X-shooter spectroscopy of young stellar objects

I. Mass accretion rates of low-mass T Tauri stars in σ Orionis*

E. Rigliaco1,2, A. Natta1,5, L. Testi1,6, S. Randich1, J. M. Alcalà3, E. Covino3, and B. Stelzer4

1 INAF/Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5, 50125 Firenze, Italy
e-mail: rigliaco@lpl.arizona.edu
2 Department of Planetary Science, Lunar and Planetary Lab, University of Arizona, 1629, E. University Blvd, 85719 Tucson AZ, USA
3 INAF/Osservatorio Astronomico di Capodimonte, Salita Moariello, 16, 80131 Napoli, Italy
4 INAF/Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy
5 DIAS/Dublin Institute for Advanced Studies, Burlington Road, Dublin 4, Ireland
6 ESO/European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany

Received 17 June 2012 / Accepted 27 September 2012

ABSTRACT

We present high-quality, medium-resolution X-shooter/VLT spectra in the range 300–2500 nm for a sample of 12 very low mass stars in the σ Orionis cluster. The sample includes eight stars with evidence of disks from Spitzer and four without disks, with masses ranging from 0.08 to 0.3 M⊙. The aim of this first paper is to investigate the reliability of the many accretion tracers currently used to measure the mass accretion rate in low-mass young stars and the accuracy of the correlations between these secondary tracers (mainly accretion line luminosities) found in the literature. We use our spectra to measure the accretion luminosity from the continuum excess emission in the UV and visual; the derived mass accretion rates range from 10⁻⁸ M⊙ yr⁻¹ down to 5 × 10⁻¹¹ M⊙ yr⁻¹, allowing us to investigate the behavior of the accretion-driven emission lines in very low mass accretion rate regimes. We compute the luminosity of ten accretion-driven emission lines from the UV to the near-IR, which are all obtained simultaneously. In general, most of the secondary tracers correlate well with the accretion luminosity derived from the continuum excess emission. We recompute the relationships between the accretion luminosities and the line luminosities, and we confirm the validity of the correlations given in the literature, with the possible exception of Hα. Metallic lines, such as the CaII IR triplet or the Na I line at 589.3 nm, show a larger dispersion. When looking at individual objects, we find that the hydrogen recombination lines, from the UV to the near-IR, give good relationships between the accretion luminosities and the line luminosities, and we confirm the validity of the correlations given in the literature correlations may be due to the use of nonsimultaneous observations of lines and continuum. Three stars in our sample deviate from this behavior, and we discuss them individually.

Key words. stars: low-mass – accretion, accretion disks – line: formation – open clusters and associations: individual: σ Orionis

1. Introduction

Accretion of matter onto T Tauri stars is an important aspect of the star formation process and plays a fundamental role in shaping the structure and evolution of proto-planetary disks. Magnetospheric accretion (Uchida & Shibata 1985; Koenigl 1991; Shu et al. 1994) is the accepted paradigm that explains

* Based on observations collected at the European Southern Observatory, Chile. Program 084.C-0269(A), 086.C-0173(A).

The intensity of the continuum emission, its wavelength dependence, and the intensity and profiles of the various emission lines can be used to derive quantitative information about the accretion process itself (e.g., Hartmann et al. 2006). In particular, the integrated continuum and line luminosity \( L_{\text{acc}} \) is proportional to the mass accretion rate, which can be computed from it once the ratio of the stellar mass to radius is known. Measurements of \( L_{\text{acc}} \) require well-calibrated observations of the continuum flux over a wide range of wavelengths, as well as an adequate knowledge of the photospheric and chromospheric spectrum of the star, which need to be subtracted from the observed flux to isolate the accretion emission. This has been possible for a relatively small sample of objects only (Hartigan et al. 1995, 1991; Muzerolle et al. 2003; Valenti et al. 1993; Calvet & Gullbring 1998; Gullbring et al. 1998; Herczeg & Hillenbrand 2008, hereafter HH08). However, it has been noticed that in these objects the luminosity or flux of several lines correlates quite well with \( L_{\text{acc}} \). Using these correlations, it has been possible to estimate \( L_{\text{acc}} \) and therefore \( M_{\text{acc}} \) in many young stars. These secondary indicators span a huge range of wavelength. In the far-ultraviolet (FUV) Herczeg et al. (2002) and Yang et al. (2012) found that the OI 1103.4 nm triplet, SiIV 139.4,
140.3 nm doublet and CIV\(\lambda 154.9\) nm doublet are tightly correlated with \(L_{\text{acc}}\). In the soft X-rays, Telleschi et al. (2007) and Curran et al. (2011) found that the low-density plasma component in the post-shock region correlates with \(M_{\text{acc}}\). From the near-UV to the near-IR several hydrogen recombination lines can be used to estimate \(L_{\text{acc}}\) (H\(\alpha\), H\(\beta\), H\(\gamma\), H\(\delta\), Pa\(\beta\), Pay), as well as other lines CaII\(\lambda 854.2\) nm, CaII\(\lambda 866.2\) nm, HeI\(\lambda 587.6\) nm, NaI\(\lambda 589.3\) nm, as shown by Fang et al. (2009), Mohanty et al. (2005), HH08, Natta et al. (2004), and Gatti et al. (2008), among many others. The excess emission in the \(U\)-band is also well correlated with \(L_{\text{acc}}\) (Gallimore et al. 1998), and can be used to measure it when the reddening is low. Finally a widely used accretion indicator is the H\(\alpha\) 10% line width, which has been found to be correlated with \(M_{\text{acc}}\) (Natta et al. 2004), although with high dispersion. The existence of secondary indicators in different regions of the spectrum is very important, as the more direct method of measuring \(L_{\text{acc}}\) integrating the excess emission over the whole wavelength range is often impractical or altogether impossible. It is, therefore, necessary to estimate the relative reliability of the different indicators over the widest possible range of the parameters, i.e., \(L_{\text{acc}}, M_{\text{acc}},\) or \(M_{\star}\).

When several indicators are measured for the same object, the accretion rate may differ by a factor of ten or more. Since in many cases different indicators are not observed simultaneously, one possible reason is the well-known time variability of the pre-main sequence stars (Joy 1945; Herbst et al. 1994, 2007). Up to now it has been difficult to observe several accretion tracers simultaneously, especially because they span from the UV wavelength region (e.g., the Balmer series lines) to the near-IR (e.g., Pa\(\beta\), Pay and B\(\gamma\) hydrogen recombination lines). This means that when comparing nonsimultaneous observations of these indicators an error caused by the time variability cannot be ruled out. This observational gap can be filled in with the use of broad spectral range spectrographs such as X-shooter at the VLT. X-shooter is an ideal instrument for comparing different indicators over the widest possible regions of the spectrum is very important, as the more direct method of measuring \(L_{\text{acc}}\), integrating the excess emission over the whole wavelength range is often impractical or altogether impossible. It is, therefore, necessary to estimate the relative reliability of the different indicators over the widest possible range of the parameters, i.e., \(L_{\text{acc}}, M_{\text{acc}},\) or \(M_{\star}\).

Table 1. Journal of the observations.

| RA              | Dec             | obs date (y-m-d) | texp (s) | Name      |
|-----------------|-----------------|------------------|----------|-----------|
| 05:38:13.18     | −02:26:8.629    | 2011-01-11       | 900 × 2  | SO397     |
| 05:38:23.58     | −02:20:47.47    | 2011-01-11       | 900 × 4  | SO490     |
| 05:38:25.41     | −02:42:41.15    | 2009-12-24       | 900 × 6  | SO500     |
| 05:38:34.04     | −02:36:37.33    | 2009-12-22       | 600 × 2  | SO587     |
| 05:38:38.57     | −02:41:55.79    | 2009-12-24       | 900 × 4  | SO641     |
| 05:38:39.01     | −02:45:31.97    | 2009-12-24       | 600 × 2  | SO646     |
| 05:38:54.91     | −02:28:58.19    | 2009-12-24       | 1200 × 2 | SO797     |
| 05:39:19.38     | −02:35:2.831    | 2009-12-22       | 900 × 4  | SO848     |
| 05:39:11.41     | −02:33:32.8     | 2009-12-22       | 900 × 4  | SO925     |
| 05:39:20.25     | −02:38:25.8     | 2009-12-25       | 1200 × 2 | SO999     |
| 05:39:53.63     | −02:33:42.88    | 2011-01-13       | 900 × 2  | SO1260    |
| 05:39:54.22     | −02:27:32.87    | 2011-01-12       | 900 × 4  | SO1266    |
| 16:07:49.59     | −39:04:28.79    | 2011-04-06       | 300 × 2  | Sz94      |

Notes. The last column shows the identification name, as reported in Hernandez et al. (2007).

