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Exploring the substellar IMF in the Taurus cloud

New brown dwarfs in the Taurus star forming region

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Abstract. Recent studies of the substellar population in the Taurus cloud have revealed a deficit of substellar objects by a factor $\simeq 2$ compared to the Trapezium cluster population (Briceno et al. 1998; Luhman 2000). If confirmed, the higher low-mass cutoff in Taurus could have strong implications on IMF and substellar formation models. However, all studies to date have concentrated on the highest stellar density regions of the Taurus cloud. Reipurth & Clarke (2001) have proposed that brown dwarfs are stellar embryos ejected from their birth site early in their evolution. In order to test this scenario and investigate a possible spatial segregation between stars and brown dwarfs, we have performed a large scale optical survey of the Taurus cloud covering a total area of $\simeq 30$ deg^2 down to a mass detection limits of 15 M_{Jup}. We first present results from a spectroscopic follow-up of a subsample of substellar candidates that revealed 4 new Brown Dwarfs and one Very Low Mass Taurus member. We then discuss the selection of candidates from a larger scale optical survey and the implications for the substellar IMF in Taurus.

1. Introduction

Recent works by Briceno et al. (1998); Luhman (2000), and Luhman et al. (2003), have revealed a factor of two deficit of Brown Dwarfs in the Taurus cloud compared to the Trapezium cluster, possibly indicating that sub-stellar object formation depends on the environment. However, Luhman (2004) report that the Taurus deficiency in brown dwarfs could be less pronounced than previously thought. As most of these studies are concentrated on high stellar density regions, the possibility remains that in Taurus Brown Dwarfs have scattered away from their birth sites as proposed by Reiputh & Clarke 2001. The availability of large visible and infrared cameras now allows to quickly survey large portions of the sky encompassing tens of square degrees. In order to check for the existence of an ejected brown dwarf population in Taurus, we have performed a large optical survey covering a total of 27 deg^2 (taking into account overlap between fields). This survey includes an initial 3.6 deg^2 performed with the CFHT12k camera in the R, I, & z' filters, followed by a complementary larger one using CFHT12k and Megacam in the I & z' filters (see Table 1). We estimate our completeness limits to be I=22, z=21, corresponding to a

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Instrument	date	Area (deg^2)	Band	Completeness limit	Mass limit (A_V = 5, 5Myr)
CFHT12k	1999-2001	3.6	R, I, z'	23, 22, 21	$15M_j$
CFHT12k	2002	8.8	I, z'	22, 21	$15M_j$
Megacam	2003-2004	24	i', z'	24, 23	$10M_j$

Table 1. Survey overview

mass detection limit of 15 M_jJup for an age ≤ 5 Myrs and $A_V \leq 5$.

We first discuss spectroscopic follow-up observations of a sub-sample of Taurus substellar candidates identified from the first CFHT12k survey. We have developped a numerical fitting procedure for spectral type and reddening determination and investigate various critera for Taurus membership assessment. We then present preliminary results on the complete optical survey, concentrating on the candidate selection method. We finally summarize current estimates of the substellar mass function in Taurus.

2. Spectroscopic analysis

2.1. Candidate selection

We idenfity a sample of Taurus Brown Dwarf candidates from the first survey conducted with the CFHT12K camera between 1999 and 2001 (covering 3.6 deg^2). Candidates were selected by combining our optical photometry (R, I and z' band) with 2MASS near-infrared photometry (J, H, K). We require that the candidates fullfill the following criteria:

- a position in the I/(R-I) and I/(I-z') color magnitude diagrams compatible with Brown Dwarf and Very Low Mass stars younger than 10Myr (at the Taurus distance of 140pc),
- a 2MASS counterpart,
- colors compatible with a spectral type later than M4 in the (I-J)/(J-K) diagram.

