NEAR-INFRARED SPECTROSCOPIC MONITORING OF EXOR VARIABLES: FIRST RESULTS*

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ABSTRACT

We present low-resolution (R ~ 250) spectroscopy in the near-IR (0.8–2.5 μm) of the EXor variables. These are the initial results (obtained during the period 2007–2008) from a long-term photometric and spectroscopic program aimed at studying the variability in the accretion processes of pre-main-sequence stars, by correlating the continuum fluctuations with the spectroscopic properties. Eight sources have been observed in different epochs, for a total of 25 acquired spectra. EXor spectra show a wide variety of emission features dominated by H i recombination (Paschen and Brackett series). We have investigated whether line and continuum variability could be due to a variable extinction, but such a hypothesis is applicable only to the peculiar source PV Cep. By comparing the observed spectra with a wind model, mass loss rates in the range (2–10) × 10^{-8} M⊙ yr^{-1} are derived, along with other wind parameters. Consistent results are also obtained by assuming that H i lines are due to accretion. A CO overtone is also detected in the majority of the sources both in absorption and in emission. It appears to come from regions more compact than winds, likely the stellar photosphere (when in absorption) and the circumstellar disk (when in emission). Na i and Ca i IR lines behave as the CO does, thus they are thought to arise in the same locations. For some targets multiple spectra correspond to different activity stages of the source. Those exhibiting the longest continuum variation at 2 μm (ΔK > 1 mag) present a significant line flux fading during the continuum declining phases. In particular, CO absorption (emission) appears associated with inactive (active) stages, respectively.

Key words: circumstellar matter – infrared: stars – stars: emission-line, Be – stars: formation – stars: pre-main sequence – stars: variables: other

Online-only material: color figures

1. INTRODUCTION

EXor stars, originally defined by Herbig (1989), are pre-main-sequence (PMS) objects, with ages of about 10^6 years, characterized by intense (3–4 magnitudes) and short-lived (months, one year) outbursts superposed to longer (some years) quiescence periods. According to a widely accepted picture, such objects are accreting material from a circumstellar disk, through rapid and intermittent accretion events that generate thermal instabilities in the disk itself and, eventually, outburst phenomena (Hartmann & Kenyon 1985). Indeed the accreted matter migrates toward the central star and it is suddenly halted where the inner disk is truncated (at few stellar radii) by the dipolar stellar magnetic field; then it is channeled onto the stellar surface along the magnetic field lines (e.g., Shu et al. 1994). When such material violently falls onto the stellar surface it produces a shock that cools by emitting a hot continuum, often called veiling. As a consequence of the accretion event, strong winds (in some cases also collimated jets) emerge from the rotating star/disk system. While the accretion phenomenology is difficult to directly observe, the observations of young objects more likely reveal the presence of outflowing matter whose rate is often exploited to quantitatively determine the rate of the infalling one, by invoking the rough proportion M_{wind}/M_{acc} < ~ 0.1 (Shu et al. 2000; Königl & Pudritz 2000).

The interaction with a close binary companion is also invoked as an alternative mechanism to produce accretion disk instabilities and consequent outbursts (Clarke et al. 1990; Bonnell & Bastien 1992). Indeed, the majority of EXor stars do have a close companion which could trigger the flares when it passes at the periastron. A suggestion in this sense has been provided to account for the rapid variations of UZ Tau E (Jensen et al. 2007), and an increasing number of observational studies are currently oriented in this direction. However, extending the close companion interpretation to the whole class has not been able to explain the complex phenomenology (e.g., the timescale variability) observed in EXors. The present paper focuses on the correlations between continuum and line variability, be they intrinsic to the source or triggered by the external environment. Continuum and line observations at different frequencies trace phenomena that occur in completely different regions of these complex systems (from the outer disk to the stellar surface and even in the external envelope and in the chromosphere). Although the flaring-up events represent a very important phase of the PMS life, the continuum and spectral line variability are rarely correlated and very few spectroscopic studies exist to date that compare outburst versus quiescence observational properties. Herbig (2007) provides an optical monitoring of EX Lup (the prototype of the EXor class) which covers a long period during which four subsequent flares occurred. The spectroscopic consequences of the outburst are the appearance of both a hot continuum and an emission line structure where inverse P Cyg absorption features are superposed. Five EXor candidates (NY Ori, V1118 Ori, V1134 Ori, V1184 Tau, and V350 Cep) have been compared both photometrically and spectroscopically with EX Lup, looking for common features (Herbig 2008). Spectroscopic monitoring studies in the visual band have been presented for other EXors, namely DR Tau (Beristain et al. 1998), VY Tau (Herbig 1990), PV Cep (Cohen et al. 1981). Typically, when the star is...
inactive the spectrum shows absorption features of a M0 star, while a remarkable emission spectrum appears during the active phases. Similar studies in the IR band are still lacking, although they should be crucial during both inactive and active phases: in the former stages they allow us to investigate how the properties of the circumstellar matter prior to the outburst will influence, through the accretion, the outburst itself; in the latter stages the IR spectroscopy is a suitable tool to sample how the circumstellar material is altered by intermittent mass loss. In this wavelength range, the only monitored variation is a decrease of the line emission intensity by more than a factor of six detected in the near-IR spectrum of the EXor V1118 Ori, passing from active to inactive status (Lorenzetti et al. 2007, hereinafter Paper II).

Quite recently different outbursting and fading phases of another young object, i.e., V1647 Ori, have been spectroscopically monitored in the IR (Gibb et al. 2006; Acosta-Pulido et al. 2007) demonstrating how the post-outburst phase is characterized by a declining temperature of the hot CO gas formed in the inner part of the disk, and by a substantial decrease of the fast wind. In particular, after one year of quiescence, $H$ and $He$ recombination are decreased by one order of magnitude and CO lines appear in absorption instead of in emission (Aspin et al. 2008). These latter authors argue in favor of the membership of this embedded object to the EXor class (instead to the FUor one), because the former stages they allow us to investigate how the properties of the circumstellar matter prior to the outburst will influence, through the accretion, the outburst itself; in the latter stages the IR spectroscopy is a suitable tool to sample how the circumstellar material is altered by intermittent mass loss. In this wavelength range, the only monitored variation is a decrease of the line emission intensity by more than a factor of six detected in the near-IR spectrum of the EXor V1118 Ori, passing from active to inactive status (Lorenzetti et al. 2007, hereinafter Paper II).

Long-slit spectroscopy was carried out in the standard ABB’A’ mode with a total integration time ranging between 800 and 1200 s. In Table 2 the log of our observations is given. The spectral images were flat-fielded, sky-subtracted, and corrected for the optical distortion in both the spatial and spectral directions. The object spectra were corrected for the atmospheric spectral response dividing them by the spectrum of a telluric O-type star, having normalized this later for the blackbody spectrum at the stellar temperature and replaced its intrinsic hydrogen absorption lines with the blackbody function at the same wavelengths. Wavelength calibration was derived from the OH lines present in the raw spectral images, while flux calibration was obtained from our photometric data taken to implement our database on IR observations of EXors.

Photometry, carried out on the same night as the spectroscopy, is given in Table 2 in the form of $J$, $H$, and $K$ magnitudes, provides an indication of the current brightness status of the source compared with the historical behavior derived from the literature (see Paper II). Table 2 is complemented with information about the spectroscopic observations in the near-IR (1–2.5 $\mu$m) available in the literature.  

3. RESULTS

The results given here represent the first survey of EXor spectra carried out in a systematic way, namely by observing a complete sample with the same equipment and by adopting the same observational modalities and reduction techniques. For two objects (NY Ori and V1143 Ori) these represent the first near-IR spectra ever obtained. In the following, the EXor source V1118 Ori will be incorporated in the discussion, although its spectroscopic data have been already presented elsewhere (Papers I and II). The calibrated spectra are given in Figures from 1 to 7 and the derived unreddened line fluxes in Tables from 3 to 9. The lines showing an S/N between 2 and 3 are still listed in the Tables and marked with an asterisk, but they are not considered in the following analysis. In these Tables, for any line flux the equivalent width (EW) is given as well. The EW does not represent a straightforward spectral diagnostic, since it crucially depends on the continuum level; however, since their values vary significantly, EWs are signaling that spectroscopical variations do not merely follow the continuum ones.

