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Medium-resolution optical spectroscopy of young stellar and sub-stellar M-dwarfs in the Cha I dark cloud *

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Abstract. We obtained medium-resolution spectra of the bona-fide brown dwarf Cha Hα 1, the five brown dwarf candidates Cha Hα 2 to 6, two additional late M-type brown dwarf candidates, all originally selected by Hα emission, and four previously known T Tauri stars, all located in Chamaeleon I. The spectral types of our targets range down to M8. We show their spectra and also list their IJK magnitudes from DENIS. All objects have radial velocities consistent with kinematic membership to Cha I and show Li 6708Å absorption. Our Cha I brown dwarf candidates with lithium are young or sub-stellar or both. Cha Hα 1, 3, 6, and 7 are certainly brown dwarfs: Either they are as old or older than the Pleiades and should have burned all their original lithium if they were late M-type stars, or, if they are younger than the Pleiades, $\leq$ 125 Myrs, they are sub-stellar because of the young age and the late spectral types ($\geq$ M7), according to three different sets of evolutionary tracks and isochrones. To classify Cha Hα 2, 4, 5, and 8 as either stellar or sub-stellar, evolutionary tracks of higher reliability are needed.

Key words: Stars: formation – late-type – low-mass, brown dwarfs

1. Introduction: Young brown dwarfs

Recently, Comerón et al. (1999, henceforth CRN99) performed an Hα objective-prism survey in the Chamaeleon I dark cloud, a site of on-going and/or recent low- and intermediate-mass star formation, and presented six new low-mass late-type ($\geq$ M6) objects with Hα emission, called Cha Hα 1 to 6. Their strong Hα emission, if having the same origin as in T Tauri stars (TTS), is an indicator of youth, and therefore of membership to the star forming region at $\sim$ 160 pc. Luminosities obtained from VIJHK photometry made it possible to place the objects in the H-R diagram where, according to different sets of pre-main sequence evolutionary tracks, they all lie near or below the hydrogen burning limit. Follow-up spectroscopy with high S/N of the lowest-mass object, Cha Hα 1, confirmed its sub-stellar nature (Neuhäuser & Comerón 1998, henceforth NC98) and allowed an accurate determination of its spectral type to be M7.5-M8. Comparision with evolutionary tracks and isochrones yielded a mass of $\sim 0.04\ M_\odot$ and an age of $\sim$ 1 Myrs. Cha Hα 1 is the first brown dwarf (BD) detected in X-rays (NC98).

Young brown dwarfs were also found in other star forming regions, namely ρ Oph (Rieke & Rieke 1990; Comerón et al. 1993, 1998; Luhman et al. 1997; Wilking et al. 1999), Taurus (Luhman et al. 1998; Briceño et al. 1998; White et al. 1999; Reid & Hawley 1999), and Orion (Béjar et al. 1999).

The sub-stellar nature of suspected brown dwarfs can usually be confirmed by detection of lithium 6708Å absorption, because lithium is burned rapidly and fully by proton capture in low-mass, i.e. fully convective stars (Magazzù et al. 1993) with masses above $\sim 0.06\ M_\odot$. This lithium test cannot be applied to very young objects, which are not old enough, yet, to have burned all their initial lithium: for example, objects younger than $\sim$ 10 Myr with a mass below $\sim 0.3\ M_\odot$ have burned less than 1% of their original lithium, and the percentage is even lower for less massive objects of the same age (D'Antona & Mazzitelli 1997, Baraffe et al. 1998, and A. Burrows, private communication). For this reason, a lithium detection in the spectrum of a suspected brown dwarf member of a star forming region does not directly confirm its substellar character, but it does support strongly its membership in the star forming region (the alternative possibility, namely the object is evolved and foreground, automatically implies that it is a brown dwarf because of the lithium detection). Once such membership and, hence, distance is established, the mass can be inferred from the

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* Based on observations collected at the European Southern Observatory 3.5m NTT on La Silla during program 63.L-0023.

