Photometric and Spectroscopic monitoring of YSOs in nearby star forming regions. I. Eruptive YSOs

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Mid-infrared (mid-IR) variability in young stellar objects (YSOs) is driven by several physical mechanisms, which produce a variety of amplitudes and light curve shapes.

Rotational modulation of stellar (hot, cold) spots, leads to (nearly) sinusoidal or irregular variability.

Variable extinction: periodic (AA Tau-like) or aperiodic (UXors) fades due to obscuring circumstellar material.

Variable disk accretion is predicted by models of episodic accretion to drive secular variability, including in the mid-IR.

The impact of ***episodic accretion*** on stellar and planet formation.

- Invoked as one of the accretion models that could explain the observed spread in the luminosity of protostars in areas of star formation [1].
- Long-lasting impact on the structure of the central star [2,3].
- Accretion outbursts alter the chemistry of protoplanetary discs [4] and the location of the snow-line of various ices [5].
- Could affect orbital evolution of any planets, if present [6,7].
- The observations of calcium–aluminum-rich inclusions in chondrites [8] could be evidence for past large eruptions in our own Solar system.

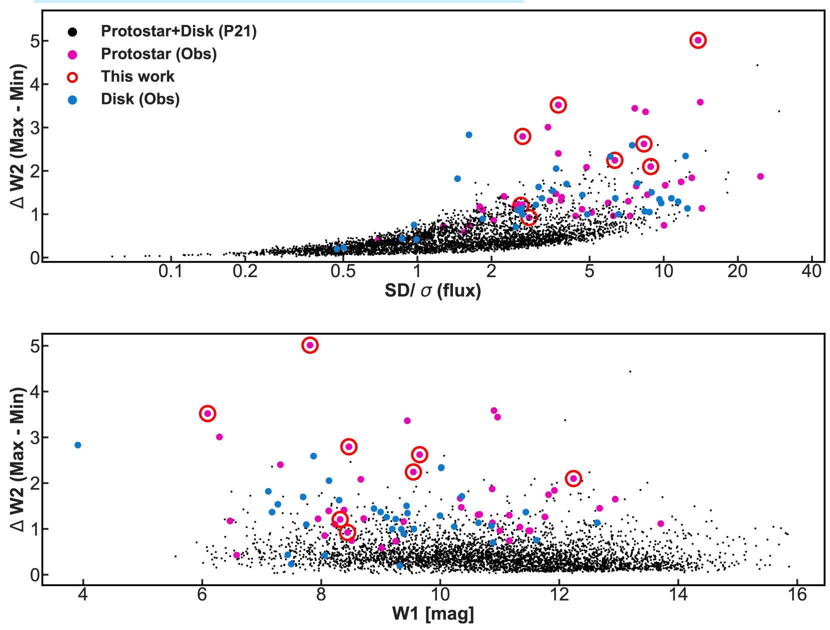
Classical definition of YSOs with the largest changes in disk accretion (a.k.a. ***eruptive variable YSOs***)

- ***FUors*** — Photometry: decades-long outbursts (e.g. the archetype of the class, FU Ori went into outburst in 1936 and is still ongoing) Spectroscopy: FUors have deep absorption (similar to supergiant spectra) because the emission is produced in a viscously-heated inner disk, with extraordinary accretion rates ($10^{-4} - 10^{-5}$ $M_\odot$ yr^{-1}, ***see*** [9])
- ***EX Lupi-type*** — Photometry: outbursts lasting weeks to up to a couple of years Spectroscopy: EXors have accretion rates of $\sim 10^{-7}$ $M_\odot$ yr^{-1} [10]; their inner disks are passively heated by stellar radiation, leading to a warm surface layers that produce bright CO emission.

However, the majority of YSO outbursts discovered over the last ~10 years, show a mixture of spectrophotometric characteristics and have blurred the FUor/EX Lupi-type classification scheme. These type of objects have been classified as *Peculiar, MNors or V1647 Ori-like* [11].

Adding new objects to the YSO eruptive variable class aids our understanding of the episodic accretion phenomenon and its possible impact on stellar and planetary formation.

Park et al. (2021) [13], analysed 6.5 yr of NeoWISE light curves (3-5 μm) of ~7000 nearby YSOs and found an increase in the fraction of variability and variability amplitude for objects at younger stages of evolution.



To help interpret these light curves, we have obtained low/high-resolution near-IR spectra (IRTF/SpeX, Palomar/TripleSpec, Gemini/GNIRS, Gemini/IGRINS, Gemini/Flamingos-2) of 78 objects from this sample of YSOs.

(top) $\Delta W2$ vs SD/σ (standard deviation over magnitude uncertainty) and W1 magnitude (bottom) for all of the YSOs (shown in black) analysed in [13] YSOs with spectroscopic data are shown in blue (disks) and pink (protostars) circles. Finally, YSOs presented in this work as candidate eruptive variables are marked by large red open circles.

