Accretion in Brown Dwarfs: an Infrared View *

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Abstract. This paper presents a study of the accretion properties of 19 very low mass objects (M*∼0.01–0.1 M⊙) in the regions ChaMaeleon I and ρ Oph. For 8 objects we obtained high resolution Hα profiles and determined mass accretion rate ˙Mac and accretion luminosity Lac. Paβ is detected in emission in 7 of the 10 ρ Oph objects, but only in one in Cha I. Using objects for which we have both a determination of Lac from Hα and a Paβ detection, we show that the correlation between the Paβ luminosity and luminosity Lac, found by Muzerolle et al. (1998) for T Tauri stars in Taurus, extends to objects with mass ∼0.03 M⊙; L(Paβ) can be used to measure Lac also in the substellar regime. The results were less conclusive for Brγ, which was detected only in 2 objects, neither of which had an Hα estimate of Lac. Using the relation between L(Paβ) and Lac we determined the accretion rate for all the objects in our sample (including those with no Hα spectrum), more than doubling the number of substellar objects with known ˙Mac. When plotted as a function of the mass of the central object together with data from the literature, our results confirm the trend of lower ˙Mac for lower M*, although with a large spread. Some of the spread is probably due to an age effect; our very young objects in ρ Oph have on average an accretion rate at least one order of magnitude higher than objects of similar mass in older regions. As a side product, we found that the width of Hα measured at 10% peak intensity is not only a qualitative indicator of the accreting nature of very low mass objects, but can be used to obtain a quantitative, although not very accurate, estimate of ˙Mac over a large mass range, from T Tauri stars to brown dwarfs. Finally, we found that some of our objects show evidence of mass-loss in their optical spectra.

1. Introduction

Several objects of very low mass discovered in regions of star formation have infrared excess typical of circumstellar disks (e.g., Natta and Testi 2001, Testi et al. 2002, Persi et al. 2002) and show signs of accretion-related activity (Jayawardana et al. 2002, White and Basri 2003, Muzerolle et al. 2003): they undergo an evolutionary phase similar to that of classical T Tauri stars (TTS) (Jayawardana et al. 2003). This evidence sets potentially important constraints on the formation of very low mass objects, and on the dominance of dynamical processes in star formation in general (e.g., Bate et al. 2002), which, however, need to be made more quantitative. Statistics of disks, measurements of their masses, characterization of the accretion as a function of the mass of the central objects in regions of different age and properties are required, and are being accumulated, exploiting fully the capabilities of 8-m class telescopes.

In this paper we discuss one important parameter in this scenario, namely the accretion rate in very low mass objects, which, together with the disk mass, determines the timescale for disk survival. Mass accretion rates have been determined for a handful of very low mass objects, mostly from model-fitting of the Hα profiles (Muzerolle et al. 2003). The results indicate that the trend of lower accretion rates for objects of lower mass, known for TTS (White and Ghez 2001, Rebull et al. 2000) continues in the substellar regime, where typical accretion rates are much lower than in TTS and can be as low as 5×10−12 M⊙/yr (Muzerolle et al. 2003). There is also evidence that, again as for TTS (e.g., Calvet et al. 2000), the fraction of accreting objects among very low mass objects is higher in younger regions (Jayawardana et al. 2002, 2003). All this points to a continuity in the accretion properties across the range of mass explored so far, which suggests a similar formation mechanism from solar to sub-stellar masses.

These results, however, are based on few measurements only, and need to be confirmed. In particular, it is important to extend them to younger, more embedded regions, where the use of Hα to derive the accretion rate is made hard or altogether impossible by the high extinction. In
that offered a.

We used the 0.6 arcsec slit and the low resolution grisms available in electronic form at "http://www.edpsciences.org").

Visitor Mode on April 8, 2002, and partly in Service Mode

telescope. The observations were carried out partly in infrared camera and spectrograph at the ESO-VLT UT1

Near-infrared low resolution spectra in the J and K bands were obtained for all our targets using the ISAAC near-

2.2. Low resolution near-infrared spectroscopy

Near-infrared low resolution spectra in the J and K bands were obtained for all our targets using the ISAAC near-

infrared camera and spectrograph at the ESO-VLT UT1 telescope. The observations were carried out partly in Visitor Mode on April 8, 2002, and partly in Service Mode from March to July 2003 (see Table 2). For each target a series of three to five ∼45 min exposures were obtained in the period from March to June 2003. All spectra were obtained using the standard UVES setup with central wavelength 580nm. The chosen setup allowed us to cover a nominal spectral range from ∼450 to 680nm. However, due to the very low signal obtained in the blue part of the spectra (450–

2.3. High resolution optical spectroscopy

High resolution optical spectra for the eight brightest (in the optical bands) objects in our sample were collected using the UVES spectrograph on the ESO-VLT UT2 telescope (see Table 2). For each target a series of three to five ∼45 min exposures were obtained in the period from March to June 2003. All spectra were obtained using the standard UVES setup with central wavelength 580nm. The chosen setup allowed us to cover a nominal spectral range from ∼450 to 680nm. However, due to the very low signal obtained in the blue part of the spectra (450–
580 nm), only the red part was analyzed. The slit used was 12 arcsec long and 1 arcsec wide, giving a resolution R~40000. Standard calibrations were obtained by the ESO staff as part of the Service Mode and the data were reduced using the UVES pipeline. All spectra were of excellent quality and the Hα line was detected with high signal to noise in all individual spectra.