At our sensitivity and at the epoch of our survey, some objects appear as emission lines rich (UZ Tau, DR Tau, V1118 Ori, and PV Cep), other (XZ Tau, VY Tau, NY Ori, and V1143 Ori) present just few features, usually in emission: these are plausibly the brightest lines of a spectrum weaker, but intrinsically composed by the same features present in the line rich objects. These latter spectra are dominated by hydrogen recombination (Brackett and Paschen series) which signals the presence of ionized gas close to the star. In all the spectra Pa$\beta$ is detected as a broad feature at the corresponding wavelength: at $R \sim 250$, this typical feature may be due to the closeness of Pa$\beta$ and He I at 1.285 $\mu$m, however, because of its relative faintness, the latter cannot be confidently resolved.
The CO overtone features $v = 2-0, v = 3-1$ (both in emission and absorption) are clearly detected in the majority of cases (7 out of 8); the same occurs in several young stellar objects (Carr 1989), at variance with the majority of the FUor where CO bands are revealed always in absorption (Hartmann et al. 2004). The CO features are highly variable on relatively short (some months) timescales. Besides CO flux variations, during our monitoring period the CO bands have been observed even to change from emission to absorption (DR Tau, V1118 Ori, and NY Ori). Such behavior is quite typical of low-luminosity young stellar objects, as monitored by Biscaya et al. (1997).

Atomic features of both Na I at 2.208 $\mu$m and, more rarely, Ca I at 2.267 $\mu$m, are also detected: in emission in those
cases of CO emission, and in absorption when also CO occurs in absorption. This circumstance suggests the presence of a common origin for Na, Ca, and CO transitions; this topic will be discussed in Section 4.5. We note that a Na I line has been also detected, in absorption (Herbig et al. 2001), in the near-IR spectrum of EX Lup, the prototype of the EXor class.
Figure 3. Near-IR spectrum of VY Tau. Detected lines are identified and listed in Table 5.

(A color version of this figure is available in the online journal.)

Figure 4. Near-IR spectrum of DR Tau. Detected lines are identified and listed in Table 6.

(A color version of this figure is available in the online journal.)

Hydrogen and ionized iron emission are absent at our sensitivity level in all the spectra indicating that shocks are not a major excitation mechanism in EXor environments. Indeed, weak-shock-excited features below our sensitivity threshold have been detected in a few cases (see Table 2): in particular we mention here the blueshifted [Fe II] emission lines (at 1.53 and...
1.64 μm) likely associated with the spatially resolved jet of PV Cep (Hartmann et al. 1994).

By looking at the near-IR continuum shape of our sources, a broad water absorption feature near 1.9 μm seems recognizable in some objects (mainly XZ Tau, UZ Tau, and VY Tau). Some evidence appears also in favor of a similar water feature near 1.4 μm, which usually goes with the 1.9 μm one in very late low-mass stars and brown dwarfs (Lançon & Rocca-Volmerange...
These three sources indeed present the latest spectral types among the EXor sample and display also other (Na i, Ca i) photospheric absorptions (see Sections 4.3 and 4.4), suggesting a similar origin for the water bands, as well.

As a general trend, the observed spectra of the EXor are much more similar to those of accreting T Tauri stars (Greene & Lada 1996) than the FUor ones. All these latter have spectra always dominated by absorption lines (Reipurth & Aspin 1997), apart from a couple of exceptions.

Spectroscopic variability is more or less evident in all the monitored sources and is often accompanied by significant variations of the line EWs (see Tables from 3 to 9); this means that spectroscopical variations are not a mere consequences of the continuum ones, but they are related to the source brightness through a less trivial link.

4. DISCUSSION

Before analyzing in the next sections the results of our near-IR spectral survey, we briefly comment on the variability presented by the EXor near-IR spectra collected so far in the literature.

The last 30 years of near-IR spectroscopic results of EXor are summarized below in Table 10 along with the data of the present survey (given in boldface). Literature data are available only for the indicated transitions and are given in the form of calibrated flux densities or EW, accordingly to the original papers. This twofold way of presenting the data forces us to examine line flux and EW variability of a given source as two separate sets. A first glance at Table 10 indicates that only 14 spectra in total were known prior to our survey, hence it is clearly evident that studying IR line variability of EXors has not represented so far a major interest, despite the significant spectral changes detected at optical wavelengths that, however, sample inner and warmer regions. The previous few and sparse observations indicate that some IR line variation (by about a factor of 2) was recognizable but on very uncertain timescales. Taking into account also our data, we can estimate an IR line variability from a factor of 2 up to an order of magnitude and typical timescales from months to years, respectively.

4.1. Spectroscopic Versus Photometric Variability

The initial results of our ongoing survey are plotted in Figures 8 and 9, where the fluxes of few prominent lines observed in different dates are depicted as a function of the source brightness in the corresponding band ($J$ for Paβ and Paγ and $K$ for Brγ and CO (2–0)). We remind that spectroscopy and photometry are contemporary. Together with the new results, we include for completeness also our data of V1118 Ori as anticipated above. By examining both Figures, we see that the H recombination line plots show a similar behavior, while the CO 2–0 correlation with the $K$ mag appears quite different since this feature is detected both in emission (solid symbols) and in absorption (open symbols) for different continuum levels. The recombination lines exhibit an overall trend, according to which the brightest line fluxes are associated with brightest sources. Moreover, some sources (VY Tau, DR Tau, NY Ori, and PV Cep) present line fluxes which tend to increase as the continuum increases. This consideration seems not to be applicable to all the individual sources; indeed, XZ Tau and UZ Tau show constant line fluxes while the source brightens, although by a small amount (less than 0.5 mag). Two interesting cases are represented by V1118 Ori and PV Cep. Both sources exhibit a large continuum variation ($ΔJ ≳ 1.2$ mag, $ΔK ≳ 1.0$ mag the former, and $ΔJ ≳ 2.2$ mag, $ΔK ≳ 1.2$ mag the latter) associated with a significant (more than a factor of 6 and 2, respectively) flux variation of the recombination lines. Noticeably, V1118 Ori is the only source deliberately monitored.
### Table 3
Line Emission Fluxes of XZ Tau

| \(\lambda_{\text{vac}}\) (\(\mu\)m) | Ident. | \(F \pm \Delta F\) | \(EW\) | \(F \pm \Delta F\) | \(EW\) | \(F \pm \Delta F\) | \(EW\) |
|---|---|---|---|---|---|---|---|
| 0.923 | Pa9 | <11 | ... | <6 | ... | ... | ... |
| 0.955 | Pa8 | ... | ... | 3.5 \pm 1 | −5 | 2.1 \pm 0.4 | −3 |
| 1.005 | Pa8 | 4 \pm 1 | −7 | 5 \pm 1 | −7 | 1.8 \pm 0.4 | −2 |
| 1.094 | Paγ | 4 \pm 2* | −8 | 3.5 \pm 1 | −4 | 8 \pm 4* | −8 |
| 1.117 | ? | ... | ... | 4 \pm 1 | −5 | ... | ... |
| 1.288 | Paβ | 6 \pm 1 | −10 | 6 \pm 2 | −7 | 6 \pm 1 | −7 |
| 1.328 | ? | 3.2 \pm 0.6 | −5 | 3.4 \pm 0.6 | −4 | 1.8 \pm 0.6 | −2 |
| 2.166 | Brγ | 2.4 \pm 0.2 | −4 | 2.5 \pm 0.2 | −4 | 1.6 \pm 0.4 | −2 |
| 2.208 | Naτ | −2.5 \pm 0.6 | +4 | −2.5 \pm 0.6 | +4 | −2.4 \pm 0.6 | +4 |
| 2.267 | Caτ | −2.6 \pm 0.6 | +5 | −1.2 \pm 0.6* | +2 | <1.8 | ... |
| 2.293 | CO 2–0 | −2.5 \pm 0.6 | +5 | −2.7 \pm 0.6 | +5 | −5.3 \pm 0.4 | +8 |
| 2.323 | CO 3–1 | ... | ... | ... | ... | −4.4 \pm 0.4 | +7 |

**Notes.**
- Fluxes marked with an asterisk are those derived at a 2 < S/N < 3 level; they will not be used in the following analysis.
- Fluxes and errors are given in units of 10^{-15} erg s^{-1} cm^{-2}, while EW are expressed in (Å).
- The values of \(\lambda_{\text{vac}}\) are not given since their difference \(\lambda_{\text{vac}}\) is always less than the spectral resolution element.

