EXORCISM: A Spectroscopic Survey of Young Eruptive Variables (EXor and Candidates)

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Abstract

We present an optical/near-IR survey of 11 variable young stars (EXors and EXor candidates) aimed at deriving and monitoring their accretion properties. About 30 optical and near-infrared spectra (~1500–2000) were collected between 2014 and 2019 with the Large Binocular Telescope (LBT). From the spectral analysis we have derived the accretion luminosity (Lacc) and mass accretion rate (Macc), the visual extinction (A_v), the temperature and density of the permitted line formation region (T, n_H), and the signature of the outflowing matter. Two sources (ASASSN-13db and iPTF15aqf) have been observed in outburst and quiescence, three during a high level of brightness (XZ Tau, PV Cep, and NY Ori), and the others in quiescence. These latter have Lacc and Macc in line with the values measured in classical T Tauri stars of similar mass. All sources observed more than once present Lacc and Macc variability. The most extreme case is ASASSN-13db, for which Macc decreases by two orders of magnitude from the outburst peak in 2015 to quiescence in 2017. Also, in NY Ori Lacc decreases by a factor 25 in one year. In 80% of the sample we detect the [O I] 6300 Å line, a tracer of mass loss. From the variability of the Hα/[O I] 6300 Å ratio, we conclude that mass accretion variations are larger than mass loss variations. From the analysis of the H I recombination lines, a correlation is suggested between the density of the line formation region, and the level of accretion activity of the source.

Unified Astronomy Thesaurus concepts: Star formation (1569); Pre-main sequence stars (1290); Eruptive phenomena (475); Stellar mass loss (1613)

1. Introduction

EXor objects (named after the prototype EX Lupi, Herbig 1989) are Pre-Main Sequence (PMS) stars showing episodes of eruptive accretion caused by magnetospheric accretion events (Shu et al. 1994). Since the unsteady mass accretion is a central theme in the star formation process (e.g., Cieza et al. 2018), these objects have been the subject of many investigations (Kuffmeier et al. 2018; Contreras Peña et al. 2019; Meng et al. 2019; MacFarlane et al. 2019a, 2019b; see also Audard et al. 2014) for a comprehensive view of the EXor phenomenon). EXors are characterized by outbursts of short duration (typically months) occurring at different timescales (months, years) and showing amplitudes of several magnitudes at optical and near-IR wavelengths. An evolutionary scheme has been proposed in which EXors represent a less energetic (and possibly) later stage than the powerful FU Orionis eruptions (FUors, Hartmann & Kenyon 1985; Hartmann et al. 1993), although EXors present substantial differences, such as shorter and more frequent outbursts, spectra dominated by emission lines instead of absorption lines, and smaller values of the mass accretion rate during outbursts (10⁻⁷–10⁻⁶ M⊙ yr⁻¹ versus 10⁻⁵–10⁻⁴ M⊙ yr⁻¹). Yet, at present, a detailed model for the disk structure and its evolution does not exist for EXors and different hypotheses have been proposed for the possible trigger of their outbursts: thermal instability in the disk (e.g., Audard et al. 2014 and references therein), gravitational perturbations induced by a binary companion (Lodato & Clarke 2004) or by the migration of a giant planet (Bonnell & Bastien 1992), or sudden changes in the stellar magnetic activity (D’Angelo & Spruit 2012; Armitage 2016).

Observational constraints to theoretical models are nowadays provided by photometric monitoring programs (e.g., Granke et al. 2008; Morales-Calderójn et al. 2011; Guo et al. 2020) and by ongoing all-sky surveys (e.g., Gaia,7 All-Sky Automated Survey for Supernovae (ASASSN),8 Intermediate Palomar Transient Factory (iPTF),9 Panoramic Survey Telescope & Rapid Response System (Pan-STARRS)10, and VISTA Variables in the Via Lactea (VVV)11 which systematically follow (although often at a poor level of sensitivity) the photometric variations of many EXors and EXor candidates, thus allowing us to track the changes of their integrated properties (light curves, spectral energy distributions (SEDs), and colors). A dramatic improvement in this context will be provided in the next future by the the Vera Rubin Observatory,12 which will

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7 https://sci.esa.int/web/gaia
8 http://www.astronomy.ohio-state.edu/asassn/index.shtml
9 https://www.ptf.caltech.edu/iptf
10 https://panstars.stsci.edu/
11 https://vvvsurvey.org/
12 https://www.lsst.org/
explore the southern sky with unprecedented sensitivity and cadence.

Conversely, the optical and IR spectroscopic monitoring of the EXors is currently not at a comparable level of sky coverage and cadence, despite its crucial importance for understanding how the gas properties (e.g., excitation, ionization, dynamics) vary during different activity phases. Indeed, so far, only few EXors have been spectroscopically investigated (e.g., EX Lupi: Sipos et al. 2009; Sicilia-Aguilar et al. 2012V2492 Cyg: Hillenbrand et al. 2013; V1118 Ori: Audard et al. 2010; Lorenzetti et al. 2015; Giannini et al. Guo et al.).

Our sample is divided into two groups. The first is composed of five known EXors (XZ Tau, UZ Tau E, VY Tau, NY Ori, V1143 Ori) listed in the compilation by Audard et al. (2014) and confirmed by many works in literature as members of the class. In addition, we have also obtained multi-epoch spectroscopy of the classical EXor V1118 Ori at both optical and IR wavelengths. These data are not discussed here since they have been separately presented in a series of dedicated papers (Giannini et al. 2020 and references therein).

The second group, generically named as “EXor candidates” in Table 1, consists of six sources that have been reported through different alerts (e.g., astronomers’ telegrams and public surveys alerts) for being young and highly variables objects (ΔV ≳ 2 mag). Here we briefly comment on each of them. Two objects, namely V1647 Ori and PV Cep, are present in the Audard et al. (2014) compilation, but their nature is still controversial. V1647 Ori has been previously classified as a candidate FUor, but it is currently considered as a peculiar object, since its spectrum now differs significantly from that of a bona fide FUor (Connelley & Reipurth 2018), showing both FUor and EXor features. A few more objects with similar characteristics have been identified during the VVV spectroscopic survey and dubbed “MNors” (Contreras Peña et al. 2017). PV Cep and DR Tau were originally included in the first list of EXor variables by Herbig (1989).

Table 1 lists our targets with their general properties. It provides coordinates, distance, location, binarity, and jet or outflow detection. Together with the name given in the Simbad Astronomical Database, we report other designation(s) commonly used in the literature.

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PV

| Simbad Name | R.A. (J2000) (h:m:s) | Decl. (J2000) (°;′;″) | D (pc) | Location | Binarity | Jet/Outflow | Other Designation | Ref |
|-------------|----------------------|------------------------|--------|----------|----------|-------------|------------------|-----|
| EXors       |                      |                        |        |          |          |             |                  |     |
| XZ Tau      | 04:31:40.21          | +18:13:57.23           | 150    | L1551    | Y(0°20)  | HH152/Y     | Haro6-15–SVS169  | 1   |
| UZ Tau E    | 04:32:43.07          | +25:52:31.03           | 130.4  | B19      | Y(0°34)  | .../...     | UZ Tau A         | 2   |
| VY Tau      | 04:39:17.41          | +22:47:53.43           | 153.4  | L1536    | Y(0°66)  | Y(7)/...    | SVS38            | 3,4 |
| NY Ori      | 05:35:36.01          | −05:12:25.33           | 403.5  | ONC      | ...      | .../...     | Parenago 2119    | 5   |
| V1143 Ori   | 05:38:03.90          | −04:16:42.88           | 395.3  | L1640    | ...      | .../...     | Sugano’s obj     | 5   |

EXor candidates

| DR Tau      | 04:47:06.21          | +16:58:42.88           | 193.0  | L1558    | N        | Y/...      | ...              | 6   |
| ASASSN-13db | 05:10:11.08          | −03:28:26.33           | 387.1  | near L1615/16 | ...      | ...         | ...              | ... |
| V1647 Ori   | 05:46:13.14          | −00:06:04.93           | 412.9  | Mc Neil’s nebula | N(?)    | HH23(?)/Y  | Mc Neil’s Nebula | 7,8,9 |
| iPTF15aqf   | 07:09:21.40          | −10:29:34.44           | 1315.7 | CMa      | ...      | .../...     | 2MJ07092139-1029344 | 10,11,12 |
| PV Cep      | 20:45:53.94          | +67:57:38.77           | 356.5  | L1158    | N        | HH315/Y    | ...              | 13  |
| V350 Cep    | 21:43:00.01          | +66:11:28.0            | 872.5  | NGT129   | ...      | .../...     | ...              | 13  |

Note. 1: Distances taken from GAIA EDR3 (Gaia Collaboration et al. 2016). Gaia Collaboration et al. (2021); “assumed. References: 1, Coffey et al. (2004); 2, Jensen et al. (2007); 3, Leinert et al. (1993); 4, Banzatti et al. (2019); 5, Herbig (2008); 6, Kun et al. 2016; 7, Arce et al. (2010); 8, Young et al. (2015); 9, Akeson et al. (2019); 10, Joncour et al. (2017); 11, Li et al. (2015); 12, Banzatti et al. (2014); 13, Principe et al. (2018).

13 https://www.eso.org/sci/facilities/develop/instruments/SoXS.html

14 http://simbad.u-strasbg.fr/simbad/
Cep repeatedly undergoes intense outbursts (up to 5 mag) of short duration and brightness between that of FUors and EXors (Andreasyan et al. 2021). Its high luminosity (∼100 $L_\odot$) is likely attributable to a young Herbig Ae star (see e.g., Lorenzetti et al. 2011). DR Tau has progressively increased its brightness by about three magnitudes between 1960 and 1980. Since then, its average brightness has been at the same level but still with remarkable photometric fluctuations with amplitude up to ∼1 mag in the optical (Banzatti et al. 2014 and references therein). Similarly, the $B$ magnitude of V350 Cep changed from $>21$ to $<17$ between 1954 and 1978. Afterward, the source has remained at roughly the same level of brightness, with the exception of at least two fading events of about 2 mag in $B$ in 1979 and 2004. For these reasons Herbig (2008) did not classify V350 Cep as an EXor. Considering its high and stable brightness level and its spectral rich in emission lines, it is likely that also V350 Cep is an object with properties in between those of FUors and EXors (Andreasyan et al. 2021). iPTF15afq is a new candidate EXor, suggested by Miller et al. (2015) on the basis of the amplitude of its outburst of about 2.5 mag (in $R$-band) and its spectrum dominated by lines in emission. ASASSN-13db (discovered by the ASASSN survey) has been originally classified as an EXor by Holoien et al. (2014). Later observations of blueshifted absorption features in several hydrogen and metallic lines suggest an intermediate behavior between EXors and FUors (Sicilia-Aguilar et al. 2017).

In Table 2, we summarize the photometric properties of the sources, with the range of variation observed in the indicated band and a short (non-exhaustive) summary of the variability history as retrieved from the literature.