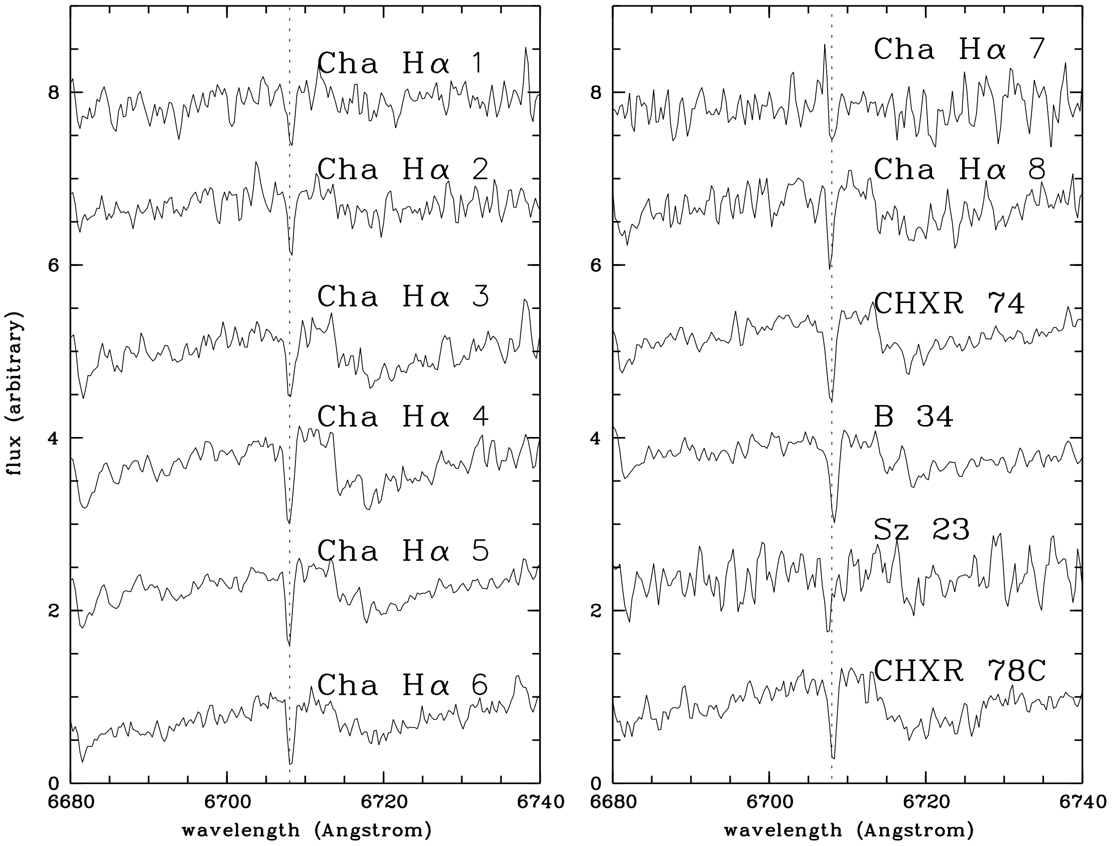

Fig. 1. Parts of our medium-resolution spectra around the lithium 6708Å line, which is detected in all objects

spectral type and luminosity by comparison to theoretical evolutionary tracks for very low mass objects.

In this paper, we present medium-resolution spectra of Cha Hα 1 to 6, two additional late M-type objects (Cha Hα 7 and 8), also first detected in an Hα objective prism survey (Comerón et al., in preparation), as well as four M-type TTS in Cha I. Signal-to-noise ratio (S/N) and resolution of these new spectra are better than those in CRN99, so that we can investigate not only Hα emission, but also lithium absorption and radial velocities.

2. Observations and data reduction

We obtained medium-resolution spectra of the Cha I low-mass objects Cha Hα 1 to 8 as well as the TTS CHXR 74, B 34, Sz 23, and CHXR 78C. The spectra were obtained in the nights of 17 and 18 April 1999 at the 3.5m-New Technology Telescope (NTT) of the European Southern Observatory (ESO) on La Silla with the ESO Multi Mode Instrument (EMMI) in the red medium dispersion mode. Grating #6 was used covering the range 6485 to 7105Å, providing a dispersion of 0.32Å per each 0.27" pixel (CCD #36), and a resolution of $\sim$ 5800 (with the 1.0" slit used). One or several spectra were obtained for each object, with exposure time and number of spectra according to the measured instrumental throughput and the available R-band photometry. To keep the cosmic ray density in the resulting images reasonably low, the longest exposure times per frame were never longer than 45 min, always placing two objects into the 330" long slit.

