SEARCH FOR VERY LOW-MASS BROWN DWARFS AND FREE-FLOATING PLANETARY-MASS OBJECTS IN TAURUS

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ABSTRACT

The number of low-mass brown dwarfs and even free floating planetary-mass objects in young nearby star-forming (SF) regions and associations is continuously increasing, offering the possibility to study the low-mass end of the initial mass function in greater detail. In this paper, we present six new candidates for (very) low-mass objects in the Taurus SF region one of which was recently discovered in parallel by Luhman et al. The underlying data we use is part of a new database from a deep near-infrared survey at the Calar Alto observatory. The survey is more than 4 mag deeper than the Two Micron All Sky Survey and covers currently ~1.5 deg². Complementary optical photometry from Sloan Digital Sky Survey were available for roughly 1.0 deg². After selection of the candidates using different color indices, additional photometry from Spitzer/IRAC was included in the analysis. In greater detail, we focus on two very faint objects for which we obtained J-band spectra. Based on comparison with reference spectra, we derive a spectral type of L2 ± 0.5 for one object, making it the object with the latest spectral type in Taurus known today. From models, we find the effective temperature to be 2080 ± 140 K and the mass 5–15 Jupiter masses. For the second source, the J-band spectrum does not provide definite proof of the young, low-mass nature of the object, as the expected steep water vapor absorption at 1.33 μm is not present in the data. We discuss the probability that this object might be a background giant or carbon star. If it were a young Taurus member, however, a comparison to theoretical models suggests that it lies close to or even below the deuterium burning limit (≈13 M_Jup) as well. A first proper motion analysis for both objects shows that they are good candidates for being Taurus members.

Key words: stars: formation – stars: late-type – stars: low-mass, brown dwarfs – stars: pre-main sequence

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1. INTRODUCTION

Taurus is certainly one of the best studied low-mass star-forming (SF) regions in the northern hemisphere. It lies at a distance of ~140 pc (Kenyon et al. 1994) and is very young (median age ~1 Myr; Briceño et al. 2003; Luhman et al. 2003). The initial mass function (IMF) in Taurus has been studied intensively in the last years using large surveys mostly in the optical. It first seemed as if at the low-mass end the number of brown dwarfs (BDs) was too small compared to the expectations of theoretical models suggests that it lies close to or even below the deuterium burning limit (~13 M_Jup) as well. A first proper motion analysis for both objects shows that they are good candidates for being Taurus members.

Luhman et al. (2009a) reported the detection of the first L0 dwarf in Taurus where the spectral type was derived from an I-band spectrum. However, this object appears to be underluminous for its assumed young age and we will discuss this object and its properties in more detail in Section 4. In theory, young objects (1–3 Myr) with L and T spectral types and corresponding effective temperatures below ~2300 K could potentially be of planetary-mass (Table 2).

For other young SF regions, the detection of L- and T-type objects has already been reported and their numbers are rather small but continuously increasing. In the 3–5 Myr old cluster, σ-Orionis one object, S Ori 70, has an observed spectral type of T5.5 ± 1 ( Zapatero Osorio et al. 2002), one object is of spectral type L4 and three objects have spectroscopically confirmed spectral types of L0–L1.5 ( Zapatero Osorio et al. 2000). If these objects are members of the young cluster then they can be considered as very good candidates for isolated planetary-mass objects (i.e., with masses M < 13 M_Jup). However, McGovern et al. (2004) found for one potential candidate in σ-Orionis (S Ori 47) spectroscopic evidence that the object is rather an object from the field than from the young cluster. Recently, Bihain et al. (2009) reported the detection of three additional objects in σ-Orionis (S Ori 72–74) with theoretical masses of a few Jupiter masses (with L–T spectral types), but spectroscopic confirmation is still pending. In addition to the objects in σ-Orionis, Lodieu et al. (2008) and Luhman et al. (2008) reported the finding of L-type objects in the Upper Sco Association.
and the Chameleon I region, respectively (median ages ~3–5 Myr).Weights et al. (2009) reported the spectroscopic confirmation of 38 very low mass objects below the hydrogen burning limit in the Orion Nebula cluster (median age ~1 Myr). Ten of their objects could have masses below the deuterium burning limit and be thus planetary-mass objects. Burgess et al. (2009) recently published the detection of a T dwarf candidate in the 3 Myr old SF region IC 348 based on methane-band imagery. They found a preliminary spectral type of T6 for the object and concluded that the detection of this source is consistent with the extrapolation of current lognormal IMF estimates down to the planetary-mass domain given the survey area and completeness of their sample. Furthermore, there are three optically classified L dwarf candidates in the field showing some spectral signatures of youth (Kirkpatrick et al. 2001, 2006;Luhman et al. 2006b). Four additional objects in young SF regions (1–3 Myr) are at the borderline between M- and L-type objects but are subject to controversial discussions in the literature: Jayawardhana & Ivanov (2006a, 2006b) derived for four objects in Chameleon, Lupus, and Ophiuchus spectral types of L0 and planetary-masses while Luhman et al. (2007) and Allers et al. (2007) derived at least for three of the objects significantly earlier spectral types (M7.25–M8.75) and higher masses. Finally, in the TW Hya associate (5–10 Myr) only with late M-type, and thus more massive, objects were found (Liu et al. 2003;Gizis 2002).

In this paper, we present new candidates for low-mass BD in Taurus. At least two objects are good candidates for being among the least massive objects known today in this SF region possibly lying below or close to the edge of isolated planetary-mass objects. For one object, we derive a spectral type of L2 ± 0.5 and a most likely mass between 5 and 15 Jupiter masses.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Omega2000 Data

In a new deep near-infrared (NIR) survey of Taurus, we focused on regions of comparably high extinction where previous optical surveys might have missed potentially young, very low-mass objects. In the first part of our ongoing survey, we observed the vicinity of 55 dense molecular cores (Onishi et al. 2002) between 2004 October and 2006 January with the wide-field NIR camera Omega2000 on the 3.5 meter telescope in Calar Alto (Spain). The camera is equipped with a 2048 × 2048 pixel HAWAII-2 detector, has a pixel scale of 0.45 pixel−1 and an effective field of view of ~15′. The 55 dense cores were covered with 24 telescope pointings. One additional field harboring a proto-BD (Apai et al. 2005) was included in the survey. Up to now the NIR observations cover an area of ~1.5 deg2 on the sky (Table 3). Each field was observed in the three NIR filters J, H, and K, with central wavelengths at 1.21, 1.65, and 2.15 μm, respectively. For two fields, the Ks-band data had to be disregarded in the data analysis as cloudy skies disturbed the observations significantly. Following a pre-defined dither pattern, 30 frames were taken on each field and filter. Each frame had an on-source integration time of 1 minute, so that after co-addition the total integration time amounted to 30 minutes per field and filter. The limiting magnitudes were ~22.0 mag in J, ~20.5 mag in H, and ~19.5 mag in Ks. The depth of the survey allows us to detect young objects (1–5 Myr) down to a few Jupiter masses in all three filters if they were present.