3. Results

3.1. Accretion rates from Hα

All eight observed objects have Hα emission, in seven cases with full width at half maximum, \( \geq 10 \) Å. Of these, five (2 in Cha I and 3 in ρ Oph) show in all our observations broad Hα profiles. This, as discussed by White and Basri (2003) and Jayawardana et al. (2002), is indication of accretion-related rather than chromospheric activity. For each of these objects, we have computed an average profile, shown in Fig. 2, and compared it to the prediction of the magnetospheric accretion models developed by Muzerolle et al. (2001) and recently applied to a sample of sub-stellar objects by Muzerolle et al. (2003).

The underlying assumption is that the entire Hα (as well as the other hydrogen lines) comes from accreting matter, and that the contamination from wind/jet emission is negligible. This is not necessarily true in all strongly accreting TTS (see, for example, Bacciotti et al. 2002), but is probably a good approximation for our objects (see §3.4).

For all objects we have adopted a stellar mass \( M_* = 50 M_\odot \), radius \( 0.5 R_\odot \) and a magnetospheric truncation radius of \( 2.2 - 3 R_* \). The results are not very sensitive to the exact values of these parameters. The fitting procedure gives for each object a value of \( \dot{M}_{ac} \) and of the inclination angle \( i \). The resulting accretion rates are given in Table 1. They range from \( 10^{-9} M_\odot/yr \) for \( \rho \) Oph-102 to \( \sim 10^{-11} M_\odot/yr \) for \( \rho \) Oph-030. The inclination angle is \( \sim 65 - 75 \) deg for Cha Hα2, \( \rho \) Oph-030, \( \rho \) Oph-032, \( \sim 80 \) deg for Cha Hα6, and \( \sim 30 \) deg for Cha Hα102. The fits are of acceptable quality, with the exception of Cha Hα2, whose broad and flat profile (clearly present in all the observations) cannot be reproduced by the current models (similar profiles are observed in few other VLMOs and discussed in Muzerolle et al. 2003). The fit can be somewhat improved by adopting an ad-hoc temperature profile for the accretion flow, whereby the temperature has been reduced relative to the fiducial model in the outer part of the flow near the disk. This results in less emission near the line center, the most uncertain part of the profiles given the approximations used in the radiative transfer calculations (see Muzerolle et al. 2001). Nevertheless, both models for Cha Hα2 have similar inclination and an accretion rate of the order of \( 10^{-10} M_\odot/yr \), which we will adopt in the following. As discussed by Muzerolle et al. (2003), the values of \( \dot{M}_{ac} \) derived from the Hα profiles should be accurate within a factor of \( \sim 3 - 5 \).

A second group of 3 objects, all in Cha I, (Cha Hα1, Cha Hα3, Cha Hα5) has always narrow Hα profiles, typical of chromospheric activity. For these objects, we estimate an upper limit to \( \dot{M}_{ac} \) of about \( 10^{-12} M_\odot/yr \), for which the magnetospheric accretion models predict a line emission below the detection limit.

In Fig. 3 we compare our estimates of \( \dot{M}_{ac} \) to those of other VLMOs and TTS from the literature. The figure plots \( \dot{M}_{ac} \) as a function of the full width of Hα measured at 10% of the peak intensity (after continuum subtraction). Dots are VLMOs (mass \( \lesssim 0.2 M_\odot \)), where \( \dot{M}_{ac} \) is measured by fitting the Hα profiles (filled dots from this paper, open dots from Muzerolle et al. 2003); pentagons are VLMOs with values of \( \dot{M}_{ac} \) high enough to produce measurable veiling in the optical (White and Basri 2003; Muzerolle et al. 2003; Barrado y Navascués et al. 2004). The squares show the location on this diagram of a sample of more massive TTS, from which \( \dot{M}_{ac} \) has been derived from veiling (Gullbring et al. 1998), and the 10% Hα width are from high resolution Hα profiles obtained by Edwards et al. 1994. The total sample spans a range of masses from about 0.04 to 0.8 \( M_\odot \). Fig. 3 shows that our determinations of \( \dot{M}_{ac} \) agree with the general trend shown by other objects from the literature, and that there is conti-
Table 1. Object Properties and Hydrogen Lines

