Subsequent outbursts of the same EXor source possibly present similar features

T. Giannini\textsuperscript{1}, A. Giunta\textsuperscript{2}, D. Lorenzetti\textsuperscript{1}, G. Altavilla\textsuperscript{1,2}, S. Antoniucci\textsuperscript{1}, F. Strafella\textsuperscript{3}, and V. Testa\textsuperscript{1}

\textsuperscript{1} INAF-Osservatorio Astronomico di Roma, Via Frascati 33, 00078 Monte Porzio Catone, Italy
e-mail: teresa.giannini@inaf.it
\textsuperscript{2} ASI – Agenzia Spaziale Italiana, Via del Politecnico, 00133 Roma, Italy
\textsuperscript{3} Dipartimento di Matematica e Fisica, Universit\`a del Salento, 73100 Lecce, Italy

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\section*{ABSTRACT}

Context. V1118 Ori is a classical EXor source whose light curve has been monitored, although not continuously, over the past 30 years. This source underwent a powerful outburst in 2005, followed by 10 years of quiescence and a less intense outburst in 2015. In 2019, a new intense brightness increase was observed ($\Delta g \sim 3$ mag).

Aims. This new accretion episode offers the opportunity to compare the photometric and spectroscopic properties of multiple outbursts of the same source. This allows us to highlight the differences and similarities among various events by removing any possible bias related to the intrinsic properties of the star-disk system.

Methods. We discovered the 2019 V1118 Ori outburst by examining the $g$-band light curve acquired by the Zwicky Transient Facility and followed the declining phase with the Rapid Eye Mount telescope in the $griz$ bands. Two near-infrared spectra were also acquired at different brightness stages with the Large Binocular Telescope.

Results. The last event shows the following characteristics: (1) an amplitude similar to that of 2015 and lower than that of 2005; (2) a duration of less than one year as in previous events; (3) a increasing (decreasing) speed of 0.018 (0.031) mag day$^{-1}$, which is different from previous cases; (4) a gradually bluing of the $[g-i]$ color is observed over time, while the $[r-i]$ color remains roughly unchanged; (5) with few exceptions, the near-infrared lines (mainly H\textsc{i} recombination) are the same as those observed in 2015; and (6) the mass accretion rate peaks at $M_{\text{acc}} \sim 10^{-7} M_\odot$ yr$^{-1}$ and decreases in about a month down to a few $10^{-8}$ $M_\odot$ yr$^{-1}$.

Conclusions. Our analysis shows that the comparison of data from different outbursts of the same source is a nontrivial exercise, which allows us to obtain important clues that are useful to drive theoretical efforts toward a better understanding of the EXor phenomenon.

Key words. stars: pre-main-sequence – stars: individual: V1118 Ori – stars: variables: T Tauri, Herbig Ae/Be

\section*{1. Introduction}

Eruptive variables belong to a class of pre-main-sequence objects usually divided into two subclasses: EXor (Herbig 1989) and the more energetic FUor (Hartmann & Kenyon 1985) systems, which both present an intermittent variability related to an unsteady mass accretion rate. The membership to either subclass depends on the different properties, such as the amplitude and duration of the bursts, the recurrence time between subsequent outbursts, and the mass accretion rate. A comprehensive account of the properties of both EXors and FUors is given by Audard et al. (2014).

In general terms, the observed features that define the EXor subclass membership are the occurrence on timescales of years of short-term outbursts (typically lasting several months) with amplitude $\Delta V$ of about 3-5 mag at optical and near-infrared (near-IR) wavelengths and spectra characterized by strong H\textsc{i} recombination lines and other atomic permitted lines (e.g., Herbig 2008; Lorenzetti et al. 2009; Sicilia-Aguilar et al. 2012; Kospál et al. 2011).