In Table 3, we list the relevant stellar parameters as given in the literature, namely the visual extinction ($A_V$), bolometric ($L_{bol}$), stellar ($L_*$) and accretion ($L_{acc}$) luminosity, spectral type (SpT) and effective temperature ($T_{eff}$), stellar mass ($M_*$), mass accretion rate ($\dot{M}_{acc}$), and evolutionary class (typically derived from the spectral slope between 2 and 24 $\mu$m). All sources but PV Cep, have mass $\lesssim 1$ $M_\odot$ and spectral types M-K. V1647 Ori and PV Cep present a high and variable $A_V$ while all other sources are only slightly extincted. Mass accretion rates have been measured for about 70% of the sample. During quiescence, they are typically of the order of $10^{-8}$–$10^{-7}$ $M_\odot$ yr$^{-1}$, but show variations up to several orders of magnitude in bursts.

In summary, our sample is composed of sources whose variability may differ in amplitude, cadence, and duration. In all cases, however, the increase of brightness has been attributed in the literature to accretion events, sometimes accompanied by significant variations of the local extinction.

### Table 2

| ID          | $\text{mag}_{\text{min}}$ | $\text{mag}_{\text{max}}$ | Banda | Bursts          | Ref     |
|-------------|---------------------------|-----------------------------|-------|-----------------|---------|
| **EXors**   |                           |                             |       |                 |         |
| XZ Tau      | 16.6–10.4                 |                             | V     | many/last       | 1,2     |
| UZ Tau E    | 15.8–12.5                 |                             | V     | many/last 2006  | 3,4     |
| VY Tau      | 15.3–9.0                  |                             | V     | 1960–1972/last  | 2,3,5,6 |
| NY Ori      | >16–13.3                  |                             | V     | many/last 2001  | 7,8     |
| V1143 Ori   | 16.7–13.5                 |                             | V     | many/last 1993  | 7,8     |
| **EXor candidates** |                   |                             |       |                 |         |
| DR Tau      | 16.0–10.5                 |                             | V     | 1960–1980       | 3,9,10,11 |
| ASASSN-13db | >17–13.2                  |                             | V     | 2013,2014–2017  | 12,13   |
| V1647 Ori   | 23.0–17.8                 |                             | $\gamma$ | 1966,2003, 2008 | 14,15,16,17 |
| iPTF15afq   | 19.0–16.7                 |                             | R     | 2015,2019       | 18,19   |
| PV Cep      | 16–11                     |                             | R     | 1977,1979,2008  | 20,21,22 |
| V350 Cep    | 21–16.5                   |                             | B     | 1978–2005       | 7,22,23 |

Note. References: 1. Coffey et al. (2004); 2. Dodin et al. (2016); 3. Herbig & Bell (1980); 4. Jensen et al. (2007); 5. Herbig (1990); 6. Stone (1983); 7. Herbig (2008); 8. Jordana-Sepiç (2017); 9. Chavarría (1979); 10. Kenyon et al. (1994); 11. Grankin et al. (2007); 12. Holoien et al. (2014); 13. Sicilia-Aguilar et al. (2017); 14. Bricetto et al. (2004); 15. Aspin et al. (2006); 16. Aspin et al. (2008); 17. Aspin & Reipurth (2009); 18. Miller et al. (2015); 19. Hillenbrand (2019); 20. Cohen et al. (1981); 21. Caratti o Garatti et al. (2013); 22. Lorenzetti et al. (2011); 23. Jordana-Sepici et al. (2018).

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3. Observations and Data Reduction

The observations were carried out between 2014 and 2019 with the 8.4 m Large Binocular Telescope (LBT) located at Mount Graham (Arizona, USA). Optical and near-IR spectra of the targets were obtained with the Multi-Object Double Spectrograph (MODS, Pogge et al. 2010) and the LBT Utility Camera in the Infrared (LUCI, Seifert et al. 2003), respectively.

Given the remarkable brightness of the sources, our project was executed as a filler program during unfavorable atmospheric conditions that usually make observations of weaker sources unfeasible. As a consequence, we were not able to complete the survey with all the needed spectra. However, the poor photometric quality of the sky (typical seeing $>1.5$") did not represent a significant problem for the validity of our results, since the flux calibration of the spectra was based on photometric observations taken close in time to the spectra.

In total, we acquired 19 spectra with MODS (11 targets) and 10 spectra with LUCI (8 targets), see the journal of observations in Table 4. Optical and near-IR spectra have been taken during the same night only for V1647 Ori, and for DR Tau at a temporal distance of 4 days. For all the other targets, optical and near-IR spectra are spaced by several months or years, and, in some cases, the spectrum of one of the two segments is missing.

MODS observations were performed with the dual grating mode (blue + red channels, spectral range 350–950 nm) by using a 0.5’’ slit ($\sim 1500$ and 1800 in the blue and red channels, respectively). The slit angle matched the parallactic angle to minimize the wavelength dependence on the slit transmission. For each source, the adopted integration time is reported in Table 4.

LUCI observations were carried out with the G200 low-resolution grating coupled with the 0.9’’75 slit. Two data sets were acquired with the standard ABB’ technique using the $zJ$ and $HK$ grisms. This provides a final spectrum covering the 1.0–2.4 $\mu$m wavelength range at $\lambda \sim 1500$. The integration time for the individual sources is provided in Table 4.

Data reduction was performed at the Italian LBT Spectroscopic Reduction Center15, by means of scripts optimized for LBT data. Data reduction steps of each MODS spectral image are correction for dark and bias, bad-pixel mapping, and the IASF-Milano Research Center15, by means of scripts optimized for LBT data. Data reduction steps of each MODS spectral image are correction for dark and bias, bad-pixel mapping, and PV Cep present a high and variable $A_V$ while all other sources are only slightly extincted. Mass accretion rates have been measured for about 70% of the sample. During quiescence, they are typically of the order of $10^{-8}$–$10^{-7}$ $M_\odot$ yr$^{-1}$, but show variations up to several orders of magnitude in bursts.

In summary, our sample is composed of sources whose variability may differ in amplitude, cadence, and duration. In all cases, however, the increase of brightness has been attributed in the literature to accretion events, sometimes accompanied by significant variations of the local extinction.

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15 http://www.iasf-milano.inaf.it/Research/lbt_rg.html
flat-fielding, sky background subtraction, and extraction of the one-dimensional spectrum by integrating the stellar trace along the spatial direction. In the optical range, few telluric features are present, the most prominent being that around 7600 Å, around which, however, there are no lines used for the subsequent accretion and ejection analysis. Therefore, we have not applied any telluric correction to the optical spectra. Wavelength calibration was obtained from arc lamps. Intercalibration between blue and red spectral segments was verified superposing the spectral range between 5300 and 5900 Å in common between the two channels. In all cases, the Blue and Red spectra resulted optimally aligned without the need for further corrections.

The raw LUCI spectral images were flat-fielded, sky-subtracted, and corrected for optical distortions in both the spatial and spectral directions. Telluric absorptions were
removed using the normalized spectrum of a telluric standard star, after the removal of its intrinsic spectral features. Wavelength calibration was obtained from arc lamps spectra. In a few cases, we applied an intercalibration correction to align the $J$ and $HK$ segments, which did not exceed 20% of the flux density.

The bad atmospheric conditions prevented us from flux calibrating the spectra by using spectrophotometric standards. Therefore, we used as absolute calibrators the acquisition images obtained immediately before the spectral images in the filter specified in Table 4. Photometry was obtained by taking as reference all the visible stars in the field, for which either a PAN-STARRS$^{16}$ (in the optical) or a 2MASS$^{17}$ (in the near-IR) photometry is available. In few cases, namely when not enough reference sources were present in the acquisition image or our target appeared saturated, we used the photometry retrieved from public databases and obtained a few days before or after the LBT observation (as specified in the note of Table 4).

### 4. Light Curves

To establish the level of accretion activity of each target at the time of the LBT observation we collected data from public surveys (ZTF, ASASSN, and AAVSO$^{18}$) to derive the optical light curves of the sources over several years, which are displayed in Figure 1. For NY Ori and V1647 Ori, only the light curves of the ASASSN survey are available. Unfortunately, the ASASSN images of these sources are strongly contaminated by the diffuse emission of the ONC and McNeil’s nebulae, where NY Ori and V1647 Ori are respectively located (Aspin et al. 2009; Herbig 2008). Therefore, these two light curves are not shown.

In the following, we briefly comment on the light curves of the remaining nine objects.

1. XZ Tau. The $V$ band magnitude varied between $\sim$14.5 and 12 mag within a 6 yr period. Our MODS spectra cover both a high- and low-level brightness state.
2. UZ Tau E. This source shows a very small amplitude level of variability within 5 yr. It has maintained an average brightness level around $V = 12.7 \text{ mag}$, with fluctuations of $\sim 0.3 \text{ mag}$. The spectroscopic observations were obtained at photometric levels with 0.6 mag of difference.
3. VY Tau. A remarkable brightening occurred at the beginning of 2014, unfortunately not covered by our observations. This was followed by a second low-amplitude burst about a year later. The first MODS spectrum refers to the declining phase of this burst.
4. V1143 Ori. Between 2013 and 2018 the source has remained at $V \sim 17 \text{ mag}$ with typical fluctuations of tenths of magnitude. The MODS spectrum was acquired at $V \sim 16.5 \text{ mag}$.
5. DR Tau. In the last seven years, the DR Tau average photometry has been $V \sim 12 \text{ mag}$, with large fluctuations up to 1 mag. All our observations have been performed close to the average level.
6. ASASSN-13db. This source underwent a first, short-lived outburst in 2013, followed by a second, more intense outburst from 2014 to late 2016. We have observed ASASSN-13db four times, the first three (two with MODS and one with LUCI) during the second burst and the last with MODS in 2017, when the source was back to quiescence.
7. iPTF15afq. The source underwent an outburst at the beginning of 2018 (not shown in the $r$-band light curve, see Hillenbrand 2019), followed by a quiescence period of about 2 years. A second outburst occurred in 2019, covered by our LUCI observation during the rising phase and close to the peak. A slow decay started at the beginning of 2020 and is still ongoing. The remaining three observations (between 2016 and 2018), have been taken during quiescence ($R \sim 18.5–19 \text{ mag}$), according to the light curve presented by Miller et al. (2015).
8. PV Cep. Between 2013 and 2020, PV Cep has experienced a slow increase in brightness, with a peak in 2016 ($V \sim 14.5 \text{ mag}$), followed by a decrease down to $V > 18 \text{ mag}$ at a roughly similar speed. Both our observations were conducted close to the brightness peak.
9. V350 Cep. Our first LUCI observation was taken in November 2015, at $R = 15.4 \text{ mag}$ (Semkov et al. 2017). The source experienced a deep dimming in spring 2016 followed by a new brightening. Since 2018, V350 Cep is again progressively and slowly fading from $r \sim 15.3$ to $r \sim 15.8$. Our second LUCI observation (2018) was obtained when V350 Cep was still relatively bright ($r \sim 15.5 \text{ mag}$), while the next three MODS spectra were taken when $r$ had decreased down to 15.6–15.8 mag.

Summarizing, our targets have shown a variety of behaviors during the last decade. Some of them have remained fairly constant, others have undergone strong outbursts or long-term and remarkable brightness variations. As expected, in most cases, our observations were performed during phases of quiescence. However, some exceptions exist: we have observed XZ Tau and PV Cep during a high level of their activity and even caught the outbursts of ASASSN-13db and iPTF15afq. In addition, our acquisition images of NY Ori indicate a variation of about two magnitudes in the $r$-band between 2014 ($r \sim 12$) and 2016 ($r \sim 14$).

