VARIABLE ACCRETION AND OUTFLOW IN YOUNG BROWN DWARFS

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ABSTRACT

We report on the first dedicated monitoring campaign of spectroscopic variability in young brown dwarfs. High-resolution optical spectra of six targets in nearby star-forming regions were obtained over 11 nights between 2005 January and March on the Magellan 6.5 m telescope. We find significant variability in Hα and a number of other emission lines related to accretion and outflow processes on a variety of timescales ranging from hours to weeks to years. The most dramatic changes are seen for 2MASS J1207334−393254 (2M 1207), 2MASS J11013205−7718249 (2M 1101), and Cha I−ISO 217. We observe possible accretion rate changes by about an order of magnitude in two of these objects, over timescales of weeks (2M 1207) or hours (2M 1101). The accretion “burst” seen in 2M 1101 could be due to a “clumpy” flow. We also see indications for changes in the outflow rate in at least three objects. In one case (ISO 217), there appears to be a ∼1 hr time lag between outflow and accretion variations, consistent with a scenario in which the wind forms at the inner disk edge. For some objects there is evidence for emission-line variability induced by rotation. Our variability study supports an inclination that is close to edge-on for the brown dwarf LSRcra 1. The fact that all targets in our sample show variations in accretion and/or outflow indicators suggests that studies of young brown dwarf properties should be based either on large samples or on time series. As an example, we demonstrate that the large scatter in the recently found accretion rate versus mass relationship can be explained primarily by variability. The observed profile variations imply asymmetric accretion flows in brown dwarfs, which, in turn, is evidence for magnetic funneling by large-scale fields. We show that accreting substellar objects may harbor magnetic fields with approximately kilogauss strength.

Subject headings: accretion, accretion disks — line: formation — line: profiles — stars: formation — stars: low-mass, brown dwarfs — stars: winds, outflows

1. INTRODUCTION

Brown dwarfs (BDs) are objects with masses intermediate between stars and planets. From a variety of observational studies, there is now clear evidence that many BDs with ages <10 Myr share properties with solar-mass classical T Tauri stars (CTTSs), which are in a phase of active accretion. Young BDs have been found to harbor circum-substellar disks, as indicated by near- and mid-infrared fluxes significantly higher than the photospheric fluxes from the object itself. Their spectral energy distribution in the infrared and in the submillimeter regimes is nicely reproduced by disk models with either flat or flared disk geometry (e.g., Natta et al. 2002; Jayawardhana et al. 2003a; Pascucci et al. 2003; Mohanty et al. 2004). Moreover, a large fraction of young BDs show the typical emission-line spectrum of T Tauri stars, with broad, asymmetric Hα lines and additional emission lines such as He i and O i, which is direct evidence for ongoing accretion (e.g., Jayawardhana et al. 2002, 2003b; White & Basri 2003; Muzerolle et al. 2003; Natta et al. 2004; Mohanty et al. 2005). The accretion process is also believed to produce the large-amplitude, partly irregular photometric variability observed in young BDs (Scholz & Eisloffel 2004, 2005). Finally, for some substellar objects outflows have been detected as forbidden line emission in [S ii] and [O i] (Fernández & Comerón 2001; Barrado y Navascués 2004; Barrado y Navascués & Jayawardhana 2004; Whelan et al. 2005). Thus, it is quite clear that many young BDs undergo an accretion phase, like more massive objects.

The general picture of accretion on T Tauri stars is the magnetospheric accretion model. In this view, the accretion is funneled by a large-scale magnetic field structure, which truncates the disk at a certain inner radius. The gas flows with nearly free-fall velocity from the disk to the star following the magnetic field lines and finally forms an accretion shock and hot spots near the atmosphere of the accreting object (e.g., Königl 1991; Shu et al. 1994; Hartmann et al. 1994). Many recent studies provide ample support for this idea of magnetically channeled accretion, and there is growing evidence that this scenario also applies to substellar objects.

Perhaps the most detailed view of the accretion process can be obtained by high-resolution optical spectroscopy. By analyzing the emission-line fluxes and profiles, it is possible to constrain the accretion parameters such as the infall rate or the temperature in the flow. Accreting objects, however, show a puzzling variety of emission-line profiles, from nearly symmetric and double-peaked to classical or inverse P Cygni–type features (e.g., Fernández et al. 1995; Reipurth et al. 1996). Part of this diversity may be explained by different accretion flow geometries in individual objects. But we also have to take into account that we see the star-disk system in different projections. In the two extreme cases, the line of sight can point directly to the edge of the disk (edge-on view) or to the pole (face-on view). As a consequence, for different objects the received flux comes from different parts of the disk and the object, whereas other parts may be obscured.

On the other hand, it has long been known that T Tauri stars are variable on timescales ranging from a few hours to years (e.g., Herbst et al. 1994; Johns & Basri 1995; Bouvier et al. 1999, 2003). Hot spots formed by the accretion flow corotate with the object and therefore might not always be visible to the observer. Moreover, the rotational axis can be inclined with respect to the magnetic axis, resulting in a nonaxisymmetric flow (Romanova et al. 2003). Simulations show that the magnetospheric accretion itself is unlikely to be stable over long timescales; reasons for instabilities include recurrent opening of the magnetic field lines (e.g., Uzdensky 2002; Matt & Pudritz 2005) and clumpy accretion
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TABLE 1
TARGET PROPERTIES

| Full Name                | Short Name | Spectral Type | $v_{rad}^a$ (km s$^{-1}$) | $v_{rad}^b$ (km s$^{-1}$) | Number$^b$ | H$\alpha$ VI$^c$ |
|-------------------------|------------|---------------|-----------------|----------------|-----------|----------------|
| 2MASS J1207334–393254... | 2M 1207    | M8            | 11.2            | 13             | 13        | 29            |
| 2MASS J11013205–7718249 | 2M 1101    | M8            | ~15$^d$         | ...            | 7         | 49            |
| ρ Oph–ISO 032........... | ρ Oph-32   | M7.5          | ~0$^c$          | ...            | 5         | 17            |
| Cha H$\alpha$ 1......... | ...        | M7.5          | 15.5            | 7.6            | 5         | 19            |
| Cha I–ISO 217........... | ISO 217    | M6.25         | ~15$^d$         | ...            | 5         | 39            |
| LS-RCrA 1.............. | ...        | M6.5          | ~2              | 18             | 4         | 16            |

Notes:

$^a$ References for spectral properties: Barrado y Navascués et al. 2004; Comerón et al. 2000; Fernández & Comerón 2001; Gizis 2002; Joergens 2006; Joergens & Guenther 2001; Luhman 2004; Mohanty et al. 2003, 2005; Muzerolle et al. 2005; Natta et al. 2002.

$^b$ Number of spectra in the time series.

$^c$ H$\alpha$ variability index, as defined in §3.

$^d$ Average radial velocity of Cha I brown dwarfs.

$^e$ Value of $v_{rad}$ derived in this paper.

(Mitskevich et al. 1993). All these processes can lead to variability and, in particular, to variations in the emission-line profiles. In summary, rotation, accretion instabilities, geometry effects, and differences between individual objects are mainly responsible for the different types of emission-line profiles observed for accreting objects.

From this reasoning it becomes clear that variability studies, in particular spectroscopic monitoring, can be used to obtain a close-up view of the accretion behavior of individual objects because they help disentangle the different effects that influence the line profiles. Indeed, from intensive monitoring campaigns for selected CTTs, it has been possible to derive a detailed description of the accretion process for some objects (e.g., Johns-Krull & Basri 1997; Alencar & Batalha 2002; Bouvier et al. 2003). At minimum, variability studies provide information about the range of accretion parameters on a given object, allowing us an unbiased comparison between different objects. Thus, variability studies for individual targets are a valuable complement to the statistical analysis of large object samples.