The data reduction was carried out with a dedicated pipeline developed at the MPAI. The pipeline runs within the MIDAS environment and does flat-fielding, bad pixel and cosmic ray removal, sky subtraction, and finally weighting and co-addition of the individual images to a combined final image for each field and filter. If one frame suffers substantially from bad quality, e.g., due to bad observing conditions in terms of seeing or transparency, this frame is rejected and not included in the final image. A more detailed overview concerning the pipeline is provided in the Omega2000 Handbook.

Astrometry was applied to each field by comparing the positions of detected Two Micron All Sky Survey (2MASS) point sources to those listed in the 2MASS Point Source Catalog (PSC; Cutri et al. 2003). On average, the precision of the astrometry is better than 0.25′ with respect to the known 2MASS positions.

After visual inspection of the resulting final frames, photometry was carried out with the daophot8 package within the TRAF8 environment. As the point-spread function (PSF) does not vary significantly over the chip, PSF-photometry was carried out instead of simple aperture photometry, in order to ensure reasonable flux measurements of close binaries and in more crowded regions. A reference PSF was created for each filter

| Model         | 1 Myr  | 2 Myr  | 3 Myr  | 5 Myr  |
|---------------|-------|-------|-------|-------|
| Baraffe et al. (2003) | ~20 M\textsubscript{Jup} | ... | ... | ~23 M\textsubscript{Jup} |
| ... | 10 M\textsubscript{Jup}/2250 K | ... | ... | 10 M\textsubscript{Jup}/1970 K |
| ... | 15 M\textsubscript{Jup}/2400 K | ... | ... | 15 M\textsubscript{Jup}/2260 K |
| ... | 5 M\textsubscript{Jup}/1900 K | ... | ... | ... |
| ... | 10 M\textsubscript{Jup}/2250 K | ... | ... | ... |
| ... | 15 M\textsubscript{Jup}/2450 K | ... | ... | ... |
| Burrows et al. (2003, 2006) | ... | 10 M\textsubscript{Jup}/2130 K | ... | ... |
| ... | 15 M\textsubscript{Jup}/2450 K | ... | ... | ... |

Note. Masses are given in Jupiter masses.
Field Name & R.A. (J2000) & Decl. (J2000) & No. of Exposures & Seeing (′) & Calibr. Err. (mag) & Obs. Date  & SDSS coverage  

| Field | R.A. | Decl. | No. of Exposures | Seeing | Calibr. Err. | Obs. Date | SDSS coverage |
|-------|------|-------|------------------|--------|-------------|----------|---------------|
| tc2   | 04h10m53s64 | +25°09′28.3 | 28/30 | 1.3/0.1/0.0 | 0.04/0.05/0.05 | Jan 5 | 50% |
| tc5 6_7_8 | 04h18m00s87 | +28°12′28.9 | 30/28 | 1.0/1.0/1.5 | 0.07/0.05/0.05 | Jan 5 | 100% |
| tc7 11 | 04h18m19s56 | +28°23′50.2 | 30/30 | 1.4/1.0/1.3 | 0.09/0.07/0.07 | Oct 4 | 100% |
| tc12a 12b | 04h19m03s83 | +27°19′27.4 | 30/30 | 1.6/1.7/1.7 | 0.05/0.03/0.06 | Oct 4 | 92% |
| tc13a 13b 14 | 04h19m44s22 | +27°09′52.2 | 30/27 | 1.2/1.0/1.2 | 0.06/0.07/0.05 | Jan 5 | 100% |
| tc15 16a | 04h20m35s70 | +27°05′37.2 | 30/30 | 1.4/1.3/1.3 | 0.08/0.08/0.08 | Dec 5 | 100% |
| tc16a 16b 17 | 04h21m22s49 | +26°59′08.0 | 30/30 | 1.6/1.4/1.3 | 0.09/0.05/0.07 | Dec 5 | 100% |
| tc19   | 04h23m36s53 | +25°05′55.3 | 30/30 | 1.3/1.3/1.2 | 0.06/0.04/0.05 | Dec 5 | 100% |
| tc20 21_22 | 04h23m55s75 | +26°36′38.4 | 30/30 | 1.8/1.7/1.2 | 0.05/0.05/0.06 | Oct 4 | 100% |
| tc23 24 | 04h26m33s31 | +24°38′47.4 | 30/30 | 1.4/1.5/1.3 | 0.06/0.04/0.05 | Oct 4 | 100% |
| tc25 26a 26b | 04h27m53s53 | +26°19′01.0 | 30/30 | 1.2/1.6/1.2 | 0.04/0.06/0.05 | Dec 5 | 100% |
| tc28 29 | 04h29m40s00 | +24°29′34.1 | 30/28 | 1.9/2.4/2.4 | 0.06/0.04/0.06 | Oct 4 | 100% |
| tc35 36a 36b | 04h35m44s37 | +24°09′11.8 | 29/30 | 1.2/1.1/1.0 | 0.06/0.06/0.06 | Jan 5 | 77% |
| tc37 38 39 41 | 04h39m28s62 | +25°47′29.6 | 29/29 | 1.0/1.0/1.1 | 0.09/0.07/0.05 | Jan 5 | 100% |
| tc42a 42b 42c | 04h40m36s19 | +25°29′53.4 | 29/30 | 0.9/1.0/0.9 | 0.07/0.05/0.05 | Jan 5 | 100% |
| tc43 44 | 04h41m28s61 | +25°54′15.5 | 29/30 | 1.0/1.1/1.0 | 0.06/0.05/0.10 | Jan 5 | 100% |
| tc50 | 04h41m30s00 | +25°42′30.0 | 30/30 | 1.2/1.2/1.1 | 0.07/0.06/0.06 | Dec 5 | 100% |

Notes. Column (4) shows the number of 1-minute exposures per field and filter that were finally co-added to create the final images. The seeing (Column (5)) was estimated during the data reduction in the respective NIR filters. The sixth column shows the mean transformation error for each field and filter resulting from the photometric calibration with 2MASS data.

and field individually and then applied to all sources detected with a 3σ confidence level. The resulting tables containing the fluxes for each field and filter were then cross-matched in order to identify sources that were detected in all three filters. For the cross-matching, the coordinates of the measured flux peaks were required to match within 2 pixels.

Finally, the photometric calibration was achieved by comparing the measured instrumental magnitudes to those listed in the 2MASS PSC. Here, only objects with the best “quality flag” and “read flag” in the 2MASS PSC were considered serving as photometric reference sources. Typically between 50 and 100 objects satisfying these criteria were detected in each Taurus field. By plotting the difference between the observed instrumental magnitudes and those measured in 2MASS in one filter against an observed color (e.g., J - 2MASS vs. J - H2MASS), the color correction terms for the Omega2000 and 2MASS filter systems were derived. This procedure was done for each observed Taurus field individually as observing conditions did vary between the individual fields. The mean transformation errors for each field and filter are also given in Table 3.

2.2. SDSS Data

To differentiate between potential young members of Taurus and background and foreground contaminants/sources, it is crucial to rely not only on NIR data but to take into account also optical information. The Sloan Digital Sky Survey (SDSS) offers up to five additional bands in the optical wavelength regime9 (Finkbeiner et al. 2004) and covers parts of our NIR survey area. In the upper part of Table 3, we provide estimates for the overlap between SDSS and our fields (total ~1.0 deg²).