This selection yielded 71 candidates with I ≤ 20. A first spectroscopic follow-up of this sample, conducted at the WHT telescope with the ISIS optical low resolution spectrograph in 2000, led to the confirmation of 4 Taurus members with spectral types later than M7 (Martín et al. 2001). We discuss here results from spectroscopic studies of remaining 30 candidates conducted with the VLT/FORS1 and Keck/LRIS spectrographs between 2001 and 2003. We use both instruments in the medium spectral resolution mode ($R \sim 1000$) over the range λ = 6000-1100 Å. Long-slit spectra are bias corrected, flat-fielded and wavelength calibrated. Spectra are extracted using the IRAF[1] package *apextract*. The instrumental spectral response has been corrected using DENIS-P-J1048-3956 as a reference.

2.2. Spectral-type, reddening and luminosity class determination

Spectral types can be derived from photometric indices, such as the ones defined by Martín et al (1999). However, they may be affected by the strong extinction expected towards Taurus members. We therefore chose to apply a spectral fitting procedure similar to the one presented in Luhman et al. (1998), allowing to derive simultaneously spectral type and reddening. We built a library of reference dwarf and giant spectra spanning the range between M3 and L0. Each candidate spectrum can be fitted either by a dwarf template, a giant template or the average of the dwarf and giant templates of a given spectral type. This procedure also allows for an estimate of the luminosity class. Our fitting procedure is performed in the wavelength range 7000-8500Å.

We illustrate in Figure 1 our numerical fitting procedure. We show in the top right panel the χ^2 map in the (A_V - spectral type) plane for one of our Taurus Brown Dwarf candidate and we represent in the bottom panel the corresponding best fit solution. We also compare

