0.06^{a}
27.11.2008	4798.2	···	···	···	0.58 ± 0.04
13.2.2009	4875.5	···	9.55 ± 0.06^{b}	7.98 ± 0.05	···
10.10.2010	5479.9	11.77 ± 0.08	9.66 ± 0.05	8.13 ± 0.07	···
12.10.2010	5481.9	11.83 ± 0.09	9.64 ± 0.04	8.12 ± 0.05	···
13.10.2010	5482.7	···	9.70 ± 0.05	···	···
19.10.2010	5488.9	11.82 ± 0.07	9.63 ± 0.06	8.15 ± 0.07	···
28.10.2010	5497.8	12.01 ± 0.1	9.76 ± 0.09	8.25 ± 0.1	···
06.11.2010	5506.6	12.00 ± 0.07	9.70 ± 0.06	8.24 ± 0.08	···

Notes. [(a)] Photometry derived from the *Spitzer*-IRS flux-calibrated spectrum. [(b)] Photometry derived from the SofI flux-calibrated spectrum.

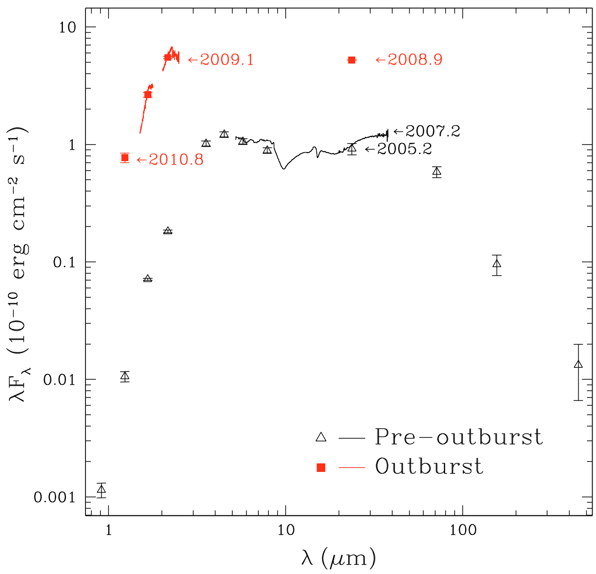

Fig. 3. Spectral energy distribution of [CTF93]216-2. *Pre-outburst data*: black triangles (photometry), and black line (*Spitzer*-IRS mid-IR spectrum). *Outburst data*: red squares (photometry), and red line (SofI NIR spectrum).

at least 2 years, with a small decrement in the *H* and K_s bands of about 0.1 mag between February 2009 and October 2010. Moreover, our latest photometry (November 2010) seems to indicate that the rate of decrease, between October and November 2010, has increased to ~0.2 mag/month in the *J* band and ~0.1 mag/month in the *H* and K_s bands. Pre- and outburst spectral energy distributions (SEDs) are shown in Fig. 3, where all available photometric and spectroscopic data (from this work and from CoG) are reported. We note that both the spectral index and bolometric luminosity have changed, as already reported in other YSO outbursts (see e.g. OO Ser, Kóspál et al. 2007). During the outburst, the YSO SED has become bluer and flatter, and the α value, computed between 2.2 and 24 μm, varied from 0.69 to –0.04. To compute L_{bol}, and estimate the outburst Δmag in the *Spitzer*/IRAC photometry, we fit the dereddened Δmag amplitude from 1.25 to 24 μm by means of a power law, obtaining $\Delta m(3.6\ \mu m) = 2.9$ mag, $\Delta m(4.5\ \mu m) = 2.6$ mag, $\Delta m(5.8\ \mu m) = 2.3$ mag, and $\Delta m(8\ \mu m) = 2.1$ mag. We also assume that the SED flux experienced no significant increase for $\lambda > 24\ \mu$m. As a result, we estimate an L_{bol} value of ~22 $L_\odot$ during the outburst, i.e., $\Delta L_{bol} \sim 20\ L_\odot$ with respect to the pre-outburst state.

3.2. Spectroscopy

Our SofI and NICS low resolution spectra (taken in February 2009 and October 2010, respectively) are shown in Fig. 4 (in black and red).

