DISCOVERY OF A BIPOLAR OUTFLOW FROM 2MASSW J1207334−393254, A 24 $M_{\rm Jup}$ BROWN DWARF

E. T. Whelan,[1] T. P. Ray,[1] S. Randich,[2] F. Bacciotti,[3] R. Jayawardhana,[2] L. Testi,[2] A. Natta,[2] and S. Mohanty[4]

ABSTRACT

The 24 $M_{\rm Jup}$ brown dwarf 2MASS 1207−3932 has for some time been known to show clear signs of classical T Tauri–like accretion. Through analysis of its oxygen forbidden emission, we have discovered that it is driving a bipolar outflow. Blue- and redshifted components to the [O I] λ6300 forbidden emission line are seen at velocities of −8 and +4 km s^{-1} (on either side of the systemic velocity). Spectroastrometry recovers the position of both components relative to the brown dwarf at ∼0.08″ (in opposing directions). A position-velocity diagram of the line region supports the spectroastrometric results. The Hα and He I λ6678 lines were also analyzed. These line regions are not offset with respect to the continuum, ruling out the presence of spectroastrometric artifacts and underlining the validity of the [O I] λ6300 results. The low radial velocity of the outflow and the relatively large offsets are consistent with 2MASS 1207−3932 having a near edge-on disk as proposed by Scholz et al. 2MASS 1207−3932 is now the smallest mass galactic object known to drive an outflow. The age of the TW Hydrae association (∼8 Myr) also makes this one of the oldest objects with a resolved jet. This discovery not only highlights the robustness of the outflow mechanism over an enormous range of masses but also suggests that it may even be feasible for young giant planets with accretion disks to drive outflows.

Subject headings: ISM: jets and outflows — stars: low-mass, brown dwarfs — stars: mass loss — techniques: high angular resolution

1. INTRODUCTION

Recent studies have highlighted the numerous ways in which young brown dwarfs (BDs) bear a striking resemblance to classical T Tauri stars (CTTSs; Jayawardhana et al. 2003b; Natta et al. 2004; Whelan et al. 2005; Scholz & Jayawardhana 2006). This comparison not only provides information relevant to theories of BD formation but also allows the validity of the accretion/ejection models for the formation of solar-mass stars to be tested in the substellar domain. Emphasis has been on probing accretion (Jayawardhana et al. 2003a; Natta & Testi 2001). While such studies point to T Tauri–like infall in BDs, relatively little is known about their outflow activity. Outflows in CTTSs are directly related to magnetospheric infall (Hartigan et al. 1994; König & Pudritz 2000); hence, it is probable that BDs demonstrating strong accretion will drive jets.

The Hα 10% line width criterion (full width of the line at 10% of the peak emission) used to distinguish accreting T Tauri stars from those where the line emission is primarily due to chromospheric activity has been successfully applied to BDs (White & Basri 2003; Jayawardhana et al. 2003b). A BD with a Hα 10% width >200 kms^{-1} is accepted as a strong accretor. High-resolution spectroscopic observations subsequently found that many of the accreting BDs also have forbidden emission lines (FELs; Fernández & Comerón 2001; Muzerolle et al. 2003). The FELs of CTTSs are important outflow tracers, and their discovery provided the first hint that accreting BDs could also power outflows. Direct imaging has proven very difficult, as expected on theoretical grounds (Masciadri & Raga 2004). An alternative approach adopted by Whelan et al. (2005) is to search for substellar outflows through the spectroastrometric analysis of FELs. Using this method, the first BD outflow, driven by ρ Oph 102, was discovered. Here the detection of a

faint bipolar jet from a second strongly accreting BD, 2MASS 1207−3932 (hereafter 2MASS 1207), using the ESO VLT is reported. These observations are part of an important ongoing study to search for outflows from BDs.

That such outflows are present is physically reasonable since it seems unlikely that the outflow mechanism has anything to do with the eventual triggering of fusion in the core. Moreover, jets from the very low mass stars Par Lup 3-4 (Fernández & Comerón 2005) and ESO Hα 574 (Comerón & Reipurth 2006) have been found recently. In addition, a molecular outflow from the L1014 dense low-luminosity core and possible BD precursor has been found by Bourke et al. (2005).

