A METHANE IMAGING SURVEY FOR T DWARF CANDIDATES IN $\rho$ OPHIUCHI

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ABSTRACT

We report on the results of the first deep, wide-field, near-infrared methane imaging survey of the $\rho$ Ophiuchi cloud core to search for T dwarfs. Among the 6587 objects detected, 22 were identified as T dwarf candidates. Brown dwarf models indicate that at the age and distance of the $\rho$ Ophiuchi cloud, these T dwarf candidates have masses between 1 and 2 Jupiter masses. If confirmed as genuine T dwarfs, these objects would be the youngest, lowest mass, and lowest gravity free-floating objects ever directly observed. The existence of these candidates suggests that the initial mass function of the $\rho$ Ophiuchi cloud extends well into the regime of planetary mass objects. A large fraction (59% ± 16%) of our T dwarf candidates appear to be surrounded by circumstellar disks, and thus represents the lowest mass objects yet found to harbor circumstellar disks.

Key words: brown dwarfs – infrared: stars – ISM: individual objects ($\rho$ Ophiuchi) – stars: pre-main sequence

1. INTRODUCTION

One of the most exciting frontiers of astrophysics research today is the discovery and characterization of sub-stellar objects, ranging from brown dwarf to planetary mass objects (planemos). Of particular interest is a class of objects known as T dwarfs. Field T dwarfs are the coolest (500 K $\leq T_{\text{eff}} \leq$ 1400 K) and least luminous brown dwarfs that are directly observable (Vrba et al. 2004; Golimowski et al. 2004; Burgasser et al. 2006; Leggett et al. 2009). The cool atmospheres of T dwarfs are rich in molecular gases, especially methane and water vapor, and condensate clouds (Ackerman & Marley 2001). In fact, strong, broad methane absorption lines in the near-infrared at 1.3–1.4, 1.6–1.8, and 2.2–2.5 $\mu$m represent the distinguishing feature of T dwarfs from hotter brown dwarfs in which the production of atmospheric methane is prohibited by collisional dissociation (Noll et al. 2000). The methane features that define T dwarfs are so broad and distinctive that the use of dedicated filters to detect them was proposed soon after the discovery of the T dwarf prototype Gliese 229B (Nakajima et al. 1995; Rosenthal et al. 1996).

Differential methane-band imaging (the acquisition of images in both a methane band and a nearby continuum band) provides an efficient method for the detection of isolated ultracool dwarfs. Since both bands can be observed nearly simultaneously, at identical airmasses, in similar seeing and transparency conditions, systematic uncertainties in aperture corrections due to seeing variations, extinction corrections due to airmass variations, and (to some extent) zero-point corrections due to transparency variations can all be canceled out. Furthermore, effects of reddening that have plagued near-infrared imaging searches for low-mass objects in the past (e.g., Luhman 2003) are minimized, since the methane and continuum band filters are adjacent to each other within the $H$ band. A detailed discussion of the method of differential methane-band imaging can be found in Tinney et al. (2005).

Most of the field T dwarfs discovered using methane imaging to date have been from follow-up observations of large-area sky surveys (e.g., Tinney et al. 2005 and references therein). Only a few investigators, so far, have searched for T dwarfs in young (1–10 Myr) star clusters (Zapatero Osorio et al. 2002; Mainzer & McLean 2003; Lucas et al. 2006; Greissl et al. 2007; Burgess et al. 2009; Scholz et al. 2009; Marsh et al. 2010). Surveying young clusters using methane imaging has several advantages. First, low-mass brown dwarfs are more luminous, and thus 2–5 orders of magnitude brighter at this stage of their evolution than those in the general field. Thus, they can be detected at greater distances than field objects. In addition, brown dwarfs in clusters have known ages, as opposed to field brown dwarfs that may have age errors of 5 billion years or more. This is a huge advantage since, for a given luminosity, knowledge of an object’s age is necessary to assign a unique mass. Young clusters also have smaller physical sizes than older optical clusters, minimizing the effect of contamination by foreground and background field brown dwarfs.