Each spectrum was extracted individually from the corresponding bias-subtracted, flat-fielded two-dimensional image using tasks in the APEXTRACT package layered on IRAF. Wavelength calibration was performed by obtaining spectra of a He-Ar lamp immediately before and after each individual exposure, to ensure that wavelength shifts due to the rotation of the instrument during the exposure in the Nasmyth focus were kept to a minimum. A full dispersion solution was obtained for one of the He-Ar spectra, which was then used as the master wavelength calibration frame. Zero-point shifts with respect to this spectrum were then obtained for each of the other He-Ar lamp exposures and applied to the extracted spectra of the targets. These zero-point shifts were based on spectra of the calibration lamp extracted over a narrow range of rows of the detector centered on the position of the object. In this way, the determined shifts included the

Table 1. M-dwarfs targets and results (*)

Object designation	α, δ (J2000.0) $11h$	$-77°$	spec[1] type	$T_{eff}^{(2)}$ [K]	I	J	K	$W_\lambda(H\alpha)$ [Å][4] CRN99	this work	W_λ(Li) [Å]	$RV_{lsr}^{(5)}$ [$km\ s^{-1}$]	Classification
					DENIS[3] [mag]							
Cha Hα 1	07:17.0	35:54	M7.5	2805	16.4	13.3	12.3	−59	−34.5	0.63:	$+0.9 \pm 5.3$	bona-fide BD
Cha Hα 2	07:43.0	33:59	M6.5	2940	15.3	12.1	10.6	−39	−71.0	0.43	$+8.4 \pm 1.9$	candidate BD
Cha Hα 3	07:52.9	36:56	M7	2890	15.0	12.3	11.1	−4.5	−14.4	0.43	$+6.9 \pm 4.9$	bona-fide BD
Cha Hα 4	08:19.6	39:17	M6	2990	14.4	12.0	11.1	−4.7	−9.7	0.48	$+6.1 \pm 3.2$	candidate BD
Cha Hα 5[6]	08:25.6	41:46	M6	2990	14.7	12.0	10.7	−7.6	−8.0	0.42	$+4.4 \pm 3.0$	candidate BD
Cha Hα 6	08:40.2	34:17	M7	2890	15.1	12.0	10.9	−59	−61.7	0.43	$+0.2 \pm 2.3$	bona-fide BD
Cha Hα 7[7]	07:38.4	35:30	M8	2720	16.7	13.5	12.4	(8)	−35.0	0.80:	-1.8 ± 6.7	bona-fide BD
Cha Hα 8[7]	07:47.8	40:08	M6.5	2940	15.6	12.7	11.5	(8)	−8.4	0.49	-2.9 ± 5.5	candidate BD
CHXR 74[9]	06:57.4	42:10	M4.5	3200	13.7	11.6	10.2	−13	−8.3	0.69	$+5.9 \pm 1.0$	T Tauri star
B 34 [10]	07:35.4	34:51	M5	3125	14.4	12.1	10.9	−5.5	−7.2	0.80	$+7.0 \pm 1.7$	T Tauri star
Sz 23[11]	07:59.4	42:40	M2.5	3500	14.6	12.0	9.9	−45	−56.5	0.34	-2.8 ± 6.0	T Tauri star
CHXR 78C	08:54.4	32:12	M5.5	3060	14.8	12.2	10.9	−3.2	−13.4	0.48	$+9.5 \pm 2.9$	T Tauri star