The SofI spectrum shows an almost featureless continuum, with strong veiling and IR excess. The absorption water band between 1.7 and 2.1 μm, typical of M spectral types with a $T_{eff} \leq 3800$ K, is clearly visible. In addition, deep CO bandhead absorption lines are detected at 2.29 μm (2–0), 2.32 μm (3–1), and 2.35 μm (4–2). Finally, Brγ emission, usually associated with accretion, is observed in our SofI spectrum. The measured Brγ flux is $9.6(\pm1.8)\times10^{-14}$ erg s^{-1} cm^{-2} ($EW \sim -3.6$ Å), peaking at 2.166 μm.

The flux of the NICS spectrum, taken 607 days later, shows a slight decrease. The continuum still has a similar shape, but the absorption H_2O band depth is more prominent. The *EW* of the CO lines slightly increases by ~1 Å (9.8 to 10.6 Å and 7.2 to 8.2 Å, for the 2–0 and 3–1 band heads, respectively). More CO lines at 2.38 μm (5-3), and 2.41 μm (6-4) are detected. In addition, a few more narrow-band absorption features become visible on the continuum, i.e. Ca I (2.26 μm), the Na I doublet (2.20-2.21 μm), Mg I (1.59–1.71 μm), and the Al I doublet (1.67–1.68 μm). No relevant features are detected in the *J* band, except for the absorption H_2O band between 1.3 and 1.5 μm. The Brγ line is not resolved, peaking at 2.166 μm. The measured flux is $9(\pm2)\times10^{-14}$ erg s^{-1} cm^{-2} ($EW \sim -3.7$ Å). We note that no signature of any emission line (such as H_2 or [Fe II]) from the jet has been detected on-source in both spectra.

To more tightly constrain the YSO spectral type, we separately compared limited regions of our spectra (in the *H* and *K* bands) to model spectra. Veiling and scattering (not taken into account by our fit) are expected to smoothly and slowly vary as a function of wavelength and thus, they should not affect the spectrum in individual bands significantly (e.g., Scholz et al. 2010). For our comparison, we used a series of AMES-DUSTY model spectra (Allard et al. 2001) with T_{eff} ranging from 2500 to 3900 K and log $g = 4.0$, as expected for young stars. We varied T_{eff} to obtain a consistent solution for the two bands, using the $A_V = 18$ mag derived by CoG. We find a reasonable match between observed and model spectra for $T_{eff} = 3200 \pm 200$ K. As an illustration, the model for 3200 K is shown in Fig. 4 (blue spectrum), shifted by -0.3×10^{-10} erg s^{-1} cm^{-2} μm^{-1} for clarity.

4. Discussion

Our discovery of the [CTF93]216-2 outburst gives us a rare opportunity to study boosted accretion in young embedded protostars, probing whether episodic mass accretion can reconcile the low accretion rates observed in young embedded protostars with the theoretical predictions.

The Brγ luminosity, corrected for the circumstellar extinction, is often used to derive an estimate of the accretion luminosity (see e.g. Muzerolle et al. 1998; Natta et al. 2006). Assuming that $A_V = 18 \pm 3$ mag and $d = 450$ pc, we derive $L(Br\gamma) \sim 3.5(0.9)\times10^{-3}\ L_\odot$ and, from the Muzerolle et al. (1998) relationship, we obtain $L_{acc} \sim 22 \pm 8\ L_\odot$, which is close to the derived $\Delta L_{bol} \sim 20\ L_\odot$ and indicates that $L_{acc} \sim \Delta L_{bol}$.