Although EXor outbursts are known to be associated with magnetospheric accretion events from the circumstellar disk (Shu et al. 1994), their nature is still very uncertain and no specific models have been developed so far. Therefore, the theoretical framework developed by Hartmann & Kenyon (1985) for FU Orionis objects is also widely adopted for EXors. More specific efforts have been performed in the last decade (D’Angelo & Spruit 2010; Vorobyov & Basu 2015), however difficulties arise in predicting the relatively short cycle time of the episodic accretion phenomena and there are only suggestions about the mechanism responsible for the outburst onset. These include thermal instabilities (e.g., Bell & Lin 1994), the presence of a massive planet (Lodato & Clarke 2004), and close interactions in a binary system (Bonnell & Bastien 1992).

Observational inputs to the current theoretical framework can be obtained by comparing the results of both photometric and spectroscopic observations at optical and near-IR frequencies of successive outbursts of the same source. This comparison allows us to highlight similarities and differences of multiple events in the same star-disk system and to remove all possible bias often introduced when considering outbursts of sources with different masses, luminosities, or evolutionary stages. In this way, the uncontaminated interplay between the outburst parameters (amplitude, duration of both rising and declining phases, and fluctuations of the local extinction) can be more accurately determined.

A suitable target for this kind of investigation is the classical EXor V1118 Ori, a source that has been monitored over the past 30 years by several authors (Audard et al. 2005, 2010 and references therein). We have been following V1118 Ori...
for more than 10 years observing both quiescent and outbursting periods (Lorenzetti et al. 2006, 2007, 2015). In particular, our monitoring of the outburst occurred in the period 2015–2016 allowed us to estimate the evolution of the mass accretion rate (compared to the immediately preceding quiescence) from \(0.3-20 \times 10^{-8}\) to \(0.2-2 \times 10^{-9}\) \(M_\odot\) yr\(^{-1}\) (Giannini et al. 2016, 2017). During 2017–2018 V1118 Ori went through a period of quiescence. In May 2019 we announced a new outburst (Giunta et al. 2019a), remarking on its peculiarity in terms of increasing and decreasing speeds (Giunta et al. 2019b). Our observations of this last event are presented in Sect. 2, while the results are discussed and compared with those of the previous outbursts in Sect. 3. Our final remarks are given in Sect. 4.

### 2. Observations and data reduction

#### 2.1. Optical photometry

In the period 2018–2019 V1118 Ori was monitored in the \(g\) band with the Zwicky Transient Facility (ZTF)\(^1\), which reported an increase of about two magnitudes (from \(g \sim 17\) to 15) between February and April 2019 (see Table 1). Owing to seasonal observability, subsequent observations could only start in late August when the source was still bright (\(g \sim 14.4\)), but already in the declining phase. The quiescence was reached again in late November.

To increase the temporal coverage, we observed V1118 Ori with the ROSS2 optical camera installed on the 60 cm robotic telescope Rapid Eye Mount (REM) at La Silla (Chile). The observations were conducted in the \(g, r, z, i\) bands and covered mainly the declining phase from August to September 2019.

The images were reduced by using standard procedures for bad pixel removal, flat fielding, and bias and dark subtraction. The aperture photometry was then obtained using as calibrators several stars in the V1118 Ori field, whose optical magnitudes have been retrieved by the PAN-STARSS Data Release 2 (DR2) Photometric Catalog\(^2\). The photometric data are listed in Table 2.

Figure 1 depicts the \(g\)-band light curve. We certainly missed the outburst peak, which occurred in the period June–August 2019. Unfortunately, no Gaia passages on V1118 Ori were performed during this period because the closest in time were carried out on August 13 (Lattanzi, priv. comm.). No alert was issued at that time. The ROSS2 observations have partially filled the observational gap, allowing us to get the highest photometric point of both the rising and declining phases: on 9 May 2019 \(g \sim 14.56\) and on 12 August 2019 \(g = 14.00\).

To get a rough estimate of the peak brightness we fit with a straight line both the rising and declining light curves, which intersect at \(g \sim 13.8\) mag (see Sect. 3.1.1). This value is comparable to the peak reached in the 2015–2016 outburst (Giannini et al. 2016), as also shown in the historical light curve presented in Fig. 2.