2. Observations and data reduction

The sample analyzed in this paper has been observed with X-shooter on VLT as part of the Italian INAF/GTO program on star-forming regions (Alcalà et al. 2011). Observations were performed in visitor mode on 21, 23 and 24 December 2009 and 11–12 January 2011. We observed 12 objects, obtaining medium-resolution spectra covering \(\sim 300–2500\) nm range. The observations log (Table 1) lists the coordinates of the targets, the exposure time, and the abbreviated object names used throughout this paper (the last row of this table reports information of a class III star with spectral type M4, observed within the GTO program in the Lupus star-forming region. This star has been used as class III template in this paper).

The targets were observed in nodding mode with the 11′′ × 1.0′′ slit in the ultraviolet arm (UVB-arm), and with 11′′ × 0.9′′ slit in the visual (VIS) and near-infrared (NIR) arms. This instrument configuration yields a resolution \(R \sim 5100\) over the UVB-arm, which covers a wavelength range \(300–590\) nm, and the NIR-arm, which covers a wavelength range 1000–2480 nm, while with the VIS-arm (wavelength range from \(\sim 580\) nm to \(\sim 1000\) nm) we achieved a resolution \(R \sim 8800\).

The data reduction was performed independently for each spectrograph arm using the X-shooter pipeline version 1.1.0, following the standard steps, which include bias subtraction, flat-fielding, optimal extraction, wavelength calibration, and sky subtraction. The extraction of the 1D spectra and the subsequent data analysis was performed in STARE mode for UVB and VIS-arms, and in NODDING mode for the NIR-arm. Flux calibration has been achieved using the context LONG within MIDIAS. For this purpose, a response function was derived by interpolating the counts/standard-flux ratio of the flux standards (observed the same night as the objects, generally under photometric sky conditions), with a third-order spline function, after airmass correction. The flux-match of the three arms is excellent (Alcalà et al. 2011), and the flux-calibrated spectra show...
on average a very good agreement with the flux derived from photometric measurements available in the literature. Only in a few cases observed in not completely photometric conditions, we have adjusted the flux-calibrated spectra shifting the spectra on the photometric flux. The data were analyzed using the task SPLIT within the IRAF\textsuperscript{2} package.

### 3. The sample

The 12 targets for this study have been selected among the sample observed in the $U$-band by Rigliaco et al. (2011a) with FORS1 at the VLT, covering a range of masses between $0.08\sim0.3\ M_{\odot}$. Objects with mid-infrared colors that suggest they are young stars possessing disks (class II), and sources without obvious IR excess emission (class III) to be used as template were selected.

Spectral types (SpT) were estimated using the various indices by Riddick et al. (2007). These authors provide calibrations specifically for young M dwarfs. The flux ratios were selected out obvious IR excess emission (class III) to be used as template. The e assigned to a given object was estimated as the average SpT derived from the flux-calibrated optical spectra. The final SpT was obtained for each star using the temperature scale of Luhman et al. (2003). Luminosities were then computed using the $I$-band magnitudes (as listed in Table 2), and the bolometric correction for zero age main sequence (ZAMS) stars as reported by Luhman et al. (2003). As described in Sect. 1, the distance of $\sigma$ Ori is 360 pc and the extinction is negligible. The uncertainty in the SpT of about half a subclass corresponds to a typical error of $\pm 70$ K on the photospheric effective temperature. The error on the luminosity is caused by the adopted bolometric correction (which is linked to the error on $T_{\text{eff}}$), to the uncertainty on the measurement of the $I$-band magnitude (assumed to be $\pm 0.2$ mag), and to the uncertainty on the distance of the cluster, which may vary from $330$ pc (Caballero 2008) to $470$ pc (De Zeeuw et al. 1999). A detailed analysis of the error caused by the uncertainty on the distance was given by Rigliaco et al. (2011c). We estimate a typical uncertainty in luminosity of $\pm 0.2$ dex. Based on the location of the targets on the HR diagram and on a comparison with the Baraffe et al. (1998) evolutionary tracks, we have estimated the object masses and ages. The properties of the stars in our sample are summarized in Table 2. The determinations of the radius and of the mass are also affected by the distance uncertainty. We assume a typical error on these parameters of $\pm 0.05$ dex.

As expected from previous photometric classification (Hernandez et al. 2007), eight stars in our sample show a spectral energy distribution (SED, in Fig. 1) with IR excess emission, in particular in the IRAC spectral range (from 3.6 $\mu$m to 8.0 $\mu$m), indicating the presence of an optically thick circumstellar disk, i.e., they are class II objects (see Fig. 1a). The remaining four stars in our sample show the typical color of the stellar photospheres and no IR excess. The SEDs of these class III objects are shown in Fig. 1b. The SEDs shown in Fig. 1 are scaled to the $J$-band flux, while in the following figures the spectra are normalized to 700 nm. Previous work on the veiling (Hartigan et al. 1995; White & Ghez 2001; Fischer et al. 2011) show that there may be some excess continuum at and beyond this wavelength, but in our sample the veiling is low (see the following sections), allowing us to use the region around 700 nm to normalize the spectra. In Fig. 1, the black points are the available photometry, $U$-band from Rigliaco et al. (2011a), $BVRI$ from the literature (see Rigliaco et al. 2011a), $JHK$ from 2MASS photometry (Cutri et al. 2003), $Z,Y$ from the UKIDSS survey, and IRAC/MIPS magnitudes from the Spitzer survey. In Fig. 1a, the red curves represent the photospheric contribution obtained using the NextGen models (Hauschildt et al. 1999a,b; Allard et al. 2000), normalized to the $J$-band, and for comparison purpose, we show as a gray region, the median SED for CTTSs in Taurus derived from previous ground-based and IRAS data (D'Alessio et al. 1999).

### 4. Balmer and Paschen continua as accretion diagnostics

The accretion luminosity is released as continuum and line emission over a wide range of wavelengths. In general, the continuum luminosity dominates over the emission in lines, which is generally neglected in the literature, although, as we will see in Sect. 4, this may not be the case at a low mass-accretion rate. We will define in the following $L_{\text{acc}}$ to be the continuum luminosity only.

The excess emission is clearly seen in the Balmer continuum, where the photospheric and chromospheric emission of the stars is very low. Of the eight class II stars in our sample, six show clear evidence of it, as seen in Fig. 2, where the spectrum of each star is compared to that of a class III object of similar spectral type, normalized at 700 nm (the adopted class III template stars for each class II object are listed in Table 3).

Most stars clearly show the Balmer jump at the Balmer edge (note that the Balmer limit occurs at 4346.7 nm, but the line blending in the Balmer series shifts the apparent jump to 370 nm).

In Table 3 we list the values of the observed Balmer jump ($B_{\text{j,obs}}$), defined as the ratio of the flux at 360 nm to the flux at 420 nm, and of the intrinsic Balmer jump ($B_{\text{j,intrinsic}}$), measured after subtracting off the photospheric template from the class II star. This value is generally computed after dereddening the spectra, but in the $\sigma$ Orionis star-forming region the extinction is negligible (Oliveira et al. 2004). The observed Balmer jump ranges between $-0.2$ and $-3.5$ for the class II objects, as shown in Table 3, Col. 3. $B_{\text{j,intrinsic}}$ for the class III objects spans between $-0.2$ and $-0.5$. In two class II objects, namely SO587 and SO1266, $B_{\text{j,obs}}$ is in the same range as that of the class III stars. These objects will be discussed below. The intrinsic Balmer jump ranges between $-1.4$ and $-14.4$, as reported in Table 3, Col. 4.

Table 2. Stellar parameters and observed properties.

| Name         | SpT | $T_{\text{eff}}$ ($K$) | Lum ($L_\odot$) | Radius ($R_\odot$) | Mass ($M_\odot$) | Class | I mag |
|--------------|-----|------------------------|-----------------|--------------------|------------------|-------|-------|
| SO397        | M4.5| 3200                   | 0.19            | 1.45               | 0.20             | II    | 14.10 |
| SO490        | M5.5| 3060                   | 0.08            | 1.02               | 0.14             | II    | 15.32 |
| SO500        | M6  | 2990                   | 0.02            | 0.47               | 0.08             | II    | 17.30 |
| SO587        | M4.5| 3200                   | 0.28            | 1.73               | 0.20             | II    | 13.72 |
| SO641        | M5  | 3125                   | 0.03            | 0.57               | 0.12             | III   | 16.36 |
| SO646        | M3.5| 3350                   | 0.10            | 0.97               | 0.30             | II    | 14.58 |
| SO797        | M4.5| 3200                   | 0.05            | 0.76               | 0.18             | III   | 15.50 |
| SO848        | M4  | 3270                   | 0.02            | 0.46               | 0.19             | II    | 16.38 |
| SO922        | M5  | 3060                   | 0.03            | 0.58               | 0.10             | III   | 16.54 |
| SO999        | M5  | 3060                   | 0.06            | 0.91               | 0.14             | III   | 15.56 |
| SO1260       | M4  | 3270                   | 0.13            | 1.12               | 0.26             | II    | 14.44 |
| SO1266       | M4.5| 3200                   | 0.06            | 0.84               | 0.20             | II    | 15.30 |

\textsuperscript{2} IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The veiling continuum emission in the Paschen continuum (i.e., for 346 nm $\leq \lambda \leq$ 820 nm) is usually a smaller fraction of the photospheric continuum than in the UV and it is more easily detected as veiling$^3$ of the photospheric absorption lines, which are filled-in by the excess continuum.

