FOUR BROWN DWARFS IN THE TAURUS STAR-FORMING REGION

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ABSTRACT

We have identified four brown dwarfs in the Taurus star-forming region. They were first selected from R and I CCD photometry of 2.29 deg² obtained at the Canada-France-Hawaii Telescope. Subsequently, they were recovered in the Two Micron All Sky Survey second incremental data release point source catalog. Low-resolution optical spectra obtained at the William Herschel Telescope allow us to derive spectral types in the range M7–M9. One of the brown dwarfs has very strong Hα emission (EW = −340 Å). It also displays Brγ emission in an infrared spectrum obtained with the Infrared Camera and Spectrograph on the Subaru telescope, suggesting that it is accreting matter from a disk. The K1 resonance doublet and the Na i subordinate doublet at 818.3 and 819.5 nm in these Taurus objects are weaker than in field dwarfs of similar spectral type, consistent with low surface gravities as expected for young brown dwarfs. Two of the objects are cooler and fainter than GG Tau Bb, the lowest mass known member of the Taurus association. We estimate masses of only 0.03 M⊙ for them. The spatial distribution of brown dwarfs in Taurus hints at a possible anticorrelation between the density of stars and the density of brown dwarfs.

Subject headings: circumstellar matter — open clusters and associations: individual (Taurus-Auriga) — stars: formation — stars: fundamental parameters — stars: low-mass, brown dwarfs — stars: pre–main-sequence

On-line material: color figure

I. INTRODUCTION

The Taurus star-forming region (SFR) has played a central role in our understanding of low-mass star formation. The dark molecular clouds in this region of the sky are conspicuously large. Early work classified them as “nebulae without definite relation to certain stars” (Cederblad 1946). The class of very young low-mass variable stars known as T Tauri stars (TTSs) is named after the prototype star T Tauri (Joy 1942), which is a member of the Taurus SFR. The importance of the Taurus SFR is that it contains many nearby TTSs (pc−distance) in loose aggregations. The ages of Taurus members range from protostars to evolved post–T Tauri stars, although the bulk of them appears to have emerged from the molecular clouds in the last 4 Myr (Palla & Stahler 2000).

Recent surveys in very young clusters have identified a population of substellar objects (M < 0.075 M⊙; Kumar 1963) that appears to be of the same order of magnitude in number as that of stars (Béjar et al. 2001; Bouvier et al. 1998). Several brown dwarfs (BDs) have been identified in SFRs such as the Chamaeleon I SFR (Comerón, Neuhauser, & Kaas 2000) and the Trapezium (Lucas et al. 2001). The initial mass function (IMF) does not appear to change much from one region to another. Taurus is interesting because it represents a loose mode of star formation (density ∼ 10³ pc−³), in contrast to that of clusters such as the Trapezium (10⁸ pc−³). Recent searches in Taurus by Briceño et al. (1998) and Luhman (2000) have failed to reveal any candidate members with spectral types later than M6.5 V, estimated to be below the substellar limit at the Taurus population age (Martín, Basri, & Zapatero Osorio 1999). Luhman (2000) has proposed that the low-mass IMF in Taurus could be truncated around the substellar limit. It is indeed important to study whether the IMF could be sensitive to the initial conditions of star formation.

In this Letter, we present the first results of a new effort to search for BDs in Taurus. We have obtained deeper images over a 5 times larger area than previous work. Spectroscopic follow-up of 30 very low mass (VLM) candidate members in the Taurus SFR has been carried out. Four candidates are confirmed as VLM objects with spectral types M7 or later, and the probability of membership in the Taurus SFR is very high. They are sufficiently cool to be considered as BDs. One of them presents strong evidence for disk accretion.

2. OBSERVATIONS AND RESULTS

Direct imaging observations of 11 fields in the Taurus SFR were obtained with the 3.6 m Canada-France-Hawaii Telescope (CFHT) CFH12k camera (Cuillandre et al. 2000) between 1999 December and 2000 December. Broadband R, I, and z as well as narrowband Hα filters were used. The field of view of the CFH12k camera is 0.327 deg². Thus, our survey covers a total area of 3.59 deg². A complete description of the survey and associated data reduction will be presented in C. Dougados et al. (2001, in preparation). The selection of Taurus low-mass candidates presented here is based on a subset of the total CFH12k survey, covering 2.29 deg² (seven fields) and including R and I photometry alone.

We selected candidate low-mass Taurus members by requiring that they lie 2 mag above the observational zero-age main sequence (ZAMS) in the I versus R−I color-magnitude diagram (20 sources). An additional 10 sources lying closer to
the ZAMS with suspected strong Hα emission from their photometry in the Hα filter were included in the spectroscopic follow-up sample. None of the Hα-selected sources turned out to be interesting. Figure 1 shows the color-magnitude diagram.