| Star      | ST  | $T_{\text{eff}}$ (K) | $\log L_\alpha$ ($L_\odot$) | $A_V$ (mag) | $M_\alpha$ (M$_\odot$) | $\log L_{\alpha}$ % | EW(He)$^a$ (Å) | EW(He)$^a$ (Å) | EW(He)$^a$ (Å) | Log $\dot{M}_{ac}$ ($M_\odot$/yr) | Log $\dot{M}_{ac}$ ($M_\odot$/yr) |
|-----------|-----|----------------------|-----------------------------|-------------|------------------------|-------------------|----------------|----------------|----------------|----------------|-----------------|
| Cha Hα1   | M7.5| 2770                 | -1.96                       | 0.2         | 40                     | 155               | 35             | <0.3          | <1             | <−12           | <−11.4          |
| Cha Hα2   | M6.5| 2910                 | -1.47                       | 0.8         | 70                     | 3066              | 33             | 0.3           | <1.5           | <−10.0         | <−10.8          |
| Cha Hα3   | M7  | 2840                 | -1.46                       | 0.3         | 60                     | 142               | 10             | <0.9          | <1.2           | <−12           | <−10.1          |
| Cha Hα5   | M6  | 2980                 | -1.31                       | 1.0         | 100                    | 137               | 6.5            | <0.9          | <1.7           | <−12           | <−10.0          |
| Cha Hα6   | M7  | 2840                 | -1.57                       | 0.26        | 50                     | 274               | 48             | <0.3          | <1             | <−10.5         | <−10.8          |
| Cha Hα7   | M8  | 2690                 | -2.19                       | 0.3         | 30                     | –                 | –              | <0.6          | <1.0           | <−11.1         | <−11.4          |
| Cha Hα9   | M6  | 2980                 | -2.26                       | 1.5         | 70                     | –                 | –              | <0.6          | <1.0           | <−11.4         | <−11.0          |
| Cha Hα10  | M7.5| 2770                 | -2.28                       | 0.1         | 40                     | –                 | –              | <0.3          | <0.9           | <−12.0         | <−12.4          |
| Cha Hα11  | M8  | 2690                 | -2.44                       | 0.0         | 30                     | –                 | –              | <0.3          | <0.9           | <−12.1         | <−12.1          |
| ρ Oph-023 | M7  | 2650                 | -1.40                       | 8.0         | 40                     | –                 | –              | 1.8           | <1             | <−9.3          | <−9.3           |
| ρ Oph-030 | M6  | 2700                 | -1.15                       | 3.0         | 60                     | 292               | 30             | 0.3           | <1             | <−10.8         | <−10.8          |
| ρ Oph-032 | M7.5| 2600                 | -1.22                       | 2.0         | 40                     | 248               | 50             | 0.4           | <0.9           | <−10.5         | <−9.8           |
| ρ Oph-033 | M8.5| 2400                 | -2.10                       | 7.0         | 10                     | –                 | –              | <0.7          | <2.1           | <−10.3         | <−10.3          |
| ρ Oph-102 | M6  | 2700                 | -1.10                       | 3.0         | 60                     | 377               | 40             | 2.0           | <1             | <−9.0          | <−9.0           |
| ρ Oph-160 | M6  | 2700                 | -1.40                       | 6.0         | 45                     | –                 | –              | 3.3           | 4.0            | <−9.0          | <−9.0           |
| ρ Oph-164 | M6  | 2700                 | -1.05                       | 6.0         | 60                     | –                 | –              | 0.80          | <1.6           | <−9.3          | <−9.3           |
| ρ Oph-176 | M6  | 2650                 | -1.15                       | 7.0         | 50                     | –                 | –              | <0.5          | <1.3           | <−9.7          | <−9.7           |
| ρ Oph-193 | M6  | 2650                 | -1.00                       | 7.5         | 60                     | –                 | –              | 1.8           | 2.9            | <−8.9          | <−8.9           |
| ρ Oph-GY10| M8.5| 2350                 | -1.44                       | 18          | 30                     | –                 | –              | <0.5          | <1.0           | <−9.0          | <−9.0           |

$^a$ Positive values indicate emission.
$^b$ Accretion rates from Hα profiles.
$^c$ Accretion rates from Paβ luminosities.

ny between measurements obtained from veiling (which are fully independent of the Hα width) and those derived from Hα profiles.