### Table 4
Line Emission Fluxes of UZ Tau E

| \(\lambda_{\text{vac}}\) (\(\mu\)m) | Ident. | \(F \pm \Delta F\) | \(EW\) | \(F \pm \Delta F\) | \(EW\) | \(F \pm \Delta F\) | \(EW\) |
|---|---|---|---|---|---|---|---|
| 0.855 | Pa15 | 9 \pm 3 | −19 | ... | ... | ... | ... |
| 0.867 | Pa13 | 6 \pm 2 | −12 | ... | ... | ... | ... |
| 0.902 | Pa10 | 3 \pm 1 | −7 | ... | ... | ... | ... |
| 0.923 | Pa9 | 6 \pm 1 | −16 | ... | ... | ... | ... |
| 0.955 | Pa8 | 6 \pm 1 | −10 | 6 \pm 1 | −5 | 15 \pm 1 | −10 |
| 1.005 | Pa8 | 5 \pm 1 | −7 | 6 \pm 1 | −5 | ... | ... |
| 1.094 | Paγ | 9 \pm 1 | −11 | 9 \pm 1 | −7 | 6 \pm 1 | −4 |
| 1.169 | ? | 4 \pm 1 | −4 | 5 \pm 1 | −5 | ... | ... |
| 1.282 | Paβ | 11.4 \pm 0.8 | −13 | 10.4 \pm 0.8 | −10 | 10 \pm 1 | −8 |
| 1.328 | ? | 5 \pm 1 | −3 | 3 \pm 1 | −3 | 3 \pm 1 | −3 |
| 1.491 | Br27 | 4 \pm 2* | −5 | ... | ... | ... | ... |
| 1.588 | Br14 | 4 \pm 2* | −4 | ... | ... | ... | ... |
| 1.611 | Br13 | 4 \pm 2* | −5 | ... | ... | ... | ... |
| 1.641 | Br12 | 4 \pm 2* | −5 | 4 \pm 2* | −5 | ... | ... |
| 1.681 | Br11 | 4 \pm 2* | −4 | ... | ... | ... | ... |
| 1.694 | ? | 4 \pm 2* | −4 | ... | ... | ... | ... |
| 1.737 | Br10 | 6 \pm 3* | −7 | ... | ... | ... | ... |
| 2.166 | Brγ | 3.3 \pm 0.8 | −6 | 5.2 \pm 0.8 | −9 | 4 \pm 1 | −6 |
| 2.208 | Naτ | −1.8 \pm 0.8* | +3 | −2.4 \pm 0.8 | +4 | −3.7 \pm 0.8 | +6 |
| 2.267 | Caτ | −2.4 \pm 0.8 | +3 | −2.6 \pm 0.8 | +5 | <2.4 | ... |
| 2.293 | CO 2–0 | −4.2 \pm 0.8 | +6 | −3.7 \pm 0.8 | +7 | −1.5 \pm 0.7* | +2 |
| 2.323 | CO 3–1 | −4.1 \pm 0.8 | +6 | ... | ... | ... | ... |

**Note.** The same as in Table 3.

### Table 5
Line Emission Fluxes of VY Tau

| \(\lambda_{\text{vac}}\) (\(\mu\)m) | Ident. | \(F \pm \Delta F\) | \(EW\) | \(F \pm \Delta F\) | \(EW\) | \(F \pm \Delta F\) | \(EW\) |
|---|---|---|---|---|---|---|---|
| 1.094 | Paγ | <1.8 | ... | 3 \pm 1 | −11 | 3.1 \pm 0.9 | −9 |
| 1.282 | Paβ | 1.9 \pm 0.4 | −6 | 1.7 \pm 0.4 | −6 | 1.9 \pm 0.4 | −6 |
| 1.327 | ? | 1.1 \pm 0.5* | −4 | <1.2 | ... | 1.5 \pm 0.4 | −6 |
| 2.166 | Brγ | 0.5 \pm 0.2* | −7 | <0.9 | ... | 0.7 \pm 0.2 | −6 |
| 2.208 | Naτ | −1.2 \pm 0.5* | +10 | <1.8 | ... | −0.4 \pm 0.2* | +2.5 |
| 2.267 | Caτ | <1.5 | ... | ... | ... | −0.5 \pm 0.2* | +4 |
| 2.293 | CO 2–0 | −0.8 \pm 0.5* | +7 | −2.0 \pm 0.5 | +19 | −0.6 \pm 0.3* | +5 |

**Note.** The same as in Table 3. Upper limits are given as 3σ values.
### Table 6
Line Emission Fluxes of DR Tau

| $\lambda_{\text{vac}}$ (\text{$\mu$m}) | Ident. | $F \pm \Delta F$ Mar 07–13 | EW | $F \pm \Delta F$ Oct 07–08 | EW | $F \pm \Delta F$ Nov 07–03 | EW | $F \pm \Delta F$ Mar 08–28 | EW |
|---|---|---|---|---|---|---|---|---|---|
| 0.847 | Pa1? | ... | ... | ... | ... | 13 ± 1 | ... | ... | ... |
| 0.855 | Pa15 | 67 ± 0.8 | −39 | 50 ± 1 | −67 | 36 ± 1 | −75 | 75 ± 1 | −73 |
| 0.867 | Pa13 | 29 ± 0.8 | −16 | 20 ± 1 | −27 | 34 ± 1 | −25 | 26 ± 1 | −26 |
| 0.886 | Pa11 | 15 + 0.8 | −7 | 5 ± 1 | −7 | 11 ± 1 | −9 | 16 ± 1 | −16 |
| 0.902 | Pa10 | 15 ± 0.8 | −8 | 4 ± 2* | −5 | 15 ± 2 | −13 | 15 ± 1 | −16 |
| 0.923 | Pa9 | 22 ± 0.8 | −11 | 9 ± 1 | −12 | 20 ± 1 | −16 | 16 ± 1 | −17 |
| 0.955 | Pa8 | 21 ± 0.8 | −14 | 9 ± 1 | −11 | 21 ± 1 | −17 | 11.0 ± 0.5 | −12 |
| 1.005 | Pa6 | 21 ± 0.8 | −13 | 12 ± 1 | −15 | 22 ± 1 | −18 | 13.4 ± 0.5 | −13 |
| 1.070 | ? | 4.4 ± 0.8 | −4 | 3 ± 1 | −4 | 7 ± 1 | −6 | 3.7 ± 0.5 | −4 |
| 1.094 | Pay | 26 ± 0.8 | −17 | 18 ± 2 | −22 | 25 ± 2 | −21 | 20.0 ± 0.5 | −20 |
| 1.117 | Ct? | 5 ± 1 | −4 | 5 ± 1 | −6 | ... | ... | 2 ± 1* | −2 |
| 1.183 | Mg I | 2 ± 1* | −1 | 2 ± 1* | −2 | 2 ± 1* | −2 | 2 ± 1* | −2 |
| 1.282 | Paβ | 37 ± 0.8 | −24 | 24 ± 2 | −26 | 32 ± 2 | −29 | 30.0 ± 0.5 | −31 |
| 1.328 | ? | 2.4 ± 0.4 | −2 | ... | ... | ... | ... | 3 ± 1 | −4 |
| 1.491 | Br27 | 2.7 ± 0.9 | −4 | ... | ... | ... | ... | ... | ... |
| 1.494 | Br26 | 2.1 ± 0.2 | −4 | ... | ... | ... | ... | 2.2 ± 0.5 | −2 |
| 1.556 | Br16 | ... | ... | ... | ... | ... | ... | 2.2 ± 0.5 | −2 |
| 1.570 | Br15 | ... | ... | ... | ... | ... | ... | 5.9 ± 0.5 | −4 |
| 1.588 | Br14 | 5.5 ± 0.6 | −6 | 3.1 ± 0.6 | −3 | 7.7 ± 0.6 | −6 | 5.9 ± 0.5 | −5 |
| 1.611 | Br13 | 6.9 ± 0.6 | −7 | 3.9 ± 0.6 | −4 | 4.7 ± 0.6 | −4 | 3.4 ± 0.5 | −3 |
| 1.641 | Br12 | 6.8 ± 0.6 | −7 | 2.7 ± 0.6 | −3 | 7.3 ± 0.6 | −6 | 3.5 ± 0.5 | −3 |
| 1.681 | Br11 | 4.8 ± 0.6 | −2 | 4.0 ± 0.6 | −2 | 7.2 ± 0.6 | −6 | 8.5 ± 0.5 | −7 |
| 1.737 | Br10 | 6.6 ± 0.6 | −7 | 4.5 ± 0.6 | −3 | 8.2 ± 0.6 | −7 | 8.1 ± 0.5 | −7 |
| 1.745 | He I? | 7.1 ± 0.6 | −7 | 2.2 ± 0.6 | −2 | 3.4 ± 0.6 | −3 | ... | ... |
| 1.945 | Br6 | 15 ± 5 | −13 | 16 ± 5 | −16 | 9.8 ± 0.5 | −10 | 14.0 ± 0.5 | −19 |
| 2.059 | He I? | 2.9 ± 0.6 | −3 | 2.4 ± 0.6 | −2 | 2.1 ± 0.6 | −2 | ... | ... |
| 2.166 | Brγ | 10 ± 1 | −8 | 6.2 ± 0.6 | −6 | 7.5 ± 0.6 | −7 | 7 ± 1 | −6 |
| 2.208 | Na I | −3.1 ± 0.4 | +3 | −2.4 ± 0.4 | +3 | −3.1 ± 0.4 | +3 | −5.7 ± 0.4 | +5 |
| 2.267 | Ca I | −2.5 ± 0.4 | +2 | −1.0 ± 0.4* | +1 | ... | ... | ... | ... |
| 2.293 | CO 2–0 | 3 ± 1 | −3 | 2.0 ± 0.6 | −2 | −7.1 ± 0.6 | +7 | −9.4 ± 0.6 | +9 |
| 2.323 | CO 3–1 | ... | ... | 2.4 ± 0.6 | −3 | −7.2 ± 0.6 | +7 | −7.8 ± 0.6 | +7 |