2. TARGET, OBSERVATIONS, AND ANALYSIS

2MASS 1207 was identified by Gizis (2002) and Mohanty et al. (2003) as a substellar member of the TW Hydrae association. Given the age of the association (∼8 Myr), the evolutionary tracks of Chabrier et al. (2000) were then used to estimate a mass of ∼35 $M_{\rm Jup}$ for this BD. More recently, the mass has been revised downward to 24 ± 6 $M_{\rm Jup}$ (Chauvin et al. 2005; Mohanty et al. 2007). The nature of this BD as a strong accretor was clearly evident from early observations. Mohanty et al. (2003) reported bright asymmetric Hα emission, with a full width at 10% of the peak flux, of >200 km s^{-1}. The new optical spectra presented here lead to a value of ∼320 km s^{-1}. Mohanty et al. (2005) were the first to observe the [O I] λ6300 line in the spectrum of 2MASS 1207, suggesting that it could be driving an outflow.

2MASS 1207 is known for its line variability. Scholz et al. (2005) studied its Hα emission over a period of 6 weeks and reported a change by a factor of 5–10 in the accretion rate during that time. They also used the shape and variability of the Hα line to infer a near edge-on orientation for the accretion disk. The prominent redshifted absorption feature in the Hα line (see Fig. 1b) is strongly dependent on the inclination i, between the rotational axis and the line of sight (Hartmann et al. 1994). The absorption feature should only be observed when the disk is seen close to edge-on (i.e., $i \geq 60°$; see Scholz et

---

[1] School of Cosmic Physics, Dublin Institute for Advanced Studies, Dublin 2, Ireland.
[2] Osservatorio Astrofisico di Arcetri, Firenze 50125, Italy.
[3] Department of Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada.
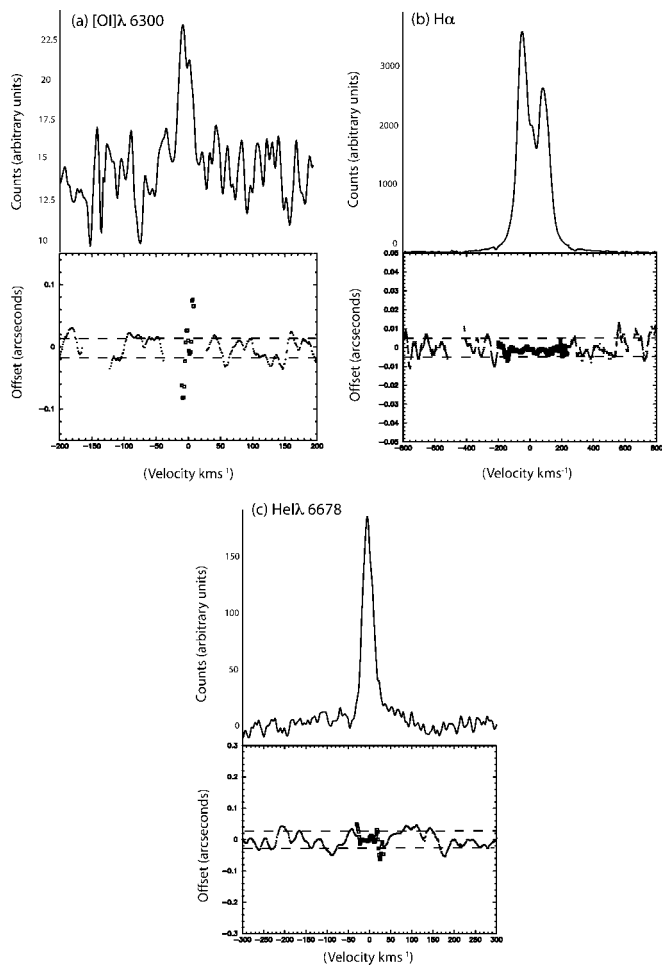[4] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138.