Figure 3 shows the CaI $\lambda$ 422.6 nm line for the eight class II stars in our sample. We find very little evidence (if any) of veiling in 6 out of 8 objects. Only in two cases (SO397 and SO1260) the line veiling is not detected, and the choice of the class III template. The large set of models we computed suggests that the first is never higher than 330 nm, the di ff the slab model that a

The best-fit models are shown in Fig. 2 for the UV continuum and Fig. 3 for the CaI line at 422.6 nm. Figure 4 shows the normalization region around 700 nm. In 7 out of 8 objects the excess emission is negligible; only in the object SO1260 this is not the case and the template normalization needs to take this into account.

The accretion luminosity is given by the emission of the adopted slab model scaled to fit the data as described above. In 6 out of 8 objects the excess luminosity is clearly detected; in two cases (SO587 and SO1266) we can only determine upper limits. It is interesting to note that the Balmer continuum accounts for about 50% of $L_{\text{acc}}$ in all objects but the two strongest accretors (SO397, where it drops to 17%, and SO1260, 26%). In these two objects the excess emission is dominated by the Paschen continuum. The correction for the emission shortward of 300 nm, which is the shortest observed wavelength in most of our spectra, is typically a factor of two.

The uncertainty on $L_{\text{acc}}$ derives firstly from the noise of the target and the template spectra, then from degeneracies in the slab model that affect the correction for the emission below 330 nm, the difficulty of constraining the emission in the Paschen continuum in objects where line veiling is not detected, and the choice of the class III template. The large set of models we computed suggests that the first is never higher than 20–30% and the uncertainty introduced by the definition on the Paschen continuum is on the same order. The slab parameters themselves are poorly constrained as many trade-offs are possible, all resulting, however, in very similar emission spectra. As far as the choice of the class III is concerned, we found that, when two templates provide an equally good fit to the observed spectra, the corresponding values of $L_{\text{acc}}$ are within 10% of each other. In one case (SO848), we found that none of our class III templates with similar spectral type reproduce the observations very well. However, even in this case, the two values of $L_{\text{acc}}$ (obtained using Sz94 and SO797 as templates) differ by only 16%. In summary, a total uncertainty of 50% is adopted for accretion luminosities $L_{\text{acc}}$ calculated with this method, which incorporates uncertainties in distance, bolometric corrections, and the exclusion of emission lines estimated in the next subsection.

$^3$ The veiling $r_\lambda$ at wavelength $\lambda$ is defined as $(F_{\text{obs}} - F_{\text{phot}})/F_{\text{phot}}$, where $F_{\text{obs}}$ is the observed flux, and $F_{\text{phot}}$ is the photospheric flux.
Line contribution to $L_{\text{acc}}$

Our estimate of $L_{\text{acc,c}}$ is obtained from the continuum emission of the accretion slab model without taking into account the contribution of the emission lines (which may vary with mass accretion rates and stellar parameters). Although the energy budget in the lines can be large, this is common practice, and excluding the line contribution makes our accretion luminosity estimates comparable to those of previous works (HH08, Valenti et al. 1993; Calvet & Gullbring 1998).

To assess the importance of line emission we computed their contribution to the accretion luminosity. The fraction of luminosity in the Balmer lines with respect to the continuum accretion luminosity $L_{\text{acc,c}}$ is reported in Table 3, Col. 5. We estimate that the high-n Balmer lines (from the 12th hydrogen recombination line ($\lambda = 375.0$ nm) to the pseudo-continuum) contain a fraction between $\sim 0.1$ and $\sim 0.4$ of the continuum accretion luminosity in 5 out of 8 of the class II objects. In SO500 the luminosity in the hydrogen recombination lines is similar to the continuum accretion luminosity, and in SO587 and SO1266, where there is an upper limit in the continuum accretion luminosity, the fraction of luminosity in the hydrogen lines is higher than one. This is not surprising because these lines are likely caused by the chromospheric activity in these two stars, and not by the accretion luminosity (see Sect. 5.3).

5. Emission lines as accretion diagnostics

As described in Sect. 1, magnetospheric accretion produces emission lines that span from UV to IR wavelengths; these lines can be used to obtain an estimate of the accretion luminosity, and are also signatures of the chromospheric activity of the star.

The Hα line luminosity has been found to be strictly related to the accretion luminosity (e.g., Muzerolle et al. 2003, 2005, HH08; Dahm 2008; Fang et al. 2009). This kind of relation has been found for other hydrogen recombination lines as well (Hβ, Hγ, H11, Paβ and Paγ; e.g. Muzerolle et al. 1998, 2003; Natta et al. 2004, HH08; Dahm et al. 2008). Unfortunately, the low signal-to-noise ratio of our NIR spectra at $\lambda > 2100$ nm prevents
Table 3. Accretion luminosities and mass accretion rates.

| Name       | Template | $B_{\text{obs}}$ | $B_{\text{intr}}$ | $L_{\text{high}}$ | log $L_{\text{acc}}$ | log $M_{\text{acc}}$ |
|------------|----------|-----------------|-------------------|-------------------|-----------------------|-----------------------|
| SO397      | SO797    | 0.85            | 1.9               | 0.16              | -2.71                 | -9.42                 |
| SO490      | SO797    | 1.50            | 10.4              | 0.36              | -3.10                 | -9.97                 |
| SO500      | SO925    | 3.52            | 13.1              | 1.05              | -3.95                 | -10.27                |
| SO587      | Sz94     | 0.50            | ...               | >1.7              | <4.00                 | <10.41                |
| SO646      | Sz94     | 1.23            | 14.4              | 0.20              | -3.00                 | -9.68                 |
| SO848      | Sz94     | 2.72            | 14.4              | 0.43              | -3.50                 | -10.39                |
| SO1260     | SO797    | 1.61            | 1.38              | 0.12              | -2.00                 | -8.97                 |
| SO1266     | SO797    | 0.18            | ...               | >1.8              | <4.85                 | <11.38                |

Notes. Column 1 shows the name of the target, Col. 2 the name of the template used to compute the accretion luminosity, Columns 3 and 4 list the observed and the intrinsic Balmer jump. Column 5 lists the fraction of accretion luminosity contained in the Balmer series lines, and $L_{\text{high}}$ refers to the luminosity of the Balmer lines at wavelengths shorter than 1.375.0 nm. The last two columns represent the accretion luminosities and the mass accretion rates obtained from the excess continuum emission.

**Fig. 3.** Ca I $\lambda 422.6$ nm absorption line in the X-shooter spectra (red-solid lines). The green line shows the spectrum of the adopted class III template and the blue-dashed line the adopted model with the emission predicted from the slab model added to the template. Fe I emission lines at 421.6, 422.7 and 423.3 nm can also be identified.

**Fig. 4.** Region around 700 nm. The red-solid lines show the class II spectra, the green line shows the spectrum of the adopted class III template and the blue-dashed line the adopted model with the emission added to the template.

us from detecting the Br$\gamma$ line reliably, hence we do not provide measurements for this line.

The CaII near-IR triplet ($\lambda\lambda 849.8, 854.2, 866.2$ nm) broad emission components are commonly attributed to accretion shocks very close to the stellar surface (Batalha et al. 1996). In particular, this triplet has been used to detect accretion in low- and intermediate-mass stars (Hillenbrand et al. 1998; Muzerolle et al. 1998; Rhode et al. 2001; Mohanty et al. 2005).

The HeI emission line at 587.6 nm is another feature that has been used to characterize accretion processes. Among pre-main-sequence stars, broadened emission line profiles of HeI transition have been linked with magnetospheric accretion flows, as demonstrated by Muzerolle et al. (1998).