For the rest of the paper, we will only focus on the overlapping regions. We matched our Omega2000 NIR catalog with the SDSS data allowing a maximum offset of 2″ for an objects’ position in both data sets.

2.3. Spitzer IRAC Data

Photometry at longer IR wavelengths allows us to detect the presence of disks around potential Taurus candidates supporting a young age of the object and thus membership of the SF region. Images taken with the IRAC instrument on board the Spitzer Space Telescope were downloaded from the data archive10 for the finally selected objects (see Section 3). The so-called “Post Basic Calibrated Data (PBCD)” were used to determine the flux of the individual candidates in the first two IRAC filters at 3.6 and 4.5 μm. Unfortunately, the sensitivity of these images is insufficient to detect some of the fainter candidates at 5.8 and 8.0 μm. The initial pixel values of the images were converted from MJy sr⁻¹ to count rates DN s⁻¹ (data numbers per second). Afterward, aperture photometry was carried out using the standard atv.pro routine inIDL with an aperture size of 2 pixel and a sky annulus from 10–20 pixel. Aperture corrections were carried out as described in the IRAC Data Handbook to obtain the final magnitudes via $m = -2.5\log(x) + \Delta m$ with x denoting the flux measured in DN s⁻¹ and $\Delta m$ being the zero point for each filter.11

9 http://photo.astro.princeton.edu/oriondatarelease/
10 These data are part of a large-scale IRAC Taurus survey (PI: Deborah Padgett) and are publicly available.
11 Zero points taken from Hartmann et al. (2005): 19.66 (3.6 μm), 18.94 (4.5 μm), 16.88 (5.8 μm), 17.39 (8 μm).
2.4. Very Large Telescope/ISAAC Data

For two of the three least luminous, and hence most interesting, objects we were granted Director’s Discretionary Time (DDT) for ISAAC on ESO’s Very Large Telescope (VLT) to obtain J-band low-resolution spectra. In low-resolution mode, ISAAC has a pixel scale of 0.147 pixel$^{-1}$ and a slit length 120″. The observations took place between 2007 February 7 and February 11. The spectra cover a wavelength range between 1.1 and 1.4 μm, and we chose a slit width of 0′.8 resulting in a resolution of $R \approx 680$. The observations were done in a nodding mode, with a 40″ nodding-throw along the slit. The detector integration time (DIT) was 120 s for both objects. The number of DIT exposures averaged out within the same frame (NDIT) and the number of frames (NINT) were 2 and 10, and 2 and 6 for CAHA Tau 1 and CAHA Tau 2, respectively. The air mass was between 1.5 and 2.0 in general, but increased up to 2.3 for the observations of CAHA Tau 2. The seeing was mostly better than 0′.8. The data reduction was done with the IRAF package onespec following the standard procedure for low-resolution spectra: sky subtraction, flat-fielding, cosmic ray removal, and finally extraction of the spectrum using an interactively fitted aperture. After wavelength calibration using argon lines, the individual spectra for each object were averaged in combination with a 3σ clipping for the individual points. Telluric lines were corrected afterward using standard stars$^{12}$ that were observed roughly at the same air mass directly after the science objects. To correct for the spectral response of the detector, we compared the observed spectra of the standard stars with theoretical models of the same spectral type and applied correction factors to obtain an identical spectral slope.

3. RESULTS

3.1. Candidate Selection

To identify potential low-mass objects of the Taurus region among the thousands of detected objects an optical/NIR color–magnitude diagram (CMD) served as starting point. In particular for fainter objects, one has to find a way to distinguish between nearby low-mass objects, distant giant stars, and also distant galaxies. While even distant galaxies with high redshifts typically have $I - J$ colors between 0 and 2.5, nearby low-mass objects normally appear significantly redder. Figure 1, where we plot K against $I - J$, takes advantage of this fact. As the overplotted theoretical isochrones (see below) are provided in the CIT photometric system, the NIR data in this figure were transformed into the CIT system. The optical data is in the Johnson–Cousin system. The required equations to transform between the different photometric systems are given in the Appendix. In the plot, we show only objects with a photometric error $< 0.1$ mag in the NIR and with a $S/N > 5$ in the SDSS i and z band. Out of more than 9000 objects that were commonly detected in the SDSS database and the NIR observations, 5251 sources fulfilled these criteria. Theoretical isochrones computed by Baraffe et al. (2002) and Chabrier et al. (2000) are overplotted in the CMD. The isochrones have an age of 5 Myr, are scaled to the mass regimes between 0.02 $M_\odot$ and 1.4 $M_\odot$ (Baraffe et al. 2002), and 0.002 $M_\odot$ and 0.075 $M_\odot$ (Chabrier et al. 2000). The assumed age is a rather conservative assumption because, as mentioned in the introduction, Taurus seems to be significantly younger ($\tau \sim 1$ Myr; Briceño et al. 2003). Since younger objects tend to appear brighter (they have larger radii) and redder (e.g., due to circumstellar material), objects falling along the isochrones or lying above them are potential Taurus candidates and should be selected. As expected, the least luminous objects are not selected as they appear too blue in $I - J$ and are thus background stars or galaxies. In total, using the isochrones as a first selection criterion, the number of objects was reduced from 5251 down to 646.

These objects are now, in a second step, plotted in a NIR color–color diagram (Figure 2). Also here the CIT photometric system is used to be consistent with the first selection step. It can be seen that most of the selected objects lie along the reddened main sequence or along the reddened giant branch. Only very few sources populate the classical TTauri star locus (Meyer et al. 1997) or show otherwise any NIR excess emission. This indicates that the sample seems to be mostly contaminated by (background) stars. To minimize the possibility of selecting these objects, we considered only objects lying on the right-hand side of a reddened M3 main-sequence star and showing positive NIR colors. This selection resulted in 22 objects which were then subject to an individual inspection on the images. As some objects were too close to the edge of the detector in some filters and one object was observed twice in two adjacent telescope pointings, the final sample of candidates consisted of 16 objects. Their positions in the color–color diagram are indicated by crosses and squares in Figure 2.

Finally, the coordinates for the 16 remaining objects were cross-checked with the SIMBAD Astronomical Database.$^{13}$ Ten objects were already listed (boxes in Figure 2), but six candidates initially did not have a counterpart in the database (crosses in Figure 2).

$^{12}$ We used the B5 stars Hip023151 and Hip023946.

$^{13}$ http://simbad.u-strasbg.fr/simbad/
For the 10 previously known objects, the names, magnitudes, spectral types, and references are summarized in Table 4 along with our new NIR photometry. We stress that the objects with known spectral type are without exception low-mass stars and BDs in Taurus. This emphasizes the quality of our selection criteria. With KNPO-Tau 4, we even re-detected an object with a spectral type as late as M9.5. However, since we applied rather strict selection criteria, we did not re-identify all of the known low-mass objects and BDs that lie in our observing fields. Some of them have, for instance, bluer $H-K$ colors than allowed by our selection criteria. One example can be seen in Figure 3. In Table 4, also the magnitudes from the 2MASS PSC are given for comparison. One can see that the 6 new low-mass candidates presented in this paper (crosses), known Taurus BD from Guieu et al. (2006a; boxes) and embedded carbon stars from Liebert et al. (2000; diamonds). The lines are the same as in Figure 2. The colors are given in the 2MASS photometric system.