#### 2.2. Spectroscopy

Near-IR spectra were collected on October 1 (MJD 58757) and October 20, 2019 (MJD 58776). Both spectra were obtained with the 8.4 m Large Binocular Telescope (LBT) located in Mount Graham (Arizona, USA) using the LUCI2 spectrometer. The observations were conducted with the G200 grating (\(zJ\) and \(HK\) filters) covering the spectral ranges \(0.9–1.2\) \(\mu\)m and

| MJD  | Date       | \(g\) (mag) |
|------|------------|-------------|
| 58204| 27 Mar. 2018| 17.15       |
| 58362| 01 Sep. 2018| 17.58       |
| 58365| 04 Sep. 2018| 17.54       |
| 58368| 07 Sep. 2018| 17.34       |
| 58371| 10 Sep. 2018| 17.24       |
| 58374| 13 Sep. 2018| 17.45       |
| 58377| 16 Sep. 2018| 17.48       |
| 58397| 06 Oct. 2018| 17.23       |
| 58425| 03 Nov. 2018| 17.50       |
| 58427| 05 Nov. 2018| 17.12       |
| 58428| 06 Nov. 2018| 17.15       |
| 58430| 08 Nov. 2018| 16.86       |
| 58431| 09 Nov. 2018| 17.19       |
| 58434| 12 Nov. 2018| 17.15       |
| 58437| 15 Nov. 2018| 16.70       |
| 58438| 16 Nov. 2018| 17.05       |
| 58439| 17 Nov. 2018| 16.96       |
| 58440| 18 Nov. 2018| 17.17       |
| 58443| 21 Nov. 2018| 17.19       |
| 58450| 28 Nov. 2018| 17.48       |
| 58462| 10 Dec. 2018| 17.24       |
| 58466| 14 Dec. 2018| 17.51       |
| 58469| 17 Dec. 2018| 17.74       |
| 58472| 20 Dec. 2018| 17.66       |
| 58476| 24 Dec. 2018| 17.44       |
| 58487| 04 Jan. 2019| 16.91       |
| 58509| 26 Jan. 2019| 16.82       |
| 58523| 09 Feb. 2019| 16.22       |
| 58542| 28 Feb. 2019| 16.64       |
| 58547| 05 Mar. 2019| 15.91       |
| 58557| 15 Mar. 2019| 16.06       |
| 58560| 18 Mar. 2019| 16.07       |
| 58573| 31 Mar. 2019| 16.00       |
| 58582| 09 Apr. 2019| 15.18       |
| 58717| 22 Aug. 2019| 14.41       |
| 58723| 28 Aug. 2019| 14.79       |
| 58726| 31 Aug. 2019| 14.40       |
| 58734| 08 Sep. 2019| 15.19       |
| 58737| 11 Sep. 2019| 14.81       |
| 58740| 14 Sep. 2019| 15.37       |
| 58745| 19 Sep. 2019| 15.52       |
| 58748| 24 Sep. 2019| 15.59       |
| 58750| 26 Sep. 2019| 15.58       |
| 58756| 02 Oct. 2019| 15.92       |
| 58763| 09 Oct. 2019| 15.64       |
| 58766| 12 Oct. 2019| 15.93       |
| 58767| 13 Oct. 2019| 16.07       |
| 58768| 14 Oct. 2019| 16.11       |
| 58775| 19 Oct. 2019| 16.38       |
| 58779| 23 Oct. 2019| 16.54       |
| 58780| 24 Oct. 2019| 16.60       |
| 58788| 01 Nov. 2019| 17.04       |
| 58799| 12 Nov. 2019| 16.85       |
| 58805| 18 Nov. 2019| 16.84       |
| 58812| 25 Nov. 2019| 17.41       |

**Notes.** Typical photometric errors are 0.05 mag.

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\(^{1}\) [https://www.ztf.caltech.edu](https://www.ztf.caltech.edu)