Therefore, we have carried out the first spectroscopic monitoring campaigns of young, accreting brown dwarfs. We selected targets that show broad and asymmetric H$\alpha$ profiles in previous studies, indicative of infalling and/or outflowing material (see §2.2). In addition, we aimed to cover a large variety of emission-line profiles and thus accretion properties. Our final sample of six objects is given in Table 1, which also contains aliases for all the targets. In the remainder of the paper, we use these short names. For all six objects, the membership in nearby star-forming regions has been confirmed spectroscopically, and all have spectral types later than M6, indicating that they are either very close to or below the substellar limit (see Luhman et al. 2003). For a more precise mass estimate for these objects, a better calibration of the substellar limit (see Luhman et al. 2003). For a more precise mass estimate for these objects, a better calibration of the stellar evolutionary tracks for young objects is required (see Baraffe et al. 2002). However, since crossing the substellar limit is not expected to alter the accretion process in any way, for convenience we call all targets “brown dwarfs” in the rest of the paper, although not all of them may be bona fide substellar objects.

The first results from this study have already been published in Scholz et al. (2005, hereafter SJB05), where we report on dramatic changes in the emission lines of the BD 2M 1207 (see Table 1). In this paper, we give a consistent description of the emission-line variability for six targets, including 2M 1207. In §2 we present our observations and data reduction. Subsequently, we give a phenomenological description of the emission-line spectra, including an analysis of the profile of the most prominent feature, the H$\alpha$ line (§3), and a survey of other features seen in our data (§4). This information is then used to constrain the accretion behavior of our targets (§5) and brown dwarfs in general (§6). Finally, we give our conclusions in §7.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Observation and Basic Reduction

All spectra for this study have been taken with the MIKE (Magellan Inamori Kyocera Echelle) spectrograph at the Magellan Clay 6.5 m telescope on Las Campanas. MIKE is a double echelle instrument, consisting of blue and red arms, providing coverage from 3400 to 5000 Å and from 4900 to 9300 Å, respectively, in our configuration. We obtained most of the time series spectra for our six targets in an observing run from 2005 March 17 to 19. Except for Cha H$\alpha$ 1, at least one additional spectrum per target was taken in a second observing run at the end of March. Three extra spectra for 2M 1207 were obtained in a preceding campaign in 2005 January–February. In total, the variability study is based on 13 spectra for 2M 1207, seven for 2M 1101, five each for ρ Oph-32, ISO 217, and Cha H$\alpha$ 1, and four for LS-RCrA 1 (see Table 2). In the main observing run, we used on-chip binning of 2 × 2 pixels in combination with slit sizes of 10.0 or 0.75, resulting in a resolution of $R \approx 20,000$. All exposures were split into three single spectra to avoid excessive contamination by cosmic rays. The two auxiliary runs had the primary goal of measuring high-precision radial velocities; therefore, we aimed for the highest possible resolution. For that reason, spectra from these runs were taken with a 0.35 slit in combination with either no or 2 × 2 binning. Therefore, the data from our primary run have in general a higher signal-to-noise ratio (S/N) but lower resolution. The exposure times for our targets were between 15 and 60 minutes. In Table 2 we list for all spectra the observing times, configurations, and exposure times. In all runs, we additionally observed a spectrophotometric standard star for order definition and (relative) flux calibration.

The basic reduction of all spectra was done using standard routines in the doceal1it package within IRAF. The procedure includes overscan subtraction, flat-field correction, sky background subtraction, order extraction, and blaze correction using the standard-star spectrum. The wavelength calibration was carried out using thorium-argon spectra; we obtained a typical precision of a few milliangstroms for the wavelength solution. Cosmic

1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
We take advantage of the fact that we expect the material in the accretion flow. To decide whether an object is accreting or not, we split the total exposure time to several spectra, these single exposures were co-added after the extraction.

### 2.2. Line Measurements

Our spectra show a variety of emission lines, which are believed to form by either accretion, outflows/winds, or magnetic activity. We selected a set of features that should allow us to disentangle the effects of these three processes and measured equivalent widths (EWs) for all of them.

The dominant emission line in all spectra is the H$_\alpha$ feature at 6562.8 Å, which has its origin in the chromosphere and/or in the accretion flow. To decide whether an object is accreting or not, we take advantage of the fact that we expect the material in the accretion flow to be moving at close to the free-fall velocity, which is $\sim$150 km s$^{-1}$, whereas the velocity for chromospheric emission is usually significantly smaller. Based on these considerations, White & Basri (2003) and Jayawardhana et al. (2003b) introduced the 10% width of the full peak height (hereafter 10% width) as a useful measurement to discriminate between accretors and non-accretors. Jayawardhana et al. (2003b) suggested a threshold of $\sim$200 km s$^{-1}$ for substellar objects, and Mohanty et al. (2005) demonstrate that this is a reasonable value for separating accreting and merely chromospherically active objects. It turned out that the 10% widths are indeed nicely correlated with the accretion rate estimate from the emission-line profile, which is particularly useful for BDs, for which the continuum is faint. It should be noted, however, that an extremely active and fast rotating object might be able to produce a 10% width of about 200 km s$^{-1}$ or more. Neither of our targets, however, is known to be an exceptionally fast rotator. The $v \sin i$ values derived so far (see Table 1) indicate rotational velocities $<20$ km s$^{-1}$.

### Table 2

| Date (2005) | UT | Slit (arcsec) | Binning | Target | Exposure Time(s) | H$_\alpha$ EW$^a$ (Å) | 10% Width$^b$ (km s$^{-1}$) | Comment |
|-------------|----|---------------|---------|--------|------------------|---------------------|----------------------|---------|
| Jan 29...... | 05:25 | 0.35 | 1 x 1 | 2M 1207 | 1 x 900 | 110 | 215 |        |
| Feb 01....  | 05:56 | 0.35 | 1 x 1 | 2M 1207 | 1 x 1200 | 64 | 215 |        |
| Mar 17...... | 00:38 | 1.0 | 2 x 2 | 2M 1207 | 3 x 600 | 334 | 308 | Double-peaked |
| Mar 18...... | 00:23 | 1.0 | 2 x 2 | 2M 1207 | 3 x 600 | 259 | 291 | Double-peaked |
| Mar 19...... | 02:06 | 1.0 | 2 x 2 | ISO 217 | 3 x 600 | 109 | 359 |        |
| Mar 27...... | 03:56 | 0.35 | 1 x 1 | 2M 1207 | 1 x 1800 | 192 | 295 | Double-peaked |
| Mar 28...... | 04:46 | 0.35 | 1 x 1 | 2M 1207 | 1 x 1800 | 183 | 279 | Double-peaked |
| Mar 29...... | 04:38 | 0.35 | 1 x 1 | 2M 1207 | 1 x 1800 | 261 | 285 | Double-peaked |
| Mar 30...... | 05:12 | 0.35 | 1 x 1 | 2M 1207 | 1 x 1500 | 322 | 304 | Double-peaked |

$^a$ The average measurement error in EW is $\sim$1 Å.

$^b$ The measurement error in 10% width is $\sim$5 km s$^{-1}$.
The profile of Hα can be used as an additional indicator for ongoing accretion: Chromospheric Hα profiles are in most cases more or less symmetric, and often a small central dip due to self-absorption in the chromosphere is seen. On the other hand, accreting objects usually exhibit strongly asymmetric profiles, with broad wings and either red- or blueshifted absorption features, indicative of high-velocity infalling or outflowing material. In the following, we therefore use the 10% width and the shape of the profile to distinguish between nonaccretors and accretors.

All our targets show emission in the higher Balmer lines Hβ and Hγ, which require higher temperature regions in comparison with Hα. Again, the width of the lines can be used to discriminate between accretors and nonaccretors. In addition, many spectra show He i, most prominently at 5875 and 6678 Å, O i at 8446 Å, and the Ca ii triplet in emission. If detected, we measured the EWs for these lines. The He i 5875 feature is known to be in absorption in many chromospherically active stars, but it can also appear in emission during flares in active M dwarfs (Saar et al. 1997 and references therein). Although young BDs are known to show very few flares (see Scholz & Eislöffel 2005), we cannot exclude that the He i 5875 emission has its origin in the chromosphere. He i 6678, O i 8446, and the Ca ii triplet, however, appear preferentially in accretors, as argued by Mohanty et al. (2005). Therefore, we use these lines as complementary information to distinguish between accretors and nonaccretors. In particular, the He i 6678 EW can be used as a strong discriminator between accretors and nonaccretors: Gizis et al. (2002) observed 676 M dwarfs, most of them active, in the solar neighborhood, and although many of them have He i 6678 emission in none, have EWs larger than 0.25 Å. For our spectra, this is lower than the detection limit; i.e., if we detect He i 6678 in emission, it is very likely caused by accretion.