### 5. Description of the Spectra

Figures 2–3 and Figures 4–5 show the MODS and LUCI spectra of our sample, respectively. Line fluxes have been derived by fitting the profiles with a Gaussian function, and the relative uncertainties have been estimated by multiplying the rms noise of the continuum close to the line times the FWHM. Appendix A (Tables 8–18) report the fluxes of lines used in the analysis.

Lines tracing accretion have been detected in all sources. In particular, the Balmer recombination lines (typically from H$_2$ to H$_6$, but for many sources up to H15) are detected in all MODS spectra. In several objects (NY Ori, DR Tau, ASASSN-13db, V1647 Ori, PV Cep) some of these lines are partially or totally seen in absorption. Note that, given the late spectral type of the sources (Table 3), the photospheric contribution to the lines seen in absorption is negligible, with the possible exceptions of NY Ori and PV Cep. Paschen and Brackett lines (both in the optical and in near-IR range) are detected in 10 and 5 objects, respectively, and appear all in emission. In all objects observed with LUCI, we detect the He I 1.08 μm line, while other He I optical lines are seen in the spectra of the brightest objects. Metallic lines of many species (Fe I, Fe II, Ti I, Ti II, Ca II, Cr I, Cr II) are also detected.
Signatures of ejection activity, such as the $[\text{O} \text{I}] 6300$ Å line, are present in all sources but VY Tau and V1143 Ori. In two objects (iPTF15afq and V350 Cep), we also detected H$_2$ emission at 2.12 μm, which is a typical tracer of molecular outflows. In XZ Tau, UZ Tau E, DR Tau, and PV Cep, we detect some $[\text{S} \text{II}]$ lines, indicative of gas with a low ionization degree. Lines of $[\text{S} \text{II}]$, $[\text{Fe} \text{II}]$, $[\text{Ni} \text{II}]$, and $[\text{N} \text{II}]$ have been detected in the spectrum of iPTF15afq, which could signal the occurrence of a high-velocity jet (Giannini et al. 2019).

In some of the LUCI spectra we have identified at least one of the two CO rovibrational band heads ($v = 2-0$ and $v = 3-1$) in emission (UZ Tau E, iPTF15afq, and PV Cep), or in absorption (VY Tau), as expected for EXor sources (e.g., Biscaya et al. 1997; Hillenbrand et al. 2013). In the remaining objects, the CO band heads are undetected, probably because the edge of the HK spectra is typically very noisy.

In general, we remark that (1) the spectra well resemble the optical/near-IR spectra of accreting T Tauri stars (e.g., Alcalá et al. 2017) and no evident differences exist among the spectra of known EXors and EXor candidates; (2) the intensity of the accretion tracers (e.g., H1, Ca II) follows the variation of the source brightness (e.g., XZ Tau, Table 8) and may even disappear or change from emission to absorption in case of an outburst event (ASASSN-13db and iPTF15afq).

Figure 1. Optical ($V$- or $r$-band) light curves retrieved from data of public surveys (ZTF, ASASSN, and AAVSO). The x-axis represents the Modified Julian Date (MJD), while some calendar dates are given on top as reference. A blue (red) vertical line indicates the date of a MODS (LUCI) observation. The black line corresponds to quasi-simultaneous MODS+LUCI observation of DR Tau. Photometry taken closest in time to the spectroscopic observation is marked with a green dot.
6. Analysis and Discussion

6.1. Extinction

The primary goal of the present work is to determine the accretion parameters \( L_{\text{acc}} \) and \( M_{\text{acc}} \) of the sample. To get a meaningful estimate of these two quantities, we first derived the visual extinction \( A_V \) toward the sources. As listed in Table 3, one or more \( A_V \) values are reported in the literature for some of them. Although these values represent an important reference, several studies have shown that a remarkable reduction (e.g., Hillenbrand et al. 2013), or less often, an increase of the extinction (in edge-on disks, Stock et al. 2020) often accompany accretion burst episodes. Therefore, we cannot assume \( A_V \) as a constant, but we need to estimate its value for each observation date. In the following, we separately discuss the methods used to derive \( A_V \) from both the optical and near-IR spectra.

6.1.1. Extinction Derived from Optical Spectra

The method used to derive the extinction from the optical spectra is described in detail in Giannini et al. (2018). This is essentially based on the empirical relationships found by Alcalá et al. (2014, 2017), between the accretion luminosity, \( L_{\text{acc}} \), and the luminosities \( L_i \) of selected emission lines (so-called “line method”). In the optical range these relationships exist for more than 20 lines, namely the H I recombination lines of the Balmer and Paschen series from \( \text{H}_{\alpha} \) to \( \text{H}_{15} \), and from \( \text{Pa}8 \) to \( \text{Pa}10 \), along with He I, O I, and Ca II lines. Therefore, the relationships provide up to around 20 independent estimates of \( L_{\text{acc}} \), namely one for each observed line \( (L_{\text{acc}(i)}) \).

In our procedure, we fit simultaneously \( L_{\text{acc}} \) and \( A_V \), this latter allowed to vary between 0 and 15 mag (in steps of 0.20 mag). The extinction law by Cardelli et al. (1989) and total-to-selective extinction ratio \( R_V = 3.1 \) are assumed. We iteratively fit \( L_{\text{acc}} \) to minimize the dispersion among the individual \( L_{\text{acc}(i)} \), computed by de-reddening the observed fluxes for the current \( A_V \) and assuming the distance listed in Table 1. The best estimate of \( A_V \) is the value for which the dispersion between the \( L_{\text{acc}(i)} \) is minimized and we assume as \( L_{\text{acc}} \) the average of the \( L_{\text{acc}(i)} \) corresponding to that of \( A_V \).

We included in the fit only the lines that do not present any absorption component. We have verified that, rather than on the individual flux errors, the main limitation of this method comes from the uncertainties on the empirical relationships (Alcalá et al. 2017), which give an error on \( A_V \) of 0.5–1.5 mag, depending on how many lines are considered in the fit. Further causes of uncertainty come from the assumptions on the extinction law and \( R_V \). For example, we have checked that if the extinction law by Weingartner & Draine (2001) is applied, the fitted \( A_V \) decreases by \( \approx 0.4 \) mag. Conversely, an increase in \( A_V \) by \( \approx 0.2–0.3 \) mag is produced for \( R_V = 5.5 \).

In Figures 6–8, we show the results of our procedure, while in Table 5, we report the fitted extinction values and the number of lines used.
An independent way to compute $A_V$ has been described by Alcalá et al. (2021, so-called “continuum” method). The observed spectrum is iteratively divided by a template of the same spectral type (SpT), artificially reddened by varying the value of $A_V$. The best estimate of $A_V$ is that for which the ratio has a flat slope. Applying this method to strong accretors, one has to correct the spectrum for the excess continuum (veiling) induced by the accretion hot spot (UV) and disk (IR) emission. This has been estimated for the majority of our sources by applying the procedure described in Appendix B. Following the prescriptions by Alcalá et al. (2014) and Fischer et al. (2011), we applied the continuum method in the spectral range between 550 and 800 nm, where the veiling excess is minimized and expected not to change more than the typical error of 0.3 associated with its determination (Appendix B). We adopted as template spectra a grid of non-accreting (Class III) YSOs of the same SpT of the observed sources (Manara et al. 2013, 2017), reddened for $A_V$ between 0 and 15 mag in steps of 0.20 mag. The results of the fitting procedure are provided in Figure 9 and the fitted $A_V$ are listed in Table 5. Noticeably, in six out of the nine optical spectra examined, the two $A_V$ determinations agree within 0.5 mag.

Finally, the case of V1647 Ori deserves a short discussion. This source is a well-known Class I/flat young source, still deeply embedded in the parental dusty envelope. As shown in several works (e.g., Nisini et al. 2016; Fiorellino et al. 2021), in embedded sources a relevant fraction of the optical emission originating close to the star is scattered in the cavity excavated inside the envelope. The effect is to enhance the emission at shorter wavelengths, that in turn simulates a lower extinction. For this reason, we consider the determination of $A_V$ (9.2 mag) derived in the optical range to be not reliable and will assume the extinction derived from the LUCI spectrum on the same date (13 mag, Section 6.1.2).

### 6.1.2. Extinction Derived from Near-IR Spectra

The $A_V$ estimate from the near-IR spectra was also obtained by applying two independent methods, briefly described in the following paragraph.

The first method is based on the [$J-H$] and [$H-K$] colors at the date of the observation. One photometric point is directly provided by the acquisition image (Table 4), while the other two are computed from the flux-calibrated spectrum convolved with the Johnson filter profiles. We estimate that this procedure leads to an uncertainty of about $\pm 0.1$ mag in each band. From the magnitudes, we have constructed the [$J-H$]
versus [H-K] color–color diagram shown in Figure 10. Here, we indicate with an arrow the direction of the extinction vector, whose length corresponds to an extinction of 5 mag. We assume the reddening law by Cardelli et al. (1989) and \( R_V = 3.1 \). We estimate \( A_V \) from the position of the observed colors and the unreddened Classical T Tauri locus (CTTs, Meyer et al. 1997) and list the values in Table 5. Considering all the uncertainties involved in this procedure (absolute spectral calibration, propagation of magnitude errors, assumptions on extinction law and \( R_V \)), we conservatively evaluate a final error on \( A_V \) of 1 mag.

All sources have low or negligible \( A_V \), with the exception of V1647 Ori (\( A_V \sim 13 \) mag). In the case of VY Tau, which is located at the left edge of Figure 10, we are not able to estimate a reliable value of \( A_V \), while for two observations (iPTF15afq and V350 Cep) we cannot apply the method because the available spectra do not cover the three bands.

The second method relies on the detection of accretion line tracers, as done for the optical spectra, see Figures 6–8. However, empirical relationships in the near-IR are available only for the Paschen lines (from Pa8 to Paβ) and for the Brγ (Alcalá et al. 2017), which are moreover less sensitive to extinction variations than the optical lines. For DR Tau, for which we have quasi-simultaneous MODS and LUCI spectra, the optical and near-IR lines have been considered all together in the fit. Conversely, as explained in the previous section, the lines of V1647 Ori observed with LUCI have been fitted separately from those observed with MODS, although the two spectra were obtained on the same date. The fitted \( A_V \) of 13 mag is in perfect agreement with that derived from the color–color diagram.

We were able to apply both methods to five spectra. The two \( A_V \) determinations are in excellent agreement in UZ Tau E and V1647 Ori (Table 5), but differ between 0.9 and 3.3 mag in the other three sources (DR Tau, PV Cep, and V350 Cep). Since we have no reason to prefer one method over the other (also considering that the lines used in the fit of \( L_{\text{acc}} \) are few), we have assumed the entire range of \( A_V \) determinations to compute the accretion parameters \( L_{\text{acc}} \) and \( M_{\text{acc}} \) (see Section 6.2).

### 6.2. Accretion Luminosity and Mass Accretion Rate

As explained in Section 6.1.1, the accretion luminosity, \( L_{\text{acc}} \), has been derived together with \( A_V \) by fitting the individual \( L_{\text{acc}(i)} \). With reference to the fits shown in Figures 6–8 we note that, in general, the \( L_{\text{acc}(i)} \) derived from the individual lines agree within the errors. There are however lines whose accretion luminosity may be up to an order of magnitude higher than the average \( L_{\text{acc}} \). In particular, we signal Ca II K and He I at 492 and 502 nm. However, thanks to the high number of lines used, \( L_{\text{acc}} \) does not change by more than 10% whether or not these three lines are included in the fit.