\(^{2}\) [https://catalogs.mast.stsci.edu/panstarrs/](https://catalogs.mast.stsci.edu/panstarrs/)
and spectral directions. The telluric features were removed by dividing the extracted spectra by that of a telluric standard star (observed on the same nights as the targets), once corrected for its intrinsic hydrogen absorption features. Wavelength calibration was obtained from arc lamps. The \( K \)-band acquisition image was used to estimate the photometry of V1118 Ori on the dates of the spectral observations (\( K = 10.08 \) on October 1 and \( K = 10.70 \) on October 20), which in turn was used for flux calibration of the \( HK \) spectral segments. The \( zJ \) spectrum taken on October 1 was calibrated using the \( z \)-band photometry of September 30, while the \( zJ \) spectrum of October 20 was simply aligned with the \( HK \) segment, applying the same calibration factor. The resulting 0.95–2.35 \( \mu \)m spectra are shown in Fig. 3, while fluxes of the relevant features identified are listed in Table 3. Since both spectra were acquired during the declining phase, it is not surprising that they are similar to the LUCI2 spectrum obtained during the same phase of the 2015–2016 outburst (Giannini et al. 2017). The most prominent lines are the H\(_1\) recombination lines of the Paschen and Brackett series, along with a couple of metallic lines of Fe\(_{i}\) and O\(_{i}\) that were not detected in 2016. The H\(_{2}\) 1.08 \( \mu \)m line is also detected in both spectra and exhibits a weak PCyg-like absorption in the October 20 spectrum, which signals outflow activity. The H\(_{2}\) 2.12 \( \mu \)m emission is only detected when the source is close to quiescence (October 20); this also happened previously (Lorenzetti et al. 2015; Giannini et al. 2017). Likely, the line is not detected during outbursts owing to an unfavorable line-to-continuum ratio when the source is bright. The fact that the H\(_{2}\) emission is substantially unrelated with the source brightness suggests that it comes from the diffuse cloud.

3. Results and discussion

3.1. Photometry

3.1.1. Increasing versus decreasing speed

As shown in Fig. 2, well-sampled monitoring of V1118 Ori was obtained for the last five outbursts, from the one occurred in 1997 to that of 2019. Therefore, V1118 Ori offers the unique possibility of comparing the speed of brightness variation (\( \Delta \text{mag}/\Delta t \)) calculated with the same method in subsequent events of the same EXor source. This speed can be easily obtained as the slope of the linear fit through the photometric points of the rising and declining phase (Fig. 1).

For the last outburst, we get \( \Delta g/\Delta t = 0.018 \text{mag day}^{-1} \) (rising) and \( 0.031 \text{mag day}^{-1} \) (declining). We estimated these values by considering as starting and ending points of the fit those from which the brightness starts (stops) to increase (decrease) monotonically. We note that this choice implies that the slope of 0.018 \( \text{mag day}^{-1} \) is the maximum speed value that can be fitted through the rising phase data.

The same method applied to the data of previous outbursts provides the \( \Delta V/\Delta t \) reported in Table 4. Broadly speaking, the majority of both increasing and decreasing speed values range between 0.011 and 0.015 \( \text{mag day}^{-1} \). Two significant exceptions are represented by the increasing speed of the 2005 outburst (0.035 \( \text{mag day}^{-1} \)) and the decreasing speed of the last event (0.031 \( \text{mag day}^{-1} \)). More importantly, the data in Table 4 show that while in 2005 the increase was faster (by more than a factor two) compared to the decrease, the reverse phenomenon occurred in the last outburst.

These differences provide indications that heating and cooling occur with different modalities in subsequent outburst events. We speculate that a role might be played by the temperature reached at the outburst peak, the quantity of gas inside the

