Multi-wavelength detection of an ongoing FUOr-type outburst on a low-mass YSO

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Introduction

FUOr-type event

- A FUOr-type event, named after the prototype FU Orionis, displays a prominent outburst in its light curve, usually with an amplitude larger than 5 mag in the optical (see the review from Fischer et al. 2022). These events are rarely detected, as once per 10^4 to 10^5 yrs per star, estimated by the total known eruptive samples (Scholz 2012; Hillenbrand & Findeisen 2015; Contreras Peña et al. 2019, and Contreras Peña submitted).
- Most FUOr-type outbursts share two common photometric signatures (Hartmann & Kenyon 1996), high amplitude (~5 mag in optical) and long duration (tens to nearly one hundred years).

FUOr-type event

- During the FUOr event, unlike the steady magnetospheric accretion seen on most disc-bearing YSOs, the disc material is directly accreted onto the star by the boundary layer accretion mode (Audard et al. 2014). The mass accretion rate during a solar mass FUOr-type outburst can reach $10^{-4} M_{\odot} \mathrm{yr}^{-1}$, orders of magnitudes higher than the steady accretion stage. Episodic accretion model spredict that most of the stellar mass is accumulated during these outbursts (Hartmann & Kenyon 1996).
- The near-infrared (NIR) spectra of FUOrs resemble a bright but cool object, with strong absorption bands mainly from the molecules in the circumstellar disc/envelope. Most FUOrs are confirmed by a combination of eruptive photometric light curves along with their unique spectral features (Connelley & Reipurth 2018; Guo et al. 2021).

Obeservation and Data Reduction

L222_78

- The eruptive behaviour of L222_78 was originally discovered in LSG23 using the Ks time series from the Via Lactea survey(VVV) Infrared Astrometric Catalogue (VIRAC2 β, Smith et al. 2018, and in prep). The VIRAC2β catalogue provides PSF (point-spread function) photometry of dozens of Ks detections (from 2010 to 2019) and two multicolour (Z, Y, J, H) epochs.

Multi-wavelength

- In 2021 and 2022, we obtained single-epoch J, H, Ks photometry of this target using the Son of ISAAC infrared imager on the ESO NTT telescope (SOFI Moorwood et al. 1998). We obtained optical to NIR photometry from the SMARTS 1 m telescope in 2022 and the Rapid Eye Mount (REM) telescope in 2023. Two epochs of r and i-band images are found in the LCO science archive (Brown et al. 2013). Plus, we retrieved g, r, and i-band images of the VPHAS+ survey taken by the VLT Survey Telescope (VST) from the ESO archive (Drew et al. 2014), and broadband calibrated images from ATLAS forced photometry server (Tonry et al. 2018a).
- We retrieved optical light curves and astrometry data from Gaia DR3.
- We obtained mid-infrared photometric data from ALLWISE (Wright et al. 2010) and NEOWISE (Mainzer et al. 2014) surveys via the NASA/IPAC Infrared Science Archive.
- Two spectra of L222_78 were observed in 2021 and 2023. The XSHOOTER spectra (Vernet et al. 2011) were obtained on the Very Large Telescope on April 16th 2021. On May 9th 2023, we obtained NIR spectra from the Folded-port Infra-Red Echellette (FIRE) spectrograph on the Magellan Baade Telescope (Simcoe et al. 2013).