[1] IRAf distributed by National Optical Observatories

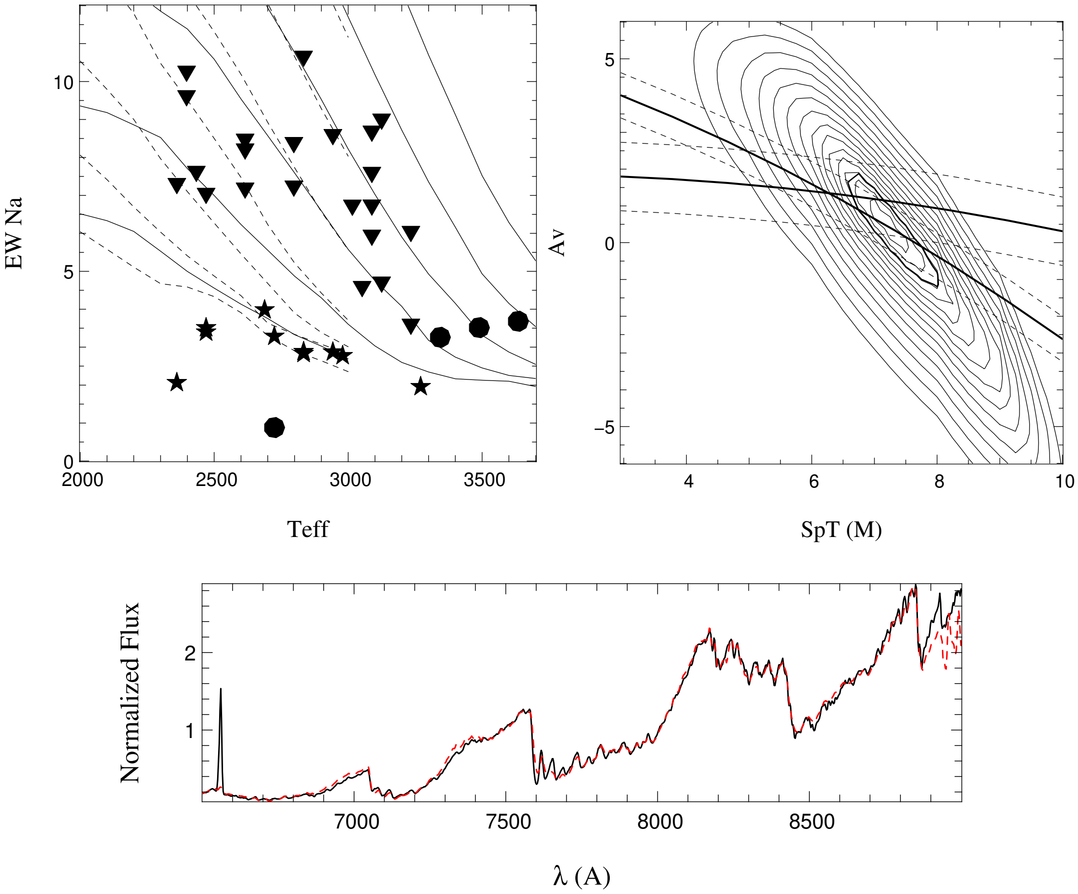

Fig. 1. *Top Left*: Sodium equivalent width *vs* effective temperature for our candidate sample. *Star* symbols represent spectra best fitted with a giant +field-dwarf average (Luminosity class IV). Curves show predictions from the models of Chabrier et al (2000), (solid lines = DUSTY models, dashed lines = COND models) spanning $log_{10}(g/go)$ =2.5 to 6.5. *Top Right*: χ^2 map obtained in the A_V-SpT plane for one of our candidate spectrum. Also plotted (solid lines) are the A_V variation *vs* SpT derived from the (I-J) and (J-H) colors using the Rieke & Lebofsky (1985) extinction law. Dashed lines correspond to 1 σ uncertainties of this calculation. In this example, both our numerical fitting procedure and the colors agree to give an M7.25 Spectral Type and A_V = 0.4 mag. *Bottom:* The best fit spectrum is shown.

in this figure our fitting determination with the A_V/spectral type relations predicted by the (I-J) and (J-H) colors. As can be seen in Fig. 1, there is a good agreement between spectral and color derivations. We estimate typical uncertainties of half a spectral class in spectral type and 0.8 in A_V. The top left panel of Figure 1 illustrates the good agreement between the luminosity class estimated from our fitting procedure and the sodium equivalent width, which is a good surface gravity indicator (Martin et al. 1999). We plot in this figure EW(NaI) versus our derived T_{eff}. Candidates best fitted by the average of a giant and a field dwarf (estimated luminosity class IV) are indicated with *Star* symbols. Their positions are consistent with the predictions from the model atmospheres of Chabrier et al. (2000) (solid and dashed lines)