**Table 2. Rapid Eye Mountometry.**

| MJD  | Date      | \( g \) (mag) | \( r \) (mag) | \( i \) (mag) | \( z \) (mag) |
|------|-----------|---------------|---------------|---------------|---------------|
| 58612| 09 May 2019 | 14.56         | 13.83         | 13.31         | 12.76         |
| 58707| 12 Aug. 2019 | 14.00         | 13.59         | 12.99         | 12.60         |
| 58710| 15 Aug. 2019 | 14.56         | 13.81         | 13.45         | 12.87         |
| 58713| 18 Aug. 2019 | 14.49         | 13.74         | 13.34         | 12.74         |
| 58716| 21 Aug. 2019 | 14.19         | 13.57         | 13.05         | 12.64         |
| 58719| 24 Aug. 2019 | 14.77         | 13.99         | 13.48         | 12.96         |
| 58722| 27 Aug. 2019 | 14.77         | 14.01         | 13.47         | 12.97         |
| 58727| 04 Sep. 2019 | 14.56         | 13.73         | 13.32         | 12.83         |
| 58730| 07 Sep. 2019 | 14.60         | 13.85         | 13.42         | 12.91         |
| 58733| 10 Sep. 2019 | 15.00         | 14.32         | 13.86         | 13.20         |
| 58736| 13 Sep. 2019 | 15.52         | 14.62         | 14.24         | 13.52         |
| 58744| 18 Sep. 2019 | 15.60         | 14.79         | 14.27         | 13.52         |
| 58747| 21 Sep. 2019 | 15.59         | 14.74         | 14.41         | 13.72         |
| 58750| 24 Sep. 2019 | 15.49         | 14.82         | 14.33         | 13.71         |
| 58753| 27 Sep. 2019 | 15.69         | 14.99         | 14.49         | 13.85         |
| 58756| 30 Sep. 2019 | 15.75         | 15.06         | 14.62         | 13.88         |

**Notes.** Typical photometric errors are 0.05 mag.

![Fig. 1. Zwicky Transient Facility (black) and REM (red) \( g \)-band photometric points of the 2019 outburst of V1118 Ori. The two dashed lines indicate the linear fits to the points of the rising and declining phases, with indicated the values of their slopes (mag day\(^{-1}\)). Both have an uncertainty of 0.002 mag day\(^{-1}\). Two continuous segments indicate the dates of the spectroscopic observations.](http://www.iasf-milano.inaf.it/Research/lbt_rg.html)
accretion columns, and the fraction of the stellar surface involved in the accretion shocks. Indeed, very different scenarios for the outburst dynamics are predicted by theoretical models, from two ordered funnel streams forming two hot spots on the stellar surface (e.g., Romanova et al. 2004) to multiple unstable “tongues” of matter that form chaotic spots with irregular shapes and positions (e.g., Romanova et al. 2008).

3.1.2. Possible outburst periodicity

In general, the intermittence of the EXor’s outbursts does not show any clear periodicity and, considering Fig. 2, V1118 Ori seems to obey the same trend. However, to have a more quantitative confirmation, we performed the Lomb–Scargle analysis for all available photometries ($V$ and $g$ bands) collected in the

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**Fig. 2.** Thirty-year period of the optical light curve of V1118 Ori. $V$-band data taken from Giannini et al. (2017) and references therein (mainly Audard et al. 2010). $R$-band photometric points retrieved from the Palomar Transient Factory survey are depicted in orange. The ZTF+REM $g$-band data of the 2019 outburst are shown in red.

**Fig. 3.** Near-IR spectra taken on October 1 (black) and October 20 (red). The main emission lines are labeled.
These were obtained from the original Johnson–Cousins photometric systems have been applied. The continuous line indicates the locus of 400–600 Myr young stars (Kraus & Hillenbrand 2007). The black arrow denotes the extinction vector for $A_V = 1$ mag, adopting the Cardelli et al. (1989) extinction law.

![Fig. 4. Diagram of $g - r$ vs. $[r - i]$. The blue dots represent the points of the 2019 outburst. The green symbols indicate the points of the 2005 and 2015 outbursts ($V < 16.5$, crosses and open squares), while red symbols indicate the colors of the subsequent quiescence phases ($V \geq 16.5$). Transformation equations between Johnson–Cousins and Sloan photometric systems have been applied. The continuous line indicates the $[r - i]$ values are 0.62, 0.47, and 0.47 mag in 2005, 2015, and 2019, respectively. Therefore, the variations of $[r - i]$ are likely to be driven by mechanisms not closely related to the outburst episodes.]

