

16–20 M_{Jup} RADIAL VELOCITY COMPANION ORBITING THE BROWN DWARF CANDIDATE Cha H α 8¹

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ABSTRACT

We report the discovery of a 16–20 M_{Jup} radial velocity companion around the very young (~ 3 Myr) brown dwarf candidate Cha H α 8 (M5.75–M6.5). Based on high-resolution echelle spectra of Cha H α 8 taken between 2000 and 2007 with UVES at the VLT, a companion was detected through RV variability with a semiamplitude of 1.6 km s⁻¹. A Kepler fit to the data yields an orbital period of the companion of 1590 days and an eccentricity of $e = 0.49$. A companion minimum mass $M_2 \sin i$ between 16 and 20 M_{Jup} is derived when using model-dependent mass estimates for the primary. The mass ratio $q \equiv M_2/M_1$ might be as small as 0.2 and, with a probability of 87%, it is less than 0.4. Cha H α 8 harbors most certainly the lowest mass companion detected so far in a close (~ 1 AU) orbit around a brown dwarf or very low mass star. From the uncertainty in the orbit solution, it cannot completely be ruled out that the companion has a mass in the planetary regime. Its discovery is in any case an important step toward RV planet detections around brown dwarfs. Further, Cha H α 8 is the fourth known spectroscopic brown dwarf or very low mass binary system with an RV orbital solution and the second known very young one.

Subject headings: binaries: spectroscopic — planetary systems — stars: individual ([NC98] Cha HA 8) — stars: low-mass, brown dwarfs — stars: pre-main-sequence — techniques: radial velocities

Online material: color figure

1. INTRODUCTION

Planetary or brown dwarf (BD) companions to BDs are of primary interest for understanding planet and BD formation. There exists no widely accepted model for the formation of BDs (e.g., the recent review by Luhman et al. 2007). The frequency of BDs in multiple systems is a fundamental parameter in these models. However, it is poorly constrained for close separations: Most of the current surveys for companions to BDs are done by direct (adaptive optics or *HST*) imaging and are not sensitive to close binaries ($a \lesssim 1$ AU and $a \lesssim 10$ AU for the field and clusters, respectively), and found preferentially close to equal-mass systems (e.g., Bouy et al. 2003; see also Burgasser et al. 2007). Spectroscopic monitoring for radial velocity (RV) variations provides a means to detect close systems. The detection of the first spectroscopic BD binary in the Pleiades, PPI 15 (Basri & Martín 1999), raised the hope of finding many more of these systems in the following years. However, the number of confirmed close companions to BDs and very low mass stars (VLMSs; $M \leq 0.1 M_{\odot}$) is still small. While several spectroscopic companions to BD/VLMSs were reported recently (e.g., Reid et al. 2002; Guenther & Wuchterl 2003; Kenyon et al. 2005; Kurosawa et al. 2006; Basri & Reiners 2006; L. Prato 2007, in preparation), many of these companion identifications are based on only 2–3 RV measurements for an individual target. To date, there are three spectroscopic BD binaries confirmed, i.e., for which a spectroscopic orbital solution has been derived: the before mentioned double-lined spectroscopic binary (SB2) PPI 15, the very young eclipsing SB2 system in Orion 2MASS J05352184–0546085 (2M0535–05; Stassun et al. 2006), and an SB2 within the quadruple GJ 569 (Zapatero Osorio et al. 2004; Simon et al. 2006). All these systems have a mass ratio close to unity. In particular, no RV planet of a BD/VLMS has been found yet.

Whether BDs can harbor planets at a few AU distance is still unknown. Among the more than 200 extrasolar planets that have been detected around stars by the RV technique, six orbit stellar M dwarfs (e.g., Udry et al. 2007), showing that planets can form also around primaries of substantially lower mass than our Sun. Observations hint that the basic ingredients for planet formation (disk material, grain growth) are also present for BDs (e.g., Apai et al. 2005). However, the only planet detection around a BD is a very wide 55 AU system (2M1207; Chauvin et al. 2005; see also Caballero et al. 2006 for another candidate), which is presumably formed very differently from the solar system and RV planets.