In the sub-stellar regime, the Hα10% width, which can be derived directly from the observations, is considered a good indicator of accretion, with the separation between accretors and non-accretors set at Hα10% width between ~200 km/s (Jayawardana et al. 2003) and ~270 km/s (White and Basri 2003). Fig. 3B confirms this result. Adopting ~200 km/s as a limit, one would misclassify one accreting object out of 23 (MHO-4, with $M_{ac}$ ~ 1 × 10$^{-11}$ $M_\odot$/yr and Hα 10% width of 154 km/s; Muzerolle et al. 2003) and two non-accreting objects (V927 Tau and USco CTI-O7) out of the 37 for which there are $M_{ac}$ upper limits (Muzerolle et al. 2003 and this paper). Furthermore, Fig. 3B shows that there is a rather good correlation between the Hα 10% width and $M_{ac}$ over the whole range of mass from BDs to TTS, so that it is possible to use the observed width not only to discriminate between accretors and non-accretors but also to get an approximate estimate of the accretion rate, without performing detailed model fits. We show in Fig. 3B the best-fit relation between these two quantities for Hα 10% width > 200 km/s, which can be expressed as:

$$\log M_{ac} = -12.89(\pm 0.3) + 9.7(\pm 0.7) \times 10^{-3} \log L_{\alpha 10\%}$$ (1)

where Hα10% is the Hα 10% width in km/s and $M_{ac}$ is in $M_\odot$/yr.

The spread is rather large, and can be due in part to the fact that in most cases the measurements used to derive $M_{ac}$ and the high-resolution Hα profiles have not been obtained simultaneously. We show, as an illustration of possible problems, the rather unusual case of the TTS DF Tau which has an accretion rate of about 10$^{-7}$ $M_\odot$/yr, based on veiling from medium-resolution spectrophotometric data obtained in 1996 (Gullbring et al. 1998). High resolution profiles of several Balmer lines obtained non-simultaneously from 1988 to 1990 by Edwards et al. (1994), show broad emission in all the lines, but with large discrepancies between them; in particular, the Hα width is smaller than that of the higher Balmer lines. One could certainly improve the correlation if larger and simultaneous sets of data for TTS were available. $M_{ac}$ values derived in this way are necessarily inaccurate for individual objects, and should be used with care. Nevertheless, they can be very useful when dealing with large samples of objects.

3.2. Paβ and Brγ as accretion indicators

Our near-IR spectroscopy does not allow us to resolve the line profiles, and we can only measure equivalent widths, listed in Table 1. Of the 9 Chamaeleon I objects, Paβ
is detected in only 1. For the others, we can set upper limits to the equivalent width (3σ) of about 0.3–0.9 Å. In Ophiucus, on the contrary, we detect Paβ emission in 7 of the 10 observed objects. Brγ is detected only in 2 objects in ρ Oph. Of the 5 objects with evidence of accretion from Hα, Paβ is detected in 4, while Brγ is not detected in any. Fig. 4 shows the spectra of the objects with line detections.

These results suggest that Brγ, which is intrinsically weaker than Paβ, is more difficult to detect even in highly reddened objects, where differential extinction favors lines at longer wavelengths. For this reason, we will focus in the following on the use of Paβ as an accretion indicator. We have therefore converted equivalent widths into fluxes using broad-band magnitudes and then correcting for extinction for the Cha I objects, while for the ρ Oph objects we have used the calibrated low-resolution spectra of Natta et al. (2002) for the continuum and corrected for extinction the resulting line fluxes.

Fig. 5 shows the relation between the Paβ luminosity (derived from the measured fluxes assuming a distance of 150 pc for Ophiucus and 160 pc for Cha I) and the accretion luminosity, computed from $M_{ac}$ and the stellar parameters given in Table 1. According to Muzerolle et al. (1998), these two quantities (rather than line flux versus $M_{ac}$) show the tightest correlation in TTS, and we have added Muzerolle’s sample to ours. The figure shows that the trend of lower Paβ luminosity for lower $L_{ac}$ extends to the very low values of $L_{ac}$ which characterize VLMOs. In fact, one can derive a rather good relation to estimate $L_{ac}$ from the Paβ luminosity over the whole range of masses from few tens of Jupiter masses to about one solar mass, shown by the dashed line in Fig. 5 and given by:

$$\log L_{ac} = 1.36(±0.2) \times \log L(Pa\beta) + 4.00(±0.2)$$

where $L_{ac}$ and $L(Pa\beta)$ are in units of $L_\odot$. Note that this relation is, within the uncertainties, identical to that derived by Muzerolle et al. (1998) for TTS over a much narrower interval of $L(Pa\beta)$.
Fig. 5. \( \text{Pa}\beta \) luminosity as a function of \( L_{\text{ac}} \). The dots are the VLMOs from this paper. The squares are T Tauri stars in Taurus-Auriga from Muzerolle et al. (1998). The dashed line is the best-fitting relation (Eq. 2).

As for \( \text{H}\alpha \) we have ignored the possibility that some \( \text{Pa}\beta \) emission may come from wind or jets, driven by accretion. In several TTS, the profiles of \( \text{Pa}\beta \) and \( \text{Br}\gamma \) are well described by magnetospheric accretion models (Folha and Emerson 2001), but there are some examples of \( \text{Pa}\beta \) wind emission (Whelan et al. 2004). Inspection of Fig. 5 shows that, very likely, any correction for a wind/jet contribution to the \( \text{Pa}\beta \) luminosity will be lost within the uncertainties of the individual measurements and the large scatter of the points. Nevertheless, the possibility of a contribution from outflowing matter to lines should be kept in mind when discussing individual objects.