For many sources, a further estimate of \( L_{\text{acc}} \) has been obtained by applying the relationships between \( L_{\text{acc}} \) and \( L_i \) by
The mass accretion rate, $\dot{M}_{\text{acc}}$, has been estimated using the relationship by Gullbring et al. (1998):

$$\dot{M}_{\text{acc}} \approx 1.25 \frac{L_{\text{acc}} R_*}{GM_*}$$

where $R_*$ and $M_*$ are the stellar mass and radius, and $G$ is the gravitational constant. We have adopted for $M_*$ the values given in the literature (Table 3) and derived $R_*$ from the relationship:

$$R_* = \frac{1}{2T_{\text{eff}}^2} \sqrt{\frac{L_*}{\pi \sigma}}$$

where $\sigma$ is the Stefan-Boltzmann constant, and $T_{\text{eff}}$ and $L_*$ are taken from Table 3.

The derived $M_{\text{acc}}$ values are listed in Table 6.

It is worth noting that no remarkable differences exist between EXors and EXor candidates, either in $L_{\text{acc}}$ or in $M_{\text{acc}}$. Typical values are $-2 \lesssim \log(L_{\text{acc}}/L_\odot) \lesssim 1$, and $-9 \lesssim \log\left(\frac{M_{\text{acc}}}{M_\odot \text{ yr}^{-1}}\right) \lesssim -7$. V1647 Ori is the object with significantly higher $L_{\text{acc}}$ (50 $L_\odot$) and $M_{\text{acc}}$ ($\sim 10^{-5} M_\odot$ yr$^{-1}$), in line with its very young age and its classification as a Class I/flat source. This source underwent two outbursts during its recent history, one in 2003–2004 (Aspin et al. 2006) and another one in 2008–2011 (Aspin 2011). During the second outburst, its $r$-band photometry was $\sim 17.77$ and $A_V = 8$ mag. In 2016, we measured $r = 18.68$, namely about 1 mag fainter. Despite that, our determination of $M_{\text{acc}}$ is about one order of magnitude higher than the estimate of $(4 \pm 2) \times 10^{-6} M_\odot$ yr$^{-1}$ measured by Aspin (2011). This disagreement is due to the higher $A_V$ (13 mag) that we have estimated from the LUCI spectrum. A considerable variability in $A_V$ is indeed exhibited by V1647 Ori. During quiescence ($r \sim 23$), $A_V$ was around 19 mag (Aspin 2011), therefore it is plausible to assume that in an intermediate stage, as that we have probed, also the extinction was in between the two extreme values of 8 and 19 mag. It would therefore be relevant to measure $M_{\text{acc}}$ during the quiescent state (namely in the conditions of maximum $A_V$) to disentangle the contributions of accretion and extinction in the large-amplitude variability exhibited by this source. The sources for which we have more than one observation are XZ Tau, UZ Tau E, NY Ori, DR Tau, ASASSN-13db, iPTF15afq, PV Cep, and V350 Cep. Of these, all but NY Ori and ASASSN-13db present an amplitude variability $\lesssim 1$ mag (Figure 1), in line with that observed in Classical T Tauri stars (Costigan et al. 2014). These magnitude fluctuations correspond to variations in $L_{\text{acc}}$ and $M_{\text{acc}}$ of a factor $\approx 1.5−3$. In general, these results confirm the accepted scenario in which accretion is a non-stationary phenomenon, although they are insufficient to explain the spread of more than two orders of magnitude.
magnitude found in the $M_{\text{acc}}$ determinations among sources of the same mass (e.g., Antoniucci et al. 2014).

However, larger magnitude fluctuations imply significant variations in $L_{\text{acc}}$ and $M_{\text{acc}}$. In ASASSN-13b, in the two years between the outburst peak and the quiescence, $L_{\text{acc}}$ changed from 0.2 to 0.03 $L_\odot$ and $M_{\text{acc}}$ from $3 \times 10^{-8}$ to $5 \times 10^{-10} M_\odot$ yr$^{-1}$. Also, in NY Ori $L_{\text{acc}}$ decreased by a factor 25 in about one year (2014 December—2016 January). Although no photometric measurements are available for the indicated period, this change in $L_{\text{acc}}$ is compatible with the variation of around 3 mag observed several times in this source (see Table 2).

6.3. Physical Conditions of the H I Lines Emitting Region

High-resolution spectroscopic observations indicate that both the high-velocity stellar winds and the gas channeled from the disk onto the stellar surface contribute to the hydrogen line profiles (e.g., Folha & Emerson 2001; Antoniucci et al. 2017a; Moura et al. 2020). Although our low-resolution observations do not allow to kinematically separate these two gas components, we can evaluate the average physical conditions of the hydrogen lines emitting regions using the observed flux ratios as temperature and density diagnostics.

Using their local line-excitation model, Kwan & Fischer (2011) provided predictions of the Balmer decrements (ratios from H$\gamma$ to H$\alpha$ with respect to H$\beta$), in the range of hydrogen density $8 \leq \log[n_\text{H}(\text{cm}^{-3})] \leq 12$, and temperature between 3750 K and 15,000 K. Similarly, Paschen decrements (ratios from Pa$\gamma$ to Pa$\beta$ with respect to Pa$\beta$), together with the ratio Br$10$/Br$\gamma$ are given by Edwards et al. (2013) for $8 \leq \log[n_\text{H}(\text{cm}^{-3})] \leq 12.4$ and $T = 5000$–20,000 K.

Fits through the intrinsic hydrogen line fluxes have been done by least squares method for sources where at least four
lines are detected. As an example, we show in Figure 11 the Balmer decrement measured in XZ Tau for the two observation dates (2014 and 2018). We plotted the H_/H/ ratios up to H14/H/ and H12/H/ for the 2014 (black) and 2018 (red) observations, respectively. First, we note the different shape of the Balmer decrement in the two dates. Following the nomenclature of Antoniucci et al. (2017b), in 2014 the decrement shape was of “type 4”, typical of strong accretors, and changed in 2018 to the “type 2” shape, which is the one most frequently seen in T Tauri stars. This shape can be explained by variation of a factor ∼2.5 in n_H, with ratios H_/H/ increasing with n_H in models with higher densities. Conversely, no clear correlation is found between the temperature and the shape of the Balmer decrement, and in particular, all the temperatures considered in the Kwan & Fischer model are compatible for the observation in 2018.

Table 7 summarizes the results for the objects of our sample, also reporting the brightness level of each source as derived from the photometric data and the number of lines involved in the fit. As pointed out for the case of XZ Tau, the temperature is not well constrained, apart from the case of UZ Tau E. It is therefore more interesting to focus on the results regarding the hydrogen density. In our previous study on the 2015 outburst of the classical EXor V1118 Ori, we highlighted the sudden increase in the hydrogen density of about two orders of magnitude, from log(n_H) = 9.4 to log(n_H) = 11.4, passing from the quiescent phase to the peak of the outburst (Giannini et al. 2017). In the objects of the sample presented here, we fit the hydrogen density in the range log(n_H) from 9.0 to 11.0, considering the uncertainties. Indeed, a certain level of correlation may be found between n_H and the activity level of the source. In Section 4 and 6.2, we identified XZ Tau, PV Cep, iPTF15afq, ASASSN-13db, and NY Ori as sources that showed considerable photometric variability during the last years, often accompanied by a significant L_acc and M_acc variations. Specifically, in XZ Tau the V band magnitude

Figure 7. As in Figure 6.
increased from $V \sim 12.8$ in 2014 to $V \sim 14.2$ in 2018. Our analysis shows that this resulted in a decrease of veiling from 0.8 to 0.0, of $M_{\text{acc}}$ by a factor of 5 and of $n_{\text{H}}$ by a factor around 2.5–3.0. PV Cep has been observed only during a period of high brightness. Close to the peak of the light curve in 2015, we fit $\log(n_{\text{H}}) = 11.0$. In ASASSN-13db and in iPTF15afq, we are able to measure $n_{\text{H}}$ only during the quiescent phase. It is interesting to note, however, that during periods of high brightness level (2014–2015 for ASASSN-13db and 2019 for iPTF15afq), the H1 lines are always seen in absorption, a signature typical of FUors or in general of sources with a high accretion rate (Connelley & Reipurth 2018). In NY Ori the situation is more controversial. From our acquisition images, we find differences of about two magnitudes in the $r$-band between 2014 ($r \sim 12$) and 2016 ($r \sim 14$). All H1 lines (from the Balmer and Paschen series) are seen in absorption in 2016, while the Paschen lines are in emission in 2014. Given the spectral type of NY Ori (K4), a possibility is that during quiescence the observed H1 lines are in absorption because they originate in the photosphere, while during outburst the accretion component in emission dominates.

In the remaining sources, which are all observed during quiescence, $\log(n_{\text{H}})$ is typically between 9.0 and 10.0. Only in V350 Cep we estimate $\log(n_{\text{H}})$ between 10.6 and 10.8 in 2015. Unfortunately, the photometric level at that date is unknown.

### 6.4. Mass Loss Variability and Forbidden Line Emission

Matter accretion from a disk necessarily imposes the removal of angular momentum through winds and jets. This makes the phenomena of mass accretion and ejection intimately correlated, so it is interesting to investigate whether they are also connected in terms of variability.
Figure 9. Ratios between observed spectra and artificially reddened and veiling-corrected templates. Ratios with minimum slopes (for which the extinction $A_V$ is estimated) are indicated in blue. For each panel, object name, date of observation, spectral type, and veiling are also reported.

