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HD 91669B: A NEW BROWN DWARF CANDIDATE FROM THE McDONALD OBSERVATORY PLANET SEARCH

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ABSTRACT

We report the detection of a brown dwarf candidate orbiting the metal-rich K dwarf HD 91669, based on radial-velocity data from the McDonald Observatory Planet Search. HD 91669b is a substellar object in an eccentric orbit ($e = 0.45$) at a separation of 1.2 AU. The minimum mass of $30.6 M_{\rm Jup}$ places this object firmly within the brown dwarf desert for inclinations $i \gtrsim 23^\circ$. This is the second rare close-in brown dwarf candidate discovered by the McDonald planet search program.

Key words: planetary systems – stars: individual (HD 91669) – stars: low-mass, brown dwarfs

Online-only material: color figure

1. INTRODUCTION

Brown dwarfs are commonly defined as substellar objects with masses between the deuterium-burning limit (about $13 M_{\rm Jup}$) and the hydrogen-burning limit (about $80 M_{\rm Jup}$). Despite the large (several hundred m s^{-1}) reflex radial-velocity signals produced by brown dwarfs in orbit around main-sequence stars, planet-search surveys monitoring thousands of stars have found remarkably few such objects in orbits with $a \lesssim 5$ AU. By contrast, nearly 300 planets have been found by the radial-velocity method. Early radial-velocity surveys by Campbell et al. (1988) and Murdoch et al. (1993) reported a distinct lack of candidate companions in the brown dwarf mass range, despite their relatively easy detectability. Campbell et al. (1988) noted that seven of the 15 targets showed velocity variability consistent with a distant companion, but the lack of astrometric variability led those authors to limit the companion mass range to ~ 1–$9 M_{\rm Jup}$. In the nearly 20 years spanned by current radial-velocity planet searches, only a handful of brown dwarf candidates have been identified, e.g., HD 114762b ($11 M_{\rm Jup}$; Latham et al. 1989; Cochran et al. 1991; Mazeh et al. 1996), HD 168443c ($18 M_{\rm Jup}$; Marcy et al. 2001), HD 202206b ($17 M_{\rm Jup}$; Udry et al. 2002), and HD 137510b ($26 M_{\rm Jup}$; Endl et al. 2004). Recently, a transiting brown dwarf has been discovered by the *CoRoT* spacecraft. This object, CoRoT-Exo-3b, has a mass of $21.7 M_{\rm Jup}$ and a radius of 1.01 $R_{\rm Jup}$, in a remarkably close orbit at 0.05 AU (Deleuil et al. 2008).

The steep rise in the planetary mass function toward lower masses (Marcy et al. 2005a) combined with the decline in lower-mass stellar companions (Mazeh et al. 2003) give evidence for the existence of a "brown dwarf desert": a paucity of brown dwarf companions orbiting within ∼3–4 AU of solar-type stars (Marcy & Butler 2000). In contrast, there is no dearth of brown dwarfs orbiting at larger separations (Gizis et al. 2001), or free floating (Reid et al. 1999). Grether & Lineweaver (2006) performed a detailed investigation of the planetary and stellar mass distributions in order to correct for biases and to assess the reality of the brown dwarf desert. Defining close companions as those with orbital periods $P < 5$ yr, Grether & Lineweaver (2006) confirmed the deficit of close brown dwarf companions and estimated the driest part of the "desert" to lie at $M = 31^{+25}_{-18}\ M_{\rm Jup}$.

It is possible that selection biases curtail the discovery rate of brown dwarfs relative to planets, as measured by published results. The push to detect lower-mass planets combined with the high value of telescope time lead planet search teams to discard targets which exhibit the large-amplitude radial-velocity variations induced by brown dwarf companions in close orbits. However, a simple bias of this nature does not seem likely to explain the factor of ∼100 deficit in the observed frequency of brown dwarf companions compared to planetary companions.

Since the radial-velocity method yields only a minimum mass for the companion, some number of brown dwarf candidates are likely to be low-mass stars orbiting at low inclinations. Some authors have combined the radial-velocity orbits with astrometric data in order to determine the inclination and true mass of the companions. In this way, the "planets" HD 38529c and HD 168443c were revealed to be brown dwarfs with masses of $37 M_{\rm Jup}$ and 34 $M_{\rm Jup}$, respectively (Reffert & Quirrenbach 2006). Bean et al. (2007) used *Hubble Space Telescope* astrometry to determine that the planet candidate HD 33636b, with a minimum mass of 9.3 $M_{\rm Jup}$, was in fact a star with a true mass of $142 M_{\rm Jup}$ orbiting at a nearly pole-on inclination $i = 4\overset{\circ}{.}1$. These examples illustrate the importance of finding brown dwarf candidates with low values of m sin i to increase the likelihood of their true mass remaining in the substellar mass range.

