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DIRECT IMAGING AND SPECTROSCOPY OF A PLANETARY-MASS CANDIDATE COMPANION TO A YOUNG SOLAR ANALOG

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ABSTRACT

We present Gemini near-infrared adaptive optics imaging and spectroscopy of a planetary-mass candidate companion to 1RXS J160929.1−210524, a roughly solar-mass member of the 5 Myr old Upper Scorpius association. The object, separated by 2.22″ or 330 AU at ∼150 pc, has infrared colors and spectra suggesting a temperature of 1800^{+200}_{-100} K, and spectral type of $L4^{+1}_{-2}$. The *H*- and *K*-band spectra provide clear evidence of low surface gravity, and thus youth. Based on the widely used DUSTY models, we infer a mass of 8^{+4}_{-2} M_{Jup}. If gravitationally bound, this would be the lowest mass companion imaged around a normal star thus far, and its existence at such a large separation would pose a serious challenge to theories of star and planet formation.

Subject headings: planetary systems — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

Since 1995, over 300 planets have been identified around stars other than the Sun,[1] revealing a remarkable diversity in the properties of planets as well as the architecture of planetary systems. Yet, the three hitherto successful planet detection techniques—radial velocity monitoring, transit searches, and microlensing surveys—are generally limited to planets in orbits much smaller than the full radial extent of our solar system. Thus, the discoveries to date, while dramatic, can only provide an incomplete picture of the overall planet population. Direct imaging can help complete the census by uncovering planets at wide separations. Furthermore, it enables extensive follow-up studies to characterize the planets. However, due to the small angular separation and the high brightness contrast between a planet and its star, direct imaging has not succeeded thus far (e.g., Lafrenière et al. 2007 and references therein). At present, our best hope lies in targeting nearby young stars for newborn planets.

During their formation, giant planets and brown dwarfs (BDs), like stars, generate heat from gravitational contraction. But, unlike stars, which eventually reach core temperatures sufficient for hydrogen fusion, these objects are left without a means of producing energy, and thus rapidly cool down and become dimmer with time. Therefore younger planets and BDs, as companions to stars, are much easier to detect directly than their older counterparts. Accordingly, the lowest mass companions imaged so far all orbit stars younger than ∼30 Myr; several of them (e.g., CHXR 73 B, Luhman et al. 2006; AB Pic B, Chauvin et al. 2005; DH Tau B, Itoh et al. 2005; GQ Lub B, Neuhäuser et al. 2005) have masses slightly above the deuterium burning limit of 13 M_{Jup}, which is often used as a boundary to differentiate planets from the more massive BDs[2], although some researchers prefer a distinction based on the formation mechanism, whereby planets form within a circumstellar disk and BDs form through cloud fragmentation. One lower mass companion (∼8 M_{Jup}) orbits the young 25 M_{Jup} BD 2MASSW J1207334−393254, rather than a star (Chauvin et al. 2004; Mohanty et al. 2007); other similar systems might exist (e.g., Béjar et al. 2008). All of these low-mass substellar companions are located at large separations from their primaries, in sharp contrast with solar system planets and extrasolar planets detected by indirect methods, possibly reflecting a fundamental difference in their formation mechanism.

Here we report the direct imaging discovery of a 6–12 M_{Jup} candidate companion to a young solar-mass star, 1RXS J160929.1−210524, in the nearby (145 ± 20 pc), 5 Myr old Upper Scorpius association (Preibisch et al. 2002).

[1] See *The Extrasolar Planets Encyclopedia* at http://exoplanet.eu/.

[2] *Working Group on Extrasolar Planets of the International Astronomical Union*; see http://www.dtm.ciw.edu/boss/definition.html.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Imaging*

Initial imaging of 1RXS J160929.1−210524 was done on 2008 April 27 in K_s using the NIRI camera (Hodapp et al. 2003) and the ALTAIR adaptive optics system (Herriot et al. 2000) at the Gemini North Telescope. We used 5 dither positions, with at each position one co-addition of twenty 0.3 s integrations in fast, high read-noise mode, and one single 10 s integration in slow, low read-noise mode, thus at each position providing an unsaturated image of the target star and a much deeper image of the field that can be registered and scaled in flux without ambiguity. Follow-up imaging in *H* and *J* was obtained on 2008 June 21 using the same instrument. For *H*, we again used 5 dither positions with thirty 0.2 s and a single 10 s co-addition at each position, and for *J* we used 7 dither positions with 10 0.5 s and a single 10 s co-addition.