Table 5

| Source                  | Date      | Continuum |          | Lines |          | Date      | Col–Col |          | Lines |
|-------------------------|-----------|-----------|----------|-------|----------|-----------|---------|----------|-------|
|                         | (yy/mm/dd)| $r_{10}$  | $A_V$    | $N_I$ | $A_V$    | (yy/mm/dd)| (mag)   | (mag) | (yy/mm/dd)| (mag) | (mag) |
| XZ Tau                  | 2014/12/21| 0.8       | 1.0–2.0  | 22    | 2.0–3.0  | ...       | ...     | ...     | ...     | ...     |
|                         | 2018/03/21| 0.0       | 1.4–3.4  | 16    | 2.8–4.4  | ...       | ...     | ...     | ...     | ...     |
| UZ Tau E                | 2014/12/22| 0.7       | 1.6–3.0  | 25    | 2.0–3.0  | 2016/01/25| 0.0–1.5 | 3       | 0.0–1.5 |
| VY Tau                  | 2014/12/21| 0.4       | 0.0–2.0  | 9     | 1.6–4.0  | 2016/03/04| ...     | 0       | ...     | ...     |
| NY Ori                  | 2014/12/21| 0.2$^b$  | ...      | 11    | 0.4–2.4  | ...       | ...     | ...     | ...     | ...     |
|                         | 2016/01/31| 0.1$^b$  | ...      | 8     | 0.5–2.9  | ...       | ...     | ...     | ...     | ...     |
| V1143 Ori               | 2014/12/21| 0.0       | 0.0–1.2  | 16    | 0.0–1.6  | ...       | ...     | ...     | ...     | ...     |
| DR Tau                  | 2014/10/31| >0.5$^b$ | ...      | 22    | 1.7–2.6  | 2018/03/23| 0.5$^b$–2.5 | 27$^a$ | 2.0–2.9 |
|                         | 2018/03/19| >0.5$^b$ | ...      | 27$^a$| 2.0–2.9  | ...       | ...     | ...     | ...     | ...     |
| ASASSN-13db             | 2014/12/21| >3        | ...      | 3     | 0.0–1.5  | 2015/02/10| 0.0–1.5 | 1       | ...     | ...     |
|                         | 2015/10/01| >3        | ...      | 3     | 0.0–1.5  | ...       | ...     | ...     | ...     | ...     |
|                         | 2017/02/21| 0.4       | 0.0–0.2  | 11    | 0.0–1.0  | ...       | ...     | ...     | ...     | ...     |
| V1647 Ori               | 2016/01/26| >2.5      | ...      | 5     | 7.7–10.6 | 2016/01/26| 12.0–14.0 | 3       | 12.0–14.0 |
| iPTF15afq               | 2016/01/27| ...       | ...      | 7     | 4.2–7.7  | 2018/01/28| ...     | 4       | 2.0–5.0 |
|                         | 2017/02/15| ...       | ...      | 5     | 5.9–8.9  | 2019/12/02| 0.3–2.3 | 0       | ...     | ...     |
| PV Cep                  | 2015/06/24| 0.0$^b$  | ...      | 11    | 4.3–6.3  | 2016/12/08| 0.0–1.0 | 5       | 1.8–5.1 |
| V350 Cep                | 2019/07/04| 0.1       | 1.4–3.0  | 15    | 1.3–2.9  | 2015/11/08| 0.8–2.8 | 4       | 0.0–1.5 |
|                         | 2019/10/02| 0.2       | 1.0–3.0  | 14    | 0.6–2.2  | 2018/09/29| ...     | 3       | 0.0–1.5 |
|                         | 2019/10/17| 0.0       | 1.3–3.3  | 16    | 0.7–2.3  | ...       | ...     | ...     | ...     | ...     |

Notes.

$^a$ Typical error on $r_{10}$ is 0.3 (Appendix B).

$^b$ Derived by assuming the $A_V$ value fitted from the accretion lines (see Appendix B for more details).

$^c$ Optical and near-infrared lines have been combined.
Mass loss rate determinations suffer from multiple assumptions on the geometry and physical conditions of the outflowing gas (e.g., Sperling et al. 2020). Therefore, rather than searching for correlations between the rates of accretion and ejection, we have preferred to look for flux variations of lines representative of the two phenomena.

The [O I] 6300 Å is the most prominent outflow emission feature. Indeed, it was detected in all our objects but VY Tau and V1143 Ori, namely the two sources with the lowest values of $\dot{M}_{\text{acc}}$.

As tracer of accretion we have selected the Hα line, both because of its brightness and, more importantly, because the ratio Hα/[O I] 6300 Å, being independent of extinction, is directly related to the intrinsic ratio between mass accretion and mass ejection rates.

Among the five sources showing a significant $\dot{M}_{\text{acc}}$ variation, we have multi-epoch determinations of the [O I] 6300 Å for XZ Tau, NY Ori, and iPTF15afq. With reference to the line fluxes reported in Appendix A, we find that in XZ Tau F([O I] 6300 Å) has remained fairly constant while F(Hα) decreased by a factor $\sim$2.4 from 2014 to 2018. This indicates that between 2014 and 2018 the variation of the mass accretion has been significantly larger than that of the mass loss. Similarly, in NY Ori, F(Hα) and F([O I] 6300 Å) decreased by a factor of seven and three in two years (2014–2016). In iPTF15afq we observe the same trend although the variation is low for both lines, due to the short temporal distance of just one year.

More striking is the trend in the classical EXor V1118 Ori. Indeed, comparing the Hα and [O I] 6300 Å fluxes during the 2015 outburst (Giannini et al. 2016, 2017), with those of quiescence (Lorenzetti et al. 2015) we find a variation of F(Hα) about ten times larger than the variation of F([O I] 6300 Å).

7. Conclusions

We analyzed optical and near-IR low-resolution spectra taken at LBT between 2014 and 2019 of a sample of 11 variable young sources, composed of five well-known eruptive variables (EXors) and six pre-main-sequence objects showing episodic variability likely attributable to intermittent accretion events (EXor candidates). Ten sources have been observed more than once, therefore allowing us to investigate for correlations between photometric and spectroscopic variability. At this stage, the collected observations represent the first flux-limited spectroscopic survey of candidate eruptive variables able to accurately determining fundamental quantities such as visual extinction; accretion parameters; physical parameters of the H1 lines emitting region, and signatures of mass
The main results of this survey can be summarized as follows:

1. The analysis of the light curves indicates that six sources (UZ Tau E, VY Tau, V1143 Ori, DR Tau, V1647 Ori, and V350 Cep) have been observed while in quiescence and another two, XZ Tau, and PV Cep, during a high level of brightness. Remarkably, ASASSN-13db and iPTF15afq have been caught during outburst.

2. All targets present lines that are tracers of accretion, like H I recombination lines, both in the optical and IR range. All IR spectra show prominent Ca II and He I 1.08 μm lines. Metallic lines of many species are also detected. Signatures of ejection activity ([O I] 6300 Å, [S II], H2 2.12 μm) characterize about 80% of the sources. No evident difference exists between the spectra of known and candidate EXors, all of them resembling spectra of accreting young T Tauri stars.

3. For many sources the veiling excess was computed. We found that a significant variation of the veiling is associated with accretion events. During the 2015 outburst of ASASSN-13db the veiling at 710 nm increased from 0.1 to >3.

4. Since the visual extinction $A_V$ closely depends on the source activity level at the time of the observation, a major effort has been made to accurately evaluate this parameter. For both optical and near-IR spectra, two independent methods (based on lines, continuum, and colors) were used to derive $A_V$ values.

5. Empirical relationships between the accretion luminosity ($L_{acc}$) and the luminosity of selected lines allowed us to determine the average accretion luminosity for each source and date of observation. The mass accretion rate was also evaluated. We did not find any remarkable difference between the $L_{acc}$ and $M_{acc}$ values of known EXors and EXor candidates of our sample, which are in the range $-1 < \log(M_{acc}/M_\odot) < 2$ and $-9 < \log(M_{acc}/M_\odot) < -8$, respectively.

6. All sources observed more than once present significant $M_{acc}$ variability even if they have been observed during quiescence. In ASASSN-13db, a decrease of $M_{acc}$ of two orders of magnitude is observed from the outburst peak to the quiescent phase. Also, the accretion luminosity of NY Ori decreased by a factor 25 in one year.

7. Physical parameters ($n_H$ and $T$) of the H I emitting region have been evaluated from the observed hydrogen line ratios by using predictions provided in the literature. These ratios are much more effective in constraining the density ($n_H$) than the temperature, which remains poorly defined. Generally, a direct correlation is recognizable between density and accretion activity of the source, with significant density increases (up to two orders of magnitudes) associated with large brightness fluctuations.

8. Tracers of mass outflows, such as the [O I] 6300 Å line, have been detected in most of the investigated sources. By comparing the [O I] variations with those of a mass accretion tracer (Hα), we conclude that mass accretion variations are larger than mass loss variations.

In the next future, other facilities appropriate for this research will be available in the southern hemisphere, which are expected both to discover large numbers of eruptive variables (e.g., VRoLSST), and to spectroscopically follow them in the optical/near-IR band (e.g., SoXS at ESO-NTT). Their observations will

| Source     | Date (yy/mm/dd) | $L_{acc}/L_\odot$ | log($M_{acc}/M_\odot$) yr$^{-1}$ |
|------------|-----------------|------------------|----------------------------------|
| XZ Tau     | 2014/12/21      | 0.30–0.90        | $-7.16$–$-6.68$                 |
|            | 2018/03/21      | 0.10–0.37        | $-7.06$–$-7.63$                 |
| UZ Tau E   | 2014/12/22      | 0.40–0.55        | $-6.92$–$-6.78$                 |
|            | 2016/01/25      | 0.28–0.50        | $-7.07$–$-6.83$                 |
| VY Tau     | 2014/12/21      | 0.004–0.04       | $-9.13$–$-8.16$                 |
| NY Ori     | 2014/12/21      | 0.60–3.60        | ...                             |
|            | 2016/01/31      | 0.03–0.33        | ...                             |
| V1143 Ori  | 2014/12/21      | 0.006–0.01       | $-9.23$–$-9.11$                 |
| DR Tau     | 2014/10/31      | 1.31–3.40        | $-7.11$–$-6.69$                 |
| ASASSN-13db| 2014/12/21      | 0.21–0.41        | $-7.48$–$-7.17$                 |
|            | 2015/02/10      | 0.11–0.14        | $-7.76$–$-7.64$                 |
|            | 2015/10/01      | 0.20–0.41        | $-7.48$–$-7.18$                 |
|            | 2017/02/21      | 0.003–0.009      | $-9.26$–$-8.85$                 |
| V1647 Ori  | 2016/01/26      | 7.24–20.89       | $-5.72$–$-5.26$                 |
| iPTF15afq  | 2016/01/27      | 0.72–3.54        | ...                             |
|            | 2017/02/15      | 2.18–11.20       | ...                             |
|            | 2018/01/28      | 0.58–1.47        | ...                             |
| PV Cep     | 2015/06/24      | 4.78–18.60       | $-6.54$–$-5.95$                 |
|            | 2016/12/08      | 2.63–8.04        | $-6.79$–$-6.31$                 |
| V350 Cep   | 2015/11/08      | 0.49–0.87        | ...                             |
|            | 2018/09/29      | 0.19–0.32        | ...                             |
|            | 2019/07/04      | 0.82–0.89        | ...                             |
|            | 2019/10/02      | 0.66–1.09        | ...                             |
|            | 2019/10/17      | 0.67–1.31        | ...                             |
Figure 11. Balmer decrement ($H_i/H_\beta$ flux ratios vs. upper level of the transition) of XZ Tau in the two dates of observation (black: 2014/12/21, red: 2018/03/21). The hydrogen density fitted for the two sets of data is reported in logarithmic scale. Different line symbols represent different temperatures as indicated in the top-right corner of the figure.