Another line that moderately correlates with the accretion luminosity is the NaI $\lambda 589.3$ nm line which is supposed to be produced in the magnetospheric infall zone. The HeI and NaI lines are usually associated with both infall and outflows (Hartigan et al. 1995; Beristain et al. 2001; Edwards et al. 2006) but throughout this paper they are used as tracers of the accretion.

The width of the H$\alpha$ line at 10% of the peak has been extensively used to discriminate between accreting and not-accreting objects and to derive an estimate of the mass accretion rate (Natta et al. 2004; White & Basri 2003). Indeed, as we can clearly see from Fig. 5, many of the class II objects have a broader H$\alpha$ line profile than the class III targets. However, in this work we decided not to use the H$\alpha$ 10% line width to measure accretion rates, because, as pointed out by Natta et al. (2004), it does not provide accurate measurements of $M_{\text{acc}}$ for individual objects.

Tables 4 and 5 list fluxes and equivalent widths (EWs) for the lines described above. We measured emission line fluxes and equivalent widths by fitting Gaussian profiles to the observed lines with the SPLOT/IRAF task. Where the line does not have
a Gaussian-like profile, the line flux and EW are measured by
directly integrating the flux along a window that includes the enti-
tire line (Fig. 5 presents a compilation of the Hα line profiles
for our class II and class III sources). The errors on the EWs
and fluxes were computed using a Monte Carlo approach: we
added a normally distributed noise to the spectrum, following
the observed optical veiling with magnetospheric accretion mod-
els (Gullbring et al. 1998, for low-mass stars in the mass range
between ~0.25–0.9 M⊙, and Calvet et al. 2004, for intermedi-
ate-mass T Tauri stars in the mass range between 1.5–4 M⊙), or, for
brown dwarfs, the Hα line profile (Muzzero 2003).

According to these studies, the accretion luminosity can be
computed from the line luminosity as

$$\log (L_{\text{acc}}/L_\odot) = b + a \times \log (L_{\text{line}}/L_\odot),$$

where the coefficients a and b are summarized in Table 6 to-
gether with their origin in the literature. In the case of the
CaII lines the equivalent widths were converted into line flux
per stellar surface area, and then correlated directly with $M_{\text{acc}}$:

$$\log M_{\text{acc}} = d + c \times \log (F_{\text{cal line}}).$$

Table 7 reports the calculated accretion luminosity for each
star based on the different emission lines. To distinguish these
values from those obtained from the continuum slab model, we
denote the line-based accretion luminosities with $L_{\text{acc,1}}$,
throughout the remainder of the paper. Table 7 lists also the
weighted mean accretion luminosity obtained from the sec-
ondary indicators, $(L_{\text{acc,1}})$. The accretion luminosity can be converted into mass accre-
tion rate, $\dot{M}_{\text{acc}}$ according to

$$M_{\text{acc}} = \left(1 - \frac{R_{\text{in}}}{R_\odot}\right)^{-1} \frac{L_{\text{acc}} R_\odot}{G M_*} \sim 1.25 \frac{L_{\text{acc}} R_\odot}{G M_*},$$

where $G$ is the universal gravitational constant and the factor
$(1 - \frac{R_{\text{in}}}{R_\odot})^{-1} \sim 1.25$ is estimated by assuming that the accreting
gas falls onto the star from the truncation radius of the disk
($R_{\text{in}} \sim 5 R_\odot$; Gullbring et al. 1998). The error introduced by
this assumption on the measured mass accretion rates, consid-
ering that $R_{\text{in}}$ for a pre-main sequence star can span from 3
to 8 $R_\odot$, is less than 20%. The stellar masses and radii are listed in
Table 2. Note that the values of $L_{\text{acc}}$ for the two CaII IR lines
are derived from the mass accretion rate, computed from Eq. (3),
and the standard relation between $L_{\text{acc}}$ and $M_{\text{acc}}$ (Eq. (4)).

5.1. Comparison of the accretion indicators

Figure 6 displays the $L_{\text{acc,1}}$ values of Table 7 (red circles) and also the accretion luminosity derived by Rigliaco et al. (2011a–c)
using the nonsimultaneous U-band excess emission (yellow trian-
gle). Even though all accretion indicators except for the U-band
were observed simultaneously, for a given star the spread be-
 tween different values of $L_{\text{acc,1}}$ is quite large, typically about one

![Fig. 5. Hα line profiles normalized at 700 nm (class II red lines, panel a), and class III cyan lines, panel b). The class II line profiles exhibit diverse morphologies that presumably arise from differing accretion rate values, gas temperature, and geometries (inclinations and magnetospheric radii).](image-url)
order of magnitude. However, as we have shown for the brown dwarf SO500 in Rigliaco et al. (2011b), for most of the stars analyzed here all values are consistent within the large error bars, and the average $L_{\text{acc,1}}$ has a smaller uncertainty (green line in Fig. 6). In particular, the total errors on $L_{\text{acc,1}}$ for each indicator are caused by the error on the line fluxes, on the adopted distance, and on the relationship used to estimate $L_{\text{acc,1}}$. The uncertainties on the flux and distance (which are about a factor 1.5 on the total accretion luminosity) are negligible with respect to the error caused by the assumed relationship, which corresponds to an uncertainty $L_{\text{acc,1}}$ of about a factor three. The uncertainty on $L_{\text{acc,1}}$ (which by our definition excludes the estimate from the $U$-band excess emission) computed averaging the accretion luminosity for each indicator weighted by the corresponding error and neglecting the upper limits, is about a factor two.

In five stars of the sample discussed in this paper, SO397, SO490, SO500, SO646, and SO1260, the accretion luminosity obtained from the Balmer excess continuum (blue line) is within the 1σ uncertainty of the average accretion luminosity obtained by using the secondary accretion indicators. The three cases for which we found no good agreement will be discussed in Sect. 5.3.

In Fig. 7 we show for each star the average mass accretion rate derived from $L_{\text{acc,1}}$ with Eq. (4) ($M_{\text{acc,1}}$) versus the mass accretion rate obtained with the same formula from the continuum accretion luminosity ($M_{\text{acc}}$). From this small sample we can conclude that the two quantities agree within the 1σ error (except for the cases discussed in Sect. 5.3) and do not show any robust trend with increasing $M_{\text{acc}}$. However, the sample considered here is small, and this question could be explored in more detail on a bigger sample of objects.

### Table 4. Hydrogen recombination line equivalent widths and fluxes.

| Target | $H\alpha$ | $H\beta$ | $H\gamma$ | $H\delta$ | $Pa\alpha$ | $Pa\beta$ |
|--------|-----------|-----------|-----------|-----------|-----------|-----------|
| SO397  | 4.25e-14  | 7.74e-15  | 4.78e-15  | 1.25e-15  | 3.64e-15  | 2.08e-15  |
| -3.39 ± 0.04 | -2.33 ± 0.03 | -2.07 ± 0.05 | -1.29 ± 0.11 | -0.09 ± 0.03 | -0.06 ± 0.04 |
| SO490  | 1.56e-14  | 2.92e-15  | 1.99e-15  | 6.11e-16  | 1.16e-15  | 4.55e-16  |
| -5.45 ± 0.06 | -3.86 ± 0.02 | -4.11 ± 0.04 | -1.98 ± 0.21 | -0.073 ± 0.03 | -0.031 ± 0.03 |
| SO500  | 7.47e-15  | 8.71e-16  | 3.53e-16  | 1.22e-16  | 3.61e-16  | 5.19e-16  |
| -12.15 ± 0.15 | -8.09 ± 0.04 | -6.26 ± 0.13 | -3.20 ± 0.29 | -0.09 ± 0.09 | -0.14 ± 0.07 |
| SO587  | 2.84e-14  | 5.98e-15  | 2.88e-15  | 6.56e-16  | 2.9e-16   | 4.6e-16   |
| -1.47 ± 0.11 | -1.04 ± 0.03 | -0.69 ± 0.05 | -0.42 ± 0.07 | -0.004 ± 0.17 | -0.007 ± 0.04 |
| SO646  | 2.32e-14  | 3.54e-15  | 2.67e-15  | 1.43e-15  | 2.26e-15  | 2.87e-15  |
| -2.34 ± 0.16 | -1.01 ± 0.02 | -1.27 ± 0.04 | -1.28 ± 0.11 | -0.096 ± 0.05 | -0.14 ± 0.03 |
| SO848  | 1.79e-14  | 4.03e-15  | 1.80e-15  | 3.09e-16  | 5.01e-16  | 6.91e-16  |
| -8.35 ± 0.50 | -9.74 ± 0.02 | -6.09 ± 0.08 | -2.01 ± 0.21 | -0.09 ± 0.05 | -0.12 ± 0.04 |
| SO1260 | 1.43e-13  | 2.58e-14  | 1.62e-14  | 4.37e-15  | 9.39e-15  | 1.33e-14  |
| -11.71 ± 0.08 | -4.43 ± 0.02 | -3.42 ± 0.02 | -0.94 ± 0.02 | -0.34 ± 0.04 | -0.52 ± 0.04 |
| SO1266 | 3.96e-15  | 9.37e-16  | 4.37e-16  | 6.74e-17  | –         | –         |
| -0.84 ± 0.04 | -0.97 ± 0.03 | -0.68 ± 0.06 | -0.51 ± 0.03 | –         | –         |