Fig. 1.—Offset-velocity diagrams in the vicinity of the [O I] λ6300, Hα, and He I lines. The line profiles are an average of three pixel rows in the spatial direction centered on the continuum. Note that the continuum has not been subtracted. The dashed lines delineate the $\pm 1\,\sigma$ error envelope for the centroid position of the continuum. As explained in the text, the line and continuum centroid errors are the same in all cases. In particular, for Hα the spectrum is smoothed so that the error in the centroid position of the wing emission is comparable to that for the continuum. The error decreases for the line peak region, as is clear in (b). The redshifted absorption feature in the Hα line is a signature of infall. The bipolar offset in [O I] λ6300 reveals the presence of an outflow. No offsets are measured in the Hα and He I lines, as expected, ruling out the possibility of spectroastrometric artifacts. Finally, the gaps in the position of the continuum blueward of the [O I] λ6300 and Hα lines mark the position of night-sky lines. The night-sky lines have been removed from the line profiles, and as found by Whelan et al. (2005), the presence or absence of these sky lines has no effect on the spectroastrometric results.

al. 2005 and Scholz & Jayawardhana 2006 for further details). Such a geometry suggests that an outflow will be in the plane of the sky. Finally, 2MASS 1207 is a binary with a planetary mass companion (Chauvin et al. 2004, 2005). To summarize, 2MASS 1207 is an ideal candidate to include in our search for outflows driven by young BDs. It is a strong accretor with known [O I] λ6300 emission.

High-resolution ($R = 40,000$) cross-dispersed spectra of 2MASS 1207 (CD3 disperser, spectral range 4810–6740 Å) were obtained with the UV-Visual Echelle Spectrograph (UVES; Dekker et al. 2000) on the ESO VLT-UT2, on 2006 May 16. The results presented in this Letter represent the sum of two 45 minute exposures with a 1″ slit. The seeing was 0.6″, and the spatial sampling was 0.182″ pixel^{-1}. The data were reduced using standard IRAF routines, and the two-dimensional spectra obtained were smoothed using an elliptical Gaussian

filter of FWHM = 0.12 Å × 0.22″. The Gaussian smoothing improved the signal-to-noise ratio (S/N) and effectively decreased the spectral and spatial resolution to $R \sim 8000$ and 0.7″, respectively. The night-sky lines were then removed. All velocities are quoted with respect to the systemic velocity of 2MASS 1207, which is measured from the Li I λ6708 line to be $+2$ km s^{-1}, in the LSR frame. The final stage in the analysis was to apply the technique of spectroastrometry to the smoothed spectra.

For the majority of protostars with jets, the FEL regions of their spectra are very obviously spatially extended, particularly at high velocities (e.g., the FELs of the CTTS DG Tau trace a $\sim$12″ knotty jet; Whelan et al. 2004). When, however, the emission is very compact and close to the source, specialized methods have to be used to probe its nature. In particular, spectroastrometry can investigate, through Gaussian fitting, the offset of emission-line features smaller than the seeing disk of the observation. The result of this technique is an offset-velocity diagram with the displacement of a spectral feature, e.g., the [O I] λ6300, line shown as a function of velocity and relative to the continuum centroid of the object (Bailey 1998; Takami et al. 2001; Whelan et al. 2004, 2005). Figure 1 shows the results of the spectroastrometry (see Whelan et al. 2005 for a thorough discussion of the method).

3. RESULTS

The [O I] λλ6300, 6363 lines are the only "traditional" FEL tracers seen in the UVES spectrum. A position-velocity (PV) diagram of the smoothed [O I] λ6300 spectrum is presented in Figure 2. Blue- and redshifted emissions are observed at velocities of ~ -8 and $+4$ km s^{-1}, respectively, and a relative displacement between the two parts of the line is apparent. Also, the relatively very small radial velocity of the outflow is consistent with the near edge-on disk hypothesis for 2MASS 1207. We observe the [O I] λ6300 line at the same velocity as reported by Mohanty et al. (2005). However, due to the use of a larger telescope (8 m as opposed to 6.5 m) and a longer exposure time, we retrieved more detailed kinematic information. Note also that Scholz et al. (2005) failed to detect forbidden emission in the spectrum of this BD. Again, this is due to the use of a smaller telescope and the larger spectral resolution of their observations ($R \sim 60,000$). The [O I] night-sky line has been removed here, and there is emission (at ~ -35 km s^{-1}) on the farside of the night-sky line position. This is probably also associated with the blueshifted outflow.