Like Hα, many emission lines of accreting objects can be formed in infalling material, as well as in the chromosphere or in outflowing material, as has been shown at least for He i (Béjar et al. 2001) and Ca ii (see Fernández & Comerón 2001). The line ratio in the Ca ii triplet, however, gives a first indication of whether the flux comes from mainly infall or outflow: For low-density outflowing material, we expect line ratios of 1 : 9 : 5, as has been observed for Herbig-Haro objects (Reipurth et al. 1986). On the other hand, line ratios close to 1 : 1 : 1 imply saturation and optically thick Ca ii emission, as argued by Graham & Heyer (1988), and are therefore evidence for an accretion-related origin.

Some objects show clear evidence for forbidden line emission, particularly in [S ii] (6730 Å) and [O i] (6300 Å). If possible, we measured EWs for these lines as well. Forbidden line emission is a clear indication for mass outflow, since these lines can only form in low-density regions, not in the accretion shock (see Hirth et al. 1997). They can therefore also be used to decide whether the permitted emission lines are mainly formed by outflow or infall.

For all line measurements, the spectra were shifted to the local stellar rest frame. We used literature radial velocities for 2M 1207, Cha H 0 1, and LS-RcTa 1 (see Table 1). The uncertainties of these measurements are at most 3 km s⁻¹. For the remaining three targets, there is no previous radial velocity measurement. Using the Li 6708 absorption feature, we are able to derive an estimate of 0 ± 3 km s⁻¹ for ρ Oph-32, which is roughly consistent with the velocity of the cloud and of young stars in ρ Oph (see Doppmann et al. 2005). 2M 1101 and ISO 217 belong to the Cha I star-forming region, where the brown dwarfs have been found to have average radial velocities of ~15 km s⁻¹ with only a small dispersion of 2–3 km s⁻¹ (Joergens & Güenther 2001; Joergens 2006). For these two targets, we therefore adopt the Cha I average value as the radial velocity. Since the radial velocity error is the main source of uncertainty in velocity, we estimate our error for all velocity values to be ~3 km s⁻¹, still lower than our spectral resolution.

### 2.3. Continuum Analysis

Our general observing strategy was to keep the exposure time as short as possible, so that we could obtain more than one spectrum per night for each of our targets. As a consequence, the S/N in the continuum is low, particularly for λ < 7000 Å, deterring us from a detailed analysis of the photospheric lines for our objects. Many important emission lines are in regions with a faint continuum, e.g., the complete hydrogen Balmer series, and we have to make sure that the continuum emission is dominated by the flux from the target and not significantly contaminated by imperfect background or flat-field correction. We compared the averaged spectral energy distribution (SED) in our data with model spectra from Allard et al. (2000), selected to match the effective temperature and gravity of our targets. Both the observed and the theoretical SEDs were normalized to the flux at 8600 Å, where we safely detect the continuum in all our spectra with S/N > 10, and the ratio between the observed and modeled spectra was computed. This ratio is expected to scatter around unity as long as the observed continuum is determined predominantly by the photospheric flux from the target. For all our targets, we find good agreement between the observed and model SEDs for λ > 4800 Å. As expected, the limit for a reliable continuum detection is a function of S/N. We conclude that all line measurements down to the Hβ line at 4861 Å are reliable.

Since all our targets are known to accrete, they might show excess continuum emission due to so-called veiling, which is produced in the accretion funnel and "fills" the photospheric absorption lines. Strong veiling is often seen in accreting T Tauri stars and is known to correlate with the accretion rates (e.g., Basri & Batalha 1990). Since the veiling is superimposed on the photospheric flux, it may prevent a reliable continuum measurement and thus influence the equivalent widths. Recent studies, however, have shown that the accretion rates steadily decrease with the mass of the central object. As a consequence, the average accretion rates of brown dwarfs are in the range of 10⁻¹¹ M⊙ yr⁻¹ (Muzerolle et al. 2003; Natta et al. 2004; Mohanty et al. 2005). Even in our sample of strongly accreting brown dwarfs, the mean accretion rate is probably only 10⁻¹¹ M⊙ yr⁻¹. At these low accretion levels, the veiling is safely below 10% at least for λ > 5500 Å (White & Basri 2003; Muzerolle et al. 2003) and thus negligible (and not detectable) in the red part of our spectra.

Veiling is a strong function of wavelength and in most cases becomes stronger in the blue spectral range. At 5000 Å it can be twice as strong as at 7000 Å, as shown for CTTSs (Alencar & Batalha 2002; Basri & Batalha 1990). Discrepancies between photospheric and observed SEDs for λ < 4800 Å, as we have detected in some cases, might therefore be caused by veiling, although this is unlikely given the fact that these discrepancies are strongest in spectra with very poor S/N, which clearly points to an instrumental effect. Therefore, our line measurements down to Hβ are probably not significantly affected by veiling.

### 3. Hα Variability

The dominant emission feature for all targets is the Hα line at 6562.8 Å. Our high-resolution spectra allow us to perform a detailed analysis of the line profile. In Figure 1 we present the average Hα profile T(v) for all six targets, calculated over the complete time series. All single spectra were normalized to the continuum level before averaging. In addition, we derived the normalized variance profile σ²(T) following Johns & Basri (1995) by calculating the variance in each velocity bin and normalizing by
This allows us to quantify the variability as a function of velocity. Both profiles are determined by averaging over a moving velocity window with a width of 10 km s\(^{-1}\); the step size is 1 km s\(^{-1}\).

To characterize the total amount of variability, Johns & Basri (1995) used the EW of the variance profile, i.e., the integral over \(\sigma^2(v)\). If we use this criterion, three of our targets are highly variable (2M 1207, 2M 1101, and ISO 217), but for the remaining three the \(\text{H}\alpha\) profile is more or less constant. Using the EW variance as a variability measurement implicitly assumes that the zero-variability level is constant with velocity, which is usually the case for stars with strong continua. In our spectra, however, the S/N changes drastically with velocity; it is much higher in the core of \(\text{H}\alpha\) than in the wings and the continuum. As can be seen from Figure 1, the normalized variance in the continuum (\(\sigma^2_{\text{C}}(v)\)) is in the range of 0.2–0.5 for our targets, implying a S/N of 1.5–2.5 in the continuum. Assuming Poisson noise, the expected \(\sigma^2_{\text{C}}(v)\) without any variability (i.e., the zero-variability level) can be estimated as \(\sigma^2_{\text{C}}(v) = \sigma^2_{\text{C,0}}(I_{1/2} I)^2\). This function is shown with dashed lines in Figure 1. As expected, the continuum is non-variable (by definition) because all spectra were normalized to the continuum before averaging. Using this zero-variability level,
it is now clear that all six targets show significant variability in the profile. As a better way to assess the total variability in Hα, we define the Hα variability index (VI), calculated by integrating the difference between the variance profile and the zero-variability level between −400 and 400 km s$^{-1}$. These values are given in the last column of Table 1.

Our targets show a large variety of Hα profiles, as apparent from the average profiles. The variance profiles exhibit in most cases a blueshifted and a redshifted peak at velocities between 50 and 150 km s$^{-1}$; sometimes a third central peak is visible. Three of our objects (2M 1207, 2M 1101, and ISO 217) show strong variability in this line with Hα VI > 25, whereas the remaining three targets are less variable. The variance profiles are in most cases quite different from the average profiles, demonstrating that the line variability is not only due to changes in the underlying continuum because in this case the two profiles would be very similar (see Johns & Basri 1995; Alencar & Batála 2002).