(*) Approximate errors are ±0.25 sub-classes in spectral type, ±50 K in T_{eff}, ±0.1 mag in IJK, ±5Å in $W_\lambda(H\alpha)$, and ±0.05Å in W_λ(Li) (but ±0.1Å in Cha Hα 1 and 7 because of lower S/N).
Notes: (1) Spectral types (ST) for Cha Hα 1 to 8 assigned from high-S/N, low-resolution spectra obtained for a much broader wavelength range (Comerón et al., in preparation) than in Fig. 1; ST for the four TTS are taken from CRN99. (2) Effective temperatures T_{eff} converted from ST using Fig. 7 in Luhman (1999) for objects intermediate between dwarfs and giants, as appropriate for young M-dwarfs. (3) DENIS data for Cha Hα 1 to 8 are from L. Cambrésy (private communication) and for TTS from Cambrésy et al. (1998), they all compare well with data given in CRN99 and Lawson et al. (1996). (4) Negative for emission. (5) Local standard of rest (lsr) radial velocity (RV). (6) Coordinates of Cha Hα 5 were slightly incorrect in NC98 and CRN99. (7) For finding charts, see Comerón et al., in preparation. (8) Not listed in CRN99. (9) Lawson et al. (1996) detected Li at low S/N and gave $W_\lambda(H\alpha) = -2.7$Å. Alcalá (1994) gave $W_\lambda(H\alpha) = -4.1$Å. (10) Alcalá (1994) gave $W_\lambda(H\alpha) = -7.7$Å and detected Li. (11) Double-peaked Hα emission, possibly a companion to VW Cha (Reipurth & Zinnecker 1993).

corrections due both to flexures of the instrument, and to the slight curvature of the spectral lines across the surface of the detector, which amounts to a significant four-pixel difference between the center and the edges. Correction for telluric features was performed by observing the bright star β Cha at intervals of about 2.5 hours per night. The high rotation velocity of this star (255 km/s, Hoffleit et al. 1982) allows an easy separation between the narrow telluric and the broad photospheric lines. The spectra of β Cha were interpolated linearly in the wavelength intervals containing photospheric lines. Then, each individual spectrum of our targets was ratioed by the one of β Cha obtained at the most similar airmass. The next step was the modification of the wavelength axis of each object to correct for the observer's motion with respect to the local standard of rest (lsr). The lsr velocities for each object were computed with the RVCORRECT task under IRAF, and the spectra were then accordingly Doppler-shifted. Finally, all the wavelength-calibrated, telluric-corrected spectra in the lsr frame for each object were added together to produce the combined spectra (Fig. 1). Radial velocities are derived by Fourier cross-correlation using the 6600 to 7100Å part of the spectrum of CHXR 74 as a reference template. The zero-point is derived from the lithium doublet, using 6707.815Å as central wavelength. The quality and S/N of the spectra were insufficient, however, to obtain reliable rotational velocities.

Results are listed in Table 1. In addition, we obtained ground-based, high-S/N, low-resolution optical and infrared spectra over a much broader wavelength range than shown in Fig. 1 or in CRN99, in order to better constrain the spectral types of the Cha Hα objects, as well as additional photometry and ISO data, all of which are to be presented elsewhere (Comerón et al., in preparation). Spectral types – as listed in Table 1 – are determined by comparison with late M-type standards (Kirkpatrick et al. 1991, 1995) and spectra indices as in CRN99. We converted them to effective temperatures T_{eff} using the relation recently presented by Luhman (1999) for young M-type objects in IC 348.

3. Results and discussion

To investigate kinematic membership to Cha I, we compare the radial velocities of our objects with those of known TTS members of Cha I and the local molecular gas, both having lsr radial velocities peaking at ~ 4 km/s with a 1 σ scatter of ~ 6 km/s (Dubath et al. 1996, Covino et al. 1997, see also our Fig. 2). The TTS observed here also have such velocities. Hence, within the errors, Cha Hα 1 to 8 all have radial velocities in this range, i.e. are kinematic members of the Cha I association (see Fig. 2).

Cha I membership can also be investigated by looking for youth signatures, such as Hα emission or lithium absorption. Gravity sensitive features and thermal infrared excess emission observed by ISOCAM will be discussed in a companion paper (Comerón et al., in preparation).

For most of our objects, $W_\lambda(H\alpha)$ is variable by a factor of ~ 2, comparing the results from CRN99 with our data.