With these advantages in mind, we have initiated the first deep, wide-field, near-infrared (NIR) methane filter imaging search for T dwarf candidates in the youngest (1–3 Myr) and nearest (d < 250 pc) star-forming regions to Earth. At this age, these brown dwarfs are at their brightest. According to isochrones for the COND model of Baraffe et al. (2003), they have planetary masses. In this Letter, we present the results of our methane imaging survey of the $\rho$ Ophiuchi cloud core. With a distance of 120–130 pc (Loinard et al. 2008; Mamajek 2008; Lombardi et al. 2008), this cloud is the closest star-forming region to Earth that has a compact core harboring several hundred ~1 Myr young stellar objects (Barsony et al. 1997; Wilking et al. 1989; Bontemps et al. 2001; Barsony et al. 2005).

2. OBSERVATIONS AND DATA REDUCTION

Near-infrared $J$, $K_s$ (1.25, 2.14 $\mu$m), CH$_4$s (1.59 $\mu$m), and CH$_4$I (1.673 $\mu$m) observations of the $\rho$ Ophiuchi cloud core were obtained during the period 2008 May 23–26 with the IRIS2 NIR imager/spectrograph on the $\rho$ Ophiuchi cloud core.
bandwidths of 0.121 and 0.122 μm, respectively. IRIS2 consists of a Hawaii 2RG CdTe 1024 × 1024 array which, when mounted at the f/8 Cassegrain focus on the AAT, yields a plate scale of 0′.45 pixel−1 with a corresponding field of view of approximately 7′7 × 7′7. The FWHM for all observations varied between approximately 2.2 and 3.1 pixels (−1′′–1′′4).

Nineteen IRIS2 fields were observed, covering an area of ~920 arcmin² on the sky. All fields were observed in the Mauna Kea Observatory (MKO) photometric system J and K_s filters in a five-point dither pattern with 30′′ offsets between each dither. Integration times at each dither position for the J and K_s filters were 15 s × 4 coadds and 6 s × 10 coadds, respectively, for a total integration time in both filters of 5 minutes. Each field was also observed in the CH_4s and CH_4l filters in a pseudo-random 16-point dither pattern within a dither box 30′′ on a side. The observations were interleaved at each dither position to minimize the number of filter changes. Thus, observations of each field were taken as follows: CH_4s, CH_4l, CH_4s, dither, CH_4s, dither, and so forth. Integration times at each dither position for both filters were 15 s × 4 coadds. The entire dither pattern was repeated twice in both filters for a total integration time of 16 minutes in each of the CH_4s and CH_4l filters. H-band images of each field were constructed by adding the corresponding CH_4 and CH_4l images for the given field.

All data were reduced using the Image Reduction and Analysis Facility (IRAF). An average dark frame was constructed from the dark frames taken at the beginning and end of each night’s observations. This dark frame was subtracted from all target observations to yield dark subtracted images. Sky frames in each filter were individually made for each observation by median-combining all five J and K_s band frames for each field, and the nearest nine CH_4s and CH_4l frames in time to the target observation. The individual sky frames were normalized to produce flat fields for each target frame. Target frames were processed by subtracting the appropriate sky frames and dividing by the flat fields. Target frames were then registered and combined to produce the final reduced images in each filter.

3. ANALYSIS

Infrared sources were identified at the K_s band using the DAOFIND routine within IRAF (Stetson 1987). DAOFIND was run on each field using an FWHM of 2.8 pixels, and a single pixel finding threshold equal to three times the mean noise of each image. Each field was individually inspected, and the DAOFIND coordinate files were edited to remove bad pixels and any objects misidentified as stars, as well as to add any missed stars to the list. Objects within 30′′ of the field edges were also removed from the list, as they were in low signal to noise regions of the image as a result of the dither pattern used. Aperture photometry was then performed on all fields in each filter using the PHOT routine within IRAF. An aperture of 4 pixels in radius was used for all target photometry, and a 10 pixel radius was used for the standard star photometry. Sky values around each source were determined from the mode of intensities in an annulus with inner and outer radii of 10 and 20 pixels, respectively. Our choice of aperture size for our target photometry ensured that the individual source fluxes were not contaminated by the flux from neighboring stars; however, they are not large enough to include all the flux from a given source. In order to account for this missing flux, aperture corrections were determined using the MKAPFILE routine within IRAF. The instrumental magnitudes for all sources were corrected to account for the missing flux.