**Notes.** Fluxes (erg s$^{-1}$ cm$^{-2}$) in the first row, equivalent widths (nm) in the second row for each target.

### Table 5. Fluxes and equivalent widths of other lines as used as accretion indicators.

| Target | $H\alpha_{\text{1.67}}$ | NaI 589.3 | CaII 842.2 | CaII 866.2 |
|--------|--------------------------|-----------|-----------|-----------|
| SO397  | 1.17e-15  | 1.61e-16  | 1.24e-15  | 1.36e-15  |
| -0.23 ± 0.01 | -0.05 ± 0.03 | -0.046 ± 0.02 | -0.02 ± 0.03 |
| SO490  | 4.13e-16  | 2.87e-17  | 1.55e-16  | <8.0e-17  |
| -0.47 ± 0.01 | -0.045 ± 0.02 | -0.018 ± 0.02 | <−0.008 |
| SO500  | 3.65e-17  | 2.55e-17  | 5.05e-16  | 4.002e-16 |
| -0.21 ± 0.03 | -0.19 ± 0.07 | -0.29 ± 0.03 | -0.19 ± 0.02 |
| SO587  | 5.84e-16  | 2.13e-16  | <3.0e-16  | <3.0e-16  |
| -0.002 ± 0.01 | -0.034 ± 0.03 | <-0.003 | <-0.003 |
| SO646  | 1.14e-15  | <4.3e-17  | 1.12e-15  | 7.20e-16  |
| -0.20 ± 0.01 | <0.007 | -0.065 ± 0.01 | -0.039 ± 0.02 |
| SO848  | 3.93e-16  | 2.61e-17  | 1.79e-15  | 1.43e-15  |
| -0.47 ± 0.03 | -0.034 ± 0.04 | -0.45 ± 0.01 | -0.33 ± 0.02 |
| SO1260 | 2.25e-15  | 6.37e-16  | 1.08e-14  | 7.88e-15  |
| -0.31 ± 0.02 | -0.09 ± 0.02 | -0.51 ± 0.01 | -0.34 ± 0.02 |
| SO1266 | 1.067e-16 | 3.81e-17 | <1.4e-16 | <1.4e-16 |
| -0.075 ± 0.02 | -0.078 ± 0.06 | <−0.013 | <−0.013 |

**Notes.** Equivalent width and line flux format as in Table 4.
Table 6. Line luminosity vs. accretion luminosity relationships for selected accretion indicators.

| Line   | a    | b    | Reference                      |
|--------|------|------|--------------------------------|
| Hα (656.3) | 1.25 ± 0.07 | 2.27 ± 0.23 | Fang et al. (2009)            |
| Hβ (486.1) | 1.28 ± 0.05 | 3.01 ± 0.23 | Fang et al. (2009)            |
| Hγ (434.1) | 1.24 ± 0.04 | 3.0 ± 0.2   | HH08                          |
| H11 (377.1) | 1.17 ± 0.03 | 3.4 ± 0.2   | HH08                          |
| HeI (587.6) | 1.42 ± 0.08 | 5.20 ± 0.38 | Fang et al. (2009)            |
| Paβ (1280)  | 1.36 ± 0.20 | 4.00 ± 0.20 | Natta et al. (2004)           |
| Paγ (1090)  | 1.36 ± 0.20 | 4.10 ± 0.20 | Gatti et al. (2008)           |
| NaI (589.3) | 1.09 ± 0.11 | 3.3 ± 0.7   | HH08                          |
| U-band     | 1.09± 0.01  | 0.98± 0.02  | Gullbring et al. (1998)       |

These results are given in Table 8 and are discussed in the following subsections.

5.2.1. Hα, Hβ, and HeI

For the Hα, Hβ, and HeI lines as accretion tracers, we refer to Fang et al. (2009). They collected young stellar objects with measured Hα, Hβ and HeI emission line luminosities from the literature (Gullbring et al. 1998, HH08; and Dahm et al. 2008 for Hα; Gullbring et al. 1998 and HH08 for Hβ, and HH08; and Dahm et al. 2008 for HeI) for a sample of low-mass stars and brown dwarfs in the Taurus Molecular Cloud and the young open cluster IC 348. Figure 8 shows the comparison between the relationships found by Fang et al. (2009) (gray short-dashed line and gray crosses), by HH08 (black long-dashed line and black asterisks), and by us (green solid line and red dots). The correlations found by HH08 and by Fang et al. (2009) have been computed by least-square fitting the point distributions and neglecting the upper limits. We did the same adding to the Fang et al. (2009) sample the targets analyzed in this paper.

From Fig. 8 it can be seen that the empirical calibration for the Hβ and HeI lines presented in the literature and the new one obtained including our targets agree very well, while the relation log $L_{\text{acc},c} – \log L_{\text{Hα}}$ found including our objects is flatter toward the low-accretion luminosity regime with respect to those found in the past. The reason for this flattening could lie in the
Table 7. Estimated \( \log L_{\text{acc}} \) \((L_{\odot})\) from the secondary accretion indicators.

| Source    | \( \log L_{\text{acc}} \) | \( \log L_{\text{acc}} \) | \( \log L_{\text{acc}} \) | \( \log L_{\text{acc}} \) | \( \log L_{\text{acc}} \) | \( \log L_{\text{acc}} \) | \( \log L_{\text{acc}} \) |
|-----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| SO397     | \(-2.44\) | \(-2.76\) | \(-2.85\) | \(-2.80\) | \(-2.37\) | \(-2.48\) | \(-2.91\) |
| SO490     | \(-2.98\) | \(-3.31\) | \(-3.32\) | \(-3.17\) | \(-3.01\) | \(-3.15\) | \(-3.81\) |
| SO500     | \(-3.39\) | \(-3.98\) | \(-4.25\) | \(-3.98\) | \(-4.51\) | \(-3.84\) | \(-3.73\) |
| SO587     | \(-2.66\) | \(-2.91\) | \(-3.12\) | \(-3.13\) | \(-2.80\) | \(-3.97\) | \(-3.32\) |
| SO646     | \(-2.77\) | \(-3.19\) | \(-3.17\) | \(-2.73\) | \(-2.39\) | \(-2.76\) | \(-2.72\) |
| SO848     | \(-2.91\) | \(-3.12\) | \(-3.38\) | \(-3.51\) | \(-3.65\) | \(-3.56\) | \(-2.36\) |
| SO1260    | \(-1.78\) | \(-2.09\) | \(-2.19\) | \(-2.17\) | \(-1.96\) | \(-1.92\) | \(-1.81\) |
| SO1266    | \(-3.73\) | \(-3.94\) | \(-4.14\) | \(-4.29\) | \(-3.85\) | \(-4.13\) | \(-4.13\) |

**Notes.** Column 1 shows the star name. Last column lists the weighted mean \( \log L_{\text{acc}} \) based on all the accretion luminosity obtained from the secondary indicators and corresponds to the green lines in Fig. 6. The other columns show \( \log L_{\text{acc}} \) obtained from the emission lines, as described in the text, and correspond to the red points in Fig. 6.

Fig. 7. Comparison between the mass accretion rates computed from the average of all indicators \((\dot{M}_{\text{acc}}, l)\) and \(\dot{M}_{\text{acc}}, c\).