The imaging data were reduced using custom IDL routines. We subtracted a sky frame constructed using the median of the images at all dither positions (with regions dominated by the target's signal masked), divided by a normalized flat field, and replaced bad pixels by a median over their neighbors. Next, we merged the long- and short-exposure images, properly scaled in intensity, and co-aligned and co-added the resulting images. A composite color image is shown in Figure 1.

2.2. *Spectroscopy*

Spectroscopic follow-up was done on 2008 June 21, using NIRI in grism mode with ALTAIR at the Gemini North Telescope. We used the *f*/32 10 pixel wide (0.214″) slit, rotated to obtain spectra of the primary and companion simultaneously. We obtained five exposures of 180 s in *K* and 210 s in *H*, at nods separated by 4.44″ along the slit. For telluric and instrumental transmission correction, the A0 V star HD 138813 was

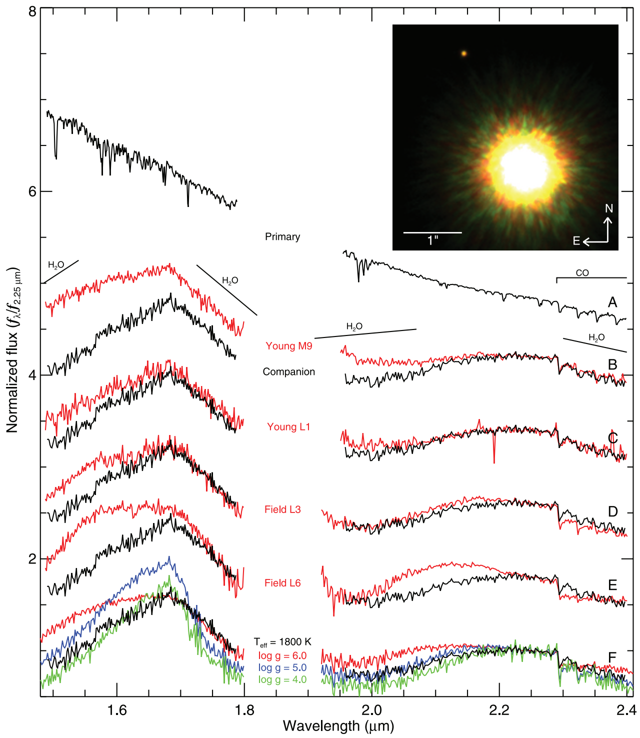

FIG. 1.—Spectra of 1RXS J160929.1−210524 and its faint candidate companion. The primary's spectrum (row A) is as expected for a K7 spectral type. The candidate companion's spectrum (black curves repeated in rows B–F) is compared with the spectra of two young BDs (red curves on rows B–C; M9, USco J160830−233511; and L1, USco J163919−253409) and two older, cooler field BDs (red curves on rows D–E; L3, 2MASSW J1506544+132106; and L6, 2MASSW J1515008+484742), as well as with theoretical spectra with different surface gravities (colored curves in row F). The spectra in rows B–F are binned to a resolving power of ∼850 and normalized at 2.25 μm. The inset at the top right shows our composite image of the two objects. Blue, green, and red represent images taken in *J*, *H*, and K_s, with intensities scaled such that they are proportional to the photon rates inferred from the 2MASS magnitudes of the primary.

observed in *K* before the science target, and HD 151787 in *H* afterward. To confirm the reliability of the data, further sets of *H* and *K* spectra were taken on 2008 August 21 and 2008 August 24, respectively. This time, in *K*, twelve 180 s exposures were taken in four groups of three 4.44″ nods, each group being further nodded by 0.3″, and in *H*, nine 180 s exposures were obtained in three similarly nodded groups. For calibration, HD 151787 was observed after the science target for both sequences.

With the wide slit, we minimize effects from the chromatic adaptive-optics-corrected point-spread function, atmospheric differential refraction (<0.03″ in-band), or small errors in nod position. Based on our imaging, slit losses should vary by at most 5% between *H* and *K*. Thus, even if the standards are taken with slightly different image quality, residual slit effects in the calibrated fluxes should be small. With the wide slit, the point-spread function sets the resolution of ∼12 Å in *H* and ∼18 Å in *K*.