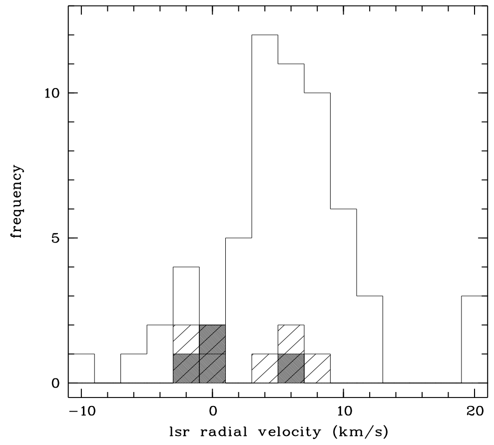

Fig. 2. Local standard of rest (lsr) radial velocities of Cha TTS (Dubath et al. 1996, Covino et al. 1997, and Table 1), candidate BDs (hatched) and bona-fide BDs (filled)

This can be taken as indication for strong chromospheric activity, i.e. young age. Furthermore, Cha Hα 1, 3, and 6, classified here as bona-fide BDs, are X-ray sources (NC98), an indication for magnetic activity, i.e. youth.

Comparing W_λ(Li) of our candidate and bona-fide BDs with TTS (Fig. 3) shows that the lithium strength seems to drop after M5 (B 34, $\log T_{eff} = 3.5$) and to increase again from $\sim$ M7 to M8. However, objects with $\leq 0.3\ M_\odot$, i.e. $\log T_{eff} \leq 3.5$, burn less than 1% of their initial lithium in the first $\sim$ 10 Myrs, so that the apparent gap may be due either to missing objects or to an effect of molecular lines (eg. TiO in late M-type objects) on the lithium curves-of-growth, i.e. on how the lithium abundance depends on T_{eff} and W_λ(Li), so that the lithium-iso-abundance lines do not increase monotonically anymore in the W_λ(Li) versus T_{eff} plot, as they do for G- and K-type stars (see Fig. 3). Moreover, the similar positions of our objects and of the Pleiades brown dwarfs (Basri et al. 1996, Rebolo et al. 1996, Stauffer et al. 1998) in the T_{eff} versus W_λ(Li) diagram, despite a difference of more than one order of magnitude in age between both populations, seem to rule out evolutionary factors as the cause of the apparent gap.

Any object with detected lithium is young or sub-stellar or both. However, for any specific age (or age range or upper age limit), any object later than some specific spectral type is a BD. For the Pleiades (125 Myrs), Martín et al. (1996) and Stauffer et al. (1998) found that any member later than M6.5 is a BD. One can also see from evolutionary tracks and isochrones that any object with an age of $\leq$ 125 Myrs which is cooler than the temperature corresponding to M6.5 lies below the hydrogen burning limit (D'Antona & Mazzitelli 1997, Burrows et al. 1997, Baraffe et al. 1998).

Cha I members are younger than the Pleiades, i.e. lie higher above the main sequence, so that they are slightly hotter at any given spectral type (Luhman et al. 1997), corresponding to roughly ± 0.25 sub-classes. Considering also ± 0.25 error in assigning the spectral classes, we should be sure that any Cha I member with spectral type M7 (i.e. T_{eff} = 2890 K, Luhman 1999) or later is sub-stellar. This is the case for Cha Hα 1, 3, 6, and 7, classified as bona-fide BDs in Table 1. This classification is correct, regardless of whether the objects are young: either they are younger than $\sim$ 125 Myrs and, hence, lie below the sub-stellar limit in the H-R diagram because of the late spectral type and the young age (see tracks and isochrones by D'Antona & Mazzitelli 1997, Burrows et al. 1997, Baraffe et al. 1998); or, alternatively, if they are not young, then they are sub-stellar because of the lithium. Actualy, because most Cha I TTS (see Lawson et al. 1996) as well as Cha Hα 1 to 6 (see CRN99) are $\sim$ 1 Myrs old, all our bona-fide and candidate BDs are probably of that young age, too, i.e. much younger than $\sim$ 125 Myrs. Given the spectral types of Cha Hα 2, 4, 5, and 8, they are located too close to the limit for definitive discrimination.