2M 1207 shows clear indications for an asymmetry on the red side, most likely caused by redshifted absorption features in parts of the time series (see SJB05). The variance profile clearly has three peaks, where most of the variability is produced in the blue wing of the line. 2M 1101 has only a minor asymmetry in the profile with a hint of a redshifted second peak. This is surprising, given the fact that the only available literature spectrum for this object shows a P Cygni–type Hα profile with very strong absorption in the blue wing (Muzerolle et al. 2005). In contrast to 2M 1207, here the variability in Hα is mainly in the red part of the line. ISO 217 has a double-peaked profile in all spectra, where the blue peak is significantly weaker than the red one. Both peaks also appear in the variance profile, but here they have about the same intensity. The remaining three targets have a single-peak profile, and the variance profiles do not show strong features. Cha Hα 1 and LS-RCrA 1 have a small central absorption dip, whereas ρ Oph-32 has a slight asymmetry on the blue side, which may be due to a blueshifted absorption feature.

As already discussed in §2.2, the 10% width can be used as a robust measurement of the accretion rate. Our time series show that the 10% width is much less sensitive to variability than the EW: Whereas the Hα EWs change by at least a factor of 2 in the time series, the 10% widths are constant within ±15% for four of six targets. For two objects, however, the 10% widths change significantly: For 2M 1207, we have already reported the strong variability in the 10% width in SJB05. We found an increase of the line width by 32% between the January and the March data, i.e., on a timescale of 6 weeks. In the March data, however, the 10%...
width is variable only to a much smaller extent. Strong line width variations are also seen for 2M 1101 (see Table 2): The 10% width roughly doubles between the third and fourth spectra, which are separated by only 8 hr. In the subsequent exposures, the line width gradually decreases. The strong increase coincides with the appearance of an asymmetric Hα profile (see above) and other accretion-related lines in the spectrum (see §4), and it is responsible for most of the variability observed for this target. We note that the third target that is highly variable in EW and profile, ISO 217, shows only minor changes in 10% width.

Another way of quantifying the asymmetry is to measure the 10% width for the blue and red sides of the profile separately. For the three targets without notable asymmetry in the line profile (Cha Hα 1, ρ Oph-32, and LS-RCr A 1), the difference between the "red" and "blue" 10% widths ranges from −20 to 20 km s$^{-1}$. The objects with asymmetric profiles and high variability in Hα, however, show strong deviations between red and blue line widths (see Fig. 4). For 2M 1207, the line is broader on the blue side in spectra with no clear second peak on the red side. As a consequence, the difference between the red and blue line widths varies over ~60 km s$^{-1}$ on timescales of a few hours. For 2M 1101 the data points are mostly negative with an average of ~−20 km s$^{-1}$, showing that the line is always broader in the red compared to the blue. This might be an indication for absorption in the blue part, which has been seen before for this object (Muzerolle et al. 2005). As already mentioned, there is no clear evidence for blue absorption from the profile shape alone. The third strongly variable target, ISO 217, shows significant asymmetry only in the first spectra, with a difference between the red and blue line widths of ~−40 km s$^{-1}$.

Two targets (2M 1207 and ISO 217) exhibit, at least in some cases, a double-peaked structure in Hα that we interpret as a superposition of a broad emission and an absorption component. To verify this hypothesis, we decompose the line for all clearly double-peaked spectra by adding two Gaussians, one for the emission and a second for the absorption component. This decomposition technique is a standard way of disentangling the effects of different components in line profiles (see, e.g., Johns-Krull & Basri 1997; Alencar & Batalha 2002). The feasibility of the method is demonstrated in Figure 5 for both objects.

For 2M 1207, the best fit closely matches the blue peak and is in reasonably good agreement with the red peak. The line wings are more intense than predicted by the Gaussian, but in general the fit is acceptable. We are, however, unable to obtain a plausible fit if we use two emission features. In the three double-peaked profiles, both components are clearly redshifted, where the emission is located at ~−22 km s$^{-1}$ and the absorption at ~−31 km s$^{-1}$. The line widths, EWs, and fluxes for the emission component are higher than those for the absorption component by a factor of 2–3 in all three spectra.

The decomposition works similarly well for ISO 217, for which we are also able to reproduce the line wings with the fit. The broad emission profile and the absorption feature are both blueshifted, but in contrast to the emission, which is constant in position within our uncertainties (average ~−8 km s$^{-1}$), the absorption feature clearly changes its position on timescales of days. It is
Fig. 4.—Asymmetry in the Hα profile, measured as the difference between the blue 10% width and the red 10% width.

Fig. 5.—Gaussian decomposition for 2M 1207 (left) and ISO 217 (right). Shown is the observed profile from an example spectrum (solid line) and the fit (dashed line), which is a co-addition of two Gaussians. The fit curve is shifted by 0.8 (left) and 0.1 (right) units for clarity.
located at $-4 \text{ km s}^{-1}$ on March 18, at $-15 \text{ km s}^{-1}$ on March 19, and at $-26 \text{ km s}^{-1}$ on March 26. The EW and flux of the emission are higher by a factor of $3-4$ than the values for the absorption.

4. EMISSION-LINE SURVEY

In the following we give a phenomenological description of the emission-line spectrum for each target separately. In addition, we check for correlations in the EWs of different lines. In general, all spectra show a strong Hα line (see § 3), and most of them exhibit other emission lines indicative of either accretion or outflows or both. All objects show variability in the emission lines, with the most dramatic changes observed for 2M 1207, 2M 1101, and ISO 217, as is also the case with Hα emission in § 3.

2M 1207.—As already discussed in SJBO5, the spectrum of 2M 1207 is dominated by a variety of accretion-related emission lines. It shows strong hydrogen Balmer lines in some cases down to H10 at 3800 Å, both He i lines, the Ca ii triplet, and O i. We do not see evidence for forbidden line emission in [S ii] or [O i] in our spectra. The intensity of the H Balmer and He i lines is strongly variable: the EWs change by a factor of 5–10. If we separate the January and March data, however, the variations in Hα, Hβ, and He i $\lambda$5875 are significantly smaller, indicating that most of the line variability is produced on timescales of a few weeks rather than days. Only He i $\lambda$6678 is not strongly enhanced in the March spectra. The Ca ii triplet lines are weakly detected in March, with more or less constant EWs of $\sim0.6$ Å, and all three lines show roughly the same intensity. Similarly, O i is only present in the March spectra. The EWs of all Balmer lines are correlated, where the best correlations are seen between neighboring lines in the series, e.g., for Hα versus Hβ and Hβ versus Hγ. He i $\lambda$5875 is correlated with all Balmer lines, except for two data points in March, where this line shows an enhancement. This “burst” is also seen in the high-energy Balmer lines but at a weaker level. Our March EWs in Hα are comparable to the literature values from Gizis (2002; EW of $\sim300$ Å), while the January data are closer to the two other more recent literature measurements (Gizis & Bharat 2004; Mohanty et al. 2003; EWs of 28 and 42 Å), indicating that the changes that we observe for 2M 1207 are not unique and that variability persists on timescales of years.

2M 1101.—Four of seven spectra for this brown dwarf show weak Hα emission with EW $\sim 15$ Å, but in three consecutive exposures on March 18 and 19 the EW is increased by a factor of $\sim6$ (see Fig. 2). This enhancement is also seen in Hβ and coincides with the appearance of Hγ. He i $\lambda$5875, and Ca ii lines, which are either very faint or not detected when Hα is weak. Hα and Hβ are clearly correlated. He i $\lambda$6678 is only seen in the first spectrum, and neither of our spectra shows a forbidden line or forbidden O i emission. We note that the only literature value for the 10% width measured by Muzerolle et al. (2005), 283 km s$^{-1}$, is higher than any of our measurements, whereas their EW is comparable to our values.

ρ Oph—32.—The Balmer lines and both He i lines are strong in all exposures, and their time evolution is comparable: All lines start on a high level, and their intensity is decreased in the last three data points. The best correlations are seen for Hα versus He i $\lambda$5875 and Hα versus Hβ. In addition, we observe weak Ca ii triplet emission, which shows a trend comparable to Hα. We do not detect emission in [S ii], [O i], and O i. Natta et al. (2004) published an EW of 48 Å, which is at the low end of our data points. Their 10% width of 248 km s$^{-1}$, however, is comparable to our values.