Table 8. Newly determined line luminosity vs. accretion luminosity relationships for selected accretion indicators.

| Line  | \( a \)  | \( b \)  |
|-------|----------|----------|
| \( H\alpha \) | \( 1.49 \pm 0.05 \) | \( 2.99 \pm 0.16 \) |
| \( H\beta \) | \( 1.34 \pm 0.02 \) | \( 3.01 \pm 0.09 \) |
| \( H\gamma \) | \( 1.30 \pm 0.02 \) | \( 3.32 \pm 0.08 \) |
| \( H\delta \) | \( 1.25 \pm 0.03 \) | \( 3.75 \pm 0.13 \) |
| \( HeI \) | \( 1.51 \pm 0.03 \) | \( 5.59 \pm 0.17 \) |
| \( Pa\beta \) | \( 1.49 \pm 0.04 \) | \( 4.59 \pm 0.14 \) |
| \( NaI \) | \( 0.76 \pm 0.10 \) | \( 3.76 \pm 0.47 \) |
| \( U\)-band | \( 1.33 \pm 0.06 \) | \( 1.55 \pm 0.18 \) |
| \( \text{Cal} 854 \) | \( 1.90 \pm 0.06 \) | \( -20.37 \pm 0.78 \) |
| \( \text{Cal} 866 \) | \( 1.41 \pm 0.08 \) | \( -17.76 \pm 0.89 \) |

From the flux-calibrated spectra of the four class III stars in our sample, we measured the flux of the \( H\alpha \) line, and using the relation reported in Table 6 we estimated the corresponding \( L_{\text{acc}} \) we should expect if the line were produced in the magnetospheric accretion framework rather than in the stellar chromosphere. The average value for the class III stars is \( \log L_{\text{acc}, H\alpha, \text{chrom}} = -4.1 \). We expect that the chromospheric emission becomes dominant already for somewhat higher values when the chromospheric contribution starts to be between...
the 10% and the 100% of the accretion luminosity. We see no clear evidence of such a flattening for the other emission lines. This leads us to speculate that as the accretion luminosity becomes increasingly lower, the first accretion tracer that starts to suffer from chromospheric contamination is the Hα line, as expected for a typical chromospheric spectrum. A detailed analysis of the class III activity from the targets observed with X-shooter during the GTO survey of star-forming regions is made in Manara et al. (in prep.).

5.2.2. Other hydrogen recombination lines

We also recomputed the relationships between $L_{\text{acc}}$ and the logarithm of $L_{\text{H}$, $\beta$, and $L_{\text{H}$, respectively, that were previously discussed by HH08. We fitted our points with those collected by HH08 ignoring the upper limits. The data and the old and new relationships are shown in Fig. 9.

In Fig. 10 we show the correlation between $L_{\text{acc}}$ and the Paβ line luminosity for the targets discussed in this paper, and for previous samples from the Ophiuchus and Cha I star-forming regions analyzed by Natta et al. (2004) and Muzerolle et al. (1998). The trend found by Natta et al. (2004) shows a good correlation over the whole range of masses from few tens of Jupiter masses to about one solar mass. Our new data confirm the trend found by Natta et al. (2004) and reinforce the strength of this line as an accretion tracer. The latter possibly showing a somewhat higher CaII emission for a given $M_{\text{acc}}$ luminosity as a function of $M_{\text{acc}}$. Consequently, Mohanty and collaborators performed separate fits for the higher and lower mass samples. Mohanty et al. (2005) speculated that the reason of this offset could lie in the methodology of $M_{\text{acc}}$ derivation for the intermediate-mass objects (U-band veiling) with respect to the low-mass objects (Hβ modeling), and/or in a different formation region of the CaII line in the two mass regimes (infalling gas or accretion shock).

We recomputed the relationship between $M_{\text{acc}}$ and the flux of the CaII 866 nm line (the green line in Fig. 11) considering the samples analyzed by Mohanty et al. (2005), HH08 and in this work (ignoring the upper limits). We find a flatter relationship with respect to those found by the other authors (see Table 8).

Even though $M_{\text{acc}}$ and the CaII 866 nm flux are correlated, the spread in flux for any given $M_{\text{acc}}$ is broader than two orders of magnitude, and it is not trivial to decide which relation should be used to obtain an estimate of $M_{\text{acc}}$ if the CaII 866 nm flux is known. This broad spread is partly due to the uncertainty in placing the continuum around the CaII Infra-Red Triplet (IRT) lines. We show in Fig. 12 the line profiles of this tracer in the

5.2.3. Other accretion tracers

A quite broad spread can be seen in Fig. 11 for the mass accretion rates retrieved using the CaII 866 nm line. We compared our results with those obtained by Mohanty et al. (2005) and HH08. Figure 11 shows their relationships. In particular, the black long-dashed line represents the linear fit of the data collected by Mohanty et al. (2005). These authors, moreover, suggested that there might be a small systematic offset between the higher mass accretors and the very low mass sample, with the latter possibly showing a somewhat higher CaII emission for a given $M_{\text{acc}}$. Consequently, Mohanty and collaborators performed separate fits for the higher and lower mass samples. Mohanty et al. (2005) speculated that the reason of this offset could lie in the methodology of $M_{\text{acc}}$ derivation for the intermediate-mass objects (U-band veiling) with respect to the low-mass objects (Hβ modeling), and/or in a different formation region of the CaII line in the two mass regimes (infalling gas or accretion shock).

We recomputed the relationship between $M_{\text{acc}}$ and the flux of the CaII 866 nm line (the green line in Fig. 11) considering the samples analyzed by Mohanty et al. (2005), HH08 and in this work (ignoring the upper limits). We find a flatter relationship with respect to those found by the other authors (see Table 8).

Even though $M_{\text{acc}}$ and the CaII 866 nm flux are correlated, the spread in flux for any given $M_{\text{acc}}$ is broader than two orders of magnitude, and it is not trivial to decide which relation should be used to obtain an estimate of $M_{\text{acc}}$ if the CaII 866 nm flux is known. This broad spread is partly due to the uncertainty in placing the continuum around the CaII Infra-Red Triplet (IRT) lines. We show in Fig. 12 the line profiles of this tracer in the
sample analyzed here. In some cases (e.g. SO397 and SO646) the line emission is superposed on the absorption profile. This could cause an error in our estimate of the line fluxes. Moreover, as already noted by Mohanty et al. (2005), the CaII IRT lines are seen in emission only in accretors, but not all accretors show emission in these lines.

New relationships, including our sample, have also been computed for the CaII854.2 nm line and NaIλ589.3 nm line, and are reported in Table 8.

Figure 13 shows the comparison of \( L_{\text{acc},c} \) and the \( U \)-band photometric excess \( (L_U) \). The \( U \)-band photometry for the X-shooter sample has been obtained by Rigliaco et al. (2011a) using FORS1 at the VLT, and thus is not simultaneous with the other accretion diagnostics analyzed since here. \( L_U \) is highly correlated with \( L_{\text{acc},c} \), as also shown by Gullbring et al. (1998). With our sample we expand the relation to lower luminosities.

The new relationship is slightly different with respect to the relation found by Gullbring et al. (1998), and this is clearly due to the extension of the sample toward lower mass accretion rate regimes. These results confirm that, if the extinction can be estimated, or if it is negligible, as in the \( \sigma \) Orionis star-forming region, good accretion luminosities can be derived from the \( U \)-band photometry, also in low-accretion luminosity regimes.

### 5.3. Notes on some targets

We have seen in Sect. 5.1 that the accretion luminosity from the Balmer and Paschen excess continuum \( L_{\text{acc},c} \) is within the \( 1\sigma \) uncertainty of the average accretion luminosity \( (L_{\text{acc},1}) \) computed considering all secondary accretion indicators observed simultaneously, for five out of eight of the targets in our sample. Here we investigate the three sources where \( L_{\text{acc},c} \) and \( L_{\text{acc},1} \) are discrepant.

**SO848:** \( L_{\text{acc},c} \) and \( (L_{\text{acc},1}) \) differ by about a factor three. Looking at Fig. 6, we can easily see that for SO848 the estimates of \( L_{\text{acc},l} \) from the CaII lines deviate from all other estimates. In the previous sections we have seen that the CaII lines are the most uncertain of the secondary accretion indicators, and that the estimate of the accretion luminosity strongly depends on the rate of accretion. If we neglect the accretion luminosity obtained from the CaII lines and recompute the average \( L_{\text{acc},l} \), we find that the discrepancy with \( L_{\text{acc},c} \) becomes less than a factor two. These differences are within our uncertainty in the estimate of \( L_{\text{acc},c} \) \((\log L_{\text{acc},c})\) neglecting the CaII points is \( \sim 3.21 \).

**SO1266:** this object shows only a few features usable for deriving the accretion luminosities, and \( (L_{\text{acc},1}) \) is the lowest of all values in our sample, while \( L_{\text{acc},c} \) is only an upper limit. Young stellar objects are generally characterized by strong and intense chromospheric activity (see Fig. 14). This activity also produces hydrogen recombination lines, as well as the CaII H&K lines, among many others. We find that the Balmer series line of the class III objects is \( \sim 80\% \) of the line luminosity of SO1266. This means that for this object, using the secondary accretion indicators, we are mainly tracing the chromospheric activity of the star, with only 20\% of the line luminosities due to the accretion activity. The lack of a detectable accretion and the shape of the SED (see Fig. 1) suggest that the disk surrounding SO1266 is a transitional disk, in which the inner part is completely or nearly completely cleared of small dust but the outer disk is optically thick (Calvet et al. 2002; Cieza 2008). Note that Hernandez et al. (2007) did not include this object among their transitional disk candidates.

