

## CROSSING THE BROWN DWARF DESERT USING ADAPTIVE OPTICS: A VERY CLOSE L DWARF COMPANION TO THE NEARBY SOLAR ANALOG HR 7672

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### ABSTRACT

We have found a very faint companion to the active solar analog HR 7672 (HD 190406; GJ 779; 15 Sge). Three epochs of high-resolution imaging using adaptive optics (AO) at the Gemini-North and Keck II Telescopes demonstrate that HR 7672B is a common proper motion companion, with a separation of  $0''.79$  (14 AU) and a  $2.16\ \mu\text{m}$  flux ratio of 8.6 mag. Using follow-up *K*-band spectroscopy from Keck AO+NIRSPEC, we measure a spectral type of L45 with an uncertainty of  $\pm 1.5$  subclasses. This is the closest ultracool companion around a main-sequence star found to date by direct imaging. We estimate that the primary has an age of 1–3 Gyr. Assuming coevality, the companion is most likely substellar, with a mass of 55–78  $M_J$  based on theoretical models. The primary star shows a long-term radial velocity trend, and we combine the radial velocity data and AO imaging to set a firm (model-independent) lower limit of 48  $M_J$ . In contrast to the paucity of brown dwarf companions at  $\lesssim 4$  AU around FGK dwarfs, HR 7672B implies that brown dwarf companions do exist at separations comparable to those of the giant planets in our own solar system. Its presence is at variance with scenarios in which brown dwarfs form as ejected stellar embryos. Moreover, since HR 7672B is likely too massive to have formed in a circumstellar disk as planets are believed to, its discovery suggests that a diversity of physical processes act to populate the outer regions of exoplanetary systems.

*Subject headings:* binaries: close — infrared: stars — planetary systems: formation — stars: individual (HR 7672) — stars: low-mass, brown dwarfs — techniques: high angular resolution

### 1. INTRODUCTION

Radial velocity surveys find that about 6% of solar-type FGK stars harbor planets within 4 AU, with  $M \sin i$  spanning 0.25–15  $M_J$ . In contrast, the same surveys find that the incidence of more massive substellar companions (15–80  $M_J$ ) at these radii is  $\lesssim 1\%$ , even though such objects are much easier to detect. The evidence for this “brown dwarf desert” first emerged from radial velocity surveys in the late 1980s and early 1990s (Campbell, Walker, & Yang 1988; Marcy & Benitz 1989; Walker et al. 1995). Their modest precisions ( $\sim 300\ \text{m s}^{-1}$ ) were sufficient to detect brown dwarfs inside 3 AU, but only a single candidate was found.<sup>2</sup> Current high-precision ( $\sim 10\ \text{m s}^{-1}$ ) radial velocity programs have identified about a dozen close companions with  $M \sin i = 15 - 60\ M_J$  (Mayor et al. 1997). However, the majority of these have been found by *Hipparcos* to be unre-

solved astrometric binaries with M dwarf companions, and the remainder are unlikely to be brown dwarfs (Halbwachs et al. 2000; Zucker & Mazeh 2001; Pourbaix & Arenou 2001). This paucity of objects stands in stark contrast to the abundance of free-floating brown dwarfs in the field (e.g., Reid et al. 1999; Kirkpatrick et al. 2000) and in young clusters down to very low masses (e.g., Bouvier et al. 1998; Luhman et al. 2000; Najita, Tiede, & Carr 2000; Liu 2001).

An unanswered observational question is whether the brown dwarf desert exists at  $\gtrsim 4$  AU, outside the region of current radial velocity surveys. A few L and T dwarf companions have been found around FGK dwarfs from the 2MASS imaging survey at very wide separations (250–2500 AU; Burgasser et al. 2000; Kirkpatrick et al. 2001; Wilson et al. 2001). The statistics are currently small, but this suggests that the brown dwarf desert does not exist at very large separations (Gizis et al. 2001). These companions might have formed during the fragmentation of the same natal molecular core as the primary. Given their mass and large separation, it is unlikely that they formed in a circumstellar disk, as planets are believed to form.

Little is known about the frequency of substellar companions at  $\approx 4$ –50 AU. In our solar system, this is the domain of giant planets and the Kuiper Belt. Hence, probing these separations around other stars can test our understanding of formation processes in the outer regions of planetary sys-

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<sup>2</sup> This object was the companion to HD 114762 with  $M \sin i = 11\ M_J$  (Latham et al. 1989). The primary star is likely seen pole-on, so its companion was believed to be stellar (Cochran, Hatzes, & Hancock 1991). Recent AO imaging has resolved a third component, a late-type dwarf at 91 AU (Lloyd et al. 2000b). This raises the possibility of dynamical interactions causing the stellar rotation axis to be misaligned with the companion orbital axis (Patience et al. 2001). Hence, HD 114762B may in fact be a substellar companion.

tems. There are clues that massive planets and/or brown dwarfs do exist at these radii: half of stars with planets have systematic long-term trends in their radial velocities due to unseen companions (Fischer et al. 2001). The orbital periods are much longer than the observing baselines, and hence the masses are poorly constrained. Because the periods are many years and/or decades, relying on radial velocities alone will require a long time to determine the companion masses. However, adaptive optics (AO) imaging with large ground-based telescopes can probe the physical nature of these companions and lend insight into the mass distribution of substellar and planetary companions.