Using the relation (2), we have derived \( L_{\text{ac}} \) and \( \dot{M}_{\text{ac}} \) for all the objects in our sample; \( \dot{M}_{\text{ac}} \) is given in the last column of Table 1. The largest differences between this determination of \( \dot{M}_{\text{ac}} \) and that from the \( \text{H}\alpha \) profile is of the order \( \pm 0.7–0.8 \) in log, i.e., a factor \( \sim 6 \) (see also Fig. 4).

3.3. Variability

Spectroscopic and photometric variability over a large interval of timescales is typical of pre-main sequence stars of all mass, including sub-stellar objects. By necessity, this introduces an artificial spread in correlation such as those of Fig. 3 and 5 when the accretion rate or luminosity and the line properties are not measured simultaneously. We expect that the quality of these correlations could improve significantly if simultaneous observations were available.

Another consequence of variability is the difficulty of assigning a well-defined accretion rate to any specific star. Variations of the \( \text{Br}\gamma \) flux are typically within a factor 2–3 (see, for example, Greene and Lada 1997; Luhman and Rieke 1998); if similar variations apply to \( \text{Pa}\beta \) (for which we could not find multiple-epoch data in the literature) this would change the estimate of \( L_{\text{ac}} \) by a factor \( \sim 2–5 \). In some cases, the lines become undetectable, and one would then classify the star among non-accretors.

Similar uncertainties are obtained if we consider the variations of the \( \text{H}\alpha \) 10% width. In our spectra (see Fig. 6), the largest variation is seen in \( \rho \text{-Oph-102} \), where the \( \text{H}\alpha \) 10% width varies from 335 km/s on May 29, 2003 to 411 km/s on June 4, 2003. According to eq.(1), the corresponding accretion rate would increase by a factor \( \sim 5 \). In all the other objects the \( \text{H}\alpha \) variations are smaller, implying a maximum change of \( \dot{M}_{\text{ac}} \) of a factor \( \sim 3 \) at most. A comparison of the sub-stellar objects in IC 348 for which \( \text{H}\alpha \) profiles have been obtained by Muzerolle et al. (2003) and Jayawardana et al. (2003b) shows variations that would result in changes of \( L_{\text{ac}} \) again by a factor \( \sim 2–5 \), according to Eq.(1).

An interesting case is that of \( \rho \text{-Oph-030} \) (GY 5), which has a strong \( \text{H}\alpha \) emission in our and Jayawardana et al. (2002) spectra (but a very different profile and a 10% \( \text{H}\alpha \) width of 292 and 352 km/s respectively) but is narrow (177 km/s) and weak in the spectrum of Muzerolle et al. (2003).

Some of these variations may be due to differences in the quality of the spectra (resolution, signal-to-noise etc.),
since all the VLMOs are very weak, often close to the instrumental limits. Still, most of the variability is likely to be real, as suggested by very similar results in TTS. For any individual object, one should have high quality spectra and long time sequences, which could provide not an instantaneous but a “typical” accretion rate. However, if we consider a large sample of objects, these individual variations will average up and will only increase the spread of any existing correlation, but not change it systematically.

3.4. Other Optical Lines

The UVES spectral range contains a number of other emission lines (in addition to Hα), usually considered good indicators of mass-loss and accretion. Table 3 gives the equivalent width of the lines (positive values for emission) and, in some cases, as for the NaD doublet, some information on their profile. The spectrum of Cha Hα is too noisy, and we have dropped this object from the table.

The HeI lines are generally interpreted as emitted in the accretion shock at the base of the infalling matter: these lines are indeed present and measurable in all the objects where we detect accretion in Hα (Cha Hα2, Cha Hα6, ρ Oph-030, ρ Oph-032 and ρ Oph-102), but not in Cha Hα3 and 5, which have narrow Hα profiles and no evidence of accretion. This result is consistent with our Hα analysis.

Some of the objects show indications of outflows. These are particularly strong in ρ Oph-102, which has emission in all the forbidden lines of [OII], [NII], [SII], and shows a P-Cygni profile in the NaD doublet (see Fig. 7), but also ρ Oph-32, Cha Hα2 and Cha Hα3 have detectable emission in some of the forbidden lines, and clear emission in the NaD doublet. All these objects are good candidates for further studies of winds and jets in VLMOs. However, there is no evidence of H2 vibrationally excited emission in the IR spectra of our objects, with the possible exception of ρ Oph-033, where, however, it is likely due to contamination from VLA 1623 (see also Williams et al. 1995).

Weak accretion-driven winds are expected in VLMOs, if they behave as TTS. Note, however, that even in ρ Oph-102 the equivalent width of Hα is much larger than that of the [SII] lines (the ratio is ∼ 200). The weakness of the forbidden lines in comparison to Hα in our objects supports the assumption that the hydrogen lines form mostly in the accreting gas (see also Fernández and Comerón 2001 and references therein).