**SO587:** in this object there is no evidence of excess continuum emission, and the estimate of \( L_{\text{acc},c} \) is an upper limit. This object has been already analyzed by Rigliaco et al. (2009). The star is most likely being photo-evaporated by the high-energy photons either from the central star or from the nearby hot star \( \sigma \) Ori. One consideration to take into account in the analysis of the emission lines of this object is that the photoevaporative processes could produce some emission in the permitted lines, which, added to the chromospheric activity of the star, could be wrongly interpreted as due to accretion. However, this hypothesis still needs to be studied in depth, e.g., by analyzing higher resolution spectra in the regions where lines produced by photo-evaporation are expected.
than one order of magnitude, which cannot be explained by temporal variability given the simultaneous observation of all accretion tracers. This wide scatter may reflect a real spread in the values of the secondary indicators for fixed accretion luminosity, owing to, e.g., different stellar and/or disk properties, or differences in wind/jet contributions. We investigated the possibility that this spread may depend on the stellar masses or different regimes of mass accretion, and we found that these dependencies can be ruled out, agreeing with the results found by Curran et al. (2011) for higher mass objects. Despite this wide spread, for a given star all accretion luminosity indicators give values of $L_{\text{acc}}$, which are consistent within the error bars, and the average value of $L_{\text{acc}}$ has a considerably reduced uncertainty, which is about a factor two. The average accretion luminosity from the secondary accretion indicators ($\langle \log L_{\text{acc}} \rangle$) ranges between $\sim -4.0$ to $\sim -1.9$ ($L_\odot$), which converts in $M_{\text{acc}}$ in the range $\sim 2 \times 10^{-9}$ to $\sim 2 \times 10^{-11}$ ($M_\odot$/yr). Moreover, $\langle \log L_{\text{acc}} \rangle$ is consistent with $\log L_{\text{acc}}$ obtained from the excess continuum emission.

3. With respect to the reliability of the secondary accretion indicators, we found that in general the hydrogen recombination lines, spanning from the UV to the NIR, give good and consistent measurements of $L_{\text{acc}}$ that often better agree than the uncertainties introduced by the adopted correlations. The average $L_{\text{acc}}$ derived from several hydrogen lines, measured simultaneously, have a much reduced error. This suggests that some of the spread in the literature correlations may be due to the use of nonsimultaneous observations of lines and continuum, and that their quality will be significantly improved when a larger sample of X-shooter spectra will be available.

4. We recomputed the relationships $\log L_{\text{acc}} - \log L_{\text{line}}$ for the secondary accretion diagnostics used in this paper, combining our new data with those available in the literature. In most cases the relationships change only within the errors but in some cases (namely $\log L_{\text{acc}} - \log L_{\text{H}_\alpha}$ and $\log L_{\text{acc}} - \log L_{\text{CaII}}$) the correlations change significantly when we include the low-accretion regime. This is shown in the paper. In particular, the correlation $\log L_{\text{acc}} - \log L_{\text{H}_\alpha}$ shows a flattening for $\log L_{\text{acc}} < \sim -3$. This could be due to the increasingly important contribution coming from chromospheric activity for weak accretors. The correlation $\log L_{\text{acc}} - \log L_{\text{CaII}}$ shows a very big spread in $\log L_{\text{CaII}}$ for any given $\log L_{\text{acc}}$. As already noted by other authors (Muzerolle et al. 1998; Mohanty et al. 2005, HH08), this indicator could provide a very uncertain estimate of $L_{\text{acc}}$ and $M_{\text{acc}}$. In general, a wider spread, as compared to the correlation with hydrogen lines, can be seen in the NaI line.

5. The comparison between $\log L_{\text{acc}}$ and $\log L_{\text{line}}$, obtained using the excess continuum emission and the emission line luminosities gives very encouraging results. The excess Balmer continuum accretion luminosities agree very well with the average ($\log L_{\text{acc}}$) in five out of eight stars of our sample. The remaining three objects do not show such agreement. We discussed these three cases separately, finding that in each case the disagreement can be attributed to peculiar characteristics of the targets (strong wind caused by photoevaporation processes acting on SO587, wrong interpretation of the chromospheric activity for SO1266, and the large uncertainty of the CaII lines as accretion tracers for SO848).

We conclude that the average accretion luminosity computed as the average of several secondary accretion indicators is as reliable as the accretion luminosity obtained from the excess continuum emission, except for peculiar cases.

Fig. 14. Each panel shows the comparison between the target stars and the templates used to obtain the continuum accretion luminosity (as listed in Table 3) in the region of the CaII H (λ393.37 nm) and CaII K (λ396.85 nm) lines. The CaII K line is blended with the Hα at λ397.0 nm. These lines are tracers of the chromospheric activity of the young stars.

6. Summary

We have analyzed the broad-band, medium-resolution, high-sensitivity X-shooter spectra of a sample of young very low mass class II and class III stars in the ρ Ori star-forming region. The sample was defined to cover the mass range $\sim 0.08 - 0.3 M_\odot$. We focused on the accretion properties of the class II stars, while class III stars were used only as spectral templates. We carried out a comparison between several accretion diagnostics observed simultaneously, that spanned from the UV excess continuum to the IR hydrogen recombination lines, computing the accretion luminosities and the mass accretion rates. We obtain the following results:

1. We detected clear evidence of excess emission in the Balmer continuum in six out of eight class II objects. Two of these also show hydrogen Paschen continuum emission. We estimated for all eight class II sources the accretion luminosity from the excess continuum emission by fitting the observed continuum as the sum of the emission of a class III template and of a slab of hydrogen of varying density, temperature and length, under the assumption of LTE and without taking into account the contribution of the emission lines. We found that $\log L_{\text{acc}}$ ranges between $\sim -2.0$ to $\sim -4.0$ ($L_\odot$) in the objects where the excess continuum is measured, which converts to a mass accretion rate $M_{\text{acc}}$ in the range $\sim 10^{-9}$ to $\sim 5 \times 10^{-11}$ $M_\odot$/yr.

2. We estimated the accretion luminosity from ten secondary accretion indicators using the empirical relationships with line flux and/or luminosity given in the literature. The accretion luminosities computed from all observable tracers show a dispersion around the average $\langle \log L_{\text{acc}} \rangle$ value of more than one order of magnitude, which cannot be explained by temporal variability given the simultaneous observation of all accretion tracers. This wide scatter may reflect a real spread in the values of the secondary indicators for fixed accretion luminosity, owing to, e.g., different stellar and/or disk properties, or differences in wind/jet contributions. We investigated the possibility that this spread may depend on the stellar masses or different regimes of mass accretion, and we found that these dependencies can be ruled out, agreeing with the results found by Curran et al. (2011) for higher mass objects. Despite this wide spread, for a given star all accretion luminosity indicators give values of $L_{\text{acc}}$, which are consistent within the error bars, and the average value of $L_{\text{acc}}$ has a considerably reduced uncertainty, which is about a factor two. The average accretion luminosity from the secondary accretion indicators ($\langle \log L_{\text{acc}} \rangle$) ranges between $\sim -4.0$ to $\sim -1.9$ ($L_\odot$), which converts in $M_{\text{acc}}$ in the range $\sim 2 \times 10^{-9}$ to $\sim 2 \times 10^{-11}$ ($M_\odot$/yr). Moreover, $\langle \log L_{\text{acc}} \rangle$ is consistent with $\log L_{\text{acc}}$ obtained from the excess continuum emission.

3. With respect to the reliability of the secondary accretion indicators, we found that in general the hydrogen recombination lines, spanning from the UV to the NIR, give good and consistent measurements of $L_{\text{acc}}$ that often better agree than the uncertainties introduced by the adopted correlations. The average $L_{\text{acc}}$ derived from several hydrogen lines, measured simultaneously, have a much reduced error. This suggests that some of the spread in the literature correlations may be due to the use of nonsimultaneous observations of lines and continuum, and that their quality will be significantly improved when a larger sample of X-shooter spectra will be available.