Spectroscopic observations were carried out using the Intermediate-dispersion Spectrograph and Imaging System (ISIS) at the 4.2 m William Herschel Telescope (WHT) in La Palma on 2000 September 28–29. We observed 30 VLM candidates with $I < 18$. V410 Tau Anon 13 (M6.5; Briceño et al. 1998) was also observed with the same setup for comparison purposes. The R158R grating on ISIS’s red arm gave a wavelength coverage from 640.9 to 936.5 nm. The spectral resolution was 2.5 pixels (7.2 Å). The data were reduced using standard routines for bias subtraction and flat-field correction within the IRAF7 environment. Wavelength calibration was made using the spectrum of an NeAr lamp. Instrumental response was calibrated out using spectra of the flux standard Feige 24.

This Letter focuses on the four new VLM candidates for which our WHT spectra give spectral types M7 or later (Fig. 2). These objects represent an extension of the previously known Taurus members to lower masses, beyond the substellar limit. Some of the remaining 26 candidates have Hα emission and spectral types earlier than M7. They could be Taurus SFR members. We defer presentation of these stars to another paper (C. Dougados et al. 2001, in preparation). Spectral types were obtained by measuring the strength of VO absorption using indexes defined by Martín et al. (1999) calibrated with spectra of field ultracool dwarfs. We obtain a spectral type for V410 Tau Anon 13 of M6, consistent within the uncertainties (half a subclass) with the M6.5 estimate of Briceño et al. (1998).

Near-infrared photometry for the program objects was extracted from the Two Micron All Sky Survey second incremental data release point source catalog. Line-of-sight extinction was measured using the $I−J$ colors of field M dwarfs and consistent with $A_v=3$ and $I$ vs. $(R−I)_C$ color-magnitude diagram for CFH12K data. Circled dots are background stars. Filled triangles are spectroscopically confirmed new VLM Taurus members. Open triangles are previously known Taurus members recovered in the CFH12K data. The solid line is the locus of field M dwarfs taken to the Taurus distance (Weis 1984; Leggett 1992). The dashed line represents an observational boundary between Taurus members and background stars. There is only one member bluer than this line. [See the electronic edition of the Journal for a color version of this figure.]
the interstellar extinction law of Rieke & Lebofsky (1985). The astrometric, photometric, and spectroscopic information for these sources is summarized in Tables 1 and 2.

We obtained near-infrared spectra for two of these objects using the Infrared Camera and Spectrograph (IRCS; Kobayashi et al. 2000) at the Cassegrain focus of the 8 m Subaru telescope on 2001 January 9. The K-band grism gave a wavelength coverage from 1.93 to 2.48 μm, a dispersion of 6.1 Å pixel−1 and a resolution of 350 at 2.2 μm. The data were reduced using standard IRAF routines for bias subtraction, flat-field correction, and sky subtraction. Telluric bands were canceled using the spectrum of the G3 star SAO 167029. The photospheric Brγ line in SAO 167029 was removed by interpolation between adjacent continuum points. The spectra of the targets were multiplied by a blackbody with $T_{eff} = 5785$ K, adequate for the G3 spectral type of the standard star (Tokunaga 2000). The final IRCS spectra are shown in Figure 3.

3. PROPERTIES OF THE NEW TAURUS VLM MEMBERS

BDs in the Taurus SFR should be in a very early phase of gravitational contraction. Theoretical models indicate that their gravities are between 100 and 1000 times lower than for VLM stars at the bottom of the main sequence (Chabrier et al. 2000). Collisionally dominated photospheric lines are thus very good tracers of low-gravity atmospheres and can be used as a strong criterion to distinguish young BDs from old VLM stars. Luhman et al. (1998) noted that Na i and K i lines were much weaker in the M6 Taurus star V410 X-ray 3 than among field M6 dwarfs. We find that our four new Taurus VLM objects also have weaker Na i and K i lines than field dwarfs of the same spectral type (Figs. 2 and 3).

A spectral type of M6.5 is considered the boundary between stars and BDs for the Pleiades cluster age, i.e., 120 Myr. For younger ages, the boundary should stay at M6.5 or move to a slightly earlier spectral type (Martín et al. 1999). Thus, we conclude that the four objects presented in this Letter are very likely substellar members in the Taurus SFR because they have spectral types M7 or later and low-gravity indications in their spectra. Prior to this work, the coolest known Taurus member was GG Tau Bb, the faintest member of the GG Tau quadruple system. White et al. (1999) estimated an age of 1.5 Myr and a mass of 0.04 $M_\odot$ for it. GG Tau Bb has spectral type M7, $K = 12.01$, and $A_v \sim 0$. Two of our objects, namely, CFHT-BD-Tau 2 and 3, are intrinsically fainter than GG Tau Bb. Using the models of Chabrier et al. (2000), which provide the best isochrone fitting to the GG Tau quadruple system, we obtain ages of about 1 Myr and masses of about 0.03 $M_\odot$ for both CFHT-BD-Tau 2 and 3. CFHT-BD-Tau 1 and 4 appear to be more luminous than the 1 Myr isochrone. C. Dougados et al. (2001, in preparation) will present a detailed discussion of the position of these objects in the H-R diagram.