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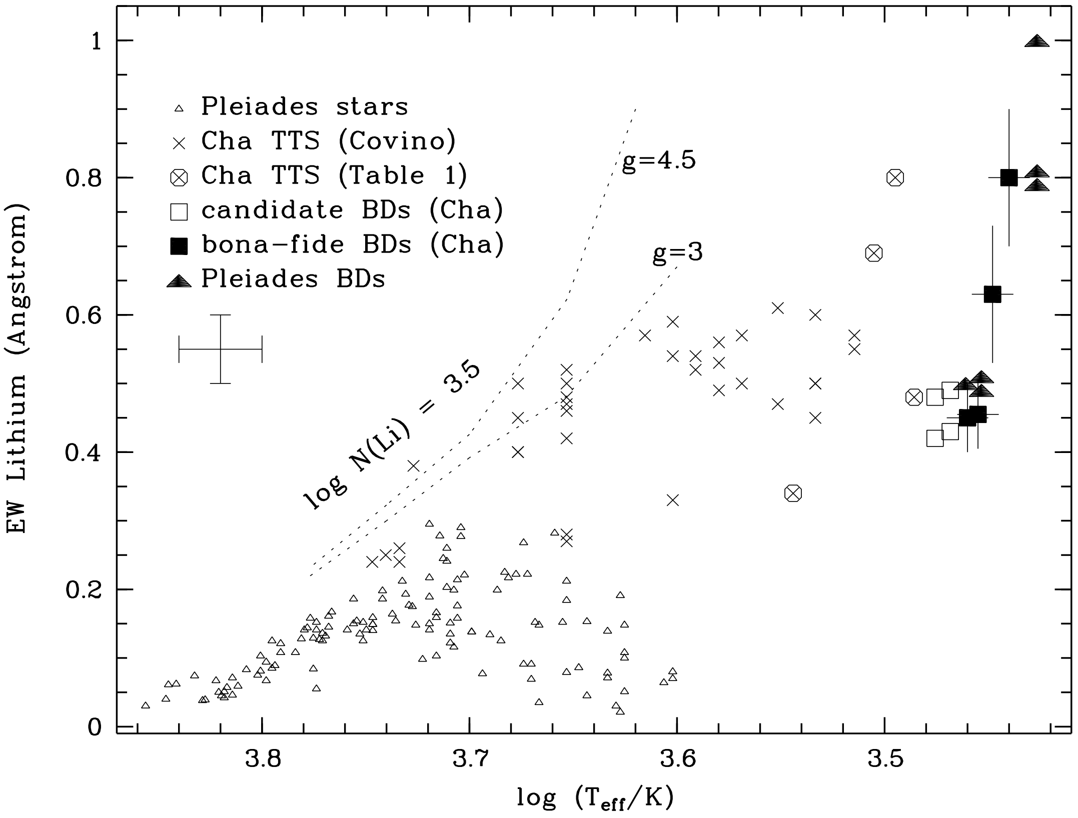

Fig. 3. Equivalent width W_λ(Li) versus effective temperature T_{eff} for Pleiades stars (Soderblom et al. 1993), Pleiades BDs (Basri et al. 1996, Rebolo et al. 1996, Stauffer et al. 1998), TTS in Cha (from Covino et al. 1997 and our Table 1), and Cha I bona-fide and candidate BDs. The lines indicate the primordial lithium log N(Li)= 3.5 for sub-giants ($\log g = 3.0$) and dwarfs ($\log g = 4.5$) from Pavlenko & Magazzù (1996) fitting well as upper envelope to the G- and K-type TTS; lithium curves-of-growth for M-type objects are not yet available. For the F- to K-type TTS and Pleiades, we have converted spectral types to T_{eff} using Bessell (1979, 1991), for the M-type objects using Fig. 7 in Luhman (1999) for objects intermediate between dwarfs and giants, taking into account that Pleiades BDs are slightly colder than Cha I BDs at any given spectral type (Luhman et al. 1997)

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