We note that this behavior cannot be attributed to a continuous decrease of the visual extinction since, as we show in Sect. 3.2.2, the $A_V$ measured during the three outbursts was roughly the same ($A_V \sim 1.5$ mag). Therefore, we interpret the steadily decreasing $[g - r]$ value over the past 15 years with a gradual increase in the temperature of the photosphere during subsequent outbursts. Vice versa, the color $[r - i]$ remains almost unchanged during the three outbursts; the average $[r - i]$ values are 0.62, 0.47, and 0.47 mag in 2005, 2015, and 2019, respectively. Therefore, the variations of $[r - i]$ are likely to be driven by mechanisms not closely related to the outburst episodes.

### 3.2. Near-IR spectroscopy

#### 3.2.1. Equivalent width versus continua

As a benefit of dealing with outbursts of the same source, we can examine in detail the simultaneous variability of the continuum and line emission, removing any significant contamination that can arise when considering multiple sources (for example, having different disk inclinations). In particular, we consider the line emission that likely originates in the accretion columns close to the stellar surface (prominent H I recombination; Muzerolle et al. 1998; Alcalá et al. 2014, 2017) in phases characterized by a different level of activity. As a premise, a correlation between H α and H β fluxes and R- and B-band continua was highlighted in a sample of EXors (Lorenzetti et al. 2015 and references therein). This supports the idea that accretion-driven mechanisms explain both line and continuum variability.

In this work, we compare the equivalent width (EW) of H I recombination lines with the underlying continuum. Having examined all the spectra of V1118 Ori that we collected so far (Lorenzetti et al. 2006, 2015; Giannini et al. 2016, 2017), we show in Fig. 5 the EW variations of both the optical (H β

### Table 3. Line fluxes.

| Line | $\lambda_{vac}$ (Å) | $F \pm \Delta F$ ($10^{-14}$ erg s$^{-1}$ cm$^{-2}$) |
|------|-----------------|----------------------------------|
| Paε | 9549 | 9.7 ± 0.6 | 2.19 ± 0.05 |
| Paδ | 10052 | 10.1 ± 0.4 | 2.19 ± 0.05 |
| Feı | 10691 | 3.4 ± 0.3 | 0.49 ± 0.05 |
| Heı | 10832 | 6.3 ± 0.3 | (∼−0.1) $^{(a)}$ 1.0 ± 0.03 |
| Paγ | 10941 | 11.7 ± 0.3 | 3.49 ± 0.02 |
| Oı | 11290 | 2.5 ± 0.3 | 0.41 ± 0.03 |
| Paβ | 12821 | 19.7 ± 0.5 | 3.84 ± 0.03 |
| Br14 | 15885 | 2.0 ± 0.5 | − |
| Br13 | 16114 | 2.5 ± 0.8 | − |
| Br12 | 16413 | 4.5 ± 1.0 | 1.0 ± 0.1 |
| Br11 | 16811 | 5.5 ± 0.4 | 1.8 ± 0.2 |
| Br10 | 17366 | 5.5 ± 0.4 | 2.0 ± 0.1 |
| Br9 | 19451 | 7.7 ± 0.6 | 1.7 ± 0.2 |
| H2 | 21218 | <0.5 $^{(b)}$ | 0.3 ± 0.1 |
| Brγ | 21661 | 6.7 ± 0.2 | 1.9 ± 0.1 |

Notes. $^{(a)}$P Cyg-like absorption. $^{(b)}$3-$\sigma$ upper limit.

### Table 4. Brightness variation speed observed during the last four outbursts of V1118 Ori.

| Outburst (year) | $R$ (rise) | $D$ (decline) | $R/D$ (mag day$^{-1}$) |
|----------------|------------|--------------|----------------------|
| 1997 $^{(a)}$ | 0.011 | 0.013 | 0.85 |
| 2005 $^{(a)}$ | 0.035 | 0.015 | 2.33 |
| 2015 $^{(a)}$ | 0.015 | 0.015 | 1.00 |
| 2019 $^{(b)}$ | 0.018 | 0.031 | 0.58 |

Notes. $^{(a)}$V-band data. $^{(b)}$g-band data.