In this paper, we derive the parameters of the host star HD 91669 (Section 3), and in Section 4 we present evidence for its brown dwarf companion, and discuss possible constraints on its true mass.

2. OBSERVATIONS AND DATA ANALYSIS

Observations were made from the 2.7 m Harlan J. Smith Telescope at the McDonald Observatory using the 2dcoudé echelle spectrograph (Tull et al. 1994) at a resolution $R = \lambda/\Delta\lambda = 60{,}000$. HD 91669 is one of ∼300 stars being monitored in the long-term planet search program, which began in 1988. Observations with the current instrumental configuration ("Phase III") began in 1998 and achieve a routine internal precision of 6–9 m s^{-1}. Complete details of the planet search at McDonald Observatory are given in Wittenmyer et al. (2006). HD 91669 was added to the program in 2004 March after a preliminary abundance analysis showed it to be a metal-rich star. At $V = 9.7$, exposure times ranged from 20–30 minutes per epoch. Radial velocities were obtained using a temperature-stabilized iodine (I_2) cell, imprinting thousands of narrow absorption lines on the stellar spectrum and providing a velocity metric (Butler et al. 1996). The iodine lines were also used to model the effects of the spectrograph's instrumental profile, as described by Valenti et al. (1995) and Endl et al. (2000). We fit Keplerian orbits to the radial-velocity data using *Gaussfit*, a least-squares and robust-estimation package (Jefferys et al. 1987).

3. STELLAR PARAMETERS

The stellar parameters $T_{\rm eff}$, log g, and Fe/H (Table 1) were determined using a standard iterative spectroscopic procedure, as described in Ramírez et al. (2007). The transition probabilities adopted for the iron lines were taken from laboratory measurements; i.e., no astrophysical log gf values were used. Effective temperatures were obtained from as many as possible of the color–temperature relations by Ramírez & Meléndez (2005). Surface gravities were determined from the location of the stars on the H-R diagram, on which the theoretical isochrones of Bertelli et al. (1994) were superimposed. We used the accurate *Hipparcos* parallaxes of the stars to calculate their absolute magnitudes before determining log g. In a similar manner, the stellar masses and radii (Table 1) were found using the derived stellar parameters and the Bertelli et al. isochrones. Details on the adopted method of log g, mass, and radius determination are given by Reddy et al. (2003) and Allende Prieto et al. (2004).

The iron abundance was inferred from a large set of unblended Fe I lines covering a wide range of line strength and about a dozen Fe II lines, which allowed us to determine accurate microturbulent velocities (v_t) and check the ionization equilibrium of iron lines, respectively. After applying the empirical correction to the iron abundance determined from Fe I lines suggested by Ramírez et al. (2007), the mean iron abundances determined separately from Fe I and Fe II lines are typically in agreement and their average value is adopted as the star's Fe/H. For HD 91669, however, the mean Fe II abundance was about 0.3 dex larger than the mean Fe I abundance, a systematic error occurring in cool metal-rich dwarf stars which has been reported by several authors (e.g., Yong et al. 2004; Allende Prieto et al. 2004; Schuler et al. 2006; Ramírez et al. 2007) and has been suggested to be due to non-LTE effects or inadequacies in the modeling of cool stellar atmospheres. Given that Fe I is the dominant species at these cool temperatures, the mean iron abundance from Fe I lines only was adopted as the star's Fe/H.

HD 91669 (=HIP 51789, NLTT 24745) is a metal-rich ([Fe/H] = +0.31) K0 dwarf which has been in the planet search program at McDonald Observatory for 4.3 yr. It has a *Hipparcos* parallax of 11.58 ± 1.48 mas, corresponding to a distance of 86.4 pc (van Leeuwen 2007). The derived log g of 4.48 refutes the K0/1 III classification reported by Houk & Smith-Moore (1988). The uncertainties on $T_{\rm eff}$ and log g given in Table 1 represent internal errors, and do not include possible systematic errors of ∼100 K in $T_{\rm eff}$ and ∼0.1 dex in log g.