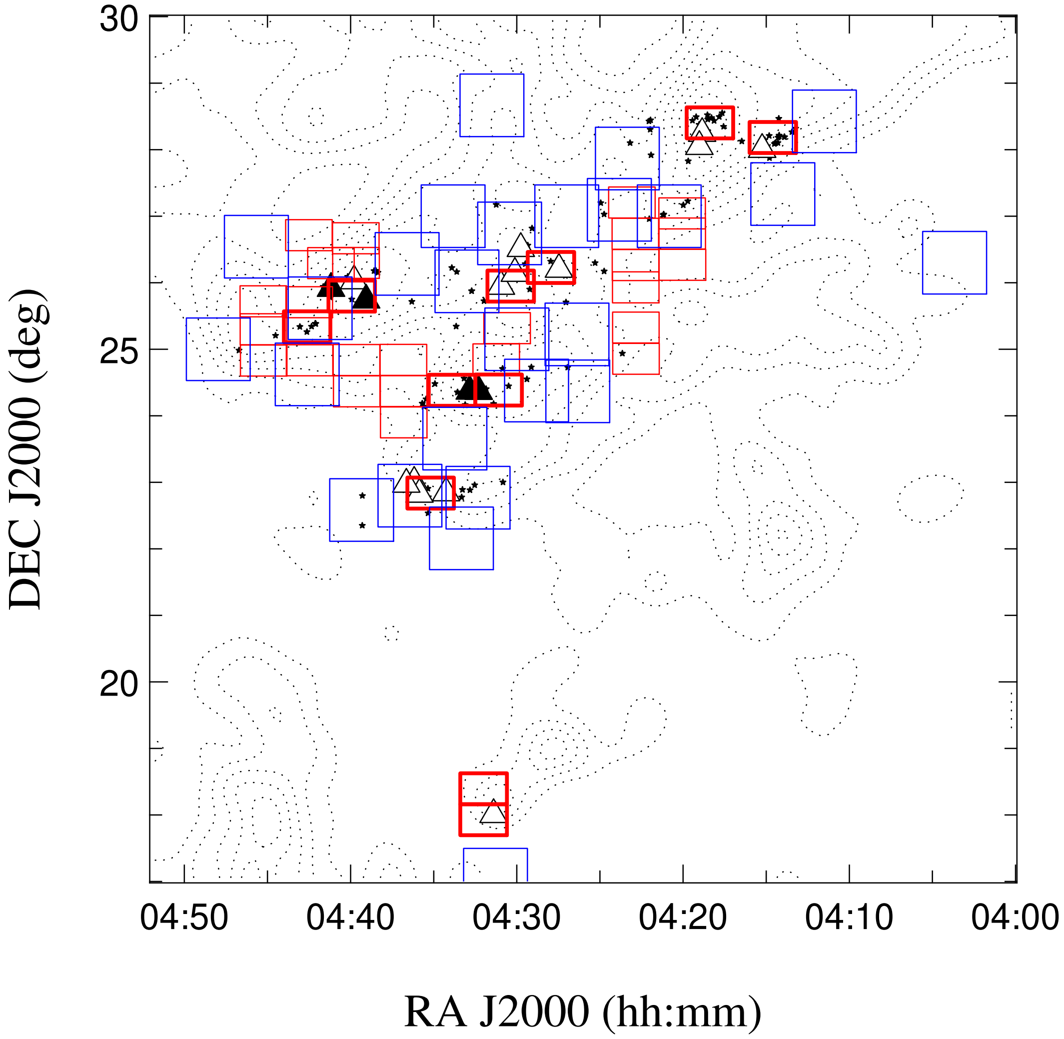

Fig. 2. Total optical survey coverage: red rectangular boxes are CFHT12k fields, and blue square box are Megacam fields. Also plotted are known T Tauri stars (star symbol) and known Taurus Brown Dwarfs (triangle), the filled triangles are the 4 Brown Dwarfs discovered in the first CFH12k 3.6deg^2 survey (plotted with thick red boxes).

and indicate surface gravities for these sources $\log_{10}(g/go) \leq 3$.

2.3. Identification of new Taurus members

3. Large scale optical survey

3.1. Photometry data

We summarize in Table 2 the properties of the new identified Taurus members in our 3.6 deg^2 survey field: we find 4 new Brown Dwarfs and

Name	ST	Av	$\log_{10}$(L/Lsun)	Teff	I	R-I	J-H	H-K	K
V410 X-ray 1	M3.50	2.0	-0.5637	3270	14.34	1.78	1.30	0.62	9.08
KPNO-Tau 10	M5.50	0.0	-1.0786	2979	14.11	2.14	0.77	0.32	10.78
KPNO-Tau-1	M9.00	0.4	-2.3976	2469	18.15	3.57	0.85	0.47	13.77
KPNO-Tau-6	M9.00	0.9	-2.2736	2469	17.90	2.66	0.80	0.51	13.69
KPNO-Tau-4	M9.75	2.5	-2.1379	2360	18.75	1.79	0.97	0.74	13.28
CFHT-VLMS-Tau 1	M5.75	6.5	-0.9217	2942	17.62	3.62	1.58	0.88	10.76
CFHT-BD-Tau 7	M6.50	0.0	-0.9755	2833	14.12	2.51	0.72	0.39	10.40
CFHT-BD-Tau 8	M6.50	1.8	-1.4550	2833	16.43	2.84	1.05	0.68	11.45
CFHT-BD-Tau 6	M7.25	0.4	-1.3832	2724	15.40	2.99	0.80	0.47	11.37
CFHT-BD-Tau 5	M7.50	9.2	-0.8774	2688	18.79	4.58	1.74	0.94	11.28