**Note.** The same as in Table 3.

### Table 7
Line Emission Fluxes of NY Ori

| $\lambda_{\text{vac}}$ (\text{$\mu$m}) | Ident. | $F \pm \Delta F$ Mar 07–15 | EW | $F \pm \Delta F$ Oct 07–14 | EW | $F \pm \Delta F$ Oct 07–15 | EW | $F \pm \Delta F$ Oct 07–24 | EW | $F \pm \Delta F$ Mar 08–29 | EW |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.005 | Paδ | 2.5 ± 0.5 | −3 | 4.0 ± 0.5 | −13 | 2.5 ± 0.5 | −8 | 2.2 ± 0.5 | −7 | 3.3 ± 0.5 | −10 |
| 1.094 | Pay | 2.5 ± 0.5 | −3 | 4.0 ± 0.5 | −13 | 2.5 ± 0.5 | −8 | 2.2 ± 0.5 | −7 | 3.3 ± 0.5 | −10 |
| 1.282 | Paβ | 3.2 ± 0.5 | −11 | 4.0 ± 0.5 | −13 | 2.5 ± 0.5 | −8 | 2.2 ± 0.5 | −7 | 3.3 ± 0.5 | −10 |
| 1.666 | Brγ | 1.5 ± 0.4 | −7 | 1.1 ± 0.4* | −5 | 0.8 ± 0.4* | −3 | 1.3 ± 0.4 | −6 | < 0.6 | ... |
| 2.208 | Na I | < 0.6 | ... | ... | ... | ... | ... | ... | ... | < 0.6 | ... |
| 2.293 | CO 2–0 | 0.6 ± 0.2 | −3 | 1.3 ± 0.5 | +6 | −0.8 ± 0.4* | +3 | < 1.2 | ... | −1.9 ± 0.3 | +8 |
| 2.323 | CO 3–1 | 0.9 ± 0.2 | −5 | ... | ... | ... | ... | ... | −1.8 ± 0.3 | +7 |

**Note.** The same as in Table 3. Upper limits are given as 3σ values.

### Table 8
Line Emission Fluxes of V1143 Ori

| $\lambda_{\text{vac}}$ (\text{$\mu$m}) | Ident. | $F \pm \Delta F$ Mar 07–17 | EW | $F \pm \Delta F$ Oct 07–15 | EW |
|---|---|---|---|---|---|
| 1.094 | Pay | < 0.3 | ... | 0.4 ± 0.2* | −13 |
| 1.282 | Paβ | < 0.3 | ... | < 0.3 | ... |
| 2.166 | Brγ | < 0.2 | ... | < 0.8 | ... |
| 2.208 | Na I | < 0.2 | ... | < 1.5 ± 0.3 | +1 |
| 2.293 | CO 2–0 | < 0.3 ± 0.1 | +33 | < 0.4 | ... |
| 2.323 | CO 3–1 | −0.3 ± 0.1 | +29 | ... | ... |

**Note.** The same as in Table 3. Upper limits are given as 3σ values.
for a longer time during a post-outburst phase, while monitoring the fading phase of PV Cep has been fortuitous, since this source belongs to the targets of our unbiased monitoring accomplished so far on a period of only one year, in principle too short to document significant variations. The sources for which the largest continuum variations (more than one mag) have been sampled, are those presenting a definite line flux increase as the continuum increases; conversely, objects showing smaller continuum fluctuations (less than half mag), show more erratic line variations and cannot be directly correlated to continuum variations, but are more likely related to local instabilities. Our preliminary conclusions need to be confirmed by continuing our IR monitoring in order to adequately sample larger variations (both in continua and lines) whose existence, according to literature data (Paper II), is well documented. The following preliminary analysis will be essentially based on a restricted sub-sample of sources that present at the moment a significant number of H1 recombination lines, namely those for which a reasonable fitting can be applied (see next Section 4.2.1). This small sample is constituted by the spectra taken in different epochs of UZ Tau, DR Tau, V1118 Ori, and PV Cep.

Whatever is (are) the mechanism(s) responsible for line emission, it is worthwhile to investigate whether extinction has a role in determining the photometric and spectroscopic variability of EXors. For that purpose, the JHK photometry contemporary to the spectra (see Table 2) is provided in the form of a two-color diagram. The color variations of the four sources of our subsample are depicted in Figure 10 and marked with progressive numbers pertaining to different epochs. For comparison purposes, in the same plot all the results of our photometric monitoring are displayed: the solid (open) symbols indicate that a contemporary near-IR spectrum exists (is absent). Figure 10 gives also the extinction vector (Rieke & Lebofsky 1985) starting from both the unreddened main sequence (solid line) and the locus of T Tauri stars (dashed line—Meyer et al. 1997).

The objects that during our monitoring period have shown the smallest fluctuations (i.e., UZ Tau E and DR Tau) are, as expected, associated with negligible color variations, apparently not related to any extinction variation. Of the two sources showing the largest photometric variations (V1118 Ori and PV Cep), the former presents some indications in favor of an extinction dependence, but we think this occurrence may be fortuitous since our prior photometric monitoring evidenced an erratic change of position on the same two-color plot (Figure 2 of Paper I). Moreover, if the extinction variation of V1118 Ori between the two epochs (i.e., $\Delta V \approx 2.5$) were genuine, it should not be enough to account for the observed $Br_γ$ fading by more than a factor of six. The colors of the remaining EXor monitored so far do not show any extinction dependence either.
Table 10
EXor Line Flux Variability in the Near-IR