The data were reduced using custom IDL routines. We first subtracted the sky background, determined from exposures at different nods, divided by a normalized flat field, and masked bad pixels. The images were then rectified, using cubic interpolation, for the slight curvature of the traces. We extracted optimally weighted fluxes using the normalized trace of the spectrum, constructed separately for each image and allowed to vary slowly with wavelength. We chose a 2.0″ width for the trace, for which chromatic effects should be less than a few percent. The companion's spectrum was extracted using the same trace, but shifted in position, truncated to 0.25″, and properly renormalized to avoid introducing additional chromatic effects. Prior to extraction, any remaining flux from the primary was removed by subtracting a straight line along the spatial direction fitted to both sides of the companion's trace. Wavelength calibration was done using exposures of an Ar arc lamp. Next, we divided the spectra by those of the telluric standard, corrected for their spectral slope using a 9520 K blackbody curve, and with hydrogen absorption lines removed by dividing by Voigt profile fits to each line. Since the *K*- and *H*-band spectra obtained in June and August were very similar, we co-added them to improve the signal-to-noise ratio. Finally, we flux-calibrated the spectra relative to the 2MASS magnitudes of the primary (using the spectral response and zero points given in Cohen et al. 2003). Synthetic 2MASS contrasts and colors for the companion computed from the flux-calibrated spectra agree within a few percent with the values obtained from the photometry.

3. ANALYSIS AND RESULTS

The position of the companion relative to the primary was found by fitting a 2D Gaussian model to both the primary and companion PSFs; the orientation of the image was obtained from the FITS header. The measurements uncertainties were estimated from the dispersions of the measurements made on all the individual images. We obtained a separation of 103.70 ± 0.06 pixels, corresponding to 2.219″ ± 0.002″ given the pixel scale of 0.0214″, and a position angle of 27.7° ± 0.1°. Systematic uncertainties are likely larger than measurement uncertainties; based on previous experience with similar observations we estimate them at ∼0.03″ for the separation and ∼0.5° for the position angle.

The relative photometry was computed using aperture photometry with a radius of one PSF FWHM. An azimuthally symmetric median intensity profile was subtracted from the images prior to measuring the flux of the companion to avoid contamination from the primary. The uncertainties were estimated from the dispersion of the measurements made on all of the individual images in each filter. The results are shown in Table 1; the near-infrared colors of the companion suggest a mid-L spectral type. For completeness, we note that four other faint sources were detected farther from the primary, but these have $J - K_s < 1.1$ and thus are likely background stars.

The spectra of both the primary and its candidate companion are shown in Figure 1, alongside template spectra of known BDs in Upper Scorpius[3] (Lodieu et al. 2008), field dwarfs[4] (Cushing et al. 2005), and synthetic spectra from the DUSTY models (Chabrier et al. 2000). The spectrum of the companion confirms that it is very cool, showing important water vapor absorption on either sides of the *H* and *K* bands and strong CO band heads beyond 2.29 μm. Compared with field dwarfs, the *H*-band spectrum of our companion has a much more triangular shape which is likely caused by lower surface gravity, as evidenced by the much better agreement with the young Upper Scorpius BDs and the low-gravity model spectra. Indeed, the model spectra show that the blue side of the *H*-band spectrum is suppressed as the surface gravity decreases; a similar

[3] See http://www.iac.es/galeria/nlodieu/publications.html.
[4] See http://irtfweb.ifa.hawaii.edu/∼spex/spexlibrary/IRTFlibrary.html.

TABLE 1
Properties of 1RXS J160929.1−210524 Ab

Parameter	Value	
	Primary	Companion
Angular separation (″)	2.219 ± 0.002	
Position angle (deg)	27.7 ± 0.1	
ΔJ (mag)	8.08 ± 0.12	
ΔH (mag)	7.75 ± 0.07	
ΔK_s (mag)	7.25 ± 0.18	
I (mag)[a]	10.99 ± 0.03	…
J (mag)[b]	9.820 ± 0.027	17.90 ± 0.12
H (mag)[b]	9.121 ± 0.023	16.87 ± 0.07
K_s (mag)[b]	8.916 ± 0.021	16.17 ± 0.18
S_ν [4.5 μm] (mJy)[c]	54.4 ± 0.7	…
S_ν [8.0 μm] (mJy)[c]	20.8 ± 0.1	…
S_ν [16.0 μm] (mJy)[c]	6.66 ± 0.04	…
$J - K_s$ (mag)	0.830 ± 0.034	1.73 ± 0.22
$H - K_s$ (mag)	0.205 ± 0.031	0.70 ± 0.19
Spectral type	K7 V ± 1	$L4^{+1}_{-2}$
$T_{\rm eff}$ (K)	4060^{+300}_{-200}[d]	1800^{+200}_{-100}[e]
Radius ($R_\odot$)[e]	1.352	0.171
Mass ($M_\odot$)[e]	$0.85^{+0.20}_{-0.10}$	$0.008^{+0.004}_{-0.002}$
Projected separation (AU)[f]	~330	