As well known the presence of Li is a strong indication of substellar nature and/or youth. The covered spectral range includes the Li i doublet at 6708 Å. We detect it in absorption in all but one objects with equivalent widths ranging between 0.2 and 0.5 Å, confirming, in combination with the late-M spectral types, that they are members of the clouds. The Li line is not detected in Cha Hα1; we believe this is due to the very low S/N of the spectrum which shows virtually no continuum (see also Jörgens and Güntner 2001).

4. Discussion

4.1. Accretion as a function of mass and age

Our sample of VLMOs more than double the number of objects with measured $M_{\text{ac}}$. We plot in Fig. 8 our results, together with a compilation of data from the literature, as a function of the mass of the central object. The data include TTS and VLMOs, spanning a range of masses of about two orders of magnitude. All the masses have been redetermined self-consistently using the same evolutionary tracks (1998 unpublished update of D’Antona and Mazzitelli 1997), and the accretion rates have been scaled to these values, when necessary. Note that we have plotted upper limits for $M_{\text{ac}}$ only for objects from this paper.

Both $M_{\text{ac}}$ and $M_*$ have large uncertainties, discussed in detail, among others, by Muzerolle et al. (2003) and in this paper. There are, however, some clear trends. First of all, Fig. 5 confirms, over a large range of masses, the trend already found by other authors (Muzerolle et al. 2003; Rebull et al. 2001) of decreasing $M_{\text{ac}}$ for decreasing $M_*$. If, for example, we compare the median $M_{\text{ac}}$ for $M_*<0.1 M_\odot$ to that in the mass interval 1–0.3 $M_\odot$, we find values of $\sim 3 \times 10^{-10}$ and $\sim 10^{-8} M_\odot$/yr, respectively (neglecting upper limits to $M_{\text{ac}}$). It is unlikely that this trend is caused by sensitivity limits. Although, as we will discuss in the following section, in many VLMOs the accretion rate is close to the model sensitivity, this is not the case of TTS (see, e.g., Muzerolle et al. 2003), so that the correlation we find neglecting upper limits is probably somewhat shallower than the true one.
Table 3. Equivalent width of other optical emission lines

| Object    | [OIII]6300 (Å) | [OIII]6363 (Å) | [NII]λ6583 (Å) | [SII]λ6716 (Å) | [SII]λ6731 (Å) | HeIλ5875 (Å) | HeIλ6678 (Å) | NaIλ5896,5890a |
|-----------|----------------|----------------|----------------|----------------|----------------|---------------|---------------|----------------|
| Cha Hα2   |                | 0.06:          | 0.06:          |                | 0.1            | 1.6           | 0.6           | E(PCyg)        |
| Cha Hα3   |                |                | 0.03:          | < 0.1          | 0.08           | < 0.1         | < 0.1         | E              |
| Cha Hα5   |                |                | 0.07           | < 0.1          | 0.08           | < 0.1         | < 2.0         | E              |
| Cha Hα6   |                |                |                | 0.07           | < 0.08         | 1.1           | 0.3           | E              |
| ρ Oph-030 |                |                |                | < 0.1          | < 0.08         | 1.0           | 0.3           | E              |
| ρ Oph-032 |                | 0.1:           | 0.12           |                | 0.07           | 0.2           | 6.0           | E              |
| ρ Oph-102 | 2:             | 0.4:           | 0.07           |                | 0.2            | 4.4           | 2.3           | E(PCyg)        |

a E: both components in emission; PCyg: additional blue-shifted absorption (see Fig. 7).

A second effect is clearly shown in Fig. 8, namely that the accretion rate, for the same mass of the central object, is higher in younger regions. The ρ Oph brown dwarfs have accretion rates of roughly $10^{-9}$–$10^{-10}$ $M_\odot/yr$, more than an order of magnitude larger than most objects of similar mass in Taurus, Chamaeleon and IC 348. An age dependence of $\dot{M}_{ac}$ is known in TTS (e.g., Calvet et al. 2000), and is suggested for VLMOs by the fact that the fraction of objects with narrow Hα profiles (non-accretors) is larger in older star forming regions (Jayawardana et al. 2002, 2003a). Our results confirm this trend: only 10% (1 out of 10) of the objects in our Cha I sample are accreting; if we include also the Gómez and Persi (2001) VLMOs, then the fraction becomes 28% (5 out of 18 objects).

The dependence of $\dot{M}_{ac}$ on age makes it hard to determine the exact relationship of $\dot{M}_{ac}$ vs. $M_*$ from samples where objects in regions of very different age are collected together, as in Fig. 8. For example, the ρ Oph BD population selected by Natta et al. (2002) is particularly young, and it would be interesting to compare their accretion rates to equally young TTS in ρ Oph, rather than to TTS in Taurus. Also, there are a few VLMOs in Taurus, Cha I and IC348 with very large accretion rates, comparable or even higher than those of the ρ Oph VLMOs. Some of these estimates need to be confirmed, and the possibility of having detected a flare ruled out. Still, one wonders if they could be much younger than the average population of the star-forming region to which they belong.