| Source      | Date          | Pay  | Paβ  | Bry  | CO (2–0) | Statusa | Ref |
|-------------|---------------|------|------|------|----------|---------|-----|
| XZ Tau      | 1983 Nov      | ...  | ...  | 2.1±0.5 | ...       | H?      | 2   |
|             | 1986 May–1987 Jan | ...  | ...  | 0.42±0.07 | ...       | H?      | 3   |
|             | 1988 Nov–1989 Jan | ...  | 2.4±0.4 | 0.9±0.1 | ...       |         | 4   |
|             | 07 Mar        | <0.6 | 6±1  | 2.4±0.2 | −2.5±0.6 | 1      |     |
|             | 07 Oct        | 3.5±1 | 6±2  | 2.5±0.2 | −2.7±0.6 | 1      |     |
|             | 08 Mar        | <1.2 | 6±1  | 1.6±0.4 | −5.3±0.4 | 1      |     |
| UZ Tau E    | 07 Mar        | 9±1  | 10.9±0.8 | 4.5±0.8 | −4.2±0.8 | 1      |     |
|             | 07 Oct        | 9±1  | 10.4±0.8 | 5.2±0.8 | −3.7±0.8 | 1      |     |
|             | 08 Mar        | 6±1  | 10±1 | 4±1   | <2.0     | 1      |     |
| VY Tau      | 07 Mar        | <1.8 | 1.9±0.4 | <0.6   | <1.0     | 1      |     |
|             | 07 Oct        | 3±1  | 1.7±0.4 | <0.9   | −2.0±0.5 | 1      |     |
|             | 08 Mar        | 3.1±0.9 | 1.9±0.4 | 0.7±0.2 | <0.9     | 1      |     |
| DR Tau      | 88 Nov - 89 Jan | ...  | 12±1.2 | 3.2±0.5 | ...       | I?      | 4   |
|             | 07 Mar        | 26±0.8 | 37±0.8 | 10±1  | 3±1     | 1      |     |
|             | 07 Oct        | 18±2 | 24±2 | 6.2±0.6 | 2.0±0.6 | 1      |     |
|             | 07 Nov        | 25±2 | 32±2 | 7.5±0.6 | −7.1±0.6 | 1      |     |
|             | 08 Mar        | 20.0±0.5 | 30.0±0.5 | 7±1   | −9.4±0.6 | 1      |     |
| V1118 Ori   | 05 Sep        | 2.5±0.2 | 4.1±0.1 | 1.2±0.2 | 1.2±0.4 | H      | 5   |
|             | 06 Sep        | <0.4 | <0.6 | <0.2   | ...      | 6      |     |
| NY Ori      | 07 Mar        | 2.5±0.5 | 3.2±0.5 | 1.5±0.4 | 0.6±0.2 | 1      |     |
|             | 07 Oct        | 3±0.5 | 4.0±0.5 | <1.2   | <1.5     | 1      |     |
|             | 07 Oct        | 1.5±0.5 | 2.5±0.5 | <1.2   | <1.2     | 1      |     |
|             | 07 Oct        | <1.5 | 2.2±0.5 | 1.3±0.4 | <1.2     | 1      |     |
|             | 08 Mar        | 1.7±0.5 | 3.3±0.5 | <0.6   | −1.9±0.3 | 1      |     |
| V1143 Ori   | 07 Mar        | <0.3 | <0.3 | <0.2   | −0.3±0.1 | 1      |     |
|             | 07 Oct        | <0.6 | <0.3 | <0.8   | <0.4     | 1      |     |
| PV Cep      | 86 Jul        | ...  | ...  | 0.44±0.05 | ...       | ...     | 3   |
|             | 86 Oct        | ...  | ...  | 0.80±0.12 | ...       | ...     | 3   |
|             | 07 Mar        | 1.2±0.2 | 3.8±0.2 | 8.5±0.4 | 9.7±0.7 | 1      |     |
|             | 07 Oct        | 0.9±0.2 | 3.7±0.2 | 7.8±0.4 | 11.4±0.7 | 1      |     |
|             | 07 Oct        | 1.0±0.2 | 3.5±0.2 | 7.3±0.4 | 8.8±0.7 | 1      |     |
|             | 08 Apr        | 3.2±0.2 | 5.3±0.2 | 8.3±0.4 | 18±0.7  | 1      |     |
|             | 08 Apr        | 2.6±0.2 | 6.1±0.2 | 9.6±0.4 | 11.6±0.7 | 1      |     |
| Equivalent Width (in Å) |
| XZ Tau      | 02 Nov        | −1.0 | ...  | ...    | ...      | 7      |     |
|             | 07 Mar        | ...  | −10  | −4     | +5       | 1      |     |
|             | 07 Oct        | −4   | −7   | −4     | +5       | 1      |     |
|             | 08 Mar        | −7   | −2   | +8     | ...      | 1      |     |
| UZ Tau E    | 02 Nov        | −4.0 | ...  | ...    | ...      | H?      | 7   |
|             | 07 Mar        | −11  | −13  | −6     | +6       | 1      |     |
|             | 07 Oct        | −7   | −10  | −9     | +7       | 1      |     |
|             | 08 Mar        | −4   | −8   | −6     | ...      | 1      |     |
| VY Tau      | 07 Mar        | ...  | −6   | ...    | ...      | 1      |     |
|             | 07 Oct        | −11  | −6   | ...    | +19      | 1      |     |
|             | 08 Mar        | −9   | −6   | −6     | ...      | 1      |     |
| DR Tau      | 98 Jan        | ...  | −21.22 | −7.3  | ...      | I      | 8   |
|             | 02 Nov        | −12.3/13.7 | ...  | ...    | ...      | 7      |     |
|             | 07 Mar        | −17  | −24  | −8     | −3       | 1      |     |
|             | 07 Oct        | −22  | −26  | −6     | −2       | 1      |     |
|             | 07 Nov        | −21  | −29  | −7     | +7       | 1      |     |
|             | 08 Mar        | −20  | −31  | −6     | +9       | 1      |     |
| V1118 Ori   | 05 Sep        | −20  | −40  | −30    | −30      | 5      |     |
|             | 06 Sep        | ...  | ...  | ...    | ...      | 6      |     |
| NY Ori      | 07 Mar        | −8   | −11  | −7     | −3       | 1      |     |
|             | 07 Oct        | −9   | −13  | −5     | ...      | 1      |     |
|             | 07 Oct        | −5   | −8   | −3     | ...      | 1      |     |
|             | 07 Oct        | −7   | −6   | ...    | ...      | 1      |     |
|             | 08 Mar        | −5   | −10  | ...    | +8       | 1      |     |
| V1143 Ori   | 07 Mar        | ...  | ...  | ...    | +33      | 1      |     |
|             | 07 Oct        | ...  | ...  | ...    | ...      | 1      |     |
| PV Cep      | 86           | ...  | ...  | <−3.1  | ...      | 3      |     |
|             | 94 Jun        | ...  | ...  | −4.4   | 9        | 10     |     |
|             | 95 Jan        | −18.2| −2.4 | ...    | ...      | 10     |     |
|             | 07 Mar        | −25  | −48  | −17    | −20      | 1      |     |
|             | 07 Oct        | −18  | −40  | −11    | −13      | 1      |     |
Table 10  
(Continued)

| Source | Date  | Paγ | Paβ | Brγ | CO (2–0) | Status | Ref  |
|--------|-------|-----|-----|-----|----------|--------|------|
| 07 Oct | −17   | −28 | −11 | −10 | 1        | 1      |
| 08 Apr | −17   | −16 | −7  | −13 | 1        | 1      |
| 08 Apr | −16   | −20 | −8  | −9  | 1        | 1      |

Notes. References to the Table: (1) Present paper; (2) Evans et al. 1987; (3) Carr 1990; (4) Giovanardi et al. 1991; (5) Paper I; (6) Paper II; (7) Edwards et al. 2006; (8) Muzerolle et al. 1998; (9) Biscaya et al. 1997; (10) Greene & Lada 1996.

* H = high, I = intermediate, L = low, r = rising, d = declining.

Figure 8. Observed Paγ and Paβ fluxes as a function of brightness in the J band. Data points of the source V1118 Ori are connected with a straight line. (A color version of this figure is available in the online journal.)

Figure 9. Observed Brγ and CO 2–0 fluxes as a function of brightness in the K band. Open symbols indicate that CO line is in absorption. Data points of the source V1118 Ori are connected with a straight line. (A color version of this figure is available in the online journal.)

Figure 10. Near-IR two color diagram of a selected subsample of EXors (see the text) in different epochs. The solid line marks the unreddened main sequence, whereas the dashed one is the locus of the T Tauri stars (Meyer et al. 1997). Dotted lines represent the reddening law (Rieke & Lebofsky 1985) where different intervals of AV (in mag) are indicated by open squares. (A color version of this figure is available in the online journal.)

The sole source for which a variable extinction seems to be the most plausible reason for its photometric and spectroscopic fluctuations is PV Cep. By comparing the photometric data (Table 2) and its consequent location in Figure 10 along the extinction vector, one can see that all the bright phases correspond to diminishing AV values, while fading is always associated with an AV increasing. More quantitatively, AV varied between 9.0 and 14.5 mag during our monitoring period (see also Table 11). We have corrected the observed line fluxes (just Paβ and Brγ for having a check) by using the adequate AV as derived from the photometry of that epoch (Figure 10); by doing so, the intrinsic Paβ and Brγ fluxes relative to different dates become substantially equal (within a factor less than 1.5) and the intrinsic line ratios Paβ/Brγ all remain in the range 2.5–3.5 (Table 11). This result gives strong support to the hypothesis that line flux variation in PV Cep is due to a variable extinction more than to modification in the accretion (or mass loss) rate.

Such AV variation can be translated into the volume density needed to pass from AV = 9.0 to AV = 14.5 through the relationship giving the column density, N(H2) = AV/1021/R cm−2, where R represents the size of the obscuring matter. Even assuming a size equal to five stellar radii of a M0 star, we would obtain a volume density n ≈ 4 × 109 cm−3, a value surprisingly high if it were uniformly distributed on such a large volume. Instead, a similar amount of dust can be
supposed to be organized in much smaller structures, such as disk inhomogeneities, that repeatedly cross the line of sight. Indeed, the time elapsed from maximum to minimum light (80 days) is large enough to cover many tens of stellar radii by traveling at the Earth velocity.