Thus, ground-based AO imaging provides a key capability for finding substellar companions to main-sequence stars, providing sensitivity at radii outside radial velocity searches but closer than ordinary imaging surveys. Recently, Els et al. (2001) have found a common proper motion companion to the extrasolar planet star GL 86. Their coronagraphic AO imaging finds a companion at a separation of  $1''.7$  (19 AU). The companion is among the coolest known, probably at the transition between L- and T-type objects based on IR photometry.

Aside from implications for understanding the planetary formation process, brown dwarf companions to main-sequence stars are interesting in their own right. Since a brown dwarf does not have a stable source of internal energy, its age and mass are degenerate for a given spectral type—young lower mass brown dwarfs can have same temperature as older higher mass brown dwarfs. By finding brown dwarf companions to main-sequence stars, we can break this degeneracy by measuring the age of the primary and assuming that the components are coeval. Combined with theoretical models for the cooling history of substellar objects, we can determine masses for brown dwarfs.

Here we report the discovery and characterization of a common proper motion companion to HR 7672 (HD 190406, 15 Sge, GJ 779) using the AO systems at the Gemini-North and Keck II telescopes. The star lies at a distance of 17.7 pc and has a spectral type of G1 V. Cayrel de Strobel (1996) classified it as a solar analog, and its higher level of activity than the Sun suggests a young age. Our observations and astrometry of HR 7672B appear in § 2. We present temperature and mass determinations for the companion based on near-IR AO photometry, spectroscopy, and radial velocity data in § 3. In § 4, we summarize our results and offer some implications for the formation of substellar objects around solar-type stars.

## 2. OBSERVATIONS AND ASTROMETRY

### 2.1. Imaging

We first imaged HR 7672 on 2001 June 24 UT using the Gemini-North 8.1 m telescope with the Hokupa'a AO system (Graves et al. 1998). The associated imaging camera QUIRC has a scale of  $19.98 \pm 0.08$  mas pixel<sup>-1</sup>. Conditions were nonphotometric with variable transmission due to patchy cloud cover. We obtained data in the *K'*-band filter (1.9–2.3  $\mu$ m; Wainscoat & Cowie 1992), taking both short- and long-exposure images to cover a large dynamic range. In the latter, the primary is saturated. The AO images have a  $0''.10$  FWHM core, with much of the light in a broader seeing limited halo, typical for images with only modest AO

correction. We identified a faint point source close to the primary.<sup>3</sup>

To check for common proper motion, we obtained second and third epoch imaging using the AO system (Wizinowich et al. 2000) on the Keck II 10 m telescope on 2001 August 22 and December 10 UT. We used the slit-viewing camera of the facility near-IR spectrograph NIRSPEC (McLean et al. 1998) and a narrowband Br $\gamma$  filter (2.155–2.175  $\mu$ m). The camera has a pixel scale of  $16.74 \pm 0.05$  mas pixel<sup>-1</sup>. Conditions were photometric, and the AO-corrected images have a  $0''.05$  FWHM. The companion was easily seen in individual images.

The imaging data were reduced in a standard fashion. We subtracted an average bias from the images. We constructed flat fields either from images of the lamp-illuminated interior of the dome (for the Gemini data) or from images of twilight sky (for the Keck data). Then we created a master sky frame from the median average of the bias-subtracted, flat-fielded images and subtracted it from the individual images. Images were registered and stacked to form a final mosaic, although the astrometric measurements were actually made on the individual images. Figure 1 shows the Gemini AO discovery image.

To determine the separation and position angle (P. A.) for the companion, we measured the individual reduced images and averaged the results, with the uncertainties determined from the standard errors. These errors were then added in quadrature to the errors in the calibration of the cameras' pixel scales and orientations. For the Keck AO data, the astrometry was straightforward, given the high quality of the data: the companion was well separated from the primary, so we simply computed the centroid of the two components. We also used the 2001 August data to measure a 2.16  $\mu$ m flux ratio of  $8.62 \pm 0.07$  mag.

For the lower quality Gemini AO data, more care was required. In the short-exposure images, where the primary was unsaturated, the companion was detected only the final stacked mosaic and only at low S/N. Hence, the resulting astrometry would have had a large uncertainty, and we would not have been able to directly gauge the errors. Instead, we derived astrometry from the deep images, where the core of the primary was saturated inside the  $0''.1$ – $0''.2$  radius but the rest of the primary was detected at very high S/N. To measure the primary's position, we cross-correlated the individual saturated images with an unsaturated short-exposure image. We then removed the primary by subtracting its azimuthally averaged radial profile and measured the companion's centroid. We then averaged the results to get the separation and P.A. We verified that these results are robust by (1) doing the measurements with several different point-spread functions (PSFs) and (2) generating artificial data sets of saturated images from the short exposure images. Both of these confirm our quoted measurement accuracy.

Table 1 presents our astrometry for the companion. HR 7672 has a high proper motion,  $(-394.07, -406.42) \pm (0.63,$

<sup>3</sup> We also detected three faint sources farther away. We had previously observed this field using the AO system on the Shane 3 m telescope at Lick Observatory (Bauman et al. 1999). *K*-band images taken with the science camera IRCAL (Lloyd et al. 2000a) on 1999 August 2 UT showed sources at (*d*, P.A.) = ( $10''.0$ ,  $142^\circ$ ), ( $7''.9$ ,  $178^\circ$ ), and ( $5''.6$ ,  $256^\circ$ ), all around 8–10 mag fainter than the primary