The results of a spectroastrometric analysis of the smoothed spectrum is shown in Figure 1a. The first step in this analysis is to map the position of the BD through Gaussian fitting of the spatial profile of the continuum. Since the optical continuum emission from a BD is by definition much weaker than for a CTTS, it is necessary to bin or smooth the BD continuum in order to increase the spectroastrometric accuracy. The error in the spectroastrometric analysis depends strongly on the S/N and is given by $\sigma_{centroid}$ = seeing (mas)$/2.3548\sqrt{N_p}$, where N_p is the number of detected photons. Once the continuum is mapped, it is subtracted, and the spatial profile of the pure line emission analyzed. An approach first adopted by Whelan et al. (2005) was to bin the continuum and line emission in such a way so as to ensure that a comparable number of photons are sampled at each point. In other words, the spectroastrometric accuracy achieved in the line and continuum is comparable. Here in the same way the continuum emission and the [O I] λ6300 line emission are smoothed so that the spectroastrometric errors in both regions are the same. The blue- and redshifted com-
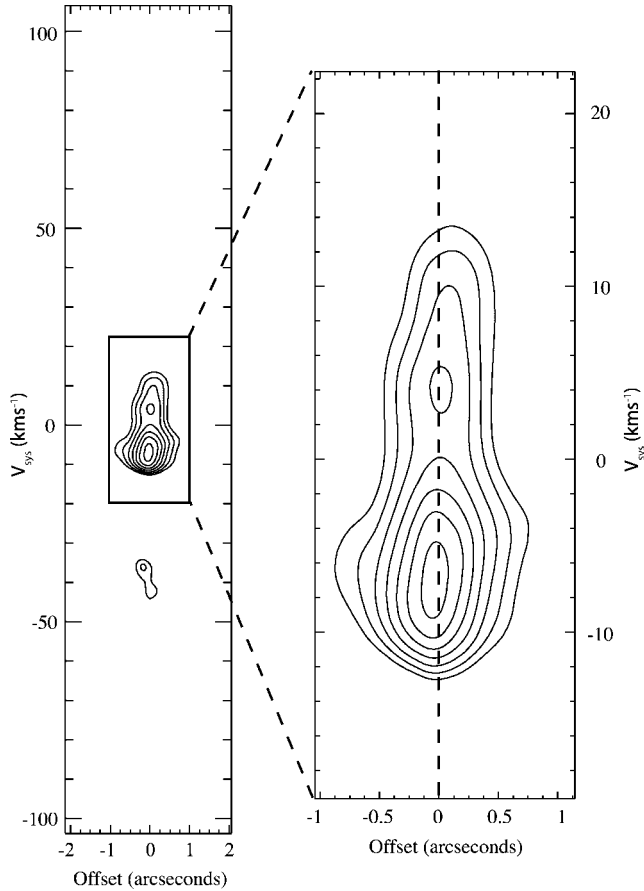
FIG. 2.—Continuum-subtracted PV diagram of the [O I] λ6300 line in 2MASS 1207. Here the spectrum was smoothed in both the spectral and spatial directions using an elliptical Gaussian function of FWHM = 0.12 Å × 0.22″. The contours begin at 3 times the rms noise and increase in intervals of the rms noise. The zero spatial offset line is measured from an accurate mapping of the continuum position using spectroastrometry. The red- and blueshifted components to the line are obvious, and an opposing offset in these components is suggested. This offset is recovered using spectroastrometry (see Fig. 1). The [O I] λ6300 night-sky line has been removed from the spectrum, and the feature blueward of this sky line at ∼−35 km s^{-1} is probably also part of the blueshifted outflow.

ponents to the [O I] λ6300 line are found to be offset in opposing directions to an absolute distance of ∼80 mas (see Fig. 1a). Hence, it is clear that the [O I] λ6300 emission originates in a faint bipolar outflow driven by 2MASS 1207. The 1 σ error in the measurements of 18 mas is marked by the dashed lines in Figure 1a. Also, as in Whelan et al. (2005), the presence or absence of the [O I] λ6300 night-sky line was found to have no effect on the spectroastrometric results.

Other lines of interest are [O I] λ6363, Hα, and He I λ6678. [O I] λ6363 is ∼3 times fainter than [O I] λ6300 and hence is just below the detection limit in the raw spectrum. By smoothing the spectrum using a large Gaussian filter (FWHM in dispersion direction = 0.35 Å), [O I] λ6363 is revealed to be at a similar velocity to [O I] λ6300, although detailed kinematic data are lost. The primary origin of the Hα and He I λ6678 lines is in the accretion flow. As this occurs on a very small scale, we do not expect to measure the spectroastrometric offset, and as can be seen in Figure 1, no offset is found, ruling out the presence of spectroastrometric artifacts (Brannigan et al. 2006). The Hα line is often seen in CTTSs to have an outflow component. However, at these scales, any outflow component would certainly be extremely weak relative to the bulk of the Hα emission and therefore, again, very difficult to detect. As the Hα line is much brighter than any other part of the spectrum, and as any outflow signature would be found in the wings, the line and the continuum are smoothed in such a way that the error in the continuum and the line wings are comparable. All that is seen is a tightening of the Hα position (due to the higher S/N) as one moves toward the peak of the line (Fig. 1b).