The fact that PV Cep is a peculiar young object was already stated many years ago (Cohen et al. 1981), through studies of the varying bi-conical nebula associated with the star (GM29—Gyu’budgayan & Magakyan 1977). This object shows simultaneously continuum variations due to extinction and episodic mass ejection phenomena. Indeed, the fan-shaped morphology of the varying nebula and the strongest P-Cygni profiles in the hydrogen lines at the maximum light suggest, respectively, that a circumstellar disk intermittently obscures the star and that the greatest brightness may occur close to the highest mass ejection events. Cohen et al. (1981) presented also optical continuum variations of PV Cep, whose time-scales and amplitudes are well in agreement with our observations. Further support to the disk presence is given by the ice absorption feature around 3 μm that has been interpreted as a common manifestation associated with edge-on morphologies (van Citters & Smith 1989).

The peculiarity of PV Cep (with respect to the other EXors) displayed by our data and confirmed by the literature, suggests some caveat in dealing with it as a confirmed member of the class. Maybe PV Cep could be an EXor in a less evolved stage as other candidates seem to be (see Section 4.5).

4.2. \( \text{H} \alpha \) Recombination

\( \text{H} \alpha \) recombination lines largely dominate our near-IR spectra of EXor, hence we will rely on them to probe the gas emitting region and to discuss the correlation between line emission and continuum variability.

The debate whether near-IR hydrogen lines observed in T Tauri stars originate in the winds or arise in the accretion regions is still open: the former is supported by: (i) the univocal presence of winds; (ii) the presence of P-Cygni profiles; (iii) recent spectro-astrometric studies of T Tauri stars (Whelan et al. 2004); (iv) the same magnetospheric accretion models. Analogously, also the mass accretion scenario (e.g., Hartmann et al. 1994) sits on theoretical (e.g., Shu et al. 1994) and observational (e.g., Kenyon et al. 1994) basis. Winds and accretion flows may concur to originate the hydrogen line emission: both environments are opaque to the Lyman continuum photons, but hydrogen is photoionized, in any case, by the Balmer continuum photons (Natta et al. 1988; Basri & Bertout 1989). Whatever the emission region (infall envelope or wind), it is worthwhile noting that the powering mechanism is likely the same, namely the accretion which onsets the wind.

In the framework of the wind hypothesis, we model the behavior of those sources where a significant number of \( \text{H} \alpha \) recombination lines have been observed with a wind model (Nisini et al. 2004) that considers a spherically symmetric envelope with a constant rate of mass loss \( (M = 4\pi r^2 \rho(r) v(r)) \). The emitting gas is assumed to be in LTE and the adopted gas law is

\[
v(r) = v_i + (v_{\text{max}} - v_i)[1 - (R_e / R^e)],
\]

where \( v_i \) and \( v_{\text{max}} \) are the initial and maximum wind velocities, respectively, while \( R_e \) is the stellar radius. The best fit to the data points is obtained for the set of parameters, namely the envelope size \( R_{\text{out}} \) (expressed in units of stellar radii \( R_\star \)) and the gas temperature \( T \), given in columns 4 and 5 of Table 11, respectively. We have assumed input values equal for all the objects for the remaining parameters, they are: the initial gas velocity \( v_i = 30 \text{ km} \text{ s}^{-1} \); the envelope’s internal radius \( R_i = 1 R_\star \); where \( R_\star \) has the value corresponding to the stellar spectral type; and the exponent \( \alpha = 0.2 \). The adopted \( A_T \) values (column 2 of Table 11) are taken from the literature (Table 1) or from our photometry. For the investigated sources, some model fitting to the data is depicted in Figures 11–13, as an example; observational data are shown as line ratios of the Paschen and Brackett series with respect to the Paβ and Brγ, respectively.

To evaluate the uncertainties on the derived parameters and to check the sensitivity of our model, we computed the range of variation for each input parameter that is allowed to eventually provide line flux predictions comparable (within a 50% extent) to the observed values. Such analysis indicates that gas temperature is one of the less sensitive parameters: variations between 5000 K and 10,000 K do not affect the fit significantly. Conversely, other parameters are quite critical and their variability ranges are consequently rather narrow: about 50% for \( M, R_i = 1–2 R_\star \), 50% for the envelope thickness. Table 11 gives, for each date, the ratio between the observed (corrected for extinction) and predicted (by our model) values of Paβ (column 6) and Brγ (column 7). Paβ/Brγ ratios, both predicted (column 8) and observed (column 9) are listed, as well. Such a comparison (observations versus model) allows us to verify the goodness of the obtained fit. Due to the uncertainties

| Source      | Date       | \( A_T \) (mag) | \( R_{\text{out}} \) (\( R_\star \)) | \( T \) (K) | \( \text{Paβ} \) (mod/obs) | \( \text{Brγ} \) (mod) | \( \text{Paβ}/\text{Brγ} \) (mod) | \( \text{Paβ}/\text{Brγ} \) (obs) | \( M_{\text{out}} \) (10\(^{-7} M_\odot \text{ yr}^{-1}) |
|-------------|------------|----------------|-----------------|---|-----------------|----------------|-----------------|-----------------|-----------------|
| UZ Tau E    | 07 Mar 12  | 1.5            | 3.0             | 6000 | 1.2             | 0.9             | 4.4             | 3.3             | 0.1             |
|             | 07 Oct 11  | 1.5            | 3.0             | 6000 | 1.0             | 0.9             | 4.4             | 2.5             | 0.1             |
| DR Tau      | 07 Mar 13  | 1.9            | 3.0             | 7400 | 1.0             | 1.0             | 3.6             | 3.7             | 0.6             |
|             | 07 Oct 08  | 1.9            | 3.0             | 6400 | 1.0             | 1.3             | 3.8             | 3.9             | 0.3             |
|             | 07 Nov 03  | 1.9            | 3.0             | 6400 | 1.0             | 1.0             | 3.1             | 4.3             | 0.6             |
|             | 08 Mar 28  | 1.9            | 3.0             | 8000 | 1.0             | 1.0             | 4.0             | 4.3             | 0.4             |
| V1118 Ori   | 05 Sep 10  | 0              | 5.0             | 8000 | 1.1             | 1.1             | 3.6             | 3.4             | 0.4             |
| PV Cep      | 07 May 13  | 11             | 5.0             | 6000 | 1.0             | 0.7             | 0.6             | 2.3             | 9.7             |
|             | 07 Oct 15  | 13             | 7.0             | 6000 | 1.0             | 0.6             | 0.7             | 3.3             | 5.1             |
|             | 07 Oct 27  | 11             | 20              | 6000 | 1.0             | 0.4             | 1.3             | 2.5             | 2.0             |
|             | 08 Apr 01  | 9              | 4.5             | 6000 | 1.0             | 0.8             | 0.8             | 2.5             | 21              |
|             | 08 Apr 12  | 9              | 4.5             | 6000 | 1.0             | 0.6             | 0.9             | 2.5             | 6.7             |
|             | 08 Jun 10  | 14.5           | 3.5             | 7000 | 1.0             | 1.0             | 0.4             | 3.5             | 22              |
|             | 08 Jun 18  | 14.5           | 4.0             | 6000 | 1.0             | 0.9             | 0.4             | 3.2             | 8.2             |
of the observations and even more to those of modeling, we
assume that fit to the data can be considered as acceptable
when (i) the ratios $\frac{P_{\alpha \beta}}{P_{\alpha \beta}}$ (mod/obs) and $\frac{B_{\alpha \gamma}}{B_{\alpha \gamma}}$ (mod/obs) range
between 0.7 and 1.5; and (ii) the ratio $\frac{P_{\alpha \beta}}{B_{\alpha \gamma}}$ derived from
the model does not differ from the observed one by more than
50%. Such requirements are well fulfilled in all cases listed in
Table 11. The sole exception is represented by some values of
PV Cep (see the caveat in Section 4.1), which indeed shows
observed ratios $\frac{P_{\alpha \beta}}{B_{\alpha \gamma}}$ lower than those of other sources
and not compatible with any reasonable combination of input
parameters. Finally column 10 of Table 11 lists the mass loss
rate ($\dot{M}_{\text{wind}}$) derived from our model: these values range between
$10^{-8}$ and $10^{-7}$ $M_\odot$ yr$^{-1}$ (apart two determinations for PV Cep),
namely they are consistent with the range of values inferred by
independent determinations on active T Tauri stars (Hartigan
et al. 1995).