RV surveys for planets around such faint objects, as BD/VLMSs are, require monitoring with high spectral dispersion at 8–10 m class telescopes. While being expensive in terms of telescope time, this is, nevertheless, extremely important for our understanding of planet and BD formation. Within the course of an RV survey for (planetary and BD) companions to the very young BD/VLMSs in Cha I (Joergens & Guenther 2001; Joergens 2006), evidence for a very low mass companion orbiting the BD candidate Cha H α 8 was found (Joergens 2005, 2006). We report here on follow-up RV monitoring, which confirms the companion and, combined with previous RV measurements, allows us to determine an RV orbit.

2. THE HOST OBJECT Cha H α 8

Cha H α 8² has been identified as very low mass member of the nearby Chamaeleon I star-forming region (~ 160 pc) by an H α objective prism survey and low- and medium-resolution spectroscopy (Comerón et al. 1999, 2000; Neuhäuser & Comerón 1998, 1999). Membership in the Cha I association and, therefore, the youth of Cha H α 8 are well established based on H α and X-ray emission, lithium absorption, and RVs (see references above; Joergens & Guenther 2001; Stelzer et al.

¹ Based on observations obtained at the Very Large Telescope of the European Southern Observatory at Paranal, Chile, in programs 75.C-0851(C), 77.C-0831(A+D), and 278.C-5061(A).

² SIMBAD name: [NC98] Cha HA 8.

TABLE 1
PROPERTIES OF Cha H α 8

Parameter	Value	Reference
Spectral type	M6.5, M5.75	1, 2
V (mag)	20.1	1
T_{eff} (K)	2910, 3024	1, 2
$\log L (L_{\odot})$	-1.65, -1.43	1, 2
$M_1 (M_{\odot})$	0.07, 0.10	1, 2
$v \sin i$ (km s $^{-1}$)	15.5 ± 2.6	3
$P_{v \sin i}$ (days)	1.9	3
ΔR (mag)	<0.02	4
Δi (mag)	<0.04	4
EW(H α) (Å)	9, 8.4, 10	1, 5, 6

REFERENCES.—(1) Comerón et al. 2000; (2) Luhman et al. 2007; (3) Joergens & Guenther 2001; (4) Joergens et al. 2003; (5) Mohanty et al. 2005; (6) Luhman 2004.

2004; Joergens 2006). Its spectral type has been determined to be between M5.75 (Luhman 2004, 2007) and M6.5 (Comerón et al. 2000). Comerón et al. (2000) estimate a mass of $0.07 M_{\odot}$ and an age of 3 Myr by employing evolutionary models by Baraffe et al. (1998). Using slightly different values for effective temperature and bolometric luminosity by Luhman (2007), a mass of $0.10 M_{\odot}$ and an age of 2.5 Myr are found by comparison with the same models. Thus, Cha H α 8 is either a BD or a VLMS. While for many of the known substellar objects in Cha I circumstellar disks were detected through mid-IR (Persi et al. 2000; Comerón et al. 2000) and L -band (Jayawardhana et al. 2003) excess emission, no indications of disk material have been found for Cha H α 8 in these works. See Table 1 for a list of properties of Cha H α 8.

3. RADIAL VELOCITIES AND ORBITAL SOLUTION

Spectroscopic observations of Cha H α 8 were carried out between 2000 and 2007 with the Ultraviolet-Visual Echelle Spectrograph (UVES) attached to the VLT 8.2 m Kueyen telescope at a spectral resolution $\lambda/\Delta\lambda$ of 40,000 in the red optical wavelength regime. RVs were measured from these spectra based on a cross-correlation technique employing telluric lines for the wavelength calibration. The errors of the relative RVs of Cha H α 8 range between 30 and 500 m s $^{-1}$. Details on the data analysis can be found in Joergens (2006).

RV measurements from spectra taken between 2000 and 2004 indicated already the presence of an RV companion to Cha H α 8 (Joergens 2005, 2006). This paper reports on follow-up RV monitoring between 2005 March and 2007 March. The new RV measurements are presented in Table 2. Using the combined RV data from 2000 to 2007, it was possible to derive

TABLE 2
NEW RV MEASUREMENTS OF Cha H α 8

Date	HJD	RV (km s $^{-1}$)	σ_{RV} (km s $^{-1}$)
2005 Mar 21	2453450.62080	15.130 ^a	0.21
2006 Apr 10	2453835.65109	16.082	0.20
2006 Jul 09	2453926.50137	16.893	0.20
2007 Mar 15	2454174.66101	17.089 ^a	0.29
2007 Mar 22	2454181.69756	16.931 ^a	0.33

NOTES.—HJD is given at the middle of the exposure; σ_{RV} is the estimated error of the relative RVs. An additional error of 400 m s $^{-1}$ has to be taken into account for the absolute RVs.