[a] From the DENIS catalog.
[b] From the 2MASS PSC and our contrast measurements.
[c] From Carpenter et al. (2006).
[d] From the spectral types based on Sherry et al. (2004).
[e] From the models of Baraffe et al. (1998, 2002) for the primary and Chabrier et al. (2000) for the companion.
[f] Assuming a distance of 150 pc (Preibisch et al. 2002).

effect is present at the blue side of the K band. Also, the triangular H-band profile is a well-known indicator of low surface gravity that has been observed and discussed in many instances in the literature (e.g., Martín & Osorio 2003; Kirkpatrick et al. 2006). Lower surface gravity would be expected for an object that has not yet fully contracted, and thus these features confirm the youth of the candidate companion. Uncertainties in the model opacities could account for the mismatch on the red side of the H-band for low gravities, and thus this should not be taken as evidence of high gravity (Leggett et al. 2001). Overall, reasonable fits of DUSTY model spectra are obtained with effective temperatures of 1700–1900 K and log g of 3.5–5.0, with a best fit for 1800 K.

The $J - K_s$ color of the companion complements the HK spectroscopy and offers one more check of its temperature. Although low-gravity BDs generally appear redder than their older counterparts for a given spectral type (Kirkpatrick et al. 2008), all but one of the known low-gravity BDs earlier than L2 in the sample of Kirkpatrick et al. (2008) are bluer than our companion; the exception being the extremely peculiar 2MASS J01415823−4633574 (L0pec, $J - K_s = 1.74$). Similarly, all Upper Scorpius BDs (M8–L2) in the sample of Lodieu et al. (2008) except for two L1, have bluer colors. Finally, most BDs later than L5, particularly those with lower gravity, have redder colors. Thus the $J - K_s$ color indicates a spectral type of L2–L5.

Given the above considerations, and based primarily on the comparison with model spectra, we infer $T_{\rm eff} = 1800^{+200}_{-100}$ K, corresponding to a spectral type of $L4^{+1}_{-2}$ given the $T_{\rm eff}$–spectral type relation of Golimowski et al. (2004). The age of the Upper Scorpius association is well constrained at 5 Myr with no significant age spread: all star formation seemingly occurred over a period of less than 1 Myr (Preibisch et al. 2002). This value of 5 Myr is consistently obtained from isochrone fitting using several different evolution models, and is in good agreement with the ~4.5 Myr kinematic age of the association, obtained by tracing back the proper motions of massive stars (Blaauw 1978). Given an age estimate of 5 ± 1 Myr and $T_{\rm eff} = 1800^{+200}_{-100}$ K for the candidate companion, the DUSTY evolutionary models yield a mass of $0.008^{+0.004}_{-0.002}\ M_\odot$, below the deuterium burning limit. The mass uncertainty quoted reflects the widest interval obtained for the quoted ranges of age and $T_{\rm eff}$. As an additional test, we can compare not just the temperature (colors), but also the magnitudes (luminosity) of the object against the model predictions: the best agreement $[(J, H, K)_{\rm obs} - (J, H, K)_{\rm model} = (0.10, 0.02, 0.06)]$ is obtained for a mass of 0.008 $M_\odot$, an age of 5 Myr, and a distance of 150 pc (see Fig. 2). Factoring in the uncertainties on the photometry measurements as well as those on the age and distance, this approach yields a mass estimate of 0.007–0.012 $M_\odot$. As yet another check, we consider the evolution models of Burrows et al. (1997); for the above $T_{\rm eff}$ and age estimates, these models yield a mass of 0.007–0.0011 $M_\odot$. Of course, despite this, some fundamental shortcomings, or lack of absolute calibration, in the models used for the estimates of age, temperature, and mass could result in higher uncertainties than those presented above, but given the difficulty in quantifying such errors we can only alert the readers to this possibility.