$P_{\alpha \beta}$ and $B_{\alpha \gamma}$ line luminosity can be also independently
used to get an estimate of the $\dot{M}_{\text{acc}}$ to be compared with
$M_{\text{wind}}$ derived by our model. In that regard, the empirical
relationships given by Muzerolle et al. (1998) can be used. It
relates the emission line ($P_{\alpha \beta}$ and $B_{\alpha \gamma}$) luminosities with the
accretion luminosity as measured from the continuum excess.
We remark how the empirical nature of such relationships
allows us their applications whatever be the origin of the
recombination lines (accretion or wind). Table 12, for each
date, provides: the positive or negative luminosity variation
(integrated just over the $JHK$ bands—column 3) with respect
to luminosity value obtained in the first epoch; the extinction
correction applied for deriving the intrinsic fluxes (column 4);
the accretion luminosities values derived from equations (1) and (2) of Muzerolle et al. (1998) (columns 5 and 6); from the accretion luminosity an estimate of the mass accretion rate can be derived (column 7) (Gullbring et al. 1998) by assuming the inner radius of the accretion disk $R_i$ ($R_i = 5 R_*$), the stellar mass ($M_*$), and the stellar radius ($R_*$) according to the spectral type indicated for each source in Table 1. The derived mass accretion rates roughly exceed by an order of magnitude the mass loss ones, as predicted by wind models (see Section 1).

Therefore we can conclude that the wind scenario alone is fully consistent with the observational data. However, we are not able to rule out that the same H1 lines can be originated by accretion alone. Indeed, the latter can account for the observed Paβ/Bry ratios (roughly between 3 and 4, see Table 11) only for $M_{\text{acc}} > 10^{-3} M_\odot$ yr$^{-1}$ (Muzerolle et al. 2001— their Figure 15). Unfortunately, accretion models able to quantitatively predict in a consistent way also wind emission do not exist; hence, within this scheme, it is not easy to verify any consistency between $M_{\text{wind}}$ and $M_{\text{acc}}$.

### 4.3. CO Overtone Emission

CO emission is seen together with Bry line emission, but these two features probably come from different volumes of gas. At temperatures of about 4000 K, both CO and molecular hydrogen are dissociated by collisions. However, for density values higher than $10^7$ cm$^{-3}$ and in the presence of H$_2$, CO dominates the cooling (Scoville et al. 1980). Therefore CO bands are specific probes of the circumstellar portions where the gas is relatively warm at high densities. Recently interferometric observations of CO emission in PMS objects have confirmed that CO comes from a small region (< 1 AU), i.e., the inner gaseous disk (Tatulli et al. 2008), much more compact than that typical of the Bry emission, i.e., the stellar wind (Malbet et al. 2007). However, young stars emitting Bry from regions more compact than the dust sublimation radius, have been found as well (Kraus et al. 2008).

A number of models have been proposed for producing CO emission (for a summary see: Biscaya et al. 1997). Carr (1989) investigated an accretion disk and a neutral stellar wind scenario. Inner circumstellar disk regions (Najita et al. 1996), or infalling material heated by adiabatic compression from 3000 to 6000 K (Martin 1997), have been also proposed as regions where CO emission may arise.

However, as anticipated in Section 3, CO overtone features (typically (2–0) and (3–1)) behave in a quite variable manner in EXor. With reference to Figure 9 (bottom panel) the spectra of some sources (DR Tau, V1118 Ori, and NY Ori) present CO bands in emission (solid symbols) or in absorption (open symbols) on different epochs. For the remaining sources, CO bands, although largely variable, were detected always in emission or always in absorption, during our monitoring period. In trying to understand whether CO features are related to the continuum emission, we concentrate on the couple of sources (V1118 Ori and PV Cep) that exhibit the largest (i.e, the most significant) continuum variations ($\Delta K > 1$ mag). While brightening, V1118 Ori presents CO features passing from absorption to emission and PV Cep presents emission features of increasing intensity. This trend is the same as described above (see Section 1) for V1647 Ori, the eruptive variable recently discovered.

A plausible interpretation of our observations can be given in terms of two prevailing mechanisms. If we assume that CO absorption originated in the stellar photosphere (ref.), then it can be detected only during the more quiescent phases when the accretion rate is low, the continuum emission is low as well, and the star surface is more easily visible. When the accretion rate increases, it produces a significant increase of the UV radiation at the accretion shock that in turn heats the inner disk favoring CO emission associated with an enhanced continuum emission. It is worthwhile to continue our spectroscopical monitoring to confirm or not the proposed scenario. Further evidence that the stellar surface is more easily visible at minimum brightness was already presented in Figure 6 of Paper II where we noticed how, near the minimum, higher and more variable values of polarization were detected, suggesting that, in such conditions, we can see the heavy spotted and magnetized photosphere.

### 4.4. Na I Feature at 2.206 μm

Given its low first ionization potential (5.1 eV), sodium can be present close to low-mass late-type stars (like EXor, T Tauri) and in regions capable of shielding direct ionizing photons from earlier-type stars (e.g., circumstellar disks). The ionization structure of the emitting region can be suitably traced by the flux ratio Bry/Na I, which is free of extinction effects because of the closeness in wavelength between the two permitted lines. Hydrogen is expected to be neutral in the Na$^+$ region, thus a low

### Table 12

| Source     | Date     | $\Delta L_{HR}$ ($L_{\odot}$) | $A_V$ (mag) | $L_{\text{acc}}$(Paβ) ($L_{\odot}$) | $L_{\text{acc}}$(Bry) ($L_{\odot}$) | $M_{\text{acc}}$ ($10^{-3} M_\odot$ yr$^{-1}$) |
|------------|----------|-------------------------------|-------------|-----------------------------------|-----------------------------------|-----------------------------------------------|
| UZ Tau E   | 07 Mar 12| $\ldots$                      | 1.5         | 0.5                               | 1.0                               | 1–3                                           |
|            | 07 Oct 11| $-0.1$                        | 1.5         | 0.5                               | 1.2                               | 1–3                                           |
| DR Tau     | 07 Mar 13| $\ldots$                      | 1.9         | 2.3                               | 2.9                               | 7–9                                           |
|            | 07 Oct 08| $-0.2$                        | 1.9         | 0.9                               | 1.3                               | 3–4                                           |
|            | 07 Nov 03| $-0.1$                        | 1.9         | 2.0                               | 2.0                               | 6                                             |
|            | 08 Mar 28| $-0.1$                        | 1.9         | 1.8                               | 1.9                               | 4                                             |
| V1118 Ori  | 05 Sep 10| $\ldots$                      | 0           | 1.5                               | 2.5                               | 4–7                                           |
|            | 06 Sep 23| $-0.4$                        | 2.5         | $\ldots$                         | $\ldots$                         | $\ldots$                                      |
| PV Cep     | 07 May 13| $\ldots$                      | 11          | 41.7                              | 182                               | 25–100                                        |
|            | 07 Oct 15| $+1.3$                        | 13          | 72.4                              | 219                               | 47–130                                        |
|            | 07 Oct 27| $+2.4$                        | 11          | 38.0                              | 158                               | 23–95                                        |
|            | 08 Apr 01| $+8.0$                        | 9           | 34.7                              | 147                               | 21–88                                        |
|            | 08 Apr 12| $+7.6$                        | 9           | 40.7                              | 170                               | 24–100                                        |
|            | 08 Jun 10| $+0.6$                        | 14.5        | 37.0                              | 91.6                               | 22–55                                        |
|            | 08 Jun 18| $-0.9$                        | 14.5        | 31.5                              | 81.3                               | 19–49                                        |
value of the \( \text{Br}/\text{Na}\) ratio suggests a lower ionization; it might indicate the presence of high-density regions where photons cannot easily penetrate.