Notes. For each object magnitude from our observations as well as from the 2MASS catalog (second line of magnitudes) are given for comparison. The errors in our NIR magnitudes reflect uncertainties in the fitting of the individual PSFs as well as systematic errors resulting from the photometric calibration with the 2MASS reference sources.

References. (1) Luhman et al. 2006a; (2) Luhman et al. 2006; (3) Guieu et al. 2006; (4) White & Basri 2003; (5) Luhman et al. 1998; (6) Mohanty et al. 2005; (7) Harris et al. 1988; (8) Itoh et al. 1999; (9) Itoh et al. 2002; (10) Briceño et al. 2002; (11) 2MASS Point Source Catalogue (Cutri et al. 2003); (12) Luhman et al. 2009b.
For the six objects that were initially not listed in SIMBAD, the coordinates and photometric properties are shown in Table 5 together with estimates for their optical extinction based on extinction maps. However, during the revision process of this paper Luhman et al. (2009b) also published results for our candidate CAHA Tau 6 and found the object to be very young BD with a spectral type of M9.25 and a mass of $\sim 0.015 M_\odot$. Most interestingly, the object turned out to be a member of an isolated BD binary system with FU Tau (now FU Tau A) being the primary object, which we also re-identified among the 10 previously known objects (see Table 4). Although CAHA Tau 6 (now FU Tau B) was thus already confirmed to be a young low-mass object, we keep it in our sample in the following, especially because no NIR data has been published so far. Thus, the properties of all our initially selected six candidates are discussed in greater detail in the following sections. Figure 4 shows the NIR finding chart for CAHA Tau 1 (NIR finding charts for CAHA Tau 1–5 are available as an extended figure in the online journal). In Luhman et al. (2009b), an optical image of the CAHA Tau 6 region is provided.

### 3.2. Photometric Properties of Candidates

In the following, we will discuss the photometric properties our selected candidates. From now on, we use the 2MASS photometric system in the NIR throughout the rest of the paper as most reference sources were published with 2MASS NIR data. In Figure 3, we show again a NIR color–color diagram. This time, however, we compare the colors of our six candidates to those of previously detected BDs in Taurus from Guieu et al. (2006) and embedded carbon stars from Liebert et al. (2000). As we are interested in very low-mass objects, we show only objects from Guieu et al. (2006) with spectral types of M7 or later. We notice two things: first, the colors of most of our candidates do agree quite well with low-mass objects. Only CAHA Tau 5 appears a little too blue in $J - H$. Second, some of the carbon stars have NIR colors that are very similar to those of our young low-mass candidates. Especially, CAHA Tau 3 (and to a lesser extend also CAHA Tau 4) finds itself surrounded by carbon stars.

In Figure 5, we continue the comparison of our candidates to other young low-mass sources. This time, we increase the wavelength range in the NIR by using IRAC data at 3.6 and 4.5 $\mu$m, and we include optical colors in the diagrams. Furthermore, we add young, planetary-mass candidates in $\sigma$ Orionis from Zapatero Osorio et al. (2007) as reference objects. It shows that in the left-hand plot of Figure 5, our candidates nicely populate the region in the color–color diagram of the other young low-mass objects. Only CAHA Tau 6 appears much redder in the IRAC color, but Luhman et al. (2009b) argued that this object is indeed particularly young ($\sim 1$ Myr) and shows significant infrared emission excess. In the right-hand plot, where we have chosen a broader wavelength baseline for the colors, our candidates tend to occupy the left region of the plot, i.e., they are relatively blue in $K_s - 4.5 \mu m$ compared to the reference objects. However, the colors are, in general, agreement with those of the other young low-mass objects. Only CAHA Tau 4 lies a little offsite compared to the other candidates and, again, CAHA Tau 6 appears very red in the $K_s - 4.5 \mu m$ color.

### 3.3. J-band Spectroscopy

As seen, for instance, in Allers et al. (2006, 2007), one has to be careful if one tries to derive stellar parameters of young objects such as spectral types, effective temperatures, and masses solely from photometric measurements. Hence, we complemented our data with NIR J-band spectra for two of the three least luminous objects. We focused on these objects as they are potentially also the least massive and hence, for our purpose, most interesting candidates.

In Figure 6, we show the J-band spectra of CAHA Tau 1 and CAHA Tau 2 and compare them to data of field BDs and giants (left panel), and to young objects presented by Allers et al. (2007) and model spectra from Burrows et al. (2003).
Figure 4. Finding chart for CAHA Tau 1 taken with the Omega2000 $K_s$ filter. (An extended version of this figure is available in the online journal.)

Figure 5. Red/IR color–color diagrams comparing the six new low-mass candidates presented in this paper (crosses), known Taurus BDs from Guieu et al. (2006; boxes) and very low-mass BDs in the young $\sigma$ Orionis cluster from Zapatero Osorio et al. (2007; diamonds). The objects from Zapatero-Osorio typically have larger errors than our candidates.

The left-hand side of Figure 6 suggests that our candidates are late-type objects, as the spectrum of the early M-type giant HD 120052 does not show the deep water absorption band at the red edge of the spectrum that is seen in our candidates. Also, the general slope of the spectra is in agreement with late-type objects. Furthermore, it seems clear that our candidates have a low surface gravity, an indication for a possibly young age, as no strong spectroscopic features are present. However, in the spectrum of CAHA Tau 1, we find weak spectral signatures: there is a dip near the position of the Na I doublet around 1.14 $\mu$m and also hints for the K I doublets near 1.17–1.18 $\mu$m and 1.24–1.25 $\mu$m, which show up much stronger in the spectra of the higher surface gravity field stars. In Figure 7, a direct comparison between the J-band spectrum of CAHA Tau 1 and those of late-type field objects is shown. The overall very similar shape and slope is striking and also the existence of similar spectral features, even if they are very weak in case of CAHA Tau 1. The best overall agreement in shape and slope between a reference spectrum and CAHA Tau 1 is found for Kelu 1 AB. Based on this, we estimate the spectral type of CAHA Tau 1 to be L2 $\pm$ 0.5, which is the latest spectral type known in Taurus today. We will discuss this finding in more detail in Section 4.1.

A spectral classification for CAHA Tau 2 is difficult as its spectrum lacks any spectral lines. However, it is not unusual for young low-mass sources to have almost no spectroscopic features as can be seen in McGovern et al. (2004) and Lodieu et al. (2008). The first group published spectra of the young
Figure 6. Left panel: J-band spectra of CAHA Tau 1 and CAHA Tau 2 compared to those of field BDs and M-type (super-)giants. The reference spectra have a resolution of $R \approx 2000$ and were downloaded from the IRTF spectral library (http://irtfweb.ifa.hawaii.edu/~spex/IRTF_Spectral_Library; Cushing et al. 2005). Right panel: J-band spectra of CAHA Tau 1 and CAHA Tau 2 compared to theoretical models from Burrows et al. (2003, 2006) with $R \approx 500$ and young low-mass objects from Allers et al. (2007) with $R \approx 300$. Our candidate spectra were corrected with the $A_V$ values given in Table 5 and using the extinction law of Mathis (1990) with $R_V = 3.1$.