The primary star was classified as a member of the Upper Scorpius association by Preibisch et al. (1998) and Preibisch & Zinnecker (1999) based on lithium absorption, X-ray emission, and position in the Hertzsprung-Russell diagram; these authors determined a spectral type of M0 V based on low-resolution optical spectroscopy. New high-resolution optical spectra suggest a slightly earlier spectral type, K7 V ± 1, based on a comparison of several atomic and molecular lines with spectral templates (D. C. Nguyen 2008, private communication). This is also consistent with our near-infrared spectrum, and corresponds to 4060^{+300}_{-200} K (Sherry et al. 2004). Furthermore, for this effective temperature, the predictions of the NextGen evolutionary models (Baraffe et al. 1998, 2002), using $\alpha_{\rm mix} = 1.9$, are in very good agreement with the photometric measurements of the primary for an age of 5 Myr and a distance

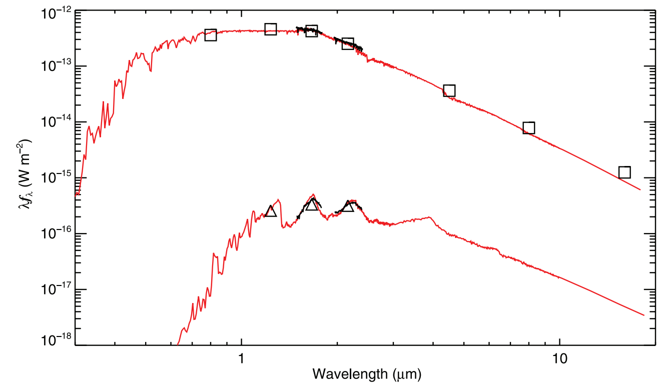

Fig. 2.—Spectral energy distribution of 1RXS J160929.1−210524 (*top*) and its faint candidate companion (*bottom*). The black curves are our spectra, the squares photometry of the primary taken from the literature, and the triangles photometry of the companion inferred from our magnitude differences (see Table 1). Overdrawn in red are models. For the primary, we used a NextGen model spectrum with $T_{\rm eff} = 4000$ K and log $g = 4.0$, and a radius of 1.352 $R_\odot$; for the companion, we used a DUSTY model spectrum with $T_{\rm eff} = 1800$ K and log $g = 4.0$, and a radius of 0.171 $R_\odot$. For both, we scaled the model fluxes to a distance of 150 pc. The slight excess at long wavelengths seen for the primary might indicate the presence of a small residual disk, although no evidence is seen for ongoing accretion (see text). Alternatively, it may simply reflect uncertainties in the model, our inferred temperature, or the reddening.

of 150 pc (see Fig. 2), and indicate a mass of $0.85^{+0.20}_{-0.10}\ M_{\odot}$. We found no evidence for ongoing accretion in the optical and near-infrared spectra, nor signs of significant reddening, consistent with the value of $A_V = 0$ reported by Preibisch & Zinnecker (1999). Carpenter et al. (2006) reports no infrared excess at 8.0 μm and 16.0 μm (see also Fig. 2) based on *Spitzer* observations; this indicates that there is little if any disk material left around the star, consistent with the absence of any spectroscopic signatures of ongoing mass accretion. Our adaptive optics images indicate that the primary is not itself a near-equal luminosity binary with a separation larger than ~0.06″ (>9 AU). A summary of the properties of the primary and companion is given in Table 1.

4. DISCUSSION

Although our photometry and spectroscopy establish that the candidate companion has low gravity and a mass below 0.012 $M_{\odot}$, they do not prove that it is physically bound to the primary star rather than a free-floating planet in the association. Based on integration of their best-fit mass function, Preibisch et al. (2002) estimate that the entire Upper Scorpius population comprises 2525 stars more massive than >0.1 $M_{\odot}$, distributed over an area of ~150 deg^2. Assuming very conservatively that there are as many free-floating planets in the association as there are stars >0.1 $M_{\odot}$, the probability that one would fall within 2.5″ from any of the 85 stars we have observed would be only 0.002. Thus this scenario is unlikely. Verification of common proper motion over the next few years will nevertheless be important, although it would not readily confirm physical association of the two objects given the small internal velocity dispersion of the association. The latter would require detection of orbital motion, which could take several years given the small orbital motion expected (~2 mas yr^{-1}).

Previous direct imaging surveys for planets around nearby solar-type stars have put upper limits of ~6% on the fraction of stars with planets more massive than 5 $M_{\rm Jup}$ at separations over ~50 AU (Lafrenière et al. 2007 and references therein). Our single candidate in a sample of ~85 stars is consistent with these results, and confirms that planets on wide separations are rare also at ages of a few Myr.