Table 7
Hydrogen Physical Parameters Derived from Balmer, Paschen, and Brackett Line Ratios

| Source      | Date (yy/mm/dd) | Bright. level | Series | $N_{\text{lines}}$ | Log[$n_H$(cm$^{-3}$)] | $T$ (K)    |
|-------------|-----------------|---------------|--------|-------------------|------------------------|------------|
| XZ Tau      | 2014/12/21      | H             | Ba     | 11                | 9.8                    | 7500–8750  |
|             | 2018/03/21      | L             | Ba     | 9                 | 9.4                    | all        |
| UZ Tau E    | 2014/12/22      | L             | Ba     | 11                | 9.8                    | 7500–8750  |
| VY Tau      | 2016/01/25      | I             | Pa+Br  | 4                 | 10.6–10.8              | 5000–12500 |
| NY Ori      | 2014/12/21      | H             | Pa     | 11                | 9.2–9.4                | all        |
| V1443 Ori   | 2014/12/21      | I             | Ba     | 11                | 9.2–9.4                | all        |
| DR Tau      | 2014/10/31      | L             | Ba+Pa  | 9                 | 10.0–10.8              | 5000–12500 |
|             | 2018/03/19-23   | L             | Ba+Pa+Br | 20          | 10.6–11.0              | 8750-12,500|
| ASASSN-13db | 2017/02/21      | L             | Ba     | 5                 | 9.4                    | all        |
| V1647 Ori   | 2016/01/26      | ?             | Ba+Pa  | 4                 | 9.0–10.0               | 8750–12,500 |
| iPTF15afq   | 2016/01/27      | L?            | Pa     | 5                 | 9.0–10.6               | all        |
|             | 2018/01/28      | L?            | Pa+Br  | 4                 | 10.4–11.0              | all        |
| PV Cep      | 2015/06/24      | H             | Pa     | 4                 | 11.0                   | 8750–12,500 |
|             | 2016/12/08      | H             | Pa+Br  | 6                 | 9.0–10.4               | all        |
| V350 Cep    | 2015/11/08      | I             | Pa+Br  | 5                 | 10.6–10.8              | all        |
|             | 2019/07/04      | I             | Ba+Pa  | 8                 | 9.2–9.8                | all        |
|             | 2019/10/02      | I             | Ba+Pa  | 8                 | 9.2–9.8                | all        |
|             | 2019/10/17      | I             | Ba+Pa  | 8                 | 9.2–9.8                | all        |

Note.
* Brightness level as retrieved from photometric data. H, high; I, intermediate; L, low.
probably deeply modify our knowledge of the eruptive accretion phenomenon. In such a framework, we hope that our coherent database will represent a valuable reference study.

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Appendix A

In this Appendix we give the Tables of the lines fluxes used in the analysis (Tables 8–18). We report the line identification and wavelength (air wavelength for optical lines ($\lambda$ 1 $\mu$m)), along with the measured flux $cgs$ units) for each date of observation.

| Line            | $\lambda_{\text{air}}$ (Å) | $F \pm \Delta F$ ($10^{-14}$ erg s$^{-1}$ cm$^{-2}$) |
|-----------------|-----------------|-----------------|
| H15             | 3711.977        | 3.2 ± 0.2       |
| H14             | 3721.938        | 3.5 ± 0.2       |
| H13             | 3734.368        | 3.6 ± 0.2       |
| H12             | 3750.151        | 4.1 ± 0.2       |
| H11             | 3770.630        | 3.7 ± 0.2       |
| H10             | 3797.898        | 5.3 ± 0.2       |
| H9              | 3835.384        | 6.3 ± 0.3       |
| H8              | 3889.049        | 7.4 ± 0.2       |
| Ca II K         | 3933.660        | 51.3 ± 0.1      |
| Ca II H/H7      | 3968.470        | 47.9 ± 0.1      |
| H6              | 4101.702        | 13.8 ± 0.2      |
| H7              | 4340.464        | 20.4 ± 0.2      |
| H/$\beta$       | 4861.325        | 50.2 ± 0.3      |
| He I            | 5015.678        | 9.2 ± 0.2       |
| He I            | 5875.621        | 7.1 ± 0.2       |
| [O I]           | 6300.304        | 12.4 ± 0.6      |
| [O I]           | 6363.776        | 3.7 ± 0.6       |
| H$\alpha$       | 6562.800        | 364 ± 0.6       |
| He I            | 6678.151        | 3.7 ± 0.6       |
| [S II]          | 6730.82         | 4.1 ± 0.6       |
| O I             | 7773.055        | 2.6 ± 0.9       |
| O I             | 8446.360        | 19.4 ± 1.2      |
| Ca II           | 8498.020        | 217 ± 1.2       |
| Ca II           | 8542.090        | 207 ± 1.2       |
| Ca II           | 8662.140        | 181.9 ± 1.2     |
| Pa9             | 9229.015        | 15.2 ± 1.8      |
### Table 9

**UZ Tau E: Observed Lines**

| Line     | $\lambda_{\text{air}}$ (Å) | $F \pm \Delta F$ (10^{-14} erg s^{-1} cm^{-2}) | $\lambda_{\text{vac}}$ (Å) | $F \pm \Delta F$ (10^{-14} erg s^{-1} cm^{-2}) |
|----------|-----------------------------|-----------------------------------------------|-----------------------------|-----------------------------------------------|
| H15      | 3711.977                    | 1.7 ± 0.6                                     | Paδ                         | 10,052.128                                   |
| H14      | 3721.938                    | 2.5 ± 0.6                                     | He I                        | 10,833.2                                     |
| H13      | 3734.368                    | 2.5 ± 0.6                                     | Paγ                         | 10,941.090                                   |
| H12      | 3750.151                    | 3.2 ± 0.6                                     | Paβ                         | 12,821.59                                    |
| H11      | 3770.630                    | 3.7 ± 0.6                                     | Br12                        | 16,411.674                                   |
| H10      | 3797.898                    | 5.0 ± 0.6                                     | Br11                        | 16,811.111                                   |
| H9       | 3835.384                    | 6.9 ± 0.9                                     | Br10                        | 17,366.850                                   |
| H8       | 3889.049                    | 8.8 ± 0.7                                     | CO 2-0                      | 22,930.0                                     |
| Ca II K  | 3933.660                    | 20.8 ± 0.7                                    | CO 3-1                      | 23,230.0                                     |
| Ca II H/H7| 3968.470                   | 23.1 ± 0.7                                    | ...                         | ...                                           |
| He I     | 4026.191                    | 1.4 ± 0.7                                     | ...                         | ...                                           |
| Hδ       | 4101.702                    | 14.8 ± 0.3                                    | ...                         | ...                                           |
| Hγ       | 4340.464                    | 20.0 ± 0.5                                    | ...                         | ...                                           |
| Hβ       | 4471.480                    | 3.1 ± 0.5                                     | ...                         | ...                                           |
| Hα       | 4861.325                    | 42.7 ± 0.3                                    | ...                         | ...                                           |
| He I     | 5015.678                    | 4.9 ± 0.4                                     | ...                         | ...                                           |
| He I     | 5875.621                    | 7.9 ± 0.4                                     | ...                         | ...                                           |
| [O I]    | 6300.304                    | 14.0 ± 0.4                                    | ...                         | ...                                           |
| [O I]    | 6363.776                    | 3.3 ± 0.4                                     | ...                         | ...                                           |
| Hα       | 6562.800                    | 357 ± 0.4                                     | ...                         | ...                                           |
| He I     | 6678.151                    | 3.6 ± 0.4                                     | ...                         | ...                                           |
| [S II]   | 6730.82                     | 2.1 ± 0.4                                     | ...                         | ...                                           |
| He I     | 7065.190                    | 3.6 ± 0.9                                     | ...                         | ...                                           |
| O I      | 8446.360                    | 22.4 ± 0.9                                    | ...                         | ...                                           |
| Ca II    | 8498.020                    | 92.4 ± 1.0                                    | ...                         | ...                                           |
| Ca II    | 8542.090                    | 81.2 ± 1.0                                    | ...                         | ...                                           |
| Ca II    | 8662.140                    | 78.8 ± 1.0                                    | ...                         | ...                                           |
| Pa9      | 9229.015                    | 17.9 ± 1.3                                    | ...                         | ...                                           |

### Table 10

**VY Tau: Observed Lines**

| Line     | $\lambda_{\text{air}}$ (Å) | $F \pm \Delta F$ (10^{-14} erg s^{-1} cm^{-2}) | $\lambda_{\text{vac}}$ (Å) | $F \pm \Delta F$ (10^{-14} erg s^{-1} cm^{-2}) |
|----------|-----------------------------|-----------------------------------------------|-----------------------------|-----------------------------------------------|
| H10      | 3797.898                    | 0.16 ± 0.0                                    | He I                        | 10,833.2                                     |
| H9       | 3835.384                    | 0.19 ± 0.0                                    | CO 2-0                      | 22,930.0                                     |
| H8       | 3889.049                    | 0.33 ± 0.12                                   | CO 3-1                      | 23,230.0                                     |
| Ca II K  | 3933.660                    | 1.94 ± 0.12                                   | ...                         | ...                                           |
| Ca II H/H7| 3968.470                   | 2.55 ± 0.12                                   | ...                         | ...                                           |
| Hδ       | 4101.702                    | 0.47 ± 0.02                                   | ...                         | ...                                           |
| Hγ       | 4340.464                    | 0.97 ± 0.02                                   | ...                         | ...                                           |
| Hβ       | 4861.325                    | 2.83 ± 0.13                                   | ...                         | ...                                           |
| Hα       | 6562.800                    | 11.3 ± 0.28                                   | ...                         | ...                                           |
| Pa9      | 9229.015                    | 2.37 ± 0.68                                   | ...                         | ...                                           |
### Table 11
**NY Ori: Observed Lines**

| Line         | \( \lambda_{\mu} \) (Å) | \( F \pm \Delta F \) (10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\)) |
|--------------|---------------------------|----------------------------------|
| H15         | 3711.977                  | 1.7 ± 0.4                        |
| H14         | 3721.938                  | 2.2 ± 0.4                        |
| H13         | 3734.368                  | 2.4 ± 0.6                        |
| H12         | 3750.151                  | 3.4 ± 0.4                        |
| H11         | 3770.630                  | 3.0 ± 0.4                        |
| H10         | 3797.898                  | 1.7(−3.6) ± 0.4                  |
| H9          | 3835.384                  | 5.1 ± 0.4                        |
| H8          | 3889.049                  | 2.6(−4.1) ± 0.4                  |
| Ca II K     | 3933.660                  | 14.7 ± 0.1                       |
| Ca II H/H7  | 3968.470                  | 11.0(−3.4) ± 0.1                 |
| He I        | 4026.191                  | 1.4 ± 0.1                        |
| He λ        | 4101.702                  | 3.7(−5.4) ± 0.3                  |
| Heγ         | 4340.464                  | 4.9(−5.1) ± 0.3                  |
| He I        | 4471.480                  | 1.7 ± 0.3                        |
| He λ        | 4861.325                  | 9.1(−3.6) ± 0.3                  |
| He I        | 4921.931                  | 2.0(−1.5) ± 0.1                  |
| Pa10        | 6562.800                  | 2.8 ± 0.3                        |
| [O I]       | 6300.304                  | 0.9 ± 0.3                        |
| Hα          | 6562.800                  | 188 ± 0.4                        |
| Hβ          | 6678.151                  | 2.8 ± 0.3                        |
| O I         | 8446.360                  | 4.7(−2.3) ± 0.2                  |
| Pa17        | 8467.253                  | ...                              |
| Ca II       | 8498.020                  | 52.1 ± 0.2                       |
| Pa16        | 8502.483                  | ...                              |
| Ca II       | 8542.090                  | 42.4 ± 0.2                       |
| Pa15        | 8545.383                  | ...                              |
| Pa14        | 8598.392                  | 2.3 ± 0.3                        |
| Ca II       | 8662.140                  | 39.0 ± 0.2                       |
| Pa13        | 8665.018                  | ...                              |
| Pa12        | 8750.472                  | 3.7 ± 0.2                        |
| Pa11        | 8862.783                  | 4.2 ± 0.2                        |
| Pa10        | 9014.910                  | 6.1 ± 0.3                        |
| Pa9         | 9229.015                  | 10.2 ± 0.3                       |