Cha Hα 1.—The Balmer lines and the Ca ii triplet are clearly detected in all spectra. Hα and Ca ii behave very similarly, with a maximum in the third spectrum and good correlations between the EWs. On the other hand, Hβ and Hγ have their maxima in the fourth spectrum. Both He i lines can only be seen in the last two exposures and thus behave in a manner comparable to the higher Balmer lines. Clearly, there are two groups of lines, where the second group (Hβ, Hγ, and He i) appears to react delayed by a few hours with respect to the first group (Hα and Ca ii). In neither of our spectra do we find emission in [S ii], [O i], or O i. All literature EW and 10% width measurements for Hα (Comerón et al. 2000; Luhan 2004; Natta et al. 2004; Mohanty et al. 2005) are consistent with our results, indicating that Cha Hα 1 does not show dramatic changes in the emission lines over timescales of a few years.

ISO 217.—The dominant lines are Hα and the Ca ii triplet, which are very strong in all exposures; the line ratio of the triplet is always close to 1 : 1 : 1. O i is clearly detected in all spectra and Hβ and Hγ in most of them. Both He i lines are visible in the fourth spectrum, coinciding with the maximum in the higher Balmer lines, and in two of five cases we also detect forbidden line emission in [S ii]. The EWs in Hα, Ca ii, and [S ii] behave comparably, with a maximum in the third spectrum. On the other hand, the higher Balmer lines, He i, and O i are strongest in the fourth exposure and are thus apparently delayed by $\sim1$ hr. Hα shows a clear correlation with Hβ and weak correlations with Ca ii and [S ii]. Our Hα EW and 10% measurements are consistent with literature values for this target (Luhan 2004; Muzerolle et al. 2005).

LS-RCrA 1.—In our time series we see the Balmer lines, Ca ii triplet, and [S ii] in all spectra and He i $\lambda$5875 and O i in most of them. He i $\lambda$6678, however, is not detected. The central Ca ii triplet line is clearly stronger than the other two, with an average line ratio of 1 : 2 : 1. The Ca ii and [S ii] EWs show the same trend: they increase in the first three spectra and drop off in the fourth exposure. In contrast, all other lines show an additional dip in the second spectrum. Correlations are seen for Ca ii versus [S ii], Hα versus Hβ, and Hα versus He i. Whereas the Hα 10% width is more or less constant and in agreement with literature values (Barrado y Navascués et al. 2004), the EW varies strongly, although we do not observe the extreme values of $\sim360$ and $\sim240$ Å reported by Fernández & Comerón (2001) and Barrado y Navascués et al. (2004).

5. DISCUSSION OF SPECIFIC TARGETS

In the previous two sections we gave a purely phenomenological description of the emission-line variability for our six targets. In this section, we interpret these results, aiming to understand the origin of the variability and the line profiles. This has to be done for each target separately, due to differences in their behavior. We would like to emphasize that many of the conclusions in the following subsections have to be somewhat speculative, since the large number of free parameters usually allows more than one possible interpretation for the spectral variability.

5.1. 2M 1207

2M 1207, which is a likely member of the $\sim8$ Myr old TW Hya association, has already been discussed in some detail in SJBO5. Therefore, here we wish to recall the scenario used in the previous paper to explain the emission-line variability. In SJBO5 we discussed the pronounced redshifted absorption component in the Hα profiles of 2005 March; this feature disappears and reappears on a $\sim1$ day timescale, comparable to the rotation period of the object. Since redshifted absorption indicates that we see cool, absorbing gas projected against hot material, we interpreted this behavior as a consequence of a nearly edge-on view, where the inclination between the rotational axis and the line of sight is $\geq 60^\circ$. As the object rotates, the accretion funnel moves through
the line of sight. When we see a strong redshifted absorption feature, we may be looking into the accretion column. This view is supported by the evolution of the flux ratios between Hα and higher Balmer lines: In spectra with a strong redshifted absorption component in Hα, the line fluxes in the higher Balmer lines tend to be decreased relative to Hα. Thus, if absorption is present, we see on average cooler gas than in the symmetric case, in which the hot spot is unobscured.

In addition, we found a significant increase in the Hα 10% width between the January and the March runs, indicating an accretion rate change by a factor of 5–10. We would like to stress that this burst of accretion on timescales of 6 weeks is seen not only in Hα; except for He i λ6678, all other emission lines become significantly stronger in the March spectra. In fact, most of the variability in the EW is produced on timescales of weeks rather than days. Thus, the strong profile changes seen on timescales of hours in March do not significantly affect the global accretion properties of the object.

The variance profile (see Fig. 1) of 2M 1207 clearly shows that most of the Hα variability is produced on the blue side of the profile with a strong peak at about ~100 km s⁻¹, although there are also peaks at zero and redshifted velocities. Since strongly blueshifted peaks in the variance profile indicate strong variability in the wind, this could simply mean that the increase seen in the 10% width is mainly due to a burst in a hot wind. On the other hand, although the total 10% width increases by about 70 km s⁻¹ between January and March, the difference between the red and blue parts of this value does not change significantly, as long as no second peak on the red side is visible (see Fig. 4). Therefore, the 10% width increases both on the red and on the blue side. The most likely interpretation is that we observe a change in the accretion rate accompanied by a hot wind.

In two spectra in March, some lines (He i λ5875, Hβ, and Hγ) show a brief enhancement over a few hours, but Hα is not unusually strong. The origin of this event is unclear; it might be due to a flare in a hot chromospheric region or another accretion-related burst.

5.2. 2M 1101

2M 1101, a candidate late-M-type object in the Cha I star-forming region, appears to be a nonaccreting, weakly active brown dwarf in four of seven spectra. In the remaining three spectra, however, we see a clear emission burst: the EW and 10% width in Hα strongly increase and reach levels sufficiently high to classify the object as an accretor. From the 10% width we estimate an accretion rate of about 10⁻¹¹ M₀ yr⁻¹ (Natta et al. 2004) during this burst. At the same time, other lines such as Ca ii, Hγ, and He i λ5875 appear in the spectra, which are at least partly related to the accretion process (see § 2.2). Furthermore, the Hα profile exhibits a red absorption feature, which is clear evidence for infalling material. Thus, based on the 10% width, the Hα profile, and the appearance of additional emission indicators, we argue that this event is related to accretion and not to, e.g., a flare of chromospheric activity.

The origin of this behavior is unclear. It is unlikely that we just see rotationally modulated emission, i.e., a strongly asymmetric accretion flow, because the increase in the line widths happens within a few hours, whereas the high level is maintained for at least 1 day. A rotational modulation would imply a more periodic behavior. To definitely exclude a rotational origin for the observed variability, a r sin i measurement (which is not possible based on our data; see § 2.3) would be desirable.

The alternate explanation is a sudden increase of the accretion rate by at least 1 order of magnitude. We have seen a similar increase for 2M 1207 (SJB05) on timescales of a few weeks; here we may have the first evidence for strong accretion rate changes on timescales of a few hours. Such behavior would be expected if the accretion is not continuous but rather clumpy, with a typical timescale in the range of a few days for the discontinuity. Whether or not this applies to 2M 1101 could be clarified by further time series observations with better sampling.

2M 1101 has been observed before with high-resolution spectroscopy by Muzerolle et al. (2005). Remarkably, Hα shows an extreme P Cygni profile with strong absorption on the blue side in their spectra from 2003 December to 2004 January. This has already been seen for some T Tauri stars with high mass-loss rates, and the usual interpretation is that the Hα emission is predominantly formed in the wind. In contrast with this literature spectrum, our spectra show only weak evidence for outflowing material as an asymmetry in the Hα line profile (see § 3). This implies that both the infall and outflow rates are highly variable with time, again underlying the need for more detailed follow-up observations.

5.3. ρ Oph-32

The object ρ Oph-32 has broad emission lines, yet no dramatic line profile and intensity variations are seen within our time series. The Hα width exceeds 200 km s⁻¹ in all spectra, implying accretion rates between 10⁻¹⁰ and 10⁻¹¹ M₀ yr⁻¹ (Natta et al. 2004), and the asymmetry in the profile, as well as the persistent emission in Ca ii, supports that ρ Oph-32 is an active accretor, in agreement with previous studies of this object.