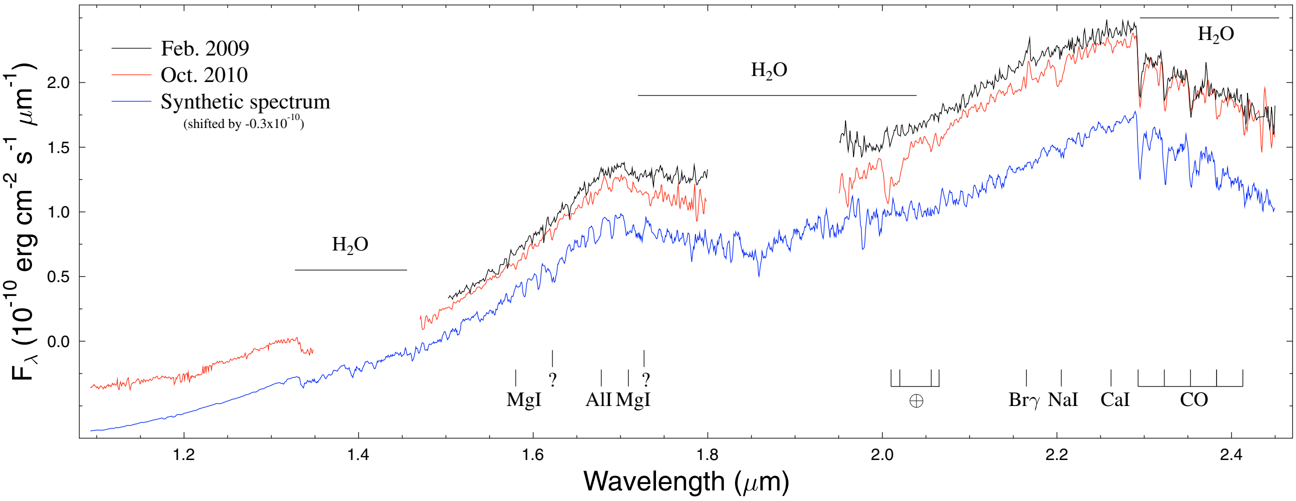

Fig. 4. Flux calibrated NIR spectra of [CTF93]216-2: SofI spectrum (black), and NICS spectrum (red). For comparison, we show an AMES-DUSTY model spectrum for effective temperature of 3200 K and $\log g$ = 4.0 (Allard et al. 2001). The DUSTY spectrum has been shifted by -0.3×10^{-10} erg s^{-1} cm^{-2} μm^{-1} for clarity. The detected features are also labelled.

On the other hand, $\dot{M}_{\rm acc}$ can be derived from $\dot{M}_{\rm acc} = L_{\rm acc} \times 1.25\ R_*/GM_*$ (Gullbring et al. 1998), where M_* and R_* are the stellar mass and radius, and the number 1.25 is derived by assuming a value of 5 R_* for the inner radius of the accretion disk.

Assuming that $T_{\rm eff}$ = 3200 ± 200 K and $L_* \sim 1.9 \pm 0.1\ L_\odot$, from Siess et al. (2000) models, we obtain $M_* = 0.24 \pm 0.04\ M_\odot$ and R_* = 4.4 ± 0.4 $R_\odot$, which gives a mass accretion rate of $\sim$1.1–1.3 $\times 10^{-6}\ M_\odot$ yr^{-1}. While M_* is well constrained by $T_{\rm eff}$, the radius R_* depends on L_*. Thus this last should be considered as an upper limit, since pre-outburst $L_{\rm acc}$ is unknown. However, even a 50% decrease in L_* would affect R_* and thus $\dot{M}_{\rm acc}$ of just 20%.

Compared to typical accretion rates of Class I YSOs with similar masses (i.e. $10^{-8}\ M_\odot$ yr^{-1}; e.g., CoG; Scholz et al. 2010; White & Hillenbrand 2004), the derived $\dot{M}_{\rm acc}$ is about two orders of magnitude higher. This value is about an order of magnitude lower than what some episodic-accretion models predict for these early YSO bursts (i.e. 10^{-5} M$_\odot$ yr^{-1}; e.g. Vorobyov 2009), which should resemble the more evolved FUor counterparts. On the other hand, we note that the magnitude of luminosity change during this outburst ($\sim$10) is similar to those of V 1647 Ori and OO Ser ($\sim$8). Our object would probably differ from the others in its pre-outburst $L_{\rm bol}$, which is about two times lower, because of its lower mass. Moreover, as already noted in previous cases (e,g. Hodapp et al. 1996; Fedele et al. 2007; Kóspál et al. 2007), the [CTF93]216-2 outburst shows similarities with both FUor and EXor events, i.e. a NIR featureless FUor spectrum with strong absorption CO band heads, but with Brγ line in emission as in EXors. The event duration (if confirmed by additional observations) and amplitude are in-between those of EXors and FUors, thus, as noted by other authors (Gibb et al. 2006; Fedele et al. 2007) EXors and FUors might not be distinct categories of eruptive events, but instead part of a continuum of outburst events.

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