### Table 12
**V1143 Ori: Observed Lines**

| Line         | \( \lambda_{\mu} \) (Å) | \( F \pm \Delta F \) (10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\)) |
|--------------|---------------------------|----------------------------------|
| H14         | 3721.938                  | 0.04 ± 0.01                      |
| H13         | 3734.368                  | 0.05 ± 0.01                      |
| H12         | 3750.151                  | 0.055 ± 0.005                    |
| H11         | 3770.630                  | 0.067 ± 0.005                    |
| H10         | 3797.898                  | 0.111 ± 0.006                    |
| H9          | 3835.384                  | 0.161 ± 0.006                    |
| H8          | 3889.049                  | 0.209 ± 0.006                    |
| Ca II K     | 3933.660                  | 0.371 ± 0.005                    |
| Ca II H/H7  | 3968.470                  | 0.540 ± 0.005                    |
| Hδ          | 4101.702                  | 0.322 ± 0.006                    |
| Hγ          | 4340.464                  | 0.370 ± 0.006                    |
| He I        | 4471.480                  | 0.043 ± 0.006                    |
| Hβ          | 4861.325                  | 0.486 ± 0.005                    |
| He I        | 4921.931                  | 0.058 ± 0.006                    |
| He I        | 5015.678                  | 0.056 ± 0.007                    |
| He I        | 5875.621                  | 0.11 ± 0.01                      |
| Hα          | 6562.800                  | 1.55 ± 0.01                      |
Table 13
DR Tau: Observed Lines

| Line     | \(\lambda_{\text{air}}\) (Å) | \(F \pm \Delta F\) (10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\)) | Line     | \(\lambda_{\text{vac}}\) (Å) | \(F \pm \Delta F\) (10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\)) |
|----------|-------------------------------|---------------------------------------------------------------|----------|-------------------------------|---------------------------------------------------------------|
| H18      | 3691.554                      | ...                                                           | H22      | 10,833.2                      | (-35.7)12.1 ± 0.1                                              |
| H17      | 3697.151                      | ...                                                           | Pa\(\delta\) | 10,052.128                    | 70.1 ± 1.8                                                    |
| H16      | 3703.852                      | ...                                                           | [S II]   | 10,339.24                     | 4.3 ± 1.8                                                    |
| H15      | 3711.977                      | 3.0 ± 0.2                                                     | He I     | 10,833.2                      | 106.0 ± 1.8                                                  |
| H14      | 3721.938                      | 4.3 ± 0.3                                                     | Pa\(\beta\) | 12,821.59                     | 173.1 ± 1.8                                                  |
| H13      | 3734.368                      | 3.5 ± 0.4                                                     | Br\(\iota\) | 15,884.880                    | 10.5 ± 1.6                                                   |
| H12      | 3750.152                      | 4.4 ± 0.5                                                     | Br\(\alpha\) | 16,113.714                    | 15.4 ± 1.6                                                   |
| H11      | 3770.630                      | ...                                                           | Br\(\beta\) | 16,411.674                    | 22.1 ± 1.6                                                   |
| H10      | 3797.897                      | ...                                                           | Br\(\iota\) | 16,811.111                    | 31.5 ± 1.6                                                   |
| H9       | 3835.384                      | ...                                                           | Br\(\iota\) | 17,366.850                    | 36.3 ± 1.6                                                   |
| Ca II K  | 3933.660                      | 53.5 ± 0.3                                                    | Br\(\gamma\) | 21661.20                      | 31.4 ± 1.8                                                   |
| Ca II H/H7 | 3968.470                     | 25.3 ± 0.3                                                    | ...      | ...                           | ...                                                          |
| He I     | 4026.191                      | 2.5 ± 0.4                                                     | ...      | ...                           | ...                                                          |
| H\(\gamma\) | 4101.702                     | (-2.53)1.0 ± 0.3                                              | ...      | ...                           | ...                                                          |
| H\(\delta\) | 4340.464                     | (-1.66)0.0 ± 0.3                                              | ...      | ...                           | ...                                                          |
| He II    | 4685.804                      | 1.9 ± 0.7                                                     | ...      | ...                           | ...                                                          |
| He I     | 4713.146                      | ...                                                           | ...      | ...                           | ...                                                          |
| H\(\beta\) | 4861.325                     | (-1.5)30.8 ± 0.1                                              | ...      | ...                           | ...                                                          |
| He I     | 4921.931                      | 15.4 ± 0.3                                                    | ...      | ...                           | ...                                                          |
| H\(\alpha\) | 5015.678                     | 17.0 ± 0.3                                                    | ...      | ...                           | ...                                                          |
| He I     | 5875.621                      | 15.3 ± 0.3                                                    | ...      | ...                           | ...                                                          |
| [O I]    | 6300.304                      | 1.8 ± 0.4                                                     | ...      | ...                           | ...                                                          |
| H\(\alpha\) | 6562.800                     | 407.5 ± 0.5                                                   | ...      | ...                           | ...                                                          |
| He I     | 6678.151                      | 7.2 ± 0.4                                                     | ...      | ...                           | ...                                                          |
| He I     | 7065.190                      | 6.8 ± 0.4                                                     | ...      | ...                           | ...                                                          |
| O I      | 7773.055                      | 12.3 ± 0.4                                                    | ...      | ...                           | ...                                                          |
| Pa25     | 8323.424                      | ...                                                           | ...      | ...                           | ...                                                          |
| Pa24     | 8333.782                      | 4.3 ± 0.4                                                     | ...      | ...                           | ...                                                          |
| Pa23     | 8345.552                      | 5.0 ± 0.4                                                     | ...      | ...                           | ...                                                          |
| Pa22     | 8359.003                      | 5.7 ± 0.5                                                     | ...      | ...                           | ...                                                          |
| Pa21     | 8374.475                      | 8.4 ± 0.6                                                     | ...      | ...                           | ...                                                          |
| Pa20     | 8392.396                      | 10.7 ± 0.6                                                    | ...      | ...                           | ...                                                          |
| Pa19     | 8413.317                      | 10.7 ± 0.5                                                    | ...      | ...                           | ...                                                          |
| Pa18     | 8437.955                      | 15.3 ± 0.6                                                    | ...      | ...                           | ...                                                          |
| O I      | 8446.360                      | 44.3 ± 0.4                                                    | ...      | ...                           | ...                                                          |
| Pa17     | 8467.253                      | 14.3 ± 0.5                                                    | ...      | ...                           | ...                                                          |
| Ca II    | 8498.020                      | 237.0 ± 0.4                                                   | ...      | ...                           | ...                                                          |
| Ca II    | 8542.090                      | 253.5 ± 0.4                                                   | ...      | ...                           | ...                                                          |
| Pa18     | 8598.392                      | 23.8 ± 0.5                                                    | ...      | ...                           | ...                                                          |
| Ca II    | 8662.140                      | 214.8 ± 0.4                                                   | ...      | ...                           | ...                                                          |
| Pa12     | 8750.472                      | 31.3 ± 0.5                                                    | ...      | ...                           | ...                                                          |
| Pa11     | 8862.783                      | 34.4 ± 0.5                                                    | ...      | ...                           | ...                                                          |
| Pa10     | 9014.910                      | 39.4 ± 0.5                                                    | ...      | ...                           | ...                                                          |
| Pa9      | 9229.015                      | 53.0 ± 0.5                                                    | ...      | ...                           | ...                                                          |
| Pa8      | 9545.971                      | 63.1 ± 2                                                      | ...      | ...                           | ...                                                          |
### Table 14
ASASSN-13db: Observed Lines

| Line          | 2014/12/21 | 2015/10/01 | 2017/02/21 | 2015/02/10 |
|---------------|------------|------------|------------|------------|
|               | $\lambda_{\text{air}}$ (Å) | $F \pm \Delta F$ $(10^{-14}$ erg s$^{-1}$ cm$^{-2}$) | $\lambda_{\text{vac}}$ (Å) | $F \pm \Delta F$ $(10^{-14}$ erg s$^{-1}$ cm$^{-2}$) |
| H9            | 3835.384   | ...        | 0.10 ± 0.02 | He I       | 10,833.2   | (−13.3) ± 0.1 |
| Ca II K       | 3933.660   | (−1.9)1.2 ± 0.2 | (−1.3)6.2 ± 0.3 | (−0.01)0.21 ± 0.01 | Paβ       | 12821.59 | 5.7 ± 1.5 |
| Ca II H/H7    | 3968.470   | (−1.0)0.9 ± 0.2 | (−1.5)3.6 ± 0.3 | (−0.01)0.32 ± 0.01 | ...       | ...     | ...     |
| Hδ            | 4101.702   | ...        | 0.25 ± 0.01 | ...        | ...       | ...     | ...     |
| Hγ            | 4304.464   | ...        | 0.31 ± 0.01 | ...        | ...       | ...     | ...     |
| Hβ            | 4861.325   | −2.6 ± 0.2 | −3.0 ± 0.3 | 0.47 ± 0.01 | ...       | ...     | ...     |
| He I          | 4921.931   | ...        | 0.08 ± 0.01 | ...        | ...       | ...     | ...     |
| He I          | 5015.678   | ...        | 0.07 ± 0.01 | ...        | ...       | ...     | ...     |
| Ca II         | 5875.621   | ...        | 0.08 ± 0.01 | ...        | ...       | ...     | ...     |
| [O I]         | 6300.304   | ...        | 0.09 ± 0.01 | ...        | ...       | ...     | ...     |
| [O I]         | 6363.776   | ...        | 0.04 ± 0.01 | ...        | ...       | ...     | ...     |
| Hα            | 6562.800   | (−1.4)11.5 ± 1.0 | (−1.4)27.3 ± 0.4 | 1.21 ± 0.01 | ...       | ...     | ...     |
| He I          | 6678.151   | ...        | 0.06 ± 0.01 | ...        | ...       | ...     | ...     |
| [S II]        | 6716.44    | ...        | 0.08 ± 0.01 | ...        | ...       | ...     | ...     |
| [S II]        | 6730.82    | ...        | 0.18 ± 0.01 | ...        | ...       | ...     | ...     |
| Ca II         | 8498.020   | 13.1 ± 0.3 | 12.8 ± 0.4 | 0.23 ± 0.01 | ...       | ...     | ...     |
| Ca II         | 8542.090   | 13.5 ± 0.3 | 13.2 ± 0.4 | 0.24 ± 0.01 | ...       | ...     | ...     |
| Ca II         | 8662.140   | 10.2 ± 0.3 | 9.8 ± 0.4 | 0.19 ± 0.01 | ...       | ...     | ...     |

### Table 15
V1647 Ori: Observed Lines

| Line          | 2016/01/26 |
|---------------|------------|
|               | $\lambda_{\text{air}}$ (Å) | $F \pm \Delta F$ $(10^{-14}$ erg s$^{-1}$ cm$^{-2}$) |
| [O I]         | 6300.304   | 0.22 ± 0.06 |
| Hα            | 6562.800   | (−0.04)0.60 ± 0.02 |
| O I           | 7773.055   | 0.03 ± 0.04 |
| O I           | 8446.360   | 0.18 ± 0.04 |
| Ca II         | 8498.020   | 1.09 ± 0.04 |
| Ca II         | 8542.090   | 1.20 ± 0.04 |
| Ca II         | 8662.140   | 1.09 ± 0.04 |
| Paδ           | 10,052.128 | 2.8 ± 0.3 |
| Paγ           | 10,941.090 | (−29.8) ± 1.0 |
| Paβ           | 12,821.59  | 73.2 ± 2.0 |
### Table 16