Last 30 years. The resulting periodogram is characterized by several peaks with little statistical significance mainly due to a very noisy quiescence level and unevenly sampled data. In any case, the presence of multiple peaks does not favor a periodical behavior of the outburst events.

### 3.1.3. Two-colors plot

The two-color diagram $[g - r]$ versus $[r - i]$ derived from REM data (blue dots) is presented in Fig. 4. For comparative purposes, we also show the colors of the period 2005–2016, taken from Audard et al. (2010) and Giannini et al. (2017). These were obtained from the original Johnson–Cousins photometric points $VR$, transformed into Sloan magnitudes$^4$. Different symbols and colors indicate different outburst episodes ($V < 16.5$) and subsequent post-outburst periods ($V \geq 16.5$). Colors of the low-mass young stellar population in Praesepe and Coma Berenices (400–600 Myr) from spectral types F8 to M3 (Kraus & Hillenbrand 2007) are also depicted as black triangles. The direction of the extinction vector is represented, adopting the Cardelli et al. (1989) extinction law.

The main difference among the three outbursts illustrated in Fig. 4 lies in the gradual bluing of the color $[g - r]$, which on average is (in mag) 1.29 in 2005, 1.00 in 2015, and 0.73 in 2019.

$^4$ http://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php
and Hα) and near-IR (Paβ and Bry) lines as a function of the magnitude of the continuum, taken almost simultaneously. Confirming the results of previous studies (PV Cep, Cohen et al. 1981, V1647 Ori, Acosta-Pulido et al. 2007), there is an anti-correlation in the optical bands. More interestingly, there is a well-defined correlation between Paβ and Bry fluxes and J and K magnitudes, which have regression coefficients of −0.99 and −0.97. This dual behavior of optical and near-IR lines is compatible with the different regions in which the lines and the continuum originate. The anti-correlation in the B and R bands indicates that the optical continuum varies more (or faster) than the Hβ and Hα line emission. This can be naturally explained considering that the continuum emission is related to the heating of the photosphere in the accretion shock, while H1 lines arise in the cooling of the gas in the accretion columns. Therefore, the observed anti-correlation simply reflects different heating and cooling times. Conversely, J- and K-band continua originate in the innermost regions of the circumstellar disk. Although the near-IR photometric variations are the result of multiple processes (e.g., viscous heating), they primarily follow the heating (or cooling) of the disk in response to the increase (or decline) in the temperature of the photosphere (Lorenzetti et al. 2007). As a consequence, J- and K-band continua are subject to a lower variation than H1 lines because the disk is more distant from the star than the accretion columns. Anyhow, both the correlation and anti-correlation exclude an extinction-driven origin of the variability, since in that case EW values should be constant for any fluctuation of the continuum.

3.2.2. Mass accretion rate and extinction variability

The mass accretion rate on the dates of the spectroscopic observations is derived by the empirical relationships between accretion luminosity ($L_{\text{acc}}$) and luminosity of lines in the accretion columns ($L_{\text{line}}$), determined in a sample of T Tauri stars in Lupus by Alcalá et al. (2017). Among the lines observed in the 2019 spectra, those for which such relationships are available are the Paschen lines from Paε to Paβ plus the Bry line. First, each line flux was converted into $L_{\text{line}}$ by adopting a distance to V1118 Ori of 400 pc (Muench et al. 2008). Then, $L_{\text{acc}}$ is estimated together with the visual extinction $A_V$ with a recursive fitting method (for a detailed explanation see Giannini et al. 2018). The mass accretion rate, $M_{\text{acc}}$, derives from $L_{\text{acc}}$ through the formula of Gullbring et al. (1998), taking $M_{\text{acc}} = 0.4 M_\odot R_\odot = 1.29 R_\odot$ (Hillenbrand 1997; Stassun et al. 1999) and a typical disk inner radius $R_\odot = 5 R_\odot$.