(A color version of this figure is available in the online journal.)

Figure 7. Comparison of CAHA Tau 1 (shown four times in red) to low-mass field reference objects (black spectra) from Cushing et al. (2005). The best overall agreement is found with Kelu 1 AB, a binary BD system where the combined spectrum has been established as reference for the spectral type L2. (A color version of this figure is available in the online journal.)

Figure 6. Left panel: J-band spectra of CAHA Tau 1 and CAHA Tau 2 compared to those of field BDs and M-type (super-)giants. The reference spectra have a resolution of $R \approx 2000$ and were downloaded from the IRTF spectral library (http://irtfweb.ifa.hawaii.edu/~spex/IRTF_Spectral_Library; Cushing et al. 2005). Right panel: J-band spectra of CAHA Tau 1 and CAHA Tau 2 compared to theoretical models from Burrows et al. (2003, 2006) with $R \approx 500$ and young low-mass objects from Allers et al. (2007) with $R \approx 300$. Our candidate spectra were corrected with the $A_V$ values given in Table 5 and using the extinction law of Mathis (1990) with $R_V = 3.1$.

(A color version of this figure is available in the online journal.)

Taurus object KPNO-Tau 4 and of $\sigma$ Ori 51 while the second group presented spectra of young L dwarfs in Upper Sco. All of these objects showed barely any spectral features in the J band, presumably due to their low surface gravity, and appear in this respect similar to CAHA Tau 2. Finally, a comparison to theoretical models and reference spectra of young low-mass objects further emphasizes the almost featureless behavior of these objects (right-hand side of Figure 6).

One thing, however, appears strange in the spectrum of CAHA Tau 2, and so far we lack a satisfying explanation if it was a young object. The drop in the flux caused by water vapor around $1.33 \mu m$ is not as steep as in the other low-mass objects including CAHA Tau 1. Although the peak flux in the J band is reached between 1.32 and 1.33 $\mu m$, as it is also the case for the reference BDs, the flux of our candidate decreases more slowly with increasing wavelength. This behavior is not typical for young, low-mass objects (see, e.g., Lodieu et al. 2008). However, J-band spectra of C-N and C-J carbon stars as presented by Tanaka et al. (2007) show a similar behavior with no significant drop in the flux up to 1.35 $\mu m$. And also the flux of the M7 III star HD108849 in Figure 6 shows a rather modest decline longward of 1.33 $\mu m$ in addition to an overall featureless J-band spectrum.

To summarize, for CAHA Tau 1 we find spectroscopic support for the young and low-mass nature of the object from both, the weak spectral features and the overall slope of the spectrum, and we can estimate a spectral type. For CAHA Tau 2, a definite spectroscopic proof that the object is indeed a young, low-mass Taurus member is pending and although the general slope is very similar to that of CAHA Tau 1 the lack of strong water absorption around $1.33 \mu m$ talks in favor of a background carbon star or giant.

3.4. Proper Motion of Taurus Members and Our Candidates

Another way to find additional support for the low-mass nature of our candidates is to analyze their proper motion. For CAHA Tau 6, Luhman et al. (2009b) already showed that it most likely shares common proper motion with FU Tau A, which itself shows a proper motion consistent with Taurus membership. Thus, we focus on the remaining five objects.

Proper motion studies of stellar members of the whole Taurus– Auriga association show a wide dispersion in proper motions along the right ascension axis, with $-5 < \mu_\alpha < 15$ mas yr$^{-1}$, but a consistently negative proper motion along the declination axis, with $-35 < \mu_\delta < -5$ mas yr$^{-1}$ (Frink et al. 1997), mostly due to the reflex motion (Jones & Herbig 1979). We have run a simulation of our fields using the Besançon model (Robin et al. 2003, 2004), adding an extinction layer at 150 pc distance with variable extinctions. The model does not include the SF region, only the smooth components of the Galactic disks and halo.

As mentioned above, we re-identified KPNO-Tau 4, a confirmed young and low-mass BD, during our selection process (see Table 4).
This simulation (see Figure 8) shows that most giant and sub-giant stars have proper motion $|\mu| < 5$ mas yr$^{-1}$, corresponding to halo-type velocities (at most) and distances larger than 10 kpc (see Section 4.2). The fraction of giant and sub-giant stars with proper motion $\mu_s < -10$ mas yr$^{-1}$ and $16 < J < 18$ is $3\% \pm 1\%$ (1σ statistical error). The fraction for the brighter M giants would be even smaller. Therefore, a significantly larger proper motion measurement would reject the giant hypothesis, while a proper motion $\mu_s > -8$ mas yr$^{-1}$ or $|\mu_\alpha| > 30$ mas yr$^{-1}$ would most likely exclude a Taurus membership. Because the Taurus proper motion space overlaps with that of disk dwarfs, proper motions cannot completely remove the field dwarf contamination. A fraction of 5% of field dwarfs with $16 < J < 18$ have a proper motion of $|\mu_\alpha| < 30$ mas yr$^{-1}$ and $\mu_s < -15$ mas yr$^{-1}$.

To complement our NIR and SDSS images, we used public data from CFHT’s 12k and MegaCam cameras, and, for CAHA Tau 1, the catalogs from the UKIDSS Galactic Plan Survey $K$-band data from the Data Release 3 (Lawrence et al. 2007). CFHT images were detrended using the Elixir pipeline (Magnier & Cuillandre 2004). Object detection and astrometry was performed using SExtractor (Bertin & Arnouts 1996) on all images (CFHT, SDSS, and OMEGA2000). Bright objects (signal-to-noise ratio (S/N) $> 100$, a few dozens) were used to derive a preliminary transformation, which is refined with all objects with S/N $> 10$ (one hundred).

For the three faintest targets, 2MASS data have too large positional uncertainties to improve the fit. The photometric errors are negligible at our targets’ brightness; the error budget is dominated by transformation errors, which includes refraction, instrumental distortions, and proper motions of the reference stars. Therefore, we set the positional accuracies to a minimum of 30 mas, typical of the best position dispersion measured by scamp for bright stars. This dispersion rises to 80 mas in some cases (e.g., when using SDSS as the reference catalog). We then fit a proper motion on the CFHT, SDSS, O2000, and UKIDSS positions when a detection was found within 1′ of the O2000 position, for all objects with SDSS $z$ and O2000 $K_s$ magnitudes similar to our candidates (see Table 6 and Figure 9). We have not corrected for the velocities of the stars which form our reference grid, and we present relative proper motions only. The Besançon simulation shows that stars brighter than $J < 16$ mag have a small averaged proper motion of $\langle \mu_\alpha \rangle = 2$ mas yr$^{-1}$ and $\langle \mu_\delta \rangle = -4$ mas yr$^{-1}$, although some have large proper motions.