Compared to known star-planet systems, the inferred mass for the candidate companion of 1RXS J160929.1−210524 is near the high end of the range. What stands out even more is the large separation of >300 AU. The simplest explanations would be that there is no physical association or that the companion has recently been ejected. Both appear unlikely, however, and thus it seems worthwhile to speculate about possible formation scenarios. In situ growth via core accretion (Pollack et al. 1996) appears unlikely: the formation timescale would greatly exceed the age of the system, even if a disk could survive long enough. On the other hand, at smaller separations this mechanism could build a ~5 $M_{\rm Jup}$ planet in 1–5 Myr (Pollack et al. 1996; Alibert et al. 2005), which might then migrate outwards through interactions with a disk or other massive planets (either can be quite rapid; Pepliński et al. 2008; Veras & Armitage 2004). A problem with this alternative, however, is that a planet formed through core accretion may not be able to reach the observed temperature (Marley et al. 2007). In situ formation via gravitational instability (Boss 1997) is another possibility, but it would require a rather massive ($\gtrsim$0.2–0.35 $M_{\star}$) disk. Typical disks around T Tauri stars contain only 0.01–0.1 $M_{\star}$ of material (Scholz et al. 2006), but more massive disks may exist during earlier protostellar phases. Still, the thermal state of the disk may prevent fragmentation even at radii as large as required here (Matzner & Levin 2005). Lastly, this system may have formed like a binary star, through the fragmentation of a prestellar core. Current star formation simulations, however, find it difficult to make binaries with extreme mass ratios and very low mass components (Bate et al. 2003).

Future observations could look for additional closer-in companions, evidence of a large debris disk, and whether the object we found is in a highly eccentric or nearly circular orbit. If bound, the very existence of the 1RXS J1609−2105 system poses a challenge to theories of planet and star formation, and may well suggest that there is more than one mechanism in nature for producing planetary mass companions around normal stars.

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REFERENCES

Alibert, Y., et al. 2005, A&A, 434, 343
Baraffe, I., et al. 1998, A&A, 337, 403
———. 2002, A&A, 382, 563
Bate, M. R., Bonnell, I. A., & Bromm, V. 2003, MNRAS, 339, 577
Béjar, V. J. S., et al. 2008, ApJ, 673, L185
Blaauw, A. 1978, in Problems of Physics and Evolution of the Universe, ed. L. Mirzoyan (Yerevan: Armenian Academy of Sciences), 101
Boss, A. P. 1997, Science, 276, 1836
Burrows, A., et al. 1997, ApJ, 491, 856
Carpenter, J. M., et al. 2006, ApJ, 651, L49
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Chauvin, G., et al. 2004, A&A, 425, L29
———. 2005, A&A, 438, L29
Cohen, M., Wheaton, W. A., & Megeath, S. T. 2003, AJ, 126, 1090
Cushing, M. C., Rayner, J. T., & Vacca, W. D. 2005, ApJ, 623, 1115
Golimowski, D. A., et al. 2004, AJ, 127, 3516
Herriot, G., et al. 2000, Proc. SPIE, 4007, 115
Hodapp, K. W., et al. 2003, PASP, 115, 1388
Itoh, Y., et al. 2005, ApJ, 620, 984
Kirkpatrick, J. D., et al. 2006, ApJ, 639, 1120
———. 2008, ApJ, in press (arXiv:0808.3153)
Lafrenière, D., et al. 2007, ApJ, 670, 1367
Leggett, S. K., et al. 2001, ApJ, 548, 908
Lodieu, N., et al. 2008, MNRAS, 383, 1385
Luhman, K. L., et al. 2006, ApJ, 649, 894
Marley, M. S., et al. 2007, ApJ, 655, 541
Martín, E. L., & Osorio, M. R. Z. 2003, ApJ, 593, L113
Matzner, C. D., & Levin, Y. 2005, ApJ, 628, 817
Mohanty, S., et al. 2007, ApJ, 657, 1064
Neuhäuser, R., et al. 2005, A&A, 435, L13
Pepliński, A., Artymowicz, P., & Mellema, G. 2008, MNRAS, 387, 1063
Pollack, J. B., et al. 1996, Icarus, 124, 62
Preibisch, T., & Zinnecker, H. 1999, AJ, 117, 2381
Preibisch, T., et al. 1998, A&A, 333, 619
———. 2002, AJ, 124, 404
Scholz, A., Jayawardhana, R., & Wood, K. 2006, ApJ, 645, 1498
Sherry, W. H., Walter, F. M., & Wolk, S. J. 2004, AJ, 128, 2316
Veras, D., & Armitage, P. J. 2004, MNRAS, 347, 613