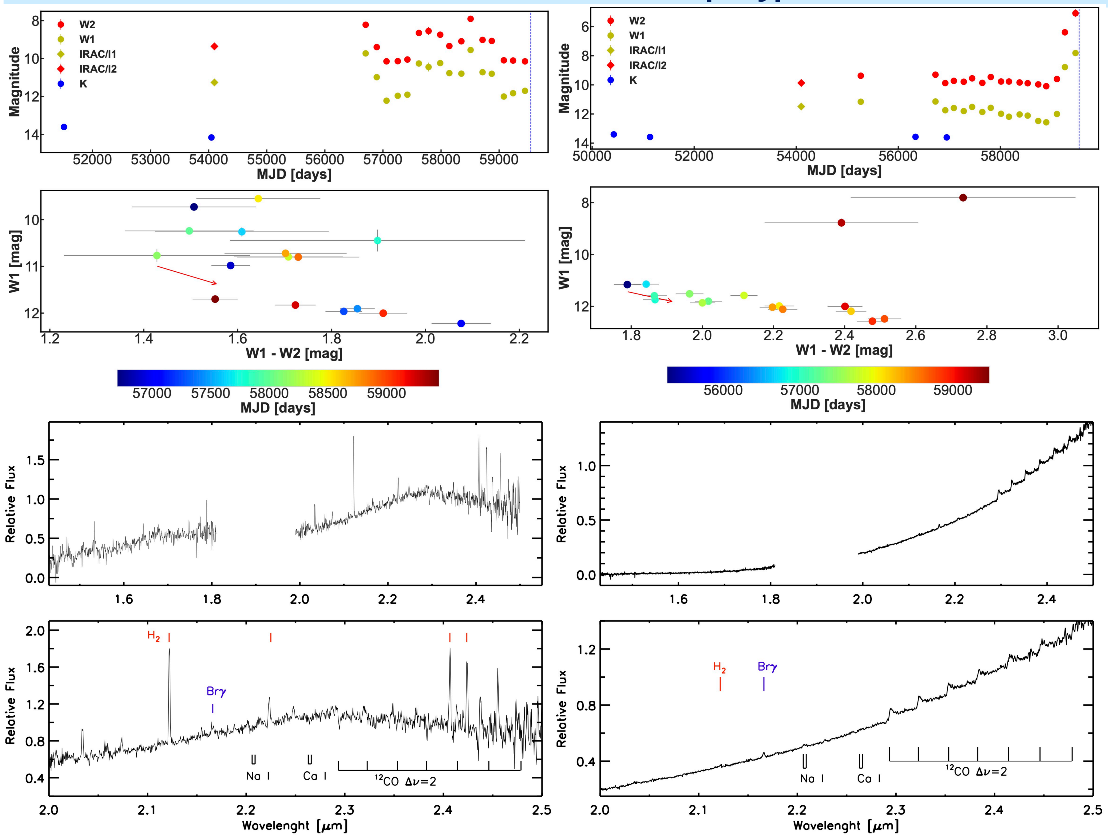
References:
[1]W. J. Fischer, et al., arXiv:2203.11257 (2022); [2] Baraffe et al., A&A, 597, A19 (2017);[3] M. Kunitomo, et al., A&A, 599, A49 (2017); [4]E. Artur de la Vilarmois, A&A, 626, A71 (2019);[5]L. Cieza et al., Nature, 535, 258 (2016);[6]A. Boss, ApJ, 764, 194 (2013); [7] J. C. Becker et al., ApJ, 919, 76 (2021); [8] G. Wurm, H. Haack, Met. & Pl. Sc. 44, 689 (2009).[9] L. Hartmann. & S. J. Kenyon ARA&A, 34, 207 (1996); [10]C. Aspin, et al., ApJ, 719, 50 (2010);[11] M. Connelley & B. Reipurth, ApJ, 861, 145 (2018); [12] C. Contreras Pena et al., MNRAS, 465, 3039(2017); [13] W. Park, J.-E. Lee, C. Contreras Pena, et al., ApJ, 920, 132 (2021);
[14] H. Liu, et al., ApJ, 936, 152 (2022); [15] N. Calvet, et al., ApJ, 380, 617(1991); [16] S. E. Dahm, L. A. Hillenbrand, AJ, 160, 278 (2020); [17] Z. Guo, et al., MNRAS, 513, 1015(2022); [18]G. Baek, et al., ApJ, 895, 27 (2020);

Here, we present the analysis of nine nearby YSOs (d<1 kpc) that show the characteristics of known classes of eruptive variable YSOs.