The data set used for these measurements is far from optimal: we compare positions obtained with four different instruments, with the first epochs obtained in the red and the last epoch(s) obtained in the NIR. We did not find any correlation between positional shifts and hour angles, or filter bands, so that most of the transformation error budget is likely to be due to the imperfect corrections of the (relative) instrumental optical distortions, and the proper motion dispersions of the reference objects. Because we could not calculate a global astrometric solution simultaneously for all instruments, proper motion measurements could not be determined during the registration process itself.
3.4.1. CAHA Tau 1 and 2

Despite these limitations, we find that the proper motions of CAHA Tau 1 and CAHA Tau 2 are compatible with typical Taurus members’ proper motions (Figures 8 and 9). In order to judge whether the giant hypothesis is rejected, we need to know how significantly they differ from $\mu = 5$ mas yr$^{-1}$. Because of the short time baseline and the required proper motion accuracy, it is important to have a good estimate on the proper motion errors, which will be smaller than the signal by a factor of a few at most. A first estimate of the positional accuracy of each data set is given by the shift dispersion of the bright reference stars, subtracting the estimated reference catalog errors, to which we add the photonoise of the candidate. However, this might be a lower limit for CAHA Tau 1 as it is located in a corner of the CFHT CCDs, in an empty area. The location of CAHA Tau 2 is more central and favorable. The colors of the candidates are typical of the bulk of the reference stars. Many reference stars are background stars with significant reddening, and therefore red colors. Furthermore, the difference in colors does not correlate with proper motions or dispersions around the proper motion fit. The large number of CFHT images at a given epoch for CAHA Tau 1 allows us to measure the positional dispersion. As described above, we used this value as a proxy for the positional accuracy. Unfortunately, this robust method cannot be used for OMEGA2000, and even less for the UKIDSS single image. Moreover, the UKIDSS DR3 catalog comes with no astrometric errors, and the proper motion fit relies crucially on this single point, as it extends by one year the time baseline.

We derive the proper motion error from the dispersion of the proper motions of objects of similar magnitudes as our targets. We correct for the intrinsic dispersion based on the Besançon model simulation, although we estimate that measurement errors, which will be smaller than the signal by a factor of a few at most, are the main contributor to the total dispersion. These two arguments suggest that our error estimates are correct within a few mas yr$^{-1}$.

In that case, the proper motion of CAHA Tau 1 is incompatible with a giant star proper motion at the 1.3$\sigma$ level; CAHA Tau 2 at the 1.9$\sigma$ level. We note that the fit of CAHA Tau 2 proper motion along the right ascension is not good, and a value larger than ‘Taurus members’ proper motions cannot be confidently excluded.

3.4.2. CAHA Tau 3, 4, and 5

Unfortunately, the situation for CAHA Tau 3, CAHA Tau 4, and CAHA Tau 5 is different. The data set for these targets is more limited than for CAHA Tau 1 and CAHA Tau 2, in particular no UKIDSS data are available. Also the positional dispersions of reference stars is larger, pointing to a poorer registration. Based on the current data, we find that the proper motions we measure for CAHA Tau 3 do not correspond to the typical proper motions of known Taurus members (see Table 6 and Figure 8). However, the current error bars are large and our measurements are not stable against the registering parameters’ fine tuning, so that further observations are required to ensure a robust measurement. The proper motions of CAHA Tau 4 and CAHA Tau 5 are in agreement with a Taurus membership but have little contamination rejection power.

4. DISCUSSION

4.1. CAHA Tau 1—the First L2 Dwarf in Taurus

From the results shown above, we believe that CAHA Tau 1 is a young, low-mass object in Taurus with spectral type L2 ± 0.5 and thus so far the object with the latest spectral type in Taurus (Luhman et al. 2009a). To estimate its effective temperature, we used the relation between spectral type and $T_{\text{eff}}$ (see Table 7). In the HR diagram (Figure 8), we plot the points for CAHA Tau 1 as well as for other objects found by Golimowski et al. (2004). Overplotted in the diagram are isochrones (1, 5, 10, 50, and 100 Myr) and mass tracks (5, 10, 15, 30, and 50 $M_{\text{Jup}}$). Three points are noteworthy. (1) For most objects, the derived properties are in good agreement with young (≤ 10 Myr), low-mass (≤ 30 $M_{\text{Jup}}$) objects. (2) CAHA Tau 2 (number 1 in the plot) lies below the 1 and 5 Myr isochrones and, depending on its actual age, its observed properties translate into a most likely mass between 5 and 15 $M_{\text{Jup}}$ based on theoretical models (Table 7). It is thus the coolest Taurus member known today and only the second object in the region with a mass most likely below the Deuterium burning limit making it a free floating planetary-mass object. (3) The other object that was recently identified as a Taurus member of planetary-mass with only 4–7 $M_{\text{Jup}}$ (Luhman et al. 2009a; 2MASS 0419+2712, number 2 in the plot) falls nicely between the 1 and 5 Myr isochrones and, depending on its actual age, its observed properties translate into a most likely mass between 5 and 15 $M_{\text{Jup}}$ based on theoretical models (Table 7). It is thus the coolest Taurus member known today and only the second object in the region with a mass most likely below the Deuterium burning limit making it a free floating planetary-mass object.
the different temperature scales. However, 2MASS 0419+2712 appears still too low in the diagram compared to the other sources. As a second source of uncertainty, we speculate that part of this might result from underestimating the extinction toward the source. Even if no disk, and in particular no edge-on disk creating significant extinction, appears to be present (Luhman et al. 2009a), the assumed value of $A_J = 0$ mag, hence no extinction, for 2MASS 0419+2712 might be too low. We note that also in the case of the L0 dwarf in Chameleon I (Luhman et al. 2008) no extinction was assumed. Finally, we mention that it could still be possible that 2MASS 0419+2712 is indeed older than typical Taurus members or it is not associated with the main Taurus population and further away than the assumed 140 pc. In all these cases, the mass of the object would be higher than the current estimates of a few Jupiter masses. More spectroscopic data and a proper motion analysis might yield additional insight into this puzzle.

As CAHA Tau 1 fits nicely on the HR diagram, we compare its broadband spectral energy distribution (SED) with simulations. In Figure 11, we plot the dereddened photometry together with a theoretical model SED for a 3 Myr object of 10 Jupiter masses with $T_{\text{eff}} = 2040$ K (Burrows et al. 2003, 2006). The fluxes were normalized to unity in the $H$ band. The observed photometry was corrected for extinction using the value for $A_V$ given in Table 5, and the extinction curve from Mathis (1990) with $R_V = 3.1$. The agreement between the model and the observations is very good and only the observed $K$ band and 4.5 $\mu$m fluxes appear a little too high compared to the simulations. At least for the flux at 4.5 $\mu$m, it might well be that circum(sub-)stellar material creates excess emission above the photosphere. Zapatero Osorio et al. (2007) also found excess emission for their young, very low-mass objects but mostly longward of 5 $\mu$m. It would be nice to check whether the apparent emission excess we see in CAHA Tau 1 extends also to longer wavelengths.