Photometric calibration was accomplished using the list of standard stars of Persson et al. (1998). The standards were observed on the same nights and through the same range of air masses as the ρ Ophiuchi cloud. Zero points and extinction coefficients were established for each night. All magnitudes and colors were transformed to the CIT system using MKO to 2MASS (Two Micron All Sky Survey) and 2MASS to CIT photometric color transformation equations. Because of the extensive spatial overlapping of the cloud images, a number of sources were observed at least twice. We compared the JHK_s, CH_4s, and CH_4l magnitudes of 200 duplicate stars identified in the overlap regions. For all stars brighter than the completeness limit of our survey, the photometry of the duplicate stars agreed to within 0.15 mag.

The completeness limit of our observations was determined by adding artificial stars at random positions to each of the 19 fields in all four filters and counting the number of sources recovered by DAOFIND. Artificial stars were added in 12 separate half-magnitude bins, covering a magnitude range of 16.00–22.00, with each bin containing 100 stars. The artificial stars were examined to ensure that they had the same FWHM as the real sources in each image. Aperture photometry was performed on all sources to confirm that the assigned magnitudes of the added sources agreed with those returned by PHOT. All photometry agreed to within 0.10 mag. DAOFIND and PHOT were then run and the number of identified artificial sources within each half-magnitude bin was tallied. This process was repeated 20 times. We estimate that our survey is 90% complete to J = 20.50, H = 20.00, K_s = 18.50, CH_4s = 19.25, and CH_4l = 19.25.

4. RESULTS

T dwarf candidates were initially identified by having methane colors indicative of a T dwarf (e.g., Table 3 in Tinney et al. 2005) and H-band magnitudes brighter than the completeness limit of H = 20.0. Models for T dwarfs (i.e., the COND models of Baraffe et al. 2003) indicate that our survey is sensitive down to T8 spectral types, even through A_V = 10. The resulting list of 565 candidates was further winnowed by examining each individual candidate to ensure that it was indeed fainter in the CH_4l image as compared to the CH_4s image. Our final list of 22 T dwarf candidates is shown in Table 1. In the table, we list an ID number for each candidate in Column 1, the R.A. (J2000) and decl. (J2000) in Columns 2 and 3, the near-infrared magnitudes and colors in Columns 4–11, visual extinction estimates for each candidate T dwarf in Column 12, and an estimated spectral type for each candidate based on the methane colors (CH_4s–CH_4l) in Column 13. The methane colors were calculated as outlined in Tinney et al. (2005). Estimates for A_V were computed by dereddening each object in a JHK_s color–color diagram as discussed below. In Figure 1, we present CH_4s (left) and CH_4l (right) images of the latest T spectral-type object in Table 1. North is up and east is to the left, with each image centered on the T dwarf candidate. As one can see, the T dwarf candidate is fainter in the CH_4l image as compared to the CH_4s image.

In Figure 2, we present the JHK_s color–color diagram for the T dwarf candidates in Table 1. In the diagram, we plot the locus

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6 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

7 See http://www.astro.caltech.edu/~jmc/2mass/v3/transformations/.
Figure 1. CH4s (left) and CH4l (right) images of object 11 from Table 1. North is up and east is to the left in each image. Each image is of the same scale, as indicated by the scale bar in the CH4s image. Object 11 is circled and labeled in each filter. Although it appears asymmetric in the images, the object has a PSF which is Gaussian with an FWHM of 1.1. Note that this candidate methane absorbing young object is brighter in the CH4s filter than in the CH4l filter, resulting in a negative CH4s–CH4l color. This behavior is distinctive. The faint background star just to the east of object 11 is brighter in the CH4l filter than in the CH4s filter, as expected for main-sequence dwarfs (an M8 star will have an unreddened positive CH4s–CH4l color of +0.17 mag, for example).