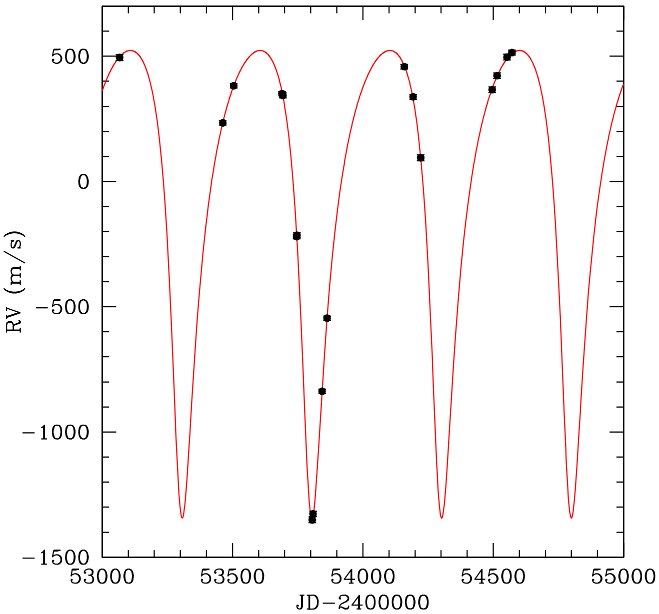

Figure 1. Keplerian orbital solution for HD 91669. The residual rms about this fit is 6.3 m s^{-1}.

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

Table 1
HD 91669 Stellar Parameters

Parameter	Value
$T_{\rm eff}$	5185 ± 87 K
log g	4.48 ± 0.20
v_t	0.85 km s^{-1}
Mass	$0.914^{+0.018}_{-0.087}$ $M_\odot$
$[Fe/H]$	+0.31 ± 0.08
log $R'_{\rm HK}$	−4.66 ± 0.18

Table 2
HD 91669 Companion Parameters

Parameter	Value
Period	497.5 ± 0.6 days
T_0	53298.4 ± 0.6 JD-2400000
e	0.448 ± 0.002
ω	161.3 ± 0.5°
K	933.0 ± 3.1 m s^{-1}
$m \sin i$	30.6 ± 2.1 $M_{\rm jup}$
a	1.205 ± 0.039 AU
χ^2_ν	0.41
rms (m s^{-1})	6.3
$N_{\rm obs}$	18

4. COMPANION PARAMETERS

We present 18 radial-velocity observations of HD 91669 spanning 4.3 yr which indicate a massive substellar companion (Figure 1). For the adopted stellar mass $M_* = 0.914\ M_\odot$, HD 91669b has a minimum mass of $m\sin i = 30.6 \pm 2.1 M_{\rm Jup}$ (Table 2). With a separation $a = 1.205$ AU, and a distance of 86.4 pc, the angular separation of HD 91669b would be 14 mas. It is conceivable that a stellar companion may be ruled out by direct imaging, but the 14 mas projected separation of HD 91669b is considerably smaller than the limits achieved by current AO and coronagraphic surveys (e.g., Nielsen et al. 2008). For randomly distributed inclinations, the mean value of sin i is $\pi/4 = 0.785$. Applying this adjustment to the minimum mass,

Table 3
2.7 m Radial Velocities for HD 91669

JD-2400000	Velocity (m s^{-1})	Uncertainty (m s^{-1})
53066.87750	495.1	12.3
53462.78781	233.9	9.2
53504.63667	382.0	8.5
53689.98969	350.7	8.6
53692.99313	343.1	9.7
53745.96115	−220.3	9.2
53746.97586	−214.2	9.2
53805.84071	−1351.1	11.5
53808.79440	−1326.5	10.3
53843.70848	−837.7	8.9
53862.65416	−545.6	8.4
54158.85204	458.1	9.5
54192.73118	338.0	9.3
54221.74547	94.8	11.8
54495.90692	366.4	10.6
54514.80082	422.5	10.9
54552.84010	496.4	11.5
54571.70919	514.4	9.9

the true mass of HD 91669b would be 39.0 M_{Jup}, remaining comfortably below the hydrogen-burning limit of 80 M_{Jup}. For a true mass in the stellar regime, the inclination must be $i < 22\overset{\circ}{.}5$. The probability that such an object would have that inclination or smaller is given by

$$\mathrm{Prob}(i < i_c) = 1 - \cos(i). \quad (1)$$

For HD 91669, this *a priori* probability is 7.6%. Kürster et al. (2008) were able to combine *Hipparcos* astrometry with a radial-velocity orbital solution to place additional constraints on the inclination of GJ 1046b, a brown dwarf candidate in close orbit about an M2.5 star.