In spite of the large uncertainties that affect individual objects, these preliminary results show that it is now possible, with the advent of 8-m class telescopes that give access to the VLMOs population, to quantify the dependence of $\dot{M}_{ac}$ on mass and age, overcoming, due to the large range of $M_*$, that one can explore, the uncertainties of individual measurements. For this one needs larger and more homogeneous samples of stars (not only VLMOs but also TTS) in a variety of star-forming regions.

![Fig. 8. Accretion rate as a function of the mass of the central object. Filled dots and squares are VLMOs in ρ Oph and Cha I, respectively, from this paper; $\dot{M}_{ac}$ has been determined from L(Paβ) as described in §3.3. Arrows are 3σ upper limits. Open squares are objects in Cha I from Gómez and Persi (2001) with Paβ emission, where $\dot{M}_{ac}$ has been determined from L(Paβ). Objects in IC 348 (Muzerolle et al. 2003) are shown by diamonds, in TW Hya (Muzerolle et al. 2000) by pentagons, in Taurus (White and Ghez 2001, White and Basri 2003) by crosses. We do not plot objects from the literature with no detected accretion.](image-url)

4.2. Disks and Accretion

Classical TTS show a clear correlation between accretion and the presence of a circumstellar disk. Disks are detected around a number of VLMOs, which show mid-
infrared fluxes well in excess of the photospheric ones (e.g., Comerón et al. 1998 Persi et al. 2000 Bontemps et al. 2001), modeled as the emission of disks heated by radiation from the central objects (Natta and Testi 2001 Testi et al. 2002 Natta et al. 2002).

Table 4 summarizes the information on the presence of a mid-IR excess in our sample objects. All 10 objects in ρ Oph have been detected by ISOCAM at 6.7 and 14.3 μm (Bontemps et al. 2001), and the correlation between disk and accretion, i.e., broad Hα and/or emission in the hydrogen IR lines, is basically confirmed by the results of this paper.

The Chamaeleon sample is in a way more intriguing. Three objects (Cha Ho1, Cha Ho2, Cha Ho9) have excess emission at 6.7 and 14.3 μm (Persi et al. 2000), modeled by Natta and Testi (2001) as due to disks. Of these, Cha Ho2 is clearly accreting, Cha Ho1 and Cha Ho9 (for which we have no Hα profile) do not. Three objects have been detected at 6.7 μm, but not at 14.3 μm; of these, Cha Ho3 and Cha Ho5 do not show evidence of accretion in Hα nor in Paβ or Brγ, while Cha Ho6 has broad Hα, but no emission in the IR lines. Finally, three (Ho7, Ho10 and Ho11) have no detected mid-IR excess and no IR line emission.

It appears from these results that disks are detected more easily than accretion, and that there is a population of VLMOs with evidence of disks but no detectable accretion activity. This is somewhat different from TTS, where most WTTS have no evidence of accretion but also no detectable IR excess (as some of the Cha I objects). This is probably due to the fact that even in very active VLMOs the accretion rate is close to the sensitivity limit of the various methods one can use, making it difficult to discriminate between “accretors” and “non-accretors”.

On the contrary, in TTS typical accretion rates are at least two orders of magnitude higher than the sensitivity limit of veiling measurements and/or Hα profile fitting (Gullbring et al. 1998 Mužerolle et al. 2003), and the separation between accreting and non-accreting objects is therefore much more meaningful.

One of the implications of the very low accretion rates that characterize BDs is that their disks should live long. If we assume, for example, that the disk mass scales with the mass of the central objects in BDs as in TTS, we have typical disk masses of about 10^{-3} M⊙; with an accretion rate of ∼ 3 × 10^{-10} M⊙/yr, as measured in ρ Oph, the disk will live at least 3 × 10^{6} years, as a typical TTS. This agrees with the results of Liu et al. (2003), who found no significant difference in the fraction of disks between BDs and TTS, and that the age of the TTS with disks was similar to that of TTS without disks.

It is more difficult to use this same result to rule out “truncated” disks, as those produced by the dynamical ejection of stellar embryos predicted, e.g., by Bate et al. (2003). Let us assume, for example, that the disk has an outer radius of 100 AU, and that, once ejected, loses all material outside a radius of about 10 AU. The mass left depends critically on the unknown surface density profile of the disk, and may range from about 1/3 (if the surface density profile was Σ ∝ R^{-1.5}) to about 1/10 (for Σ ∝ R^{-1}) of the original mass. A disk with mass of only 10^{-4} M⊙ will live about 3 × 10^{5} years, much less than a typical disk of TTSs, and also much less than the age of many BDs with infrared excess in star-forming regions (e.g., Jayawardhana et al. 2003). However, if the density profile is very peaked, the difference will not be significant, given the large uncertainties and spread of all the parameters involved. Only very accurate model predictions can be verified or falsified by this kind of arguments.