In contrast to the literature spectrum, our spectra show no forbidden line emission and no redshifted absorption in Hα. Instead, our Hα profiles show a weak “shoulder” on the blue side, which may be due to a weak blueshifted absorption feature. Thus, there is only weak if any evidence for wind in our spectra. We conclude that outflow and accretion in ρ Oph-32 are probably variable on timescales of years but more or less constant over a few weeks.

An appealing interpretation for the lack of variability is a face-on geometry for the disk and the central object. In this case, rotation can be excluded as a major cause of variability, since we see always the same hemisphere of the object. The object ρ Oph-32 exhibits strong near- and mid-infrared color excess indicative of a disk (Persi et al. 2000; Natta et al. 2002), which also favors a pole-on view because the surface area of the disk visible to the observer is maximized when viewed face-on. An alternate explanation for the lack of variability would be a more or less symmetric field configuration implying axially symmetric accretion.

5.4. Cha Hα 1

The literature data for Cha Hα 1 are ambiguous with respect to the accretion status of this object. Comerón et al. (2000) and Luhman (2004) classified it as weakly accreting based on the Hα EW, but the low 10% widths measured by Natta et al. (2004) and Mohanty et al. (2005) led them to suggest that the Hα emission of Cha Hα 1 is predominantly caused by chromospheric activity. Our Hα profiles of Cha Hα 1 indeed resemble profiles of chromospherically active stars; it is more or less symmetric, is not extraordinarily broad, and exhibits a small central absorption dip, which is usually interpreted as self-absorption in the chromosphere. The 10% widths are clearly below the threshold for ongoing accretion, indicating that accretion probably does not contribute significantly to the emission-line flux. However, we detect He i λ6678 in emission in one of our spectra with an EW of 1.6 Å, clearly too high to be explained only by activity (see § 2.2). Moreover, the EW in Hα is very high compared with nonaccreting,
active objects with similar spectral type (Barrado y Navascués & Martin 2003). Thus, we cannot rule out that Cha H\(\alpha\) 1 is weakly accreting, in addition to chromospherically active. Near- and mid-infrared color excesses provide additional support for a disk surrounding this object (Persi et al. 2000; Kenyon & Gómez 2001; Jayawardhana et al. 2003a).

There are at least two possible ways to explain why we observe two different groups of emission lines (see § 4). Let us first assume that all emission is produced by chromospheric activity. In this scenario, the object may harbor two large active regions in the chromosphere with different temperatures. One of these regions is mainly responsible for the “high-temperature lines” such as He\(\text{i}\) and the higher Balmer features. The second region is cooler and thus does not contribute to the high-energy features. H\(\alpha\) and Ca \(\text{i}\) are generated in both regions. The “delay” seen in the time evolution of both groups of lines can be explained with a phase difference between the two regions. A similar scenario is possible for the case in which Cha H\(\alpha\) 1 is weakly accreting. Here the object would have a hot accretion flow, which could be responsible for the emission in He\(\text{i}\), H\(\beta\), and H\(\gamma\), and an active chromospheric spot. If this active region appears a few hours earlier on the visible hemisphere than the accretion hot spot, we would expect a delay in the high-energy lines.

In both scenarios, the variability in the emission lines would be due to rotation. More evidence for this interpretation comes from Figure 4, where we see a hint of a period in the evolution of the asymmetry in H\(\alpha\). This is expected because both accretion and activity features should change from blue- to redshifted as they move through the line of sight. From the rotational velocity given by Joergens & Guenther (2001), we derive an upper limit for the rotation period of 3.1 days (using radii from Baraffe et al. 1998). The spectral variability implies a period in the range of a few days, consistent with the observed rotational velocity.

We tentatively conclude that the modest variability of Cha H\(\alpha\) 1 is due to rotation. This would also explain the large discrepancy in the literature values for the H\(\alpha\) EW, which were derived from single spectra, because the emission-line intensity would depend strongly on the rotational phase. The interpretation of rotationally modulated emission lines implies an asymmetry in the chromospheric active regions and (perhaps also) in the accretion geometry, as well as a nonnegligible inclination between the rotational axis and the line of sight.

5.5. ISO 217

This Cha I object at the substellar boundary is known to have intense and strongly asymmetric H\(\alpha\) emission (Luhman 2004; Muzerolle et al. 2005). Our spectra confirm this finding; they show broad and asymmetric H Balmer features, clearly indicative of ongoing accretion. Forbidden line emission provides evidence for outflowing material as well, as also implied by the presence of an H\(\alpha\) absorption feature that appears clearly blueshifted in most spectra. Correlations between the EW in [S \(\text{ii}\)], H\(\alpha\), and Ca \(\text{i}\) show that winds influence H\(\alpha\) and Ca \(\text{i}\) somewhat, whereas the “high-energy” lines that do not show any connection to [S \(\text{ii}\)] are probably dominated by accretion.

ISO 217 clearly shows variability in both accretion- and wind-related features. In comparison to 2M 1207 and 2M 1101, however, the changes in EW and 10% width are moderate; i.e., the changes in the accretion rate are well below an order of magnitude. Given our sparse sampling, this does not, of course, exclude the possibility of more dramatic changes in its accretion behavior. The variability of ISO 217 could be due to rotation, since it occurs on timescales of a few hours to days, comparable to typical rotation periods for such objects.

As can be seen in Figure 1, the variability in H\(\alpha\) appears to be dominated by the emission wings and thus the high-velocity infalling gas. In addition, there is a variation of the relative strengths of the two peaks, which is probably a consequence of a velocity change in the wind-generated absorption component. As we have shown in our decomposition procedure, the absorption moves toward the blue side within our time series by about 20 km s\(^{-1}\) (§ 3), which gradually suppresses the flux on the blue side of the profile, leading to an asymmetry of the peaks.

Perhaps the most interesting feature in our time series is the short time delay of \(~1\ hr\) between He\(\text{i}\) and higher Balmer lines and H\(\alpha\), Ca \(\text{i}\), and [S \(\text{ii}\)]. As argued above, the difference between the two groups of lines is that the second group is either exclusively or partly formed in outflows. Thus, the time delay may be explained by a time lag between wind and accretion. One explanation for such behavior is a coupling between the outflow and infall rates, as already seen in T Tauri stars (e.g., for DF Tau; Johns-Krull & Basri 1997). As in DF Tau, the wind-related feature in ISO 217 increases before the accretion-related lines. This is expected in a scenario in which the wind originates in somewhat cooler regions at the inner edge of the disk, whereas the high-energy accretion features are formed very close to the surface of the object. In this case, the time lag would correspond to the time needed for the infalling material to travel from the inner disk region, where the wind forms, to the object. Assuming free-fall velocity, the distance between the inner disk boundary (in the magnetospheric accretion scenario, the distance at which the disk is truncated by the magnetosphere) and the surface of the object would then be in the range of \(5 \times 10^3\) km, or about one object radius, a value that is not implausible for substellar objects (Muzerolle et al. 2003).

A time lag between an observed increase in wind and accretion can also be explained by rotation if wind and accretion regions are both asymmetric and spatially offset. Since the wind is believed to be collimated by the magnetic field, the effect could be enhanced if the axis of the magnetic field is inclined with respect to the rotational axes, introducing an additional asymmetry to the system.

5.6. LS-RCrA 1

The striking emission-line spectrum of this object at the substellar boundary has been reported by Fernández & Comerón (2001) and Barrado y Navascués et al. (2004). It shows all spectroscopic signs of ongoing accretion, as well as evidence for mass outflow. This is confirmed by our data: The H\(\alpha\) 10% width is well above the limit between accretors and nonaccretors in all spectra, and other indicators of accretion and outflow are also seen. Based on the 10% width, we estimate an accretion rate of about \(10^{-10} M_\odot\ yr^{-1}\), which is at the lower end of the range given in the literature (Barrado y Navascués et al. 2004).