4. SCALING DOWN FROM T TAURI JETS

While it is accepted that accretion activity in BDs is simply a scaled-down version of infall in CTTSs (Jayawardhana et al. 2003b), the presumption that BDs also drive scaled-down versions of T Tauri jets and outflows, while credible, has yet to be generally confirmed. Here the evidence gathered so far supporting the continuation of the CTT paradigm for outflow activity, into the young BD mass regime, is summarized. Table 1 presents a comparison between the three BDs whose high-resolution optical spectra have been analyzed by us to date. LS-RCrA 1 probably has the strongest FELs of any BD (Fernández & Comerón 2001), and it is very likely that these FELs are excited in a jet. Yet direct imaging and a preliminary spectroastrometric study failed to confirm such an origin for these features (Fernández & Comerón 2005; Whelan et al. 2006). In particular, spectroastrometry is difficult due to the faintness of this object, which in turn is almost certainly caused by an edge-on disk (Barrado y Navascués et al. 2004). The relatively low radial velocities of the FELs of LS-RCrA 1 support this picture. From Table 1, ρ Oph 102, 2MASS 1207, and LS-RCrA 1 appear to launch outflows of comparable velocities. Also, for 2MASS 1207 and ρ Oph 102, the [O I] λ6300 line–emitting region is offset by similar distances from the BD. Hence, these three substellar objects present a consistent picture of outflow activity in BDs, but how do their FEL regions (FELRs) compare to those of CTTSs?

TABLE 1

COMPARISON OF MASS, MASS ACCRETION RATES, AND TYPICAL FEL VELOCITIES OF THREE BDs

	BROWN DWARFS		
PARAMETER	2MASS 1207	ρ Oph 102	LS-RCrA 1
Mass (M_{Jup})	24	60	35
$\dot{M}_{\mathrm{acc}}$ ($M_{\odot}$ yr^{-1})	10^{-11}	1.25×10^{-9}	10^{-9}
[O I] λ6300 (km s^{-1}, arcsec)	+4/−8, +0.08/−0.08	−40, 0.085	−9, ...
[S II] λ6731 (km s^{-1}, arcsec)	..., ...	−45, 0.085	−15, ...
[N II] λ6583	..., ...	−45, ...	−19, ...

NOTE.—The accretion rate for ρ Oph 102 was derived using the Hα emission line and is taken from Natta et al. (2004). For 2MASS 1207 and LS-RCrA 1, Mohanty et al. (2005) used the Ca II λ8662 line fluxes to infer the mass accretion rates. The mass estimate for LS-RCr A1 is taken from Barrado y Navascués et al. (2004).

The most notable features of the FELRs of CTTSs are their blueshifted and often multicomponent nature (Hirth et al. 1997; Davis et al. 2003). The lack of redshifted FE is accounted for by the obscuring effect of the accretion disk. Only blueshifted emission is observed for ρ Oph 102, and the scale of the blueshifted offset (0.085″) reported by Whelan et al. (2005) for ρ Oph 102 would suggest a minimum (projected) disk radius of 0.1″ ($\geq$15 AU at the distance to the ρ Ophiuchi cloud) in order to hide any redshifted component. For 2MASS 1207, the fact that both blue- and redshifted FE are detected is consistent with the near edge-on disk hypothesis.

Finally, Whelan et al. (2005) discuss the distance from a typical BD at which the critical density (n_{cr}) for forbidden emission is expected to be reached, if it is assumed that BD jets are similar in temperature, line excitation, and opening angle to T Tauri jets. This distance is derived by considering how n_{cr} (2×10^6 cm^{-3} for [O I] λ6300) is expected to scale with mass flux through the jet. Using the predictions of Masciadri & Raga (2004), the distance for forbidden emission (and thus measured offsets) is estimated to be 3–10 times closer to a BD than a CTTS. The [O I] λ6300 offsets measured for 2MASS 1207 agree with this estimate. These offsets are maximized due to the probable edge-on disk geometry of 2MASS 1207. In conclusion, there is much evidence in existence to support the continuation of T Tauri–like outflow activity into the mass range of young BDs.