**iPTF15afq: Observed Lines**

| Line | λ<sub>air</sub> (Å) | F ± ΔF (10<sup>-14</sup> erg s<sup>-1</sup> cm<sup>-2</sup>) | Line | λ<sub>air</sub> (Å) | F ± ΔF (10<sup>-14</sup> erg s<sup>-1</sup> cm<sup>-2</sup>) |
|------|-----------------|---------------------|------|-----------------|---------------------|
| [O I] | 6300.304 | 0.35 ± 0.01 0.21 ± 0.01 | Paδ | 10,052.128 | 0.46 ± 0.02 −0.6 ± 0.1 |
| [O I] | 6363.776 | 0.11 ± 0.01 0.08 ± 0.01 | [S II] | 10,320.49 | 0.10 ± 0.02 ... |
| Hα | 6562.800 | 1.46 ± 0.01 1.14 ± 0.01 | [S II] | 10,336.41 | 0.16 ± 0.02 ... |
| [NII] | 6583.46 | 0.03 ± 0.01 ... | He I | 10,833.2 | 0.62 ± 0.02 −2.2 ± 0.1 |
| [S II] | 6716.44 | 0.04 ± 0.01 0.03 ± 0.01 | Paγ | 10,941.090 | 0.67 ± 0.02 −1.6 ± 0.2 |
| [S II] | 6730.82 | 0.08 ± 0.01 0.06 ± 0.01 | [Fe II] | 12,570.2068 | 0.26 ± 0.02 ... |
| [Fe II] | 7155.1742 | 0.14 ± 0.01 0.09 ± 0.01 | Paβ | 12,821.59 | 1.61 ± 0.02 −1.9 ± 0.2 |
| [Fe II] | 7167.9228 | 0.04 ± 0.01 ... | Br8 | 19,450.871 | 0.6 ± 0.1 ... |
| [Fe II] | 7288.9899 | 0.05 ± 0.01 ... | H2 1-0S(1) | 21,218 | 0.12 ± 0.02 ... |
| [Ca II] | 7323.89 | 0.10 ± 0.01 ... | Brγ | 21,661.20 | 0.54 ± 0.04 ... |
| [NII] | 7377.83 | 0.08 ± 0.01 ... | CO 2-0 | 22,930 | 2.9 ± 0.2 ... |
| [Fe II] | 7388.1673 | 0.05 ± 0.01 ... | CO 3-1 | 23,230 | 3.8 ± 0.2 (−4.0)3.6 ± 0.5 |
| [NII] | 7411.61 | 0.04 ± 0.01 ... | ... | ... | ... |
| [Fe II] | 7452.5611 | 0.06 ± 0.01 ... | ... | ... | ... |
| [Fe II] | 8387.181 | 0.09 ± 0.01 ... | ... | ... | ... |
| [Fe II] | 8446.360 | 5.13 ± 0.01 0.08 ± 0.01 | ... | ... | ... |
| Pa17 | 8467.253 | 0.04 ± 0.01 ... | ... | ... | ... |
| Ca II | 8498.020 | 8.15 ± 0.01 1.01 ± 0.01 | ... | ... | ... |
| Ca II | 8542.090 | 9.84 ± 0.01 1.07 ± 0.01 | ... | ... | ... |
| Pa14 | 8598.392 | 0.03 ± 0.01 ... | ... | ... | ... |
| Ca II | 8662.140 | 0.89 ± 0.01 ... | ... | ... | ... |
| Pa12 | 8750.472 | 0.04 ± 0.01 ... | ... | ... | ... |
| Pa11 | 8862.783 | 0.06 ± 0.01 ... | ... | ... | ... |
| Pa10 | 9014.910 | 0.09 ± 0.01 ... | ... | ... | ... |
| Pa9 | 9229.015 | 0.18 ± 0.02 0.12 ± 0.04 | ... | ... | ... |
| Pa8 | 9545.971 | 0.14 ± 0.02 ... | ... | ... | ... |
| Line | $\lambda_{\text{air}}$ (Å) | $F \pm \Delta F$ (10$^{-14}$ erg s$^{-1}$ cm$^{-2}$) | Line | $\lambda_{\text{vac}}$ (Å) | $F \pm \Delta F$ (10$^{-14}$ erg s$^{-1}$ cm$^{-2}$) |
|------|-----------------|-----------------|------|-----------------|-----------------|
|      | $\pm$ $\Delta F$ |                  |      | $\pm$ $\Delta F$ |                  |
| H15  | 3711.977        | −0.05 ± 0.02    | Pa8  | 9548.590        | 32 ± 2          |
| H14  | 3721.938        | −0.13 ± 0.02    | Pa6  | 10,052.128      | 48 ± 2          |
| H13  | 3734.368        | −0.10 ± 0.02    | [S II] | 10,320.49      | 36 ± 3          |
| H12  | 3750.151        | −0.10 ± 0.02    | [N I] | 10,400.59       | 20 ± 3          |
| H11  | 3770.630        | −0.10 ± 0.02    | He I | 10,833.2        | −43 ± 1         |
| H10  | 3797.898        | −0.15 ± 0.02    | Pa7  | 10,941.090      | 61 ± 3          |
| H9   | 3835.384        | −0.22 ± 0.02    | Pa9  | 12,821.59       | 210 ± 2         |
| H8   | 3889.049        | −0.38 ± 0.02    | Br14 | 15,884.880      | 34 ± 5          |
| Ca II K | 3933.660      | (−0.04)         | Br13 | 16,113.714      | 50 ± 5          |
| Ca II H/H7 | 3968.470  | 0.73 ± 0.02    | Br12 | 16,411.674      | 60 ± 5          |
| Hδ   | 4101.702        | −0.23 ± 0.02    | Br11 | 16,811.111      | 65 ± 5          |
| Hγ   | 4340.464        | −0.39 ± 0.02    | Br10 | 17,366.850      | 72 ± 10         |
| Hβ   | 4861.325        | (−0.39)         | Brγ  | 21,661.20       | 49 ± 8          |
| He I | 4921.931        | 0.61 ± 0.04     | C0 2-0 | 22,930       | 161 ± 20        |
| He I | 5015.678        | 0.47 ± 0.04     |      | ...            | ...             |
| [O I] | 6300.304        | 4.68 ± 0.07     |      | ...            | ...             |
| [O I] | 6363.776        | 1.61 ± 0.07     |      | ...            | ...             |
| Hα   | 6562.800        | 52.8 ± 0.04     |      | ...            | ...             |
| He I | 6678.151        | 0.65 ± 0.04     |      | ...            | ...             |
| O I  | 7773.055        | 2.11 ± 0.09     |      | ...            | ...             |
| Pa19 | 8413.317        | 2.00 ± 0.09     |      | ...            | ...             |
| Pa18 | 8437.955        | 2.51 ± 0.09     |      | ...            | ...             |
| O I  | 8446.360        | 13.9 ± 0.09     |      | ...            | ...             |
| Pa17 | 8467.253        | 3.97 ± 0.09     |      | ...            | ...             |
| Ca II | 8498.020        | 79.6 ± 0.09     |      | ...            | ...             |
| Ca II | 8542.090        | 69.4 ± 0.09     |      | ...            | ...             |
| Pa14 | 8598.392        | 4.41 ± 0.09     |      | ...            | ...             |
| Ca II | 8662.140        | 61.9 ± 0.09     |      | ...            | ...             |
| Pa12 | 8750.472        | 5.81 ± 0.09     |      | ...            | ...             |
| Pa11 | 8862.783        | 6.34 ± 0.09     |      | ...            | ...             |
| Pa10 | 9014.910        | 7.22 ± 0.13     |      | ...            | ...             |
| Pa9  | 9229.015        | 8.16 ± 0.13     |      | ...            | ...             |
Appendix B

Veiling Determination

In this section, we briefly discuss the strategy we adopted to estimate the veiling ($r$) in our sample. For a given source, we have first selected a number of BTSettl templates with temperature within 500 K of the $T_{\text{eff}}$ value given in the literature (Table 3) and $\log g$ between 3.5 and 4.5. A veiling (increasing in steps of 0.1) is then added to each template to find the value that best matches the spectral features observed in our sample of stars.

For M-type stars, which are the majority of our sources, we have fitted the portion of the continuum in the range 700–715 nm, where prominent TiO absorption bands are located (Figure 12). In all sources but two, our fit consistently provides a $T_{\text{eff}}$ in agreement with that of the literature, and determined $r$ with a typical error of 0.3, corresponding to a variation of $T_{\text{eff}}$ less than 100 K. The two exceptions are UZ Tau E and V1143 Ori ($T_{\text{eff}}$ of literature 3410 K and 3500 K, respectively). In the case of UZ Tau E, we have accurate determinations of $T_{\text{eff}} = 3600$ K and $r = 0.7$ from high-resolution observations obtained with the HARPS-N instrument at the Telescopio Nazionale Galileo (Gangi et al., in preparation). Having assumed the veiling value, we have fitted $T_{\text{eff}}$ in the MODS spectrum, which is in perfect agreement with that derived from the HARPS-N spectrum (Figure 13).

For the few sources that do not present the TiO bands because of their SpT (in particular NY Ori, DR Tau, and PV Cep), we applied an indirect method to evaluate the veiling at 710 nm. We first reddened the BTSettl template by assuming the $A_V$ derived from the "line method" (Section 6.1.1). By dividing the observed spectrum with the reddened template, we have derived the shape of the excess continuum flux. The ratio at 710 nm was then assumed as the veiling value, reported in Table 6.

We also looked for TiO spectral variations in the three sources of this subsample that were observed more than once (XZ Tau, V350 Cep, and ASASSN13-db, see Figure 14). We have found that XZ Tau shows an increase in the depth of the TiO bands between 2014 and 2018 which corresponds to a decrease in $r$ from 0.8 to 0.0. TiO bands do not appear in the spectra of ASASSN13-db during the burst phases of 2014 and 2015 while they are present during the out-of-burst phase of 2017 with a corresponding veiling of 0.4. The absence of TiO bands in 2014 and 2015 indicates that during the outburst the veiling increased to values larger than 3. Finally, the veiling measured in V350 Cep does not show variations that exceed the quoted uncertainty of 0.3.
Figure 12. Examples of BTSettl models best matching the TiO bands. Spectra are normalized to the peak of the band. For each panel, object name, date of observation, temperature of the BTSettl model, and veiling are reported. In the third panel, TiO bands are indicated.

Figure 13. Residuals on $T_{\text{eff}}$ fitting in UZ Tau E, assuming $r = 0.7$. The BTSettl model that best matches the MODS spectrum corresponds to $T_{\text{eff}} = 3600$ K, the same as that found with high-spectral resolution observations.

Figure 14. TiO bands strength variability. Spectra are normalized to the peak of the band and vertically shifted for a better visualization. Date of observation, temperature of the best matching BTSettl model, and veiling are also labeled.
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