4.2. CAHA Tau 2–5—Embedded Carbon Stars or (Super-)Giants?

While for CAHA Tau 1 there are sufficient indications that it is a young Taurus member, it has not yet been convincingly shown that our candidates 2–5 are not background carbon stars or late-type (super-)giants. And eventually only additional spectra will help to settle this open question. However, to elaborate a little further on this problem, we plot in Figure 12 a CMD with our candidates and the two groups of carbon stars we already mentioned above (Tanaka et al. 2007; Liebert et al. 2000). For completeness, CAHA Tau 1 and CAHA Tau 6 (alias FU Tau B) are also shown in the plot. One finds that the very distant and deeply embedded objects from Liebert et al. (2000) tend to be much redder than our candidates while the nearby carbon stars from Tanaka et al. (2007) have a very similar $J - K_s$ color like the bulk of our objects. Even more important, however, is the fact that all of our candidates appear fainter than even the most distant objects from Liebert et al. (2000), which are already assumed to lie in or even beyond the Galactic halo. Hence, if our candidates were distant objects then (1) they should appear redder than they are as the Taurus
Table 8

Typical Absolute K-band Magnitudes of Carbon Stars and M-type Giants and Corresponding Minimum and Maximum Distance Moduli and Distances if Our Remaining Two Least Luminous Candidates (CAHA Tau 2 and 3) were Such Objects

| Object Type       | Object Type | $M_K$ (mag) | Reference | $m_K$ – $M_K$ (mag) | Distance (kpc) |
|-------------------|-------------|-------------|-----------|--------------------|----------------|               |
|                   |             | min/max     | min/max   | min/max             |                |               |
| Carbon stars      | –6.5/–8.5   | 20.95/23.17 | 155/431   |                     |                |               |
| M6 III - M8 III   | –6.2/–7.4   | 20.65/22.07 | 135/259   |                     |                |               |
| M0 III - M2.5 III | –4.2/–6.0   | 18.65/20.67 | 54/136    |                     |                |               |

Notes. CAHA Tau 2 serves as basis for the minimum estimate ($m_K = 14.45$), CAHA Tau 3 for the maximum ($m_K = 14.67$).

* The apparent $K$-band magnitudes of CAHA Tau 2 and 3 were corrected for extinction using the optical extinction values given in Table 5 and assuming $A_K/A_V \approx 0.11$ (Mathis 1990).

References. (1) Liebert et al. 2000; Claussen et al. 1987; (2) SIMBAD Astronomical Database (2MASS catalog, Hipparcos catalog); HD 196610, HD 18191, HD 207076, HD 108849; (3) SIMBAD Astronomical Database (2MASS catalog, Hipparcos catalog); HD 213893, HD 204724, HD 120052, HD 219734.

molecular cloud should cause significant additional extinction; and (2) they should be extremely far away. In Table 8, we list the typical values for absolute $K$-band magnitudes of carbon stars and M-type giants. Based on these figures and the apparent magnitudes of our remaining two least luminous candidates (CAHA Tau 2 and 3; Table 5), we derive a range for the objects’ potential distance moduli ($m_K – M_K$). We focus again on these objects as they are intrinsically more interesting due to their faintness. Using

$$d = 10^{0.2 \cdot (m_K – M_K) + 1},$$

we can estimate the physical distances $d$ (in pc) for our candidates if they were indeed carbon stars or M-giants. It shows that the minimum distances for these objects would be around $\sim 155$ kpc for carbon stars and $\sim 135$ kpc for late-type M giants (Table 8). If the assumed extinction toward the objects (Table 5) is not underestimated, the derived distances lie way beyond the currently known extent of our Galaxy, and to our knowledge carbon stars have only been found at distances up to $\sim 130$ kpc (Mauro et al. 2007, and references therein). Only the minimum distance value for early M-type giants $\sim 60$ kpc appears still reasonable, but in Figure 6 we showed that at least CAHA Tau 2 is not an early M-type object.

The density law of halo (giant) stars at those large Galactocentric distances is largely unconstrained, so that it is difficult to estimate even roughly the number of such stars in our total data sample. Extrapolating the halo giant stellar count of Majewski et al. (2003) assuming a smooth halo and a $r^{-2}$ surface density law, we expect much less than one object in our survey area. However, it is possible that the halo be highly structured at these distances, so that the counts would be dominated by (unknown) substructures. In particular, we note that Taurus lies on the Sagittarius stream orbital plane, on its Southern arc. However, no Sagittarius tails are known past $\sim 40$ kpc, or predicted past 100 kpc (Law et al. 2005).

We think that Figure 12 and Table 8 provide additional arguments that most of our objects can be regarded as potential low-mass candidates. Especially, the least luminous objects, CAHA Tau 2 and 3, would be extremely distant if they were background objects. The only exception appears to be CAHA Tau 4. Already its photometric properties discussed in Section 3.2 showed that this object might be of different nature than the other candidates. Figure 12 further strengthens this hypothesis as CAHA Tau 4 could potentially be a (very) distant carbon star.

4.3. Comparison to Theoretical Models

Even though only spectra can eventually prove the young and low-mass nature of CAHA Tau 2–5, we provide in the following a first comparison of their photometric properties to theoretical models. The broadband SED of CAHA Tau 1 was already discussed above (Figure 11) and that of CAHA Tau 6 (alias FU Tau B) was analyzed in Luhman et al. (2009b). For the other objects, we derived estimates for effective temperatures, potential masses, and surface gravities from the models of Burrows et al. (2003, 2006; for an assumed age of 3 Myr) and Chabrier et al. (2000; for an assumed age of 1 Myr). To derive these parameters, we fitted the extinction corrected photometric values for the $I$, $R$, and $J$ band (Table 5) to model grids covering a mass regime between 5 and 70 $M_{\text{Jup}}$. The $I$, $R$, and $J$ band were chosen for the following reasons: (1) for these bands, suitable model grids covering the mass regime were accessible for both ages; (2) focusing on the shorter wavelength regime of our observations reduces the potential contamination by circumstellar material altering the NIR fluxes; (3) the $J$-band photometry has a smaller intrinsic error than the optical wavelength bands and add an additional color to our fits. For the extinction correction, we used the individual values for $A_V$ given in Table 5 and applied the extinction law from Mathis (1990). We furthermore assumed a distance of 140 pc (corresponding to a distance modulus of 5.73 mag) and adapted the photometric values of the theoretical models (originally given in absolute magnitudes) accordingly.

Table 9 summarizes the fit results assuming that our objects are indeed young, low-mass objects. Changing the distance to 160 pc (performed as an additional test case), only alter the results for one object, CAHA Tau 2, in the 1 Myr case. Here, a slightly higher mass was found compared to the value given in Table 9. Overall, this fitting exercise shows that, depending on the age, the first three objects would be among the least massive and coolest Taurus objects known today in case they were Taurus objects. In particular, CAHA Tau 2 could lie close to the deuterium burning limit and thus on the edge to planetary-mass objects. However, as already mentioned in Section 3.3, only spectra will yield the ultimate answer to spectral type and thus mass of our objects.