5. CONCLUSIONS

Our analysis of the high spatial resolution spectrum of 2MASS 1207 clearly uncovers the existence of a bipolar, T Tauri–like outflow. This result is in agreement with the classification of 2MASS 1207 as a strong accretor with forbidden emission and its proposed near edge-on disk geometry. As 2MASS 1207 is only a ~24 M_{Jup} object, it now ranks as the least massive galactic object known to drive a jet. Given the age of the TW Hydrae association, it is also one of the oldest galactic objects with a resolved jet. The age of 2MASS 1207 highlights that outflows can persist for a relatively long time, even when an object is substellar and the derived mass accretion rates are relatively low. Overall this discovery is not only intriguing but important as it emphasizes the robustness of the outflow mechanism over an enormous range of masses (up to 10^8–10^9 $M_\odot$ in active galactic nuclei), and it adds weight to the idea that at least massive planets may also be outflow sources when they form. See Quillen & Trilling (1998) for an intriguing discussion of the possibility of outflows driven by proto-Jovian planets.

REFERENCES

Bailey, J. A. 1998, Proc. SPIE, 3355, 932
Barrado y Navascués, D., Mohanty, S., & Jayawardhana, R. 2004, ApJ, 604, 284
Bourke, T. L., Crapsi, A., Myers, P. C., Evans, N. J., II, Wilner, D. J., Huard, T. L., Jørgensen, J. K., & Young, C. H. 2005, ApJ, 633, L129
Brannigan, E., Takami, M., Chrysostomou, A., & Bailey, J. 2006, MNRAS, 367, 315
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Chauvin, G., Lagrange, A.-M., Dumas, C., Zuckerman, B., Mouillet, D., Song, I., Beuzit, J.-L., & Lowrance, P. 2004, A&A, 425, L29
———. 2005, A&A, 438, L25
Comerón, F., & Reipurth, B. 2006, A&A, 458, L21
Davis, C. J., Whelan, E., Ray, T. P., & Chrysostomou, A. 2003, A&A, 397, 693
Dekker, H., D'Odorico, S., Kaufer, A., Delabre, B., & Kotzlowski, H. 2000, Proc. SPIE, 4008, 534
Fernández, M., & Comerón, F. 2001, A&A, 380, 264
———. 2005, A&A, 440, 1119
Gizis, J. E. 2002, ApJ, 575, 484
Hartigan, P., Morse, J. A., & Raymond, J. 1994, ApJ, 436, 125
Hartmann, L., Hewett, R., & Calvet, N. 1994, ApJ, 426, 669
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. 2003b, ApJ, 592, 282

Königl, A., & Pudritz, R. E. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 759
Masciadri, E., & Raga, A. C. 2004, ApJ, 615, 850
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., Huelamo, N., & Mamajek, E. 2007, ApJ, in press (astro-ph/0610550)
Muzerolle, J., Hillenbrand, L., Calvet, N., Briceño, C., & Hartmann, L. 2003, ApJ, 592, 266
Natta, A., & Testi, L. 2001, A&A, 376, L22
Natta, A., Testi, L., Muzerolle, J., Randich, S., Comerón, F., & Persi, P. 2004, A&A, 424, 603
Quillen, A. C., & Trilling, D. E. 1998, ApJ, 508, 707
Scholz, A., & Jayawardhana, R. 2006, ApJ, 638, 1056
Scholz, A., Jayawardhana, R., & Brandeker, A. 2005, ApJ, 629, L41
Takami, M., Bailey, J., Gledhill, T. M., Chrysostomou, A., & Hough, J. H. 2001, MNRAS, 323, 177
Whelan, E. T., Ray, T. P., Bacciotti, F., & Jayawardhana, R. 2006, NewA Rev., 49, 582
Whelan, E. T., Ray, T. P., Bacciotti, F., Natta, A., Testi, L., & Randich, S. 2005, Nature, 435, 652
Whelan, E. T., Ray, T. P., & Davis, C. J. 2004, A&A, 417, 247
White, R. J., & Basri, G. 2003, ApJ, 582, 1109