^a RV value is the average of two single consecutive measurements. The corresponding error σ_{RV} is the standard deviation of the individual measurements.

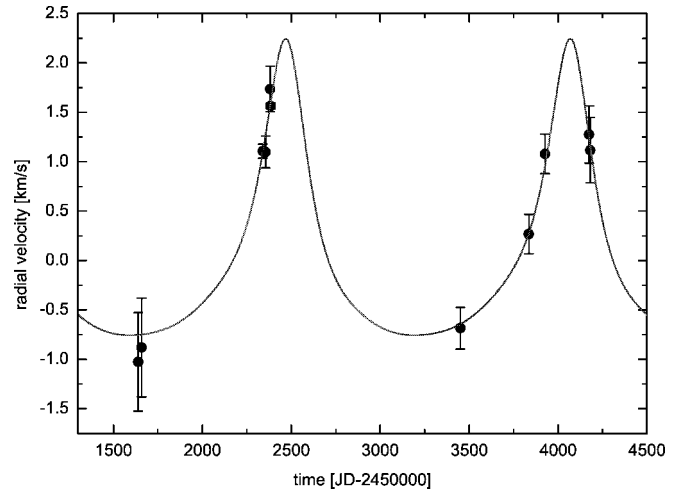


FIG. 1.—RV measurements of Cha H α 8 between 2000 and 2007 based on VLT UVES spectra. Overplotted is the best-fit Keplerian orbit, which has a semiamplitude of 1.6 km s $^{-1}$, a period of 4.4 yr, and an eccentricity of $e = 0.49$. [See the electronic edition of the Journal for a color version of this figure.]

a spectroscopic orbital solution. Figure 1 shows the RV measurements together with the RV curve of the best-fit Kepler model. The reduced χ^2 of the orbital fit is 0.42. The fitted Kepler orbit is that of a companion with a mass function of $4.6 \times 10^{-4} M_{\odot}$ orbiting Cha H α 8 with a period of 1590 days (4.4 yr) on an eccentric ($e = 0.49$) orbit and causing an RV semiamplitude of 1.6 ± 0.4 km s $^{-1}$. The semimajor axis is of the order of 1 AU. See Table 3 for the whole set of orbital elements.

4. COMPANION MASS AND SYSTEM MASS RATIO

The small RV semiamplitude of Cha H α 8 and the fact that no spectral lines of the companion were detected at any orbital

TABLE 3
ORBITAL AND PHYSICAL PARAMETERS DERIVED FOR THE BEST-FIT KEPLERIAN MODEL OF Cha H α 8

Parameter	Value
P (days)	1590.9 ± 21.1
t (HJD - 2450000)	2487.5 ± 87.3
e	0.49 ± 0.19
V (km s $^{-1}$)	15.774 ± 0.212
ω (deg)	$8.20^{+40.2}_{-8.20}$
K (km s $^{-1}$)	1.615 ± 0.366
$a_1 \sin i$ (AU)	0.21 ± 0.10
$f(m)$ ($10^{-4} M_{\odot}$)	4.599
$M_2 \sin i$ (M_{Jup})	15.6 ± 0.6^a 19.5 ± 0.8^a
a_2 (AU)	0.97 ± 0.10^a 1.10 ± 0.13^a
N_{meas}	11
Span (days)	2542
σ ($O - C$) (m s $^{-1}$)	96.7
χ^2_{red}	0.424

NOTES.—The given parameters are orbital period, periastron time, eccentricity, system velocity, longitude of periastron, RV semiamplitude, projected semimajor axis of the primary, mass function, lower limit of the companion mass, semimajor axis of the companion, number of measurements, time span of the observations, residuals, and reduced χ^2 .