YSO ID (P21)	Other name	α (J2000)	δ (J2000)	Class	Luminosity ($L_\odot$)	Distance (pc)	ΔW2 (P21)	Class (P21)	ΔW2 (this work)	Class (this work)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
D2369	LDN 1455 IRS3	03:28:00.3	+30:08:01.0	I	0.36	300	2.24	*Irregular*	2.24	*Irregular*
M457	HOPS 267	05:41:19.7	−07:50:41.0	I	1.1	429	0.79	*Irregular*	5.01	*Burst*
M713	HOPS 154	05:38:20.1	−06:59:04.9	I	0.09	389	2.15	*Irregular*	2.1	*Irregular*
D1486	2MASS J21013280+6811204	21:01:32.8	+68:11:20.0	I	6.9	341	1.98	*Burst*	2.62	*Linear*
D1826	2MASS J21533472+4720439	21:53:34.7	+47:20:44.0	F/I	3.97	800	0.92	*Linear*	0.92	*Linear*
M3159	HOPS 315	05:46:03.6	−00:14:49.2	I	6.2	427	0.44	non-variable	1.21	non-variable
D2439	[LAL96] 213	03:29:07.7	+31:21:57.0	I	25.9	300	–	–	3.52	*Curved*
D1607	GM Cha	11:09:28.5	−76:33:28.0	I	1.5	191	–	–	2.79	*Curved*
–	V565 Mon	06:58:02.7	−07:56:43.6	II	130	1150	–	–	0.4	non-variable

Table 1. Attributes of YSOs analysed in this work.

The spectro-photometric characteristics observed in our sample are consistent with recent discoveries of eruptive YSOs, as they show a mix between the classical FUor and EX Lupi-type definitions.



LDN1455 IRS3
Photometry: Irregular (but repetitive)
Spectroscopy: Absorption (FUor-like)
Does not fit the FUor/EX Lup definition

HOPS 267
Photometry: 5 mag outburst (long-lasting)
Spectroscopy: Emission (EX Lupi-type)
Does not fit the FUor/EX Lup definition

YSO ID (P21)	Other name	Light Curve	Colour	Δt (outburst)	Observations	Spectral class	Photometric Class	Final Class
D2369	LDN 1455 IRS3	*Irregular*	bluer when brighter	~4.5 yr	Bright State	FUor	V1647 Ori	V1647 Ori
M457	HOPS 267	*Burst*	redder when brighter	≥1 yr	Rising	EX Lup	V1647 Ori	V1647 Ori
M713	HOPS 154	*Irregular*	bluer when brighter	~1 yr	Bright State	FUor	EX Lup	V1647 Ori
D1486	2MASS J21013280+6811204	*Linear*	redder when brighter	≥3.5 yr	Rising	FUor	V1647 Ori	V1647 Ori
D1826	2MASS J21533472+4720439	*Linear*	bluer when brighter	≥5 yr	Bright state	EX Lup	V1647 Ori?	Outburst Candidate
M3159	HOPS 315	non-variable	bluer when brighter	≥1 yr	Rising	EX Lup	V1647 Ori	V1647 Ori
D2439	[LAL96] 213	*Curved*	redder when brighter	5 – 7 yr	quiescence	EX Lup	V1647 Ori	V1647 Ori
D1607	GM Cha	*Curved*	redder when brighter	<1.5 yr	quiescence	–	EX Lup	EX Lup
–	V565 Mon	non-variable	bluer when brighter	> 70 yr	Bright state	FUor	none	FUor-like

Table 2. Characteristics (colour variation, duration of outburst and classification based on spectroscopic and photometric characteristics of the outburst) for the YSOs in table 1.

We find one FUor-like source, one EX Lupi-type object, and six YSOs with mixed characteristics, or V1647 Ori-like objects.

A wide range in YSO outburst parameters may play a significant role in the observed spectro-photometric properties of YSO outbursts, e.g.:

(1) Central mass, maximum accretion rate during outburst: Liu et al. (2022) [14] explored the parameter space of FUor-like outbursts to understand the effect of the mass of the central star ($0.1 < M_\star < 3$ $M_\odot$) and mass accretion rate ($10^{-8} < \dot{M} < 10^{-4}$ $M_\odot$ yr^{-1}) on the observed spectral energy distributions and spectra of outbursting YSOs.

- $\dot{M} > 10^{-5}$ $M_\odot$ yr^{-1} always leads to a FUor-like spectrum, regardless of the value of mass.
- $10^{-7} < \dot{M} < 10^{-5}$ $M_\odot$ yr^{-1} In this region, the near-IR spectroscopic characteristics of YSO outbursts (specifically ^{12}CO) have contributions of both the stellar photosphere and the viscous disk. A larger stellar irradiation due to an increase in $\dot{M}$ can lead to ^{12}CO emission from the upper layers of the accretion disk ([15]). This would also influence the observed characteristics of the ^{12}CO band.

(2) Instability leading to the outburst: Instabilities driven by a stellar/planetary companion lead to periodic light curves, which have been observed in several eruptive variable YSOs [16,17]. This type of light curve has generally been classified as peculiar (or V1647 Ori-like), as they do not fit the classical definition of FUor/EX Lup-type outburst.

(3) YSO evolutionary stage: Radiative transfer modelling of the embedded YSO EC53 [18] shows that parameters such as envelope radius or cavity opening angle affect greatly the observed flux at mid-IR wavelengths. This implies that the amplitudes and light curve shapes of outbursting embedded YSOs could strongly depend on the geometry of their surrounding envelopes.