Table 2. New Taurus Brown Dwarf and VLM members

1 Very Low Mass star (spectral type M5.75). We recover in addition 5 previously known Taurus members. We compute the ratio of substellar to stellar objects in Taurus over the combined surface mapped in this study and the previous surveys of Luhman (2000) and Briceno et al. (2002). If we include the new members identified in this study as well as the previously known Taurus members in our survey fields, we obtain a ratio, as defined in Briceno et al. (2002):

$$\begin{aligned} R_{ss} &= N(0.08-0.02M_{\odot})/N(0.08-10M_{\odot})) \\ &= 15/107 = 0.14 + -0.04 \end{aligned}$$

We include only sources with $A_V \leq 4$, which corresponds to a mass completeness limit of 0.02 $M_{\odot}$ for an age ≤ 1 Myr. Our current best estimate of the ratio of substellar to stellar objects in Taurus agrees with the previous derivations of Luhman et al. (2003) and Briceno et al. (2002), and is still significantly lower than the one derived for the Trapezium cluster population. However, if brown dwarfs have been ejected from their birth sites with expected escape velocities of 1-2 km.s^{-1}, they could have travelled as far as $\simeq 1°$ in 3 10^6 yrs, the median age of the Taurus population, and could therefore have escaped detection. Covering fields peripheric to the main stellar birth sites is therefore mandatory for a firm conclusion on the lack of brown dwarfs in Taurus. This is the aim of the larger scale optical survey conducted in 2002 and 2003. We present below preliminary results from this larger scale study.

We mapped 27 deg^2 (taking into account overlap between fields) of the Taurus cloud at I and z' with the CFHT12k and Megacam cameras installed on the Canada France Hawaii telescope (see Table 1 and Figure 2). We reach a detection limit of I=22-24, allowing to detect in Taurus a Brown Dwarf / planet of mass 15-10 M_{Jup}. Reduction of the raw images was performed at the CFHT institute, including bias and dark subtraction, flat-fielding and fringing correction. Aperture photometry was obtained with SExtractor (Bertin & Arnouts 1996), astrometric calibration was performed with the USNO catalog. Our final catalog includes over 1.5×10^6 point sources.

3.2. Candidate sample

We apply a selection procedure similar to the one outlined in the previous section, namely by cross-correlating our optical catalog with the 2MASS point source catalog. We estimate extinction values towards individual sources in the (I-J)/(J-K) color-color diagram with a dereddening procedure similar to the one proposed by Luhman et al. (2003). We then select candidate Taurus members by requiring that they lie above the 10 Myrs isochrone from Chabrier et al. (2000) in the *dereddened* I/(I-z) and J/(J-H) color-magnitude diagrams. We stress that the main limitation of our selection procedure comes from the magnitude limits of the 2MASS survey: only 3% of the optical sources that lie above the 10 Myrs isochrone in the I/(I-z) diagram have 2MASS counterparts. The 2MASS detection limits (H < 15) set the mass completeness limit of our selection procedure to $\simeq 30M_j$. We end up with a final sample of ~230 candidate Taurus Brown Dwarfs and Very Low Mass among which 20 show colors typical of late (>M5) spectral types.

4. Perspectives

Spectroscopic follow-up of our candidate sample will be conducted both in the optical and near-infrared domains this coming winter at the Keck, TNG and WHT telescopes. With a typical galactic contamination rate of 70 % in previous surveys, we therefore expect that this study will uncover ≥ 60 new Taurus members. Our optical survey is conducted in collaboration with ongoing large scale mappings of the Taurus cloud: one conducted with the XMM-Newton telescope (PI:Manuel Guedel) covering a total of ≃ 5°, the other with SIRTF (PI: D. Padgett) which will cover 28 deg^2 sensitive down to $3M_j$ at 4.5 microns.

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