^a The derived values are based on two available estimates for the primary mass of 0.07 and $0.10 M_{\odot}$. No further errors on the primary mass, e.g., as introduced by the use of evolutionary models, have been taken into account here.

phase hint already at a small companion mass. The mass of the companion $M_2 \sin i$ cannot be determined directly from a single-lined RV orbit but depends on the primary mass. Unfortunately, in the case of Cha H α 8, the primary mass is not very precisely determined (as is common in this mass and age regime). Using the two available estimates for the primary mass (0.07 and 0.10 M_\odot ; see § 2), the mass of the companion $M_2 \sin i$ is inferred to be 15.6 and 19.5 M_{Jup} , respectively. This does not take into account further possible errors on the primary mass, as e.g., introduced by evolutionary models. Given the uncertainty of the RV semiamplitude (0.4 km s $^{-1}$) of the orbit solution, it cannot be ruled out that the companion has a mass $M_2 \sin i$ in the planetary mass regime ($<13 M_{\text{Jup}}$). The reason for this is the limited phase coverage of the available RV data, in particular at maximum RV. For example, for an RV semiamplitude of 1.4 km s $^{-1}$, the companion mass $M_2 \sin i$ would be 11.6 M_{Jup} ($M_1 = 0.07 M_\odot$).

Based on the assumption of randomly oriented orbits in space, the following statements about the mass ratio of the system can be made: With a 50% probability (inclination $i \geq 60^\circ$), the mass ratio $q \equiv M_2/M_1$ is ≤ 0.2 , and with 87% probability ($i \geq 30^\circ$), q is ≤ 0.4 . Comparing the mass ratio of Cha H α 8 with that of other BD/VLM spectroscopic binaries ($q > 0.6$; Basri & Martín 1999; Stassun et al. 2006; Simon et al. 2006), with a probability of more than 90%, Cha H α 8 has the smallest known mass ratio ($q \leq 0.5$). We note that these probabilities are valid for both considered values of M_1 . Further, these are the probabilities for randomly oriented orbits. They are even higher for spectroscopic systems since this search method has a bias toward high inclinations.

5. ACTIVITY

In the following, the question is addressed whether the detected RV variability with a semiamplitude of 1.6 km s $^{-1}$ can be caused by chromospheric or accretion activity, both of which are common phenomena for very young stars and are observed also for substellar objects. Cha H α 8 shows signs of chromospheric activity through H α (Comerón et al. 2000; Luhman 2004; Mohanty et al. 2005) and X-ray emission (Stelzer et al. 2004). Chromospheric activity can cause photometric and RV variability on the timescale of the rotation period through asymmetries in the surface brightness and spectral line shape, respectively. The rotation period of Cha H α 8 is of the order of a few days based on measurement of its spectroscopic velocity $v \sin i$ (Joergens & Guenther 2001; see Table 1) and in accordance with absolute rotation periods determined for BD/VLMs in the same region ($P_{\text{rot}} = 2\text{--}5$ days; Joergens et al. 2003). Photometric and RV variability of Cha H α 8 on this timescale is of rather low amplitude: Photometric monitoring in the Bessel R and Gunn i filters (Joergens et al. 2003) over 6 nights shows that peak-to-peak variability amplitudes are $\Delta R < 0.02$ mag and $\Delta i < 0.04$ mag, respectively. Further, while we report here on RV variability with a period of a few years, the RV variability of Cha H α 8 on timescales of days is quite small: Investigation of RVs measured with time offsets of a few days in 2000 ($\Delta t = 19$ days), 2002 March (16 days), 2002 April (3 days), and 2007 (7 days) shows that peak-to-peak RV differences on timescales of a few days do not exceed 0.17 km s $^{-1}$ and can account for only about a tenth of the total recorded variability amplitude. Therefore, the detected long-period RV variability cannot be explained by rotational modulation due to chromospheric activity. Accretion, on the other hand, can cause RV variability on various timescales.

However, since no signs of significant accretion were detected for Cha H α 8 (H α equivalent width ≤ 10 Å, no Ca II $\lambda 8662$ emission detected; Mohanty et al. 2005), accretion processes are unlikely to cause the detected RV variability.