Table 1

| ID   | R.A. (J2000)° | Decl. (J2000)° | $J^b$ | $H^b$ | $K^b$ | CH4b | CH4l | J – H | H – K | CH4(s–l) | A$_v$ | Sp. T  |
|------|---------------|---------------|-------|-------|-------|-------|------|-------|-------|---------|------|-------|
| 1    | 16:25:49:48   | −24:20:02:09  | 20.98 | 18.58 | 17.72 | 17.66 | 17.89 | 2.40  | 0.86  | −0.43   | 13.2 | T4.5  |
| 2    | 16:25:55:56   | −24:24:47:45  | >21.00| 19.43 | 18.15 | 18.37 | 18.86 | >1.57 | 1.28  | <−0.56  | >−5.6 | >T5  |
| 3    | 16:25:55:57   | −24:26:59:57  | >21.00| 19.28 | 18.28 | 18.23 | 18.61 | >1.72 | 1.00  | <−0.57  | >12.3 | >T5  |
| 4    | 16:25:58:03   | −24:33:00:94  | 20.12 | 18.41 | 17.14 | 17.61 | 17.96 | 1.71  | 1.27  | −0.44   | 6.9  | T4.5  |
| 5    | 16:25:59:37   | −24:16:16:28  | >21.00| 18.87 | 17.66 | 17.94 | 18.21 | >2.13 | 1.21  | <−0.51  | >15.6 | >T4.5 |
| 6    | 16:26:15:24   | −24:33:58:21  | >21.00| 18.34 | 17.64 | 17.91 | 18.12 | >2.16 | 1.20  | <−0.45  | >15.4 | >T4.5 |
| 7    | 16:26:26:76   | −24:39:29:73  | 20.92 | 18.75 | 17.42 | 17.79 | 18.03 | 2.17  | 1.33  | −0.43   | 12.1 | T4.5  |
| 8    | 16:27:04:19   | −24:27:06:31  | >21.00| 19.46 | 17.58 | 18.41 | 18.92 | >1.54 | 1.88  | <−0.58  | >5.4  | >T5  |
| 9    | 16:27:12:11   | −24:17:13:05  | 20.25 | 19.15 | 17.88 | 18.03 | 18.49 | 1.10  | 1.27  | −0.46   | 0.0  | T4.5  |
| 10   | 16:27:16:62   | −24:22:33:63  | >21.00| 19.37 | 17.75 | 18.29 | 18.55 | >1.63 | 1.62  | <−0.34  | >6.2  | >T4  |
| 11   | 16:27:20:41   | −24:19:14:59  | >21.00| 18.80 | 17.35 | 17.59 | 18.35 | >2.20 | 1.45  | <−0.93  | >11.4 | >T6  |
| 12   | 16:27:24:81   | −24:38:33:78  | >21.00| 19.17 | 17.40 | 17.94 | 18.50 | >1.83 | 1.77  | <−0.67  | >8.0  | T5.5  |
| 13   | 16:27:30:18   | −24:39:24:66  | 20.55 | 18.94 | 17.17 | 17.94 | 18.61 | 1.61  | 1.77  | −0.75   | 6.0  | T5.5  |
| 14   | 16:27:33:25   | −24:19:03:63  | 20.82 | 19.15 | 17.93 | 18.04 | 18.69 | 1.67  | 1.72  | −0.74   | 6.6  | T5.5  |
| 15   | 16:27:33:71   | −24:19:30:43  | >21.00| 18.79 | 17.40 | 18.75 | 18.12 | >2.21 | 1.39  | <−0.44  | >11.5 | >T4.5 |
| 16   | 16:27:35:82   | −24:21:13:07  | >21.00| 19.09 | 18.23 | 17.95 | 18.46 | >1.91 | 1.06  | <−0.66  | >10.2 | >T5.5 |
| 17   | 16:27:36:71   | −24:24:40:20  | >21.00| 19.49 | 18.22 | 18.31 | 18.95 | >1.51 | 1.27  | −0.70   | >5.1  | >T5.5 |
| 18   | 16:27:41:75   | −24:16:04:89  | >21.00| 18.70 | 17.64 | 17.66 | 17.93 | >2.30 | 1.06  | <−0.47  | >13.2 | >T4.5 |
| 19   | 16:27:44:27   | −24:21:01:28  | >21.00| 18.84 | 17.62 | 17.88 | 18.12 | >2.16 | 1.22  | <−0.49  | >15.7 | >T4.5 |
| 20   | 16:28:10:81   | −24:29:04:68  | >21.00| 18.84 | 17.98 | 17.79 | 18.20 | >2.16 | 0.86  | <−0.56  | >10.2 | >T5  |
| 21   | 16:28:20:79   | −24:38:25:69  | >21.00| 18.89 | 18.02 | 17.79 | 18.12 | >2.11 | 0.87  | <−0.48  | >10.7 | >T4.5 |
| 22   | 16:28:45:89   | −24:34:20:44  | >21.00| 19.26 | 17.83 | 18.24 | 18.50 | >1.74 | 1.43  | <−0.36  | >7.2  | >T4  |