Similarly, we also tried to fit the *Hipparcos* Intermediate Astrometric Data based on the new reduction of the *Hipparcos* raw data by van Leeuwen (2007) for HD 91669 (HIP 51789) with an orbital model. We fixed the five orbital parameters derived from the radial velocities (Table 2), and fitted for the two missing orbital parameters (inclination and ascending node), and simultaneously for corrections to the five standard astrometric parameters (positions, proper motions, parallax), in an effort to get a better constraint on especially the inclination and thus on the companion mass. Note that, in order to derive constraints on the inclination, the orbit does not need to be detected; often, small inclinations (corresponding to large companion masses) can be excluded (see Reffert & Quirrenbach 2009) because they would correspond to astrometric signals much larger than the measurement precision of *Hipparcos*, which would be seen in the data. For HD 91669, inclinations smaller than $5\overset{\circ}{.}3$ and larger than $176\overset{\circ}{.}2$ can be excluded with 99.73% confidence, corresponding to a companion mass smaller than about 0.6 $M_{\odot}$. This is not a good constraint on the companion mass, but it is all that we can safely derive from the *Hipparcos* data. There are 81 field transits (individual one-dimensional measurements) for HD 91669 with a median formal error of 6.0 mas. In contrast to that, the minimum astrometric signature of the companion, assuming an inclination of 90°, is only 0.9 mas peak-to-peak. It is clear that this would be too small to be significantly detectable by *Hipparcos*. Thus, while we cannot derive a tight constraint on the companion mass, the *Hipparcos* data are at least not inconsistent with a companion mass in the brown dwarf regime.

The orbital solution has an rms of 6.3 m s^{-1}, consistent with our typical velocity precision for fainter stars in the 2.7 m planet search program (HD 91669: $V = 9.70$), and considerably smaller than the mean uncertainty of 10.0 ± 1.2 m s^{-1}. The uncertainties on the Keplerian orbital parameters are derived in two ways: (1) *Gaussfit* returns uncertainties generated from a maximum likelihood estimation that is an approximation to a Bayesian maximum a posteriori estimator with a flat prior (Jefferys 1990), and (2) we applied a Monte Carlo method similar to that of Marcy et al. (2005b). We determine the best-fit set of model parameters and subtract the Keplerian model from the data, generating a residuals file. Then we create simulated data sets retaining the epochs of observation, where the velocity at each point consists of the best-fit Keplerian model added to a residual velocity randomly drawn (with replacement) from the residuals file. In this way, each simulated velocity point is "bumped" by an amount consistent with the variations due to stellar jitter and instrumental errors. We generate 100 such realizations, fit each with a Keplerian model as above, and record the derived parameters. The 1σ uncertainty of each parameter is then taken to be the standard deviation about the mean value of the 100 sets of parameters. The parameter uncertainties shown in Table 2 are those obtained from the latter method. We note that the uncertainties of orbital parameters derived from least-squares fitting are known to be non-Gaussian (Ford 2005), and hence can be underestimated by a factor of 5–10 (O'Toole et al. 2009). The radial-velocity data are given in Table 3. The residuals to the orbit fit show no slope or evidence of residual signals; the highest periodogram peak has a false-alarm probability (FAP) of 95%.

5. SUMMARY

We have presented radial-velocity observations indicating the presence of a rare brown dwarf candidate orbiting the metal-rich K dwarf HD 91669. HD 91669b is the second brown dwarf identified in the McDonald Observatory planet search program. Like its predecessor HD 137510b (Endl et al. 2004), this object has a relatively low mass and hence a high probability of having a true mass within the substellar regime. We note that the rarity of brown dwarfs implies that the detection of two candidates in a sample of 250 stars is rather unlikely. However, the McDonald Observatory program yields a detection rate of 0.8% ± 0.6%, compared to a rate of 0.7% ± 0.2% from the California & Carnegie Planet Search (7 candidates from ~1000 target stars: Vogt et al. 2002, Patel et al. 2007). Within the limits of small-number statistics, the yields of brown dwarf candidates from these two programs are comparable.

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