In Figure 13, we compare all observed, extinction corrected magnitudes to the theoretical broadband SEDs of the best-fit...
magnitudes were corrected for extinction using the extinction law of Mathis (1990) with models given in Table 9. It shows that the magnitudes for CAHA Tau 2 and 4 at the shorter wavelength end are already in general agreement with the models, while the results for CAHA 3 and 5 show notable deviations. Even if we imply that the objects are young, low-mass objects, as done in this figure, then there are still two major sources of uncertainty: (1) the individual extinction can differ from the value derived from the extinction maps, and (2) the distance, and thus the required distance modulus, of the objects may vary. The plot for CAHA Tau 5, and partly also that for CAHA Tau 3, yield hints that the extinction might have been overestimated as the slope between the three optical SDSS bands is not as steep as required by any of the models. However, we emphasize again that only with the help of additional spectra the currently existing degeneracy between spectral type (and thus mass), $A_V$, and distance can be resolved; and we refrain from further refinements of the exercise presented here. Also, the question of NIR/MIR excess emission due to a disk can only be answered once the spectral type and $A_V$ are confirmed for each object. For instance, while CAHA Tau 4 already shows NIR excess emission with the current assumptions, CAHA Tau 2 shows only excess emission compared to the 3 Myr models.

5. CONCLUSIONS

Based on a deep NIR survey in Taurus, we identified six new candidates for low-mass objects in this young SF region. One object, CAHA Tau 6 (now FU Tau B), was independently confirmed as young, low-mass BD of spectral type M9.25 by Luhman et al. (2009b). For a second object CAHA Tau 1, we have spectroscopic evidence that it is indeed a young, very low-mass objects and we assigned a spectral of L2 ± 0.5, making it the object with the latest spectral type in Taurus. For the remaining four objects, we so far lack clear spectroscopic confirmation for their young, low-mass nature; and we can only consider them as candidates at this point in time. However, the identification of CAHA Tau 1 and CAHA Tau 6 with spectral types L2 and M9.25, respectively, as well as the re-identification of 10 additional known low-mass Taurus members during the selection process, gives us confidence for the low-mass nature of the other objects. If they turn out to be indeed young Taurus sources then a comparison to theoretical models suggests that at least a second object (CAHA Tau 2) could be among the least massive known objects in this young SF region known today. In this case, its mass would be close to or below the deuterium burning limit of $\sim 13 M_{\text{Jup}}$ and its effective temperature would lie below $\sim 2300$ K also making it an L-type object. The findings in detail are as follows.

1. **CAHA Tau 1**: The photometric properties, its proper motion, and also the shape and spectroscopic features in the $J$-band spectrum make it very likely that CAHA Tau 1 is the first Taurus member with a spectral type as late as L2 ± 0.5 and an effective temperature of $\sim 2100$ K. For an age between 1 and 5 Myr, as derived from its position in an HR diagram, this temperature corresponds to 5–15 $M_{\text{Jup}}$ and it might well be that CAHA Tau 1 is a free floating planetary-mass object. Its broadband SED is consistent with model predictions for a 3 Myr old object of 10 Jupiter masses with slight excess emission at 4.5 $\mu$m possibly arising from a circum(sub-)stellar disk.

2. **CAHA Tau 2**: The optical and NIR photometric properties support the young, low-mass hypothesis for this object. Further evidence comes from its proper motion. A first $J$-band spectrum did not unambiguously prove the young, low-mass nature as the long wavelength end resembles that of evolved stars or carbon stars. However, a comparison of the photometric properties makes this rather unlikely. Assuming that CAHA Tau 2 is young, low-mass objects, the theoretical models suggest that, depending on the age, it lies close to or below the deuterium burning limit making it another candidate for being among the least massive and coolest known Taurus members today.

3. **CAHA Tau 3**: For CAHA Tau 3, we lack spectroscopic information but its photometric properties are in good agreement with those of young, very low-mass objects. However, currently the proper motion analysis does not support a Taurus membership. Additional data is needed to reduce the large error bars and get a more robust assessment of the proper motion. Assuming a young, low-mass nature, the theoretical models suggest that CAHA Tau 3 lies somewhere at the border between M- and L-type objects with $\sim 15 M_{\text{Jup}}$. In this case, the currently applied value for the extinction is probably overestimated and needs to be revised which would again reduce the estimated mass.

4. **CAHA Tau 4 and 5**: The optical and NIR data for CAHA Tau 5 are in good agreement with young BD while CAHA Tau 4, the brightest object in our sample, lies a little bit off in the presented color–color and color–magnitude plots. Based on its photometric properties, CAHA Tau 4 could also be a (very) distant, evolved object. A fit to theoretical models for young low-mass objects shows that if CAHA

Figure 13. Observed photometric values of the remaining candidates as listed in Table 5 compared to the best-fit theoretical models shown in Table 9. The observed magnitudes were corrected for extinction using the extinction law of Mathis (1990) with $R_V = 3.1$ and the estimated values for the objects' extinction given in Table 5.
Tau 4 was a young BD then it would probably have significant NIR excess emission. Fitting models to the photometric values of CAHA Tau 5 reveals that the currently applied value for the extinction (and/or possibly also the applied distance modulus) need to be refined once spectroscopic data is available. Our PM analysis does not put conclusive constraints on the Taurus membership for both sources.

5. CAHA Tau 6: This object was identified as FU Tau B, a young, M9.25 object in a BD binary system by Luhman et al. (2009b) during the referee process of this paper. We publish here the first J-, H-, and Ks-band data for this source complementing the broadband SED from Luhman et al. (2009b).

So far we have not made an attempt to estimate the effect of our findings on the Taurus IMF. Once we know better which of the above-mentioned candidates are indeed young, low-mass sources and how many additional candidates we find in the remaining and not yet here included fields of our deep NIR survey, it is certainly worth analyzing whether our results significantly influence the low-mass end of the IMF and help to fill-up the apparent deficiency of very low-mass objects compared to late K- and early M-type Taurus members.

This paper is dedicated to our colleague, friend, and great pianist Dr. Frithjof Brauer who eventually lost his battle against cancer.

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Facilities: Calar Alto, VLT, Spitzer

APPENDIX

TRANSFORMATION EQUATIONS

A.1. 2MASS—CIT

(See, http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4b.html)

\[
(K_r)_{2MASS} = K_{CIT} - 0.019 \pm 0.004 + (0.001 \pm 0.005)(J - K_{CIT}),
\]

\[
(J - H)_{2MASS} = (1.087 \pm 0.013)(J - H)_{CIT} - 0.047 \pm 0.007),
\]

\[
(J - K_s)_{2MASS} = (1.068 \pm 0.009)(J - K_{CIT}) - 0.020 \pm 0.007),
\]

\[
(H - K_s)_{2MASS} = (1.000 \pm 0.023)(H - K_{CIT}) + 0.34 \pm 0.006).
\]

A.2. 2MASS—Bessel & Brett

(See, http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4b.html)

\[
(K_r)_{2MASS} = K_{BB} - (0.039 \pm 0.007) + (0.001 \pm 0.005)(J - K_{BB}),
\]

\[
(J - H)_{2MASS} = (0.990 \pm 0.012)(J - H_{BB}) - 0.049 \pm 0.007),
\]

\[
(J - K_s)_{2MASS} = (0.983 \pm 0.008)(J - K_{BB}) - 0.018 \pm 0.007),
\]

\[
(H - K_s)_{2MASS} = (0.971 \pm 0.022)(H - K_{BB}) + 0.034 \pm 0.006).
\]

A.3. SDSS (ugriz)—Johnson–Cousins (UBVRI)

(See, Jordi et al. 2006)

\[
\begin{align*}
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