Our IRCS data allows us to search for Brγ emission, which has been detected in classical TTSs (Muzerolle, Hartmann, & Calvet 1998). These authors found a correlation between the strength of Brγ emission and the accretion rate estimated from $U$-band excess and blue excess spectra of TTSs. We find Brγ emission in CFHT-BD-Tau 4 (Fig. 3), which also displays the strongest Hα emission in our sample (Table 2). The analogy with the TTSs suggest that CFHT-BD-Tau 4 may be accreting matter from a circumstellar disk.

V410 Tau Anon 13 is a VLM Taurus member with Hα emission [EW(Hα) = −41.3 Å; Briceño et al. 1998]. We measured a similar strength of Hα emission [EW(Hα) = −35 Å] in our WHT spectrum. Our Brγ detection for V410 Tau Anon 13 confirms that this object may be accreting matter as previously proposed by Muzerolle et al. (2000) from a high-resolution study of the Hα line profile. The continuum of the IRCS spectra of CFHT-BD-Tau 4 and V410 Tau Anon 13 are significantly redder and the CO bands are shallower than in the comparison spectrum of LHS 3003, contrary to what one would expect from the sensitivity of these bands to the surface gravity. This could be due to emission from the circumstellar disk, which could add a red continuum and could veil the CO features.

CFHT-BD-Tau 4 is located close to the Tau III group identified by Gómez et al. (1993). CFHT-BD-Tau 1, 2, and 3 could be associated with group V, for which only half a dozen members were known so far. Group V has much fewer known T Tauri members than groups II and III. We note that three out of four of our new BDs are located in a sparsely populated

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### Table 1

| Short Name   | IAU Name               | $R_e$ | $I_c$ | $J$  | $H$  | $K$  | $A_v$ |
|--------------|------------------------|-------|-------|------|------|------|-------|
| CFHT-BD-Tau 1 | CFHT-BD-Tau J043415.2+225031 | 20.87 | 17.26 | 13.74 | 12.52 | 11.87 | 3.1   |
| CFHT-BD-Tau 2 | CFHT-BD-Tau J043610.4+225956 | 20.21 | 16.69 | 13.76 | 12.76 | 12.19 | 0.0   |
| CFHT-BD-Tau 3 | CFHT-BD-Tau J043638.9+225812 | 20.33 | 16.77 | 13.70 | 12.84 | 12.34 | 0.0   |
| CFHT-BD-Tau 4 | CFHT-BD-Tau J043947.3+260139 | 19.10 | 15.64 | 12.16 | 11.01 | 10.33 | 3.0   |
| V410 Tau Anon 13 | ... | 19.83 | 16.40 | 12.90 | 11.66 | 10.94 | 3.6   |

Note.—The IAU name contains the equatorial coordinates, equinox J2000. The accuracy of the coordinates is better than 1". V410 Tau Anon 13 is included for comparison.

### Table 2

| Short Name   | EW (Hα) | EW (Na i) | EW (Brγ) | TiO Index | VO Index | Spectral Type |
|--------------|---------|-----------|----------|-----------|----------|---------------|
| CFHT-BD-Tau 1 | −19 ± 4 | <2.0      | ...      | 3.57      | 2.66     | M7            |
| CFHT-BD-Tau 2 | −13 ± 4 | <1.4      | ...      | 3.80      | 2.70     | M8            |
| CFHT-BD-Tau 3 | −55 ± 4 | <2.2      | >1.2     | 4.32      | 2.94     | M9            |
| CFHT-BD-Tau 4 | −340 ± 20 | <1.1     | −3.0     | 3.20      | 2.67     | M7            |
| V410 Tau Anon 13 | −35 ± 2 | <1.5      | −1.6     | 3.31      | 2.52     | M6            |

Note.—Spectral types are accurate to half a subclass. The Na i refers to the combined subordinate doublet at 818.3 and 819.5 nm. TiO and VO are the sum of the TiO1 and TiO2 indexes and the VO1 and VO2 indexes, respectively, defined by Martín et al. 1999.
group, and none in one of the richer groups I, II, and III, which were included in the photometric survey. The spatial distribution of BDs in Taurus may give an important clue to the dominant formation mechanism of these objects. Our results are intriguing because they suggest that the density of BDs in the Taurus SFR may be anticorrelated with the density of TTSs. Martín & Kun (1996) found an isolated group of VLM young stars at high Galactic latitude and suggested that VLM stars and BDs may form in small groups without any low-mass star. A mass segregation in Taurus would explain the lack of BDs in the searches carried out by Briceño et al. (1998) and Luhman (2000), which were limited to the dense groups of TTSs. But why is there a lack of BDs in dense groups of TTSs in the Taurus SFR? A possible answer may be that in rich groups BDs get ejected at a very early stage (Reipurth & Clarke 2001) and disperse away from the molecular clouds in a short time.

The binary frequency of TTSs in the Taurus SFR is higher than in other SFRs (Leinert et al. 1993), such as the Trapezium (Prosser et al. 1994), implying that the ejection mechanism may be more efficient in Taurus. Fully resolving this issue will, however, require studying a larger sample of Taurus BDs, which the completion of the CFH12k survey should soon provide.

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