The Ca \(\text{i}\) triplet shows a clear deviation from the 1 : 1 : 1 line ratio expected for an accretion-dominated origin; furthermore, it is correlated with [S \(\text{ii}\)]. Thus, the Ca \(\text{i}\) emission is probably at least partly formed in the wind and not only in the accretion flow. H\(\alpha\), on the other hand, behaves in the same manner as other accretion-related features, and it shows no evidence for blue-shifted absorption, indicating that the line originates primarily in the accretion flow.

LS-RCrA 1 is one of the less variable targets in our sample; the H\(\alpha\) line is more or less symmetric and does not show significant variability in the profile shape or the 10% width. This may indicate either that the system is seen close to face-on or that the accretion flow is fairly symmetric; both scenarios would avoid rotational modulation. Based on our time series, we favor the latter
explanation because we see strong forbidden line emission but no significant wind signature in Hα, which may imply that the Hα and forbidden line emission regions are spatially offset. With a face-on geometry, it is more likely that the [S ii]- and Hα-emitting regions overlap in the line of sight, producing a wind signature in Hα. On the other hand, with the disk seen close to edge-on, it is much easier to imagine that the outflow is seen against the background sky and not against the accretion flow and the object itself and is thus spatially offset from the Hα-emitting regions, which would explain the lack of blueshifted absorption in Hα.

The published studies are inconclusive about the disk orientation of LS-RCrA 1. On one hand, there is some evidence in the literature for an edge-on geometry for LS-RCrA 1 because (1) the object shows no color excess in the near-infrared, although it is accreting, (2) it appears to be underluminous, as would be expected if the object is obscured by the disk, and (3) the outflow signature is very prominent (see Fernández & Comerón 2001; Barrado y Navascués et al. 2004). However, the forbidden line emission is asymmetric and blueshifted, indicating that the receding jet may be obscured by the disk, which would argue against an edge-on scenario (Fernández & Comerón 2005). Thus, based on currently available data, it is not possible to distinguish reliably between face-on and edge-on geometries.

6. GENERAL IMPLICATIONS

Although our six targets are rather diverse in terms of their accretion properties, some general conclusions are possible. We present in this paper the first dedicated spectroscopic variability study for accreting brown dwarfs, albeit with sparse sampling for most objects. Perhaps the most important result from this program is that accreting brown dwarfs, similar to T Tauri stars, are strongly variable, both in broadband photometric time series (Scholz & Eisloeffel 2004, 2005) and in their emission-line spectra. Variability was originally the main observational feature of T Tauri stars, leading to a systematic study of these objects. It is therefore worth confirming that variability persists down to substellar masses. This completes the recently emerged picture of young brown dwarfs as very low mass T Tauri-like objects that share many properties with accreting stars.

The broad emission lines of accreting BDs show a large variety of shapes; we observe profiles ranging from double-peaked to more or less symmetric, as is the case for more massive stars. The intensity and profile shapes are variable on timescales ranging from hours to years, again in total agreement with CTTSs. One implication from this finding is a cautionary note: since accretion-related properties can be highly variable, investigations based on a single spectrum or data point are not particularly reliable. To study accretion properties, we have to work either with large samples of objects (to average over the variability) or with time series.

One particularly important recent finding, which may be strongly influenced by variability, is the relationship between object mass and accretion rate. White & Basri (2003) pointed out a positive correlation between M and ˙M, which has been specified more recently as ˙M \propto M^2 (Natta et al. 2004; Mohanty et al. 2005; Muzerolle et al. 2005). This relationship has been established using a fairly large number of objects, and in all samples the accretion rates in a given mass bin scatter by about 1 order of magnitude. In fact, it is only possible to see the accretion rate versus mass correlation when substellar objects are included, and thus the object masses cover more than 1 order of magnitude. (Otherwise, the scatter is too large.) The derived relationship has been interpreted recently as a direct consequence of Bondi-Hoyle accretion, implying that the accretion process in the inner disk is governed by the large-scale environment of the parent cloud (Padoan et al. 2005). Although this approach is able to reproduce the observed correlation, the scatter around the correlation remains unexplained.

Variability provides a straightforward solution for this problem. Two of six targets (2M 1207 and 2M 1101) in our sample show accretion rate variations by about 1 order of magnitude. Since we intentionally selected objects in which we expected to see strong changes, these may be extreme cases of accretion rate variability. On the other hand, given our sparse sampling, our variability estimates should be considered only as lower limits; we cannot exclude that our targets show larger accretion rate changes on longer timescales. Thus, we conclude that brown dwarfs can in some cases show accretion rate variations of at least 1 order of magnitude.

In the Bondi-Hoyle scenario, all objects with a given mass should have the same (average) accretion rate. Due to variability, the accretion rates based on single spectra will scatter by about 1 order of magnitude around this average value. Additional noise may be introduced by geometry and obscuration effects. Thus, the scatter observed in the mass-accretion rate relationship is not surprising—and it demonstrates that variability studies are an important complement to understand the accretion behavior of BDs.

Variability information can be used to constrain the nature of accretion and winds/outflows in substellar objects, in particular to probe the magnetospheric accretion scenario, which allows for asymmetric accretion and winds, in contrast to spherical infall. In general, there are two ways to produce variability in the emission lines: either the accretion and/or the wind is not steady, which may occur in a scenario of stochastic, clumpy flows and does not necessarily require magnetic funneling, or the magnetic field, which funnels the flow, is highly asymmetric, leading to rotationally modulated accretion and wind. It is possible to distinguish between the two scenarios by the shape of the emission lines—if the features look asymmetric and the profiles change with time, we would expect an asymmetric field geometry. That, in turn, would suggest nonspherical accretion and thus provide indirect evidence for magnetospheric accretion. We note that this argument is not reversible: the absence of emission-line variability or profile asymmetry does not rule out asymmetric accretion.

Among our targets, at least two show strong emission-line variability, both in intensity and profile shape, and an asymmetric Hα feature (2M 1207 and ISO 217). A third (2M 1101) exhibits an asymmetric profile in parts of the time series and a strong accretion burst, but as argued in § 5 the timescales of this event are barely compatible with rotational modulation. Thus, at least for one-third of our objects, an asymmetric flow geometry is required to explain the emission-line behavior, providing a strong case for magnetic funneling of accretion and winds.

Based on the available data, we can obtain an estimate of the magnetic field strengths necessary for magnetospheric accretion in substellar objects, using the relationship given by Hartmann (2002, eq. [1]) and scaling it from the stellar regime to the properties of BDs. As a cautionary note, we would like to add that this should only be considered as an order-of-magnitude estimate, mainly because of the limitations of the equation in Hartmann (2002). For example, this relationship assumes a dipolar field geometry, whereas there is clear observational evidence for more complex field structure in T Tauri stars (e.g., Johns-Krull & Gafford 2002). Given the absence of magnetic field measurements for brown dwarfs, a first estimate of the field strength—albeit crude—is still useful.

We approximate the mass of a typical BD to be about \( \frac{3}{2} M_J \) and the radius to be about \( \frac{1}{2} R_\odot \) (at 1 Myr). In addition, we scale
the accretion rate following $\dot{M} \propto M^2$ and assume that the radius at which the disk is truncated by the magnetic field is (in units of the object radius) more or less constant with mass. The latter assumption is in line with the results from profile modeling by Muzerolle et al. (2003), in which reasonable agreement between observed and modeled profiles can be achieved without major mass dependency in the (relative) size of the magnetosphere. With these prerequisites, we estimate that the ratio of the surface magnetic field strength on accreting BDs and stars is $\sim 0.6$. Since T Tauri stars have in many cases magnetic fields of several kilogauss (e.g., Symington et al. 2005), this result indicates that young substellar objects may host magnetic fields in the range of 1 kG. Although the uncertainties in the given estimate are considerable (see above), we tentatively conclude that magnetic field strengths for BDs are probably of the same order of magnitude as for stars.