In the presented EXor spectra the \( \text{Na}\) 2.206 \( \mu \text{m} \) unresolved doublet is detected both in emission and in absorption and, remarkably, this line follows the same behavior as that of the CO bands. This circumstance is depicted in Figure 14, where the ratio \( \text{CO 2–0}/\text{Na}\) is plotted versus the \( \text{Br}/\text{Na}\) ratio for the different spectra taken in different monitoring phases. Because of the closeness of the three transitions (2.166, 2.206, and 2.293 \( \mu \text{m} \)), this plot is also unaffected by extinction. The \( \text{CO 2–0}/\text{Na}\) values are all positive (two spectra of DR Tau represent the only exception), which means that \( \text{Na}\) and \( \text{CO}\) are seen either both in emission or both in absorption. Since \( \text{Br}/\text{Na}\) is detected always in emission, the \( \text{Na}\) emission cases are located in the first quadrant (upper right) while \( \text{Na}\) absorption are those in the second quadrant (upper left). Such a behavior speaks in favor of a common origin for both \( \text{Na}\) and CO features. Hence, following the interpretation given for CO features (Section 4.2), the \( \text{Na}\) line also can be originated at the star photosphere (absorption) or in the inner disk (emission), depending on the outbursting stage of the object. Confirmation that \( \text{CO 2–0}\) and likely fluorescent \( \text{Na}\) emission at 2.206 \( \mu \text{m} \) can arise in the same low-excitation region is provided by McGregor et al. (1988), who note that carbon monoxide and sodium require similar temperatures to survive: the former is collisionally excited and emits at 3000–4000 K, as discussed in Section 4.2; the latter is shielded in the same high-density environment and is excited by adequate pumping photons without radiatively ionizing \( \text{Na}\).

Figure 14 shows how the values of the ratio \( \text{F(CO 2–0)/F(Na})\) corresponding to emission cases are systematically larger (they cluster in the range 2–4) than those of absorption cases (between 1 and 2). This trend is likely related to the different physical conditions between the stellar photosphere and the circumstellar environment.

Antoniucci et al. (2007) noticed that the ratio \( \text{Br}/\text{Na}\) for jet driving sources ranges between 2 and 5, while larger values are associated with Class I sources that show no evidence of jet emission. The ratios we have obtained for the EXors (see Figure 14) are low and in the same range of the former group, although the presence of a jet does not seem a property applicable to the EXor class. A plausible explanation is that the low value of the ratio \( \text{Br}/\text{Na}\) is typical of those cases where the role of the circumstellar disc dominates. \( \text{Na}\) IR emission lines, being associated with jet driving sources or with EXor variables, come from large columns of warm and neutral material located in the inner part of the disc.

Finally, we note that all the objects present \( \text{Na}\) in absorption have also \( \text{Ca}\) in absorption at 2.267 \( \mu \text{m} \), at a comparable intensity level. This provides further support to the hypothesis that the stellar photosphere appears during the most inactive phases.

4.5. Comparison with Spectra of Candidate Sources to be EXor

In the recent years seven additional outbursting sources have been tentatively recognized as EXor, although the attribution to this class (or to the FUor one) is still debated. They are listed in Table 13 along with some relevant parameters. The available near-IR spectra, apart from one featureless exception, are all emission line spectra strictly resembling those of the EXors presented in Section 3: in fact they are largely dominated by hydrogen recombination along with other ionic contributions and CO bandhead emission around 2.3 \( \mu \text{m} \). Moving from active to inactive phases line emission tends to fade and the \( \text{P}_{\gamma}\) profiles progressively diminish. Another feature in common with the classical EXors is the photometric behavior generally becoming bluer while brightening (Paper II). All in all, candidates and confirmed members appear equivalent with respect to their spectroscopic properties; a substantial difference is that the candidates are more embedded (\( \text{AV} \approx 10 \text{mag}\)) than the other EXors, suggesting, not surprisingly, that this evolutionary stage might also occur earlier than the T Tauri phase.

5. CONCLUDING REMARKS

We have presented the first results of a long-term spectroscopic monitoring of EXors in the near-IR aimed at investigating the variability in the accretion process, and hence the modalities and timescales of the process itself. By analyzing the results, the following can be summarized:

1. The presented part of our database refers just to the starting period (2007–2008): more than 25 spectra have been obtained in different epochs and they correspond to eight sources in total. To correlate continuum and line variability, all the observations are taken by performing simultaneous photometry (\( \text{JHK}\) bands) and low-resolution (\( \text{R} \approx 250\)) spectroscopy in the near-IR (0.8–2.5 \( \mu \text{m} \)).

2. EXor near-IR spectra are line emission spectra dominated by hydrogen recombination (Paschen and Brackett series) signaling in the presence of an ionized region. CO overtone features \( v = 2–0, v = 3–1\) are commonly detected both in emission and in absorption and weaker atomic features (\( \text{Na}\) and \( \text{Ca}\)) appear in emission or absorption following the CO behavior. At our level of sensitivity, molecular hydrogen contributions are absent, suggesting that shocks do not represent a major mechanism of excitation. All in all, EXor IR spectra look like those of the accreting T Tauri stars more than those of FUor objects.

3. In dealing with the first results of a long-term monitoring program, an attempt has been made to complement our
The obtained spectra have been compared with a wind
5. The possibility that line variability is due to a variable
4. The sources for which the largest continuum variations
7. CO overtone features have been detected both in emission

| Source        | Status   | Near-IR spect. | P$_{Cyg}$ | B or R While Brightening |
|---------------|----------|----------------|-----------|--------------------------|
| SVS 13        | Rising   | Increasing CO em. | H$_2$, Na, CO, H$_2$, [Fe II] | Blueing |
| L1415 IRS     | Rising   | No IR spectrum | PC H$_\alpha$, HH + CO | Blueing |
| V1647 Ori     | Outburst | Recomb., ionic, CO | PC Paschen, He $\alpha$ | 11 |
| Fading        | CO rovibrational | ... | PC Paschen, He $\alpha$ | 13 |
| Quiescent     | Line em. steady decrease | ... | PC Paschen, He $\alpha$ | 14 |
| ISO Cha I 192 | Rising   | Recomb., ionic, CO | CO outflow | Blueing |
| OO Ser        | Rising   | Featureless, rising cont. | ... | 17 |
| Fading        | ... | ... | Blueing |
| EC 53         | Fading   | No IR spectrum | ... | 17 |
| Variab.       | No IR spectrum | ... | No color var. |
| abs. Features | ... | ... | 20 |
| GM Cep        | Rising   | No IR spectrum | PC H$_\alpha$ | Random color var. |

**Notes.**

(1) Eislöffel et al. 1991; (2) Liseau et al. 1992; (3) Carr 1990; (4) Davis et al. 2006; (5) Takami et al. 2006 (and references therein); (6) Davis et al. 2002; (7) Biscaya et al. 1997; (8) Stecklum et al. 2007; (9) Reipurth & Aspin 2004; (10) Walter et al. 2004; (11) Vacca et al. 2004; (12) Gibb et al. 2006; (13) Brittain et al. 2007; (14) Acosta-Pulido et al. 2007; (15) Aspin et al. 2008; (16) Gómez & Mardones 2003; (17) Hodapp et al. 1996; (18) Hodapp 1999; (19) Köppen et al. 2007; (20) Doppmann et al. 2005; (21) Sicilia-Aguilar et al. 2008.

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The possibility that line variability is due to a variable extinction has been explored, and appears well applicable only to the spectra taken in different epochs of the peculiar source PV Cep.

6. The obtained spectra have been compared with a wind model that considers a spherically symmetric and partially ionized envelope with a constant rate of mass loss. Mass loss rates in the range 2–10$^{-8}$ M$_\odot$ yr$^{-1}$ are derived along with additional wind parameters. A possible origin of H$_2$ lines from accretion is investigated and it also provides consistent results.

7. CO overtone features have been detected both in emission and in absorption. They are highly variable even on a short (days to months) timescale. In particular, while brightening, one source presents CO features passing from absorption to emission and another presents emission features of increasing intensity. CO absorption could be originated in the stellar photosphere, thus it can prevail only during quiescent phases when the star surface is more easily visible. When the accretion rate increases the UV radiation at the accretion shock heats the inner disk favoring CO emission.

8. Na$_i$ 2.206 μm (and more rarely Ca$_i$ 2.267 μm) is detected both in emission and in absorption and, remarkably, it follows what CO bands do. Consequently all these lines are thought to arise in the same regions: the photosphere (when in absorption), or the inner disk (when in emission).

9. Finally, a comparison is made with the outbursting sources tentatively recognized as candidate EXors. They appear quite equivalent with respect to their spectroscopic properties; a substantial difference is that the candidates are more embedded than the other EXors, suggesting that this evolutionary stage might also occur earlier than the T Tauri phase.

A systematic investigation of the quantitative (inter-) relationship between line and continuum flux variations will be possible once our survey achieves a longer coverage, and hence a larger number of significant accretion events can be sampled.

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