A final point worth mentioning is that the relation of the accretion rate with the mass and age of the central object may shed light on the physical process by which disk matter accretes onto the central star. The simplest suggestion is that the accretion rate may be related to the temperatures in the disk, which in turn are closely coupled to the luminosity of the central object. This may explain both the dependence of M_ac on M_⋆ and its decrease with time, since objects of all masses, and BDs in particular, fade as they get older. However, it is not clear that the change in temperature is big enough to account for the changes in M_ac. More subtle effects can be at work, related for example to the level of chromospheric and coronal activity (and hence X-ray fluxes) of the star and resulting disk ionization (see discussion in Mužerolle et al. 2003).
5. Summary and conclusions

We present in this paper new optical and near-infrared spectroscopic observations of a sample of 19 very low mass objects in the regions Chamaeleon I and ρ Oph. Our main aim was to test if accretion rates could be determined from the intensity of the hydrogen recombination lines in the infrared, namely Paβ and Brγ. This possibility is very important when dealing with large numbers of VLMOs in young star-forming regions such as ρ Oph, where high-resolution spectroscopy in the visual is possible for only a handful of objects.

To this purpose, we have obtained high-resolution Hα profiles of all the objects in our sample bright enough to be detectable with UVES on VLT. The comparison of the observed profiles with those predicted by magnetospheric accretion models (Muzerolle et al. 2001) shows that five objects are actively accreting, with \( M_{ac} \) in the range \( \sim 10^{-9} \) – \( 10^{-11} \) \( M_\odot/yr \), while the remaining three in Cha I have narrow and symmetric profiles, and \( M_{ac} \leq 10^{-12} \) \( M_\odot/yr \).

Paβ is detected in emission in 7 of the 10 ρ Oph objects, but only in one in Cha I. We show that the correlation between the Paβ luminosity and the accretion luminosity \( L_{ac} \), found by Muzerolle et al. (1998) for TTS in Taurus over a range of masses \( \sim 0.3–1 \) \( M_\odot \), extends to masses about ten times lower. Whereas the relation between \( L(Pa\beta) \) and \( L_{ac} \) (eq.(2)) can certainly be improved when more data will be available, it is already reasonably well defined, and can be used to measure \( L_{ac} \), and consequently \( M_{ac} \), for large samples of obscured VLMOs.

The results are so far less conclusive for Brγ for which we have a detection in only 2 objects, none with measured accretion rate.

Using eq.(2) and the measured \( L(Pa\beta) \), we determined \( M_{ac} \) for all the VLMOs in our sample, increasing the number of VLMOs with known \( M_{ac} \) by more than a factor of two. When plotted as a function of the mass of the central object together with all the existing data on VLMOs and TTS from the literature, our results confirm the trend of lower \( M_{ac} \) for lower \( M_\star \), although with a large spread. Some of the spread is likely due to an “age” effect, namely that, for a given value of \( M_\star \), \( M_{ac} \) decreases strongly with time. Our very young VLMOs in ρ Oph have on average \( M_{ac} \) at least one order of magnitude higher than objects in older star forming regions. The dependence of \( M_{ac} \) on central mass and time needs to be better constrained by future observations. However, it is already clear that these data can provide very valuable information on the accretion mechanism in disks during the pre-main–sequence evolutionary phase.

One side product of our analysis is that the width of Hα measured at 10% peak intensity correlates quantitatively with \( M_{ac} \) over a large range of \( M_{ac} \) and \( M_\star \). This supports the currently used criterion to separate accretors from non-accretors among VLMOs according to the Hα 10% width (White and Basri 2003) and confirms that a value of 200 km/s (as suggested by Jayawardana et al. 2003b) is a rather good threshold value. Furthermore, it suggests that one can use the Hα 10% width to obtain a quantitative estimate of \( M_{ac} \) over a large range of masses. Although the spread of the correlation (eq.(1)) is large, and there are a number of caveats to keep in mind, the possibility of estimating \( M_{ac} \) without going through rather time consuming model fits is interesting, and deserves further attention.

Finally, we would like to note that high-resolution near-infrared spectroscopy on 8-m class telescopes is becoming available. As with Hα for visible objects, high quality infrared line profiles can be compared to model predictions to derive accretion rates for obscured ones. The additional advantage of the IR lines is that they are likely less contaminated than Hα by wind/jet emission, flares and stellar activity in general; a sufficiently large sample of objects with measured Hα and Paβ profiles will be very valuable in providing more "calibration" points for the line intensity–accretion rate relations, and in better constraining magnetospheric accretion models.

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