Notes.

a) Coordinates listed are J2000. Units of R.A. are hours, minutes, and seconds, and units of decl. are degrees, arcminutes, and arcseconds.

b) Typical uncertainties in the listed magnitudes are 0.10–0.15 mag.

c) Extinction estimates were calculated by dereddening each source in the JHK color–color diagram, as discussed in the text.

d) Estimated spectral type based on the CH4(s–l) colors.

do) Extinction estimates were calculated by dereddening each source in the JHK color–color diagram, as discussed in the text.

5. DISCUSSION

We have completed the first deep, wide-field, NIR methane-band imaging survey of the ρ Ophiuchus cloud core to search for
The hunt for the lowest mass object that can collapse directly from the present-day interstellar medium is on (e.g., Scholz et al. 2009; Burgess et al. 2009). On theoretical grounds, there is some critical mass and density below which cloud fragmentation and gravitational collapse is not feasible (e.g., Cruz 2008 and references therein). In this context, it is highly suggestive that none of our 22 planemo candidates (and none of 9 additional planemo candidates in the CrA cloud identified by us using the same methods) have spectral types later than T6, despite the fact that our surveys are sensitive to spectral types as late as T8.

A large fraction (59% ± 16%) of our T dwarf candidates lie in the infrared excess region of the JHK_s color–color diagram. Predictions from both observations and modeling suggest that this is what one would expect from excess emission from circumstellar disks (e.g., Lada & Adams 1992; Meyer et al. 1997; Haisch et al. 2000). Scholz & Jayawardhana (2008) have recently observed excess infrared emission around four planetary mass objects in the σ Orionis cluster. The masses of these objects range from 8–20 M_Jup, significantly higher than the masses of the candidate T dwarfs in our sample (1–2 M_Jup) which show disk emission. If confirmed as bona fide T dwarfs, our sample objects represent the lowest mass sources yet found to harbor circumstellar disks.

Spectroscopic follow-up of the T dwarf candidates identified through our methane imaging is important and will be vigorously pursued. NIR spectroscopy will allow us to assign an unambiguous spectral type to each candidate, accurate to a subclass. In principle, this could be accomplished with methane filter differential photometry alone. In practice, our candidates are close to our detection limits (unlike the case for bright field T dwarfs), where photometric errors are largest, complicating spectral-type determination via differential photometry. NIR spectra will also allow us to eliminate extinction effects that skew the methane filter spectral typing. Furthermore, high-quality NIR spectra will allow us to constrain the effective temperature of our T dwarf candidates much better than using methane filters alone, and any discrepancies in model fits which might indicate unexpected condensates or perhaps local carbon abundance anomalies will be identified. When complete, our combined methane imaging and spectroscopic survey of our sample young, nearby clusters will probe low-mass star formation in a range of environments and enable robust conclusions to be drawn about the presence or absence of a minimum mass.
for star formation, and the importance or insignificance of dynamical evolution for young cluster mass functions.

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