4. We recomputed the relationships $\log L_{\text{acc}} - \log L_{\text{line}}$ for the secondary accretion diagnostics used in this paper, combining our new data with those available in the literature. In most cases the relationships change only within the errors but in some cases (namely $\log L_{\text{acc}} - \log L_{\text{H}_\alpha}$ and $\log L_{\text{acc}} - \log L_{\text{CaII}}$) the correlations change significantly when we include the low-accretion regime. This is shown in the paper. In particular, the correlation $\log L_{\text{acc}} - \log L_{\text{H}_\alpha}$ shows a flattening for $\log L_{\text{acc}} < \sim -3$. This could be due to the increasingly important contribution coming from chromospheric activity for weak accretors. The correlation $\log L_{\text{acc}} - \log L_{\text{CaII}}$ shows a very big spread in $\log L_{\text{CaII}}$ for any given $\log L_{\text{acc}}$. As already noted by other authors (Muzerolle et al. 1998; Mohanty et al. 2005, HH08), this indicator could provide a very uncertain estimate of $L_{\text{acc}}$ and/or $M_{\text{acc}}$. In general, a wider spread, as compared to the correlation with hydrogen lines, can be seen in the NaI line.

5. The comparison between $\log L_{\text{acc}}$ and $\log \langle L_{\text{acc}} \rangle$ obtained using the excess continuum emission and the emission line luminosities gives very encouraging results. The excess Balmer continuum accretion luminosities agree very well with the average ($\log \langle L_{\text{acc}} \rangle$) in five out of eight stars of our sample. The remaining three objects do not show such agreement. We discussed these three cases separately, finding that in each case the disagreement can be attributed to peculiar characteristics of the targets (strong wind caused by photoevaporation processes acting on SO587, wrong interpretation of the chromospheric activity for SO1266, and the large uncertainty of the CaII lines as accretion tracers for SO848).

We conclude that the average accretion luminosity computed as the average of several secondary accretion indicators is as reliable as the accretion luminosity obtained from the excess continuum emission, except for peculiar cases.
Acknowledgements. E.R. thanks Ilaria Pascucci for valuable discussions. The authors acknowledge C. Manara for helping with the class III targets. The authors are grateful to the ESO staff, in particular C. Martayan, for support in the observations, and P. Goldoni and A. Modigliani for their help with the X-shooter pipeline.

References

Alicalá, J. M., Stelzer, B., Covino, E., et al. 2011, AN, 332, 242
Allard, F., Hauschildt, P., & Schweitzer, A. 2000, ApJ, 539, 366
Antoniucci, S., Garcia Lopez, K., Nisini, B., et al. 2011, A&A, 534, 32
Baraffe, I., Chabrier, G., Allard, F., et al. 1998, A&A, 337, 403
Batalha, C. C., Stout-Batalha, N. M., Basri, G., & Terra, M. A. 1996, ApJS, 103, 211
Bejar, V. J. S., Zapatero-Osorio, M. R., & Rebolo, R. 1999, ApJ, 521, 671
Beristain, G., Edwards, S., & Kwan, J. 2001, ApJ, 551, 1037
Briceño, C., Vivas, A., Calvet, N., et al. 2001, Science, 291, 93
Brown, A. G. A., de Geus, E. J., & de Zeeuw, P. T. 1994, A&A, 289, 101
Caballero, J. A. 2008, MNARS, 383, 750
Calvet, N., & Gullbring, E. 1998, ApJ, 509, 802
Cieza, L., & Anderson, D. M. 2008, ASPC, 393, 35
Crida, A., Masset, F., Massot, E., & Morbidelli, A. 2010, MNRAS, 409, 1877
Curran, R., Argiroffo, C., Sacco, G., et al. 2011, A&A, 526, 104
Cutri, R. M., et al. 2003, 2MASS All Sky Catalog of Point Sources, The IRSA 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive (Pasadena, CA: NASA/IPAC), http://irsa.ipac.caltech.edu/application/Gator
Dahm, S. E. 2008, AJ, 136, 521
D’Alessio, P., Calvet, N., Hartmann, L., et al. 1999, ApJ, 527, 893
De Zeeuw, P., Hoogerwerf, R., & de Bruijne, J. 1999, A&A, 117, 354
Edwards, S., Fischer, W., Hillenbrand, L., & Kwan, J. 2006, ApJ, 646, 319
Fang, M., van Boekel, R., Wang, W., et al. 2009, A&A, 504, 461
Fedele, D., Randich, S., Natta, A., et al. 2006, A&A, 446, 501
Gatti, T., Testi, L., Natta, A., et al. 2006, A&A, 460, 547
Gatti, T., Natta, A., Randich, S., et al. 2008, A&A, 481, 423
Gullbring, E., Hartmann, L., Briceno, C., & Calvet, N. 1998, ApJ, 492, 323
Joy, A. H. 1945, ApJ, 102, 168
Hartigan, P., Kenyon, S. J., Hartmann, L., et al. 1991, ApJ, 382, 617
Hartigan, P., & Sargent, A. I. 1995, ApJ, 452, 736
Hartmann, L., D’Alessio, P., Calvet, N., & Muzerolle, J. 2006, ApJ, 648, 484
Herbst, W., Herbst, D. K., Grossman, E., & Weinstein, D. 1994, AJ, 108, 1906
Herbst, E., Eistolfel, J., Mundt, R., & Scholz, A. 2007, in Protostars and Planets V, eds. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 297
Herczeg, G., & Hillenbrand, L. A. 2008, ApJ, 681, 594
Herczeg, G., Linsky, J., Valenti, J., et al. 2002, ApJ, 572, 310
Hernández, J., Hartmann, L., Megeath, S., et al. 2007, ApJ, 662, 1067
Hauschildt, P., Allard, F., & Baron, E. 1999a, ApJ, 512, 277
Hauschildt, P., Allard, F., Ferguson, J., et al. 1999b, ApJ, 525, 871
Hillenbrand, L., Strom, S., Calvet, N., et al. 1998, AJ, 116, 1816
Houdebine, E., Mathioudakis, M., Doyle, J., & Fong, B. 1996, A&A, 305, 209
Jeffries, R. D., Maxted, P. F. L., Oliveira, J. M., & Naylor, T. 2006, MNARS, 371, L10
Ingleby, L., Calvet, N., Hernández, J., et al. 2011a, AJ, 141, 127
Ingleby, L., Calvet, N., Bergin, E., et al. 2011b, ApJ, 743, 105
Kenyon, M. J., Jeffries, R. D., Naylor, T., et al. 2005, 356, 89
Köenigl, A. 1991, ApJ, 370, L39
Luhman, K. L. 1999, ApJ, 525, 466
Luhman, K., Stauffer, J., Muench, A., et al. 2003, ApJ, 593, 1093
Mauas, P. J., & Falchi, A. 1996, A&A, 310, 245
Mohanthy, S., Jayawardhana, R., & Basri, G. 2005, ApJ, 626, 498
Muzerolle, J., Hartmann, L., & Calvet, N. 1998, AJ, 116, 455
Muzerolle, J., Calvet, N., Briceno, C., Hartmann, L., & Hillenbrand, L. 2000, ApJ, 535, L47
Muzerolle, J., Hillenbrand, L., Calvet, N., et al. 2003, ApJ, 592, 266
Muzerolle, J., Luhman, K., Briceno, C., et al. 2005, ApJ, 625, 906
Natta, A., Testi, L., Muzerolle, J., et al. 2004, A&A, 424, 603
Natta, A., Testi, L., & Randich, S. 2006, A&A, 452, 245
Oliveira, J., Jeffries, R., & van Loon, J. 2004, MNARS, 347, 1327
Pascucci, I., Sterzik, M., & Alexander, R. 2011, ApJ, 736, 13
Perryman, M. A. C., Landgren, L., Kovalevsky, J., et al. 1997, A&A, 323, L49
Ridgway, F., Roche, P., & Lucas, P. 2007, MNARS, 381, 1067
Rigliaco, E., Natta, A., Randich, S., & Sacco, G. 2009, A&A, 495, L13
Rigliaco, E., Natta, A., Randich, S., et al. 2011a, A&A, 525, 47
Rigliaco, E., Natta, A., Randich, S., et al. 2011b, A&A, 526, 6
Rigliaco, E., Natta, A., Testi, L., et al. 2011c, AN, 332, 249
Rhode, K., Herbst, W., & Mathieu, R. 2001, AJ, 122, 3258
Short, C. I., Doyle, J. G., & Byrne, P. B. 1997, A&A, 324, 196
Shu, F., Najita, J., Ostriker, E., & Wilkin, F. 1994, ApJ, 429, 781
Telleschi, A., Güdel, M., Briggs, K., et al. 2007, A&A, 468, 443
Uchida, Y., & Shibata, K. 1983, PASJ, 37, 515
Valenti, J. A., Basri, G., & Johns, C. M. 1993, ApJ, 106, 2024
White, R., & Basri, G. 2003, ApJ, 582, 1109
Yang, H., Herczeg, G., Linsky, J., et al. 2012, ApJ, 744, 121
Zapatero Osorio, M. R., Bejar, V. J. S., Pavlenko, Y., et al. 2002, A&A, 384, 937