6. DISCUSSION AND CONCLUSIONS

We have shown that Cha H α 8 has an RV companion in a ~ 1 AU orbit and that this companion is most certainly a very low mass BD. Cha H α 8 is the first small mass ratio spectroscopic binary among BD/VLMs. The discovery of the RV companion of Cha H α 8, which has an RV semiamplitude of only 1.6 km s $^{-1}$, is an important step toward RV planet detections of BD/VLMs. In fact, from the uncertainty in the orbit solution, it cannot be completely excluded that the companion of Cha H α 8 has a mass in the planetary mass regime ($<13 M_{\text{Jup}}$). Follow-up RV measurements monitoring the next phase of periastron (2011 April) are necessary to investigate this further.

The favored mechanisms for stellar binary formation—fragmentation of collapsing cloud cores or of massive circumstellar disks—seem to produce preferentially equal-mass components, in particular for close separations (e.g., Bate et al. 2003). Thus, they have difficulties to explain the formation of the small mass ratio system Cha H α 8. However, we know that close *stellar* binaries with small mass ratios do exist as well (e.g., $q = 0.2$; Prato et al. 2002), and without knowing the exact mechanism by which they form, it might be also an option for Cha H α 8.

Considering the small mass of the companion of Cha H α 8, a planet-like formation could also be possible. Giant planet formation through core accretion might be hampered for low-mass primaries, such as M dwarfs, by long formation timescales (Laughlin et al. 2004; Ida & Lin 2005); however, recent simulations hint that it can be a faster process than previously anticipated (Alibert et al. 2004).

On the other hand, giant planets around M dwarfs might form by disk instability (Boss 2006a, 2006b), at least in low-mass star-forming regions, where there is no photoevaporation of the disk through nearby hot stars (e.g., Cha I). The companion of Cha H α 8 could have been formed through disk instability, either in situ at 1 AU or, alternatively, at a larger separation and subsequent inward migration. The latter is plausible in the case of Cha H α 8 since a higher mass of the formed object favors inward migration (e.g., Boss 2005).

Cha H α 8 is outstanding among the group of spectroscopic BD/VLM binaries also by its relatively long orbital period (1590 days). In particular, this is the case when considering the extremely short period systems PPI 15 and 2M0535–05, which have periods smaller than 10 days. Cha H α 8 is part of a sample of 10 BD/VLMs in Cha I that have been monitored for RV companions since 2000. Joergens (2006; V. Joergens 2007, in preparation) finds no short-period systems (and also no equal mass binaries) in this survey, while they are easier to detect. Thus, the detection of Cha H α 8 might hint at a higher frequency of long-period ($\sim 10^3$ days) BD/VLM binaries in Cha I than short period ones (~ 10 days). This is consistent with the separation distribution for currently known substellar and very low mass stellar binaries (Burgasser et al. 2007), which has a peak at 2.5–10 AU. We note, however, that this distribution is not well constrained for separations <3 AU.

When combined with angular distance measurements or eclipse detections, spectroscopic binaries allow valuable dynam-

ical mass determinations. The mass is the most important input parameter for evolutionary models, which for masses $<0.3 M_{\odot}$ rely only on the two masses determined for the very young eclipsing BD binary 2M0535–05 (Stassun et al. 2006; Mathieu et al. 2007). Cha H α 8 is, after 2M0535–05, the second known very young BD/VLM spectroscopic binary. However, the measurement of dynamical masses for Cha H α 8 is challenging in several respects. In order to measure absolute masses of both components, one must resolve the spectral lines of both components (SB2). This is preferentially done at IR wavelengths (e.g., VLT CRIFES), where the contrast ratio between the primary and secondary is smaller (e.g., Prato 2007). Having a maximum separation of about 13 mas (~ 2 AU), the spatial resolution of current imaging instruments is not sufficient to directly resolve Cha H α 8. This has probably to await OWL (the Overwhelmingly Large Telescope). Current and upcoming interferometers, on the other hand, do provide the necessary spatial resolution, but are not sensitive enough. However, it might be possible to detect the relative astrometric signal of

the primary (a few mas). This would allow measurement of the inclination of the orbital plane and, therefore, breaking the $\sin i$ ambiguity in the companion mass. These observations might be possible with, e.g., VLT NACO or with phase-referenced astrometry with the upcoming VLT interferometer PRIMA (using available brighter reference stars in the field for fringe tracking).

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Facilities: VLT:Kueyen

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