The fit results are shown in Fig. 6 and listed in Table 5, where they are compared with the determinations of other outbursts and quiescence periods we derived by applying the same method. For the 2019 outburst, we measure a maximum $M_{\text{acc}}$ of $\sim 10^{-7} M_\odot \text{yr}^{-1}$, which is similar to the value reached in the outburst of 2015 and a factor of ten less than that of 2005. In Table 5 we also give the fitted values of the visual extinction. Interestingly, except for the last measurement in October 2019, the $A_V$ variation follows the evolution of brightness. The maximum $A_V$
of 2.5 mag is found in 2014 at the end of a long quiescence period that lasted about ten years, while \( A_V \sim 1.5 \) mag is measured at the peak of all three outbursts. The minimum \( A_V \) (<1 mag) is reached during the decline phase both in 2005 and 2016. This \( A_V \) variability might be explained in the scenario in which the onset of an outburst occurs when the material accumulated in the inner disk reaches a threshold value that corresponds to the maximum of \( A_V \). The outburst continues until the reservoir of material is over (namely the minimum of \( A_V \)) and then the material starts to accumulate again with a consequent increase of \( A_V \). Support for this scenario might be found in the case in which a significant area of the V1118 Ori (circumbinary) disk was intercepted by the line of sight. Unfortunately, the inclination of the V1118 Ori disk remains unknown even after dedicated Atacama Large Millimeter/submillimeter Array observations (Cieza et al. 2018).

4. Final remarks

We presented the optical photometry and near-IR spectroscopy of the last outburst of the classical EXor V1118 Ori, which occurred in the period January–October 2019. This one is the fifth well-sampled outburst, since 1989, characterized by a variation in brightness greater than three \( g \)-band magnitudes. Comparing the properties of the last event with those of the previous events, we can summarize the similarities and salient differences as follows:

- The outburst amplitude of the last event is similar to that of 1989, 1998, and 2015. The 2005 outburst remains the brightest. The duration is roughly the same (less than one year) for all.
- The historical light curve shows no evident periodicity, thus favoring accretion-driven rather than extinction-driven mechanisms as triggers of the outburst.
- The latest outburst showed different increase and decrease speeds of 0.018 and 0.031 mag day\(^{-1}\), as opposed to the 2005 outburst, when the increase was faster (by more than a factor two) compared to the decrease. This hints at different modalities that both regulate heating and cooling and vary from event to event.
- The last three outbursts showed a gradually blueing ([\( g \] – \( r \)]) color that we interpret with a gradual increase in the temperature of the photosphere. No significant variation is found in the ([\( r \] – \( i \)]) color.
- The low-resolution near-IR spectrum, taken near the peak of brightness, is similar to that of 2015 (in 2005 no near-IR spectra were taken). Main emission lines are the H\(_1\) Paschen and Brackett lines. As observed in 2015, He I 1.08 \( \mu m \) has a P Cyg-like profile that signals outflow activity. Faint metallic lines emission is present.
- The EW of the H\(_1\) optical lines (H\(_\alpha\) and H\(_\beta\)) are anti-correlated with the R- and B-band continua, while the EW of the near-IR lines (Pa\(_\beta\), Br\(_\gamma\)) are closely correlated with J- and K-band continua. This indicates that all the lines (both optical and near-IR) originate at the same distance from the star (i.e., in the accretion columns), intermediate between the stellar surface and the inner disk, where most of the optical and infrared continua are emitted, respectively.
- The evolution of the mass accretion rate of the last outburst is similar to that of 2015, with a peak of \( \dot{M}_{\text{acc}} \) around \( 10^{-7} M_\odot \text{ yr}^{-1} \) and a decrease down to \( \sim 3 \times 10^{-8} M_\odot \text{ yr}^{-1} \) in about a month. The evolution of the extinction during the last three outbursts was also probed and tentatively interpreted in the context of the variability of the source.

In conclusion, our analysis has demonstrated that the comparison of different outbursts of the same source is a nontrivial exercise, but rather it allows to put useful observational constraints for models of EXor phenomena.

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