Photometric features

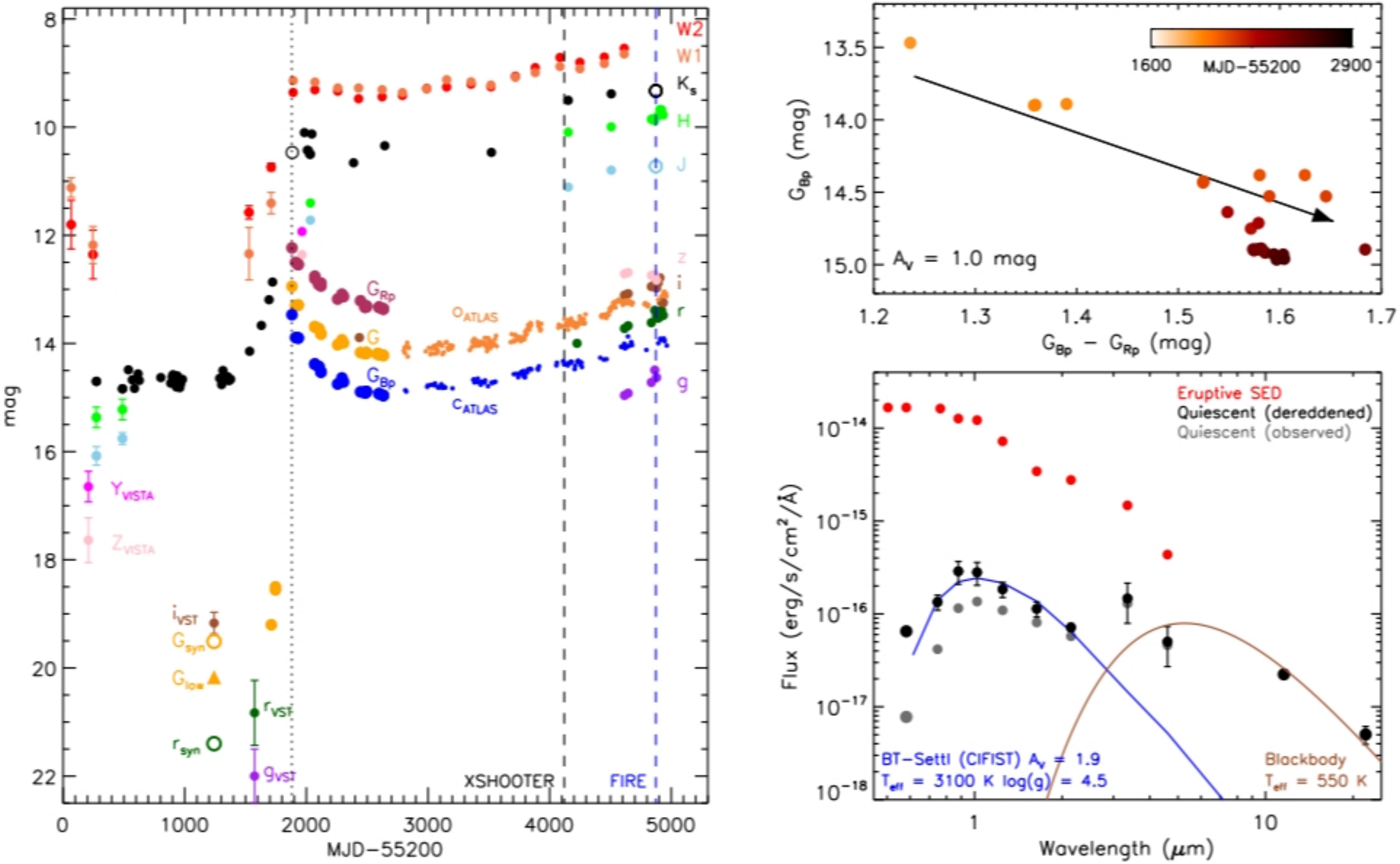
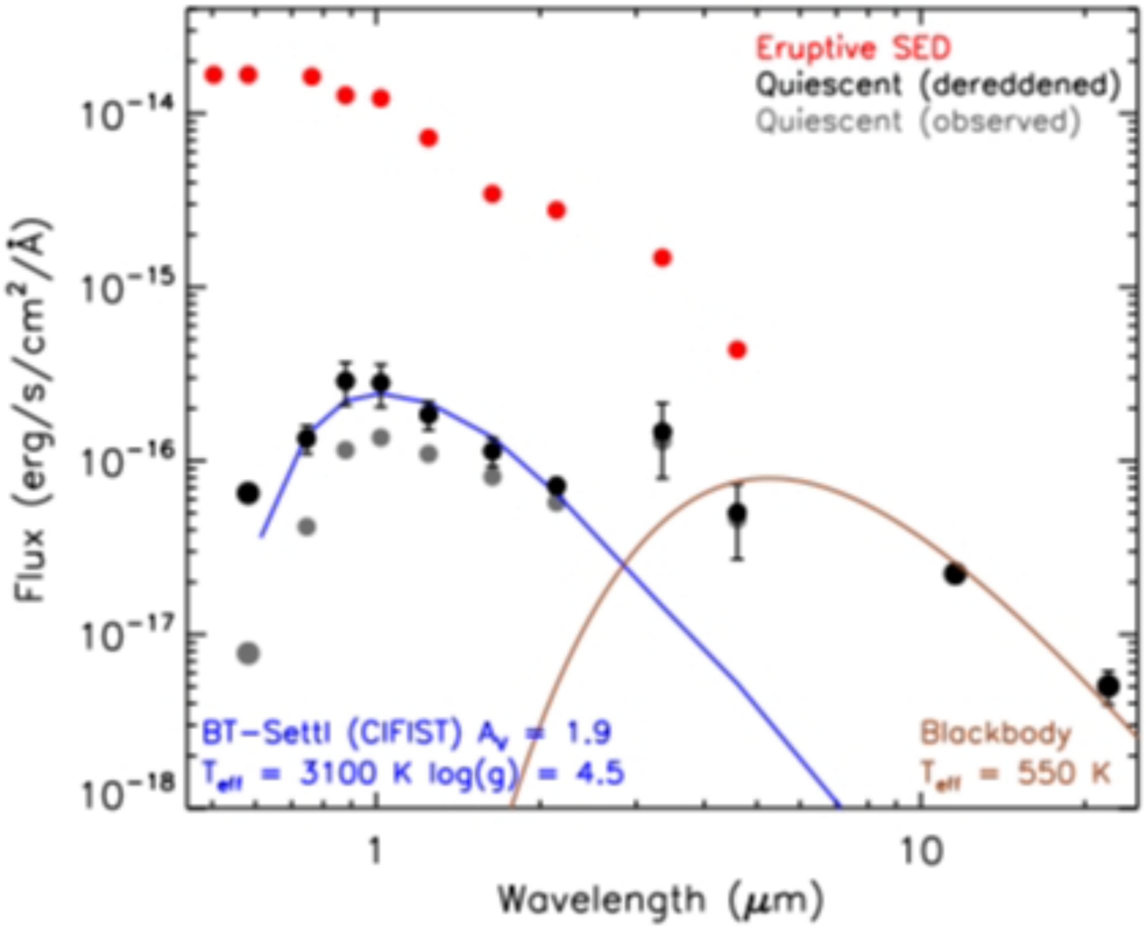


Figure 1. *Left*: Multi-wavelength light curves of L222_78, colour coded by photometric bands. Error bars less than 0.1 mag are not shown. Open symbols are synthetic magnitudes computed from the SED best-fitting atmospheric model and spectra. Vertical dashed lines mark the observation dates of two spectral epochs. The ending point of the rising stage is shown by the dotted line (around MJD 57080/2015-02-27). *Upper Right*: Gaia colour-magnitude diagram with an extinction vector ($A_V = 1.0$ mag). The data points are colour-coded by the observation time. *Lower Right*: The pre-outbursting (grey), dereddened (black) and eruptive (red) SEDs. A BT-Settl model (blue) is fit to the pre-outbursting SED and a blackbody model (brown) is fit to the IR excess beyond 2 μm.

- The variation of extinction is not unusual on FUOrs, which has been referred to as the dust grain condensation when the wind collides with the envelope (see Siwak et al. 2023) or the dust lifted by the outflow during the ejection outburst.
- A low-amplitude colourless brightening trend is detected in the ATLAS light curves (see Figure 1 and the online supplementary file), which is inconsistent with the extinction law mentioned above. The same rising trend is detected in the mid-infrared, indicating a piling up of warm material in the circumstellar disc, which resembles the behaviour of PGIR 20dci (Hillenbrand et al. 2021). We observe a change in the slope of the NIR continuum spectra, which can be interpreted as variable extinction (see §3.4). Therefore, we conclude that the recent rising trend on L222_78 is likely attributed to a mixture of increasing mass accretion rate and clearing of line-of-sight extinction. The enhancement in the mid-infrared brightness also suggests the existence of warm dust in the circumstellar disc.

SED and bolometric luminosity

- The pre-outbursting SED fitting result suggests that the progenitor has an effective temperature of 3100 K (1σ confidence: 2769 – 3373 K) and a bolometric luminosity, $L_{\rm bol} = 0.16 \pm 0.02\ L_{\odot}$.
- $G_{\rm syn} = 19.5$、 $r_{\rm syn} = 21.4$
- Under the assumption that the accretion luminosity ($L_{\rm acc}$) is roughly equal to the bolometric luminosity during the eruptive stage, we estimated the peak mass accretion rate (Macc) is 0.8 to 1.4×10^{-5} $M_{\odot}\ {\rm yr}^{-1}$, by simply applying an approximated correlation, $M_{\rm acc} = L_{\rm acc} R_{*}/(GM_{*})$, (Gullbring et al. 1998).



Rising Timescale

- The rising stage of L222_78 was captured by a broad wavelength range, including an exceptional optical amplitude ($\Delta G > 6.3$ mag) which places it as one of the highest amplitude eruptive events on YSOs. We applied analytical functions to describe the exponential rising stage in G, Ks, and $W2$ using observed and synthetic magnitudes. We adopted the two-step formalism originally designed by LSG23,

$$t < t_{1/2}: \quad m(t) = m_q - \frac{m_q - m_p}{1 + e^{-(t-t_{1/2})/\tau}} \quad (1)$$

$$t \geq t_{1/2}: \quad m(t) = m_q - (m_q - m_p)(0.5 + 0.5(t - t_{1/2})/2\tau) \quad (2)$$

- where $t1/2$ is the time when the brightness is enhanced by half of the amplitude and τ is a timescale parameter. Additionally, mq and mp are the pre-outbursting and peak magnitudes obtained from the time series which are treated as constants in our fitting. As designed, the photometric maximum (mp) is reached at $t1/2 + 2\tau$, where the rising stage ends.

Rising Timescale

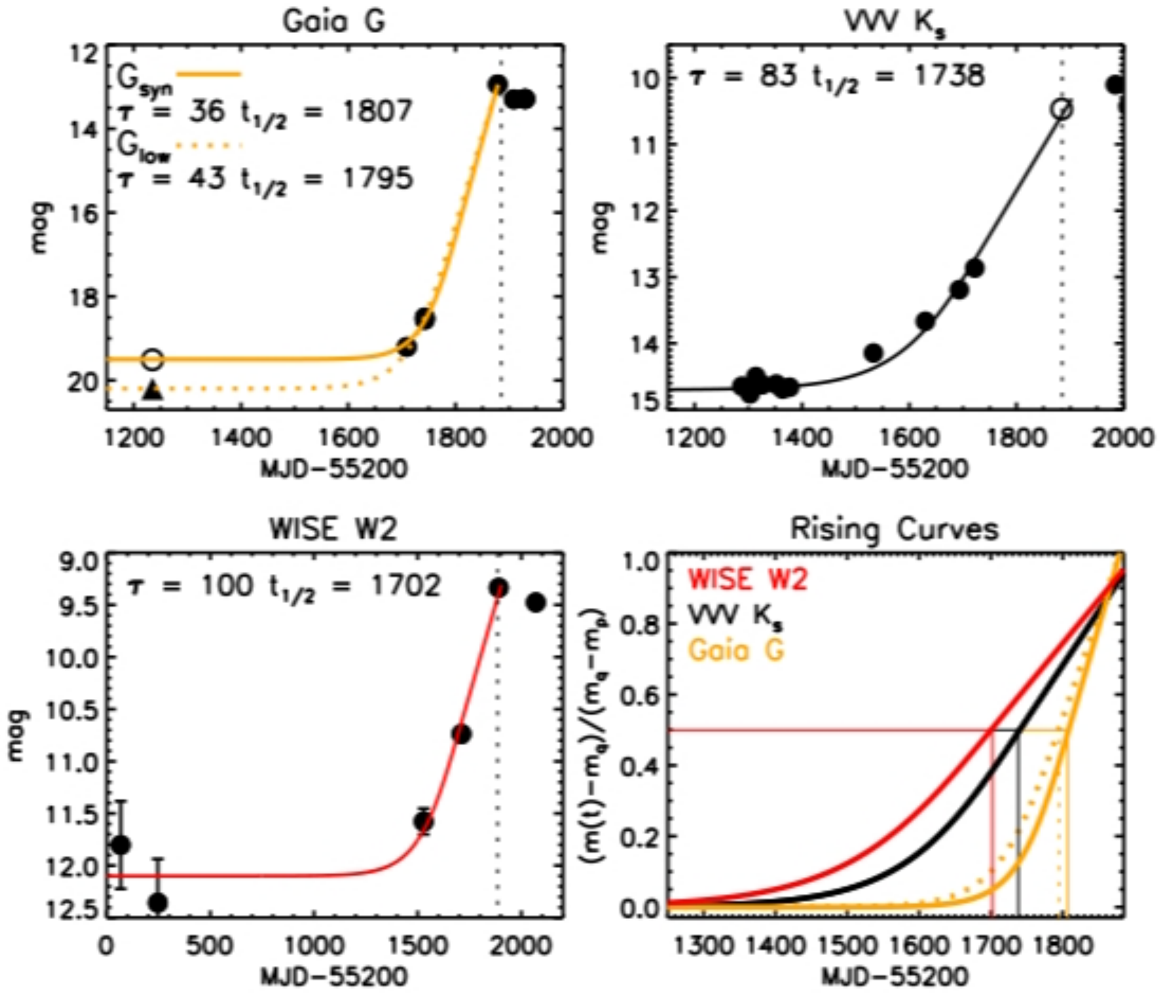


Figure 2. Rising light curves and analytical rising functions of L222_78. Synthetic brightness (open circles) and lower limit (triangle) in G are presented. The normalised curves are shown in the bottom right with $t_{1/2}$ marked out. The ending of the raising stage is marked by the dashed vertical lines.

Spectroscopic features

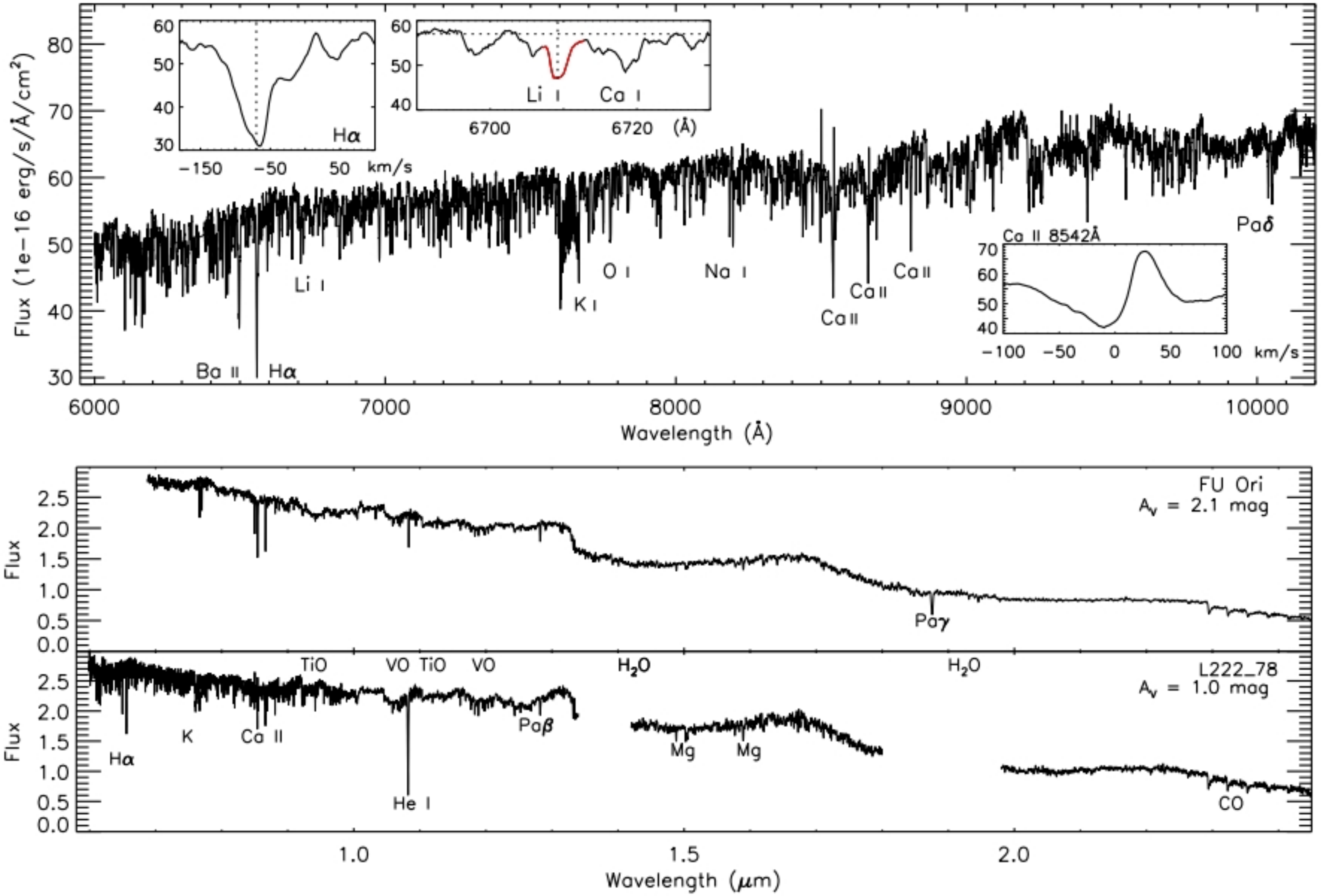


Figure 3. *Upper:* Optical spectrum of L222_78, with line profiles of Hα, Li I and Ca II absorption lines. *Lower*: Dereddened NIR spectra of FU Ori (IRTF; Connelley & Reipurth 2018) and L222_78 (XSHOOTER). Spectral features are marked individually on the plot.

Discussion and Summary

- This study presents an ongoing eruptive object located in the VdBH 221 open cluster, with a 6.3 mag outburst observed in the Gaia time series with an optical rising stage of 170 days. A short time delay (Δt 1/2 = 100 days) is observed between the infrared and optical rising stages, suggesting an outside-in propagated instability that originated in the circumstellar disc at a radius less than 0.1 AU. Some lower amplitude variations are detected after the photometric maximum, attributed to the gradual changing of line-of-sight extinction and overall mass accretion rate. The prevalence of absorption features in the optical to NIR spectra agrees with the FUOr-type outburst. We conclude that this source is a bona fide FUOr-type object based on the current evidence and the criteria proposed in Connelley & Reipurth (2018).

Thanks