7. CONCLUSIONS

This paper contains the first spectroscopic variability study for young accreting brown dwarfs. We obtained, depending on the target, 4–13 high-resolution spectra using the Magellan Clay 6.5 m telescope, covering timescales from a few hours to several weeks. Our targets are six substellar objects in nearby star-forming regions, for which signs of accretion had been noted in previous studies. We measured line widths for the most prominent emission lines, related to either accretion, winds, or both. In all spectra, the continuum is faint but not seriously affected by incomplete background subtraction or accretion veiling.

All our targets are variable in the emission lines. The most dramatic changes are seen for 2M 1207, 2M 1101, and ISO 217, whereas the remaining targets ($\rho$ Oph-32, Cha Hα 1, and LS-RCrA 1) show significantly less variability. The most prominent line in all cases is the Hα feature. Our targets exhibit a variety of Hα profiles, similarly to accreting T Tauri stars. Two objects (2M 1207 and ISO 217) have strongly asymmetric and double-peaked profiles at least in parts of the time series, produced by a superposition of broad emission and either a red- (2M 1207) or blueshifted absorption feature. 2M 1101 also exhibits a weak redshifted absorption feature in parts of our time series.

Strong changes in the Hα 10% width are seen in 2M 1207 and 2M 1101, indicating variations in the accretion rate on timescales of weeks (2M 1207) and hours (2M 1101). In both cases, this finding is supported by additional accretion indicators in the spectrum. For 2M 1101, the variations are consistent with a scenario of nonsteady, clumpy accretion. We also see evidence for strong variability in the outflow rate in at least three targets (2M 1101, $\rho$ Oph-32 and ISO 217), particularly if we compare our results with literature data. In two cases (2M 1207 and ISO 217) there are indications for a coupling between infall and outflow rate changes. In some cases the variability is best explained by rotational modulation of the emission-line flux. For LS-RCrA 1, the variability characteristic supports a close to edge-on view of the disk.

One important result from this study is a cautionary note: given that most accreting targets are strongly variable, studies of accretion-related properties have to be based either on large samples or on time series. One example is the recently found accretion rate versus mass relationship, which shows a suspiciously large scatter. We demonstrate that it is possible to explain this noise by taking into account variability information.

For at least two of six targets, we have to assume asymmetric accretion flows to interpret the emission-line shape and variations. This indirectly supports funneling of the accretion, as predicted in the magnetospheric accretion scenario for T Tauri stars, and thus provides evidence that this scenario also applies to brown dwarfs. This implies the existence of large-scale magnetic fields, which may have approximately kilogauss field strengths, in accreting substellar objects.

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REFERENCES

Alencar, S. H. P., & Batalha, C. 2002, ApJ, 571, 378
Allard, F., Hauschildt, P. H., & Schwenke, D. 2000, ApJ, 540, 1005
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
———. 2002, A&A, 382, 563
Barrado y Navascués, D., & Jayawardhana, R. 2004, ApJ, 615, 840
Barrado y Navascués, D., & Martín, E. L. 2003, AJ, 126, 2997
Barrado y Navascués, D., Mohanty, S., & Jayawardhana, R. 2004, ApJ, 604, 284
Basri, G., & Batalha, C. 1990, ApJ, 363, 654
Basiir, G., Edwards, S., & Kwan, J. 2001, ApJ, 551, 1037
Bouvier, J., et al. 1999, A&A, 349, 619
———. 2003, A&A, 409, 169
Comeron, F., Neuhäuser, R., & Kaas, A. A. 2000, A&A, 359, 269
Doppmann, G. W., Greene, T. P., Covey, K. R., & Lada, C. L. 2005, AJ, 130, 1145
Fernández, M., & Comeron, F. 2001, A&A, 380, 264
———. 2005, A&A, 440, 1119
Fernández, M., Ortiz, E., Eiroa, C., & Miranda, L. F. 1995, A&AS, 114, 439
Gizis, J. E. 2002, ApJ, 575, 484
Gizis, J. E., & Bharat, R. 2004, ApJ, 608, L113
Gizis, J. E., Reid, I. N., & Hawley, S. L. 2002, AJ, 123, 3356
Graham, J. A., & Heyer, M. H. 1988, PASP, 100, 1529
Hartmann, L. 2002, ApJ, 566, L29
Hartmann, L., Hewett, R., & Calvet, N. 1994, ApJ, 426, 669
Herbst, W., Herbst, D. K., Grossman, E. J., & Weinstein, D. 1994, AJ, 108, 1906
Hirth, G. A., Mundt, R., & Solf, J. 1997, A&AS, 126, 437
Jayawardhana, R., Ardila, D. R., Stelzer, B., & Haisch, K. E. Jr. 2003a, AJ, 126, 1515
Jayawardhana, R., Mohanty, S., & Basri, G. 2002, ApJ, 578, L141
———. 2003b, ApJ, 592, 282
Joergens, V. 2006, A&A, in press
Joergens, V., & Guenther, E. 2001, A&A, 379, L9
Johns, C., & Basri, G. 1995, AJ, 109, 2800
Johns-Krull, C. M., & Basri, G. 1997, ApJ, 474, 433
Johns-Krull, C. M., & Gafford, A. D. 2002, ApJ, 573, 685
Kenyon, S. J., & Gómez, M. 2001, AJ, 121, 2673
Königl, A. 1991, ApJ, 370, L39
Luhman, K. L. 2004, ApJ, 602, 816
Luhman, K. L., Stauffer, J. R., Muench, A. A., Rieke, G. H., Lada, E. A., Bouvier, J., & Lada, C. J. 2003, ApJ, 593, 1093
Matt, S., & Pudritz, R. E. 2005, MNRAS, 356, 167
Mitskevich, A. S., Natta, A., & Grinin, V. P. 1993, ApJ, 404, 751
Mohanty, S., Jayawardhana, R., & Barrado y Navascués, D. 2003, ApJ, 593, L109
Mohanty, S., Jayawardhana, R., & Basri, G. 2005, ApJ, 626, 498
Mohanty, S., Jayawardhana, R., Natta, A., Fujishoshi, T., Tamura, M., & Barrado y Navascués, D. 2004, ApJ, 609, L33
Muzerolle, J., Hillenbrand, L., Calvet, N., Briceño, C., & Hartmann, L. 2003, ApJ, 592, 266
Muzerolle, J., Luhman, K. L., Briceño, C., Hartmann, L., & Calvet, N. 2005, ApJ, 625, 906
Natta, A., Testi, L., Comerón, F., Oliva, E., D’Antona, F., Baffa, C., Comoretto, G., & Gennari, S. 2002, A&A, 393, 397
Natta, A., Testi, L., Muzerolle, J., Randich, S., Comeron, F., & Persi, P. 2004, A&A, 424, 603
Padoan, P., Kritsuk, A., Norman, M. L., & Nordlund, A. 2005, ApJ, 622, L61
Pasucci, I., Apai, D., Henning, Th., & Dullemond, C. P. 2003, ApJ, 590, L111
Persi, P., et al. 2000, A&A, 357, 219
Reipurth, B., Bally, J., Graham, J. A., Lane, A. P., & Zealey, W. J. 1986, A&A, 164, 51
Reipurth, B., Pedrosa, A., & Lago, M. T. V. 1996, A&AS, 120, 229
Romanova, M. M., Ustyugova, G. V., Koldoba, A. V., Wick, J. V., & Lovelace, R. V. E. 2003, ApJ, 595, 1009
Saar, S. H., Huovelin, J., Osten, R. A., & Shehberakov, A. G. 1997, A&A, 326, 741
Scholz, A., & Eisloffel, J. 2004, A&A, 419, 249
———. 2005, A&A, 429, 1007
Scholz, A., Jayawardhana, R., & Brandeker, A. 2005, ApJ, 629, L41 (SJB05)
Shu, F., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994, ApJ, 429, 781
Symington, N. H., Harries, T. J., Kurosawa, R., & Naylor, T. 2005, MNRAS, 358, 977
Uzdensky, D. A. 2002, ApJ, 572, 432
Whelan, E. T., Ray, T. P., Bacciotti, F., Natta, A., Testi, L., & Randich, S. 2005, Nature, 435, 652
White, R. J., & Basri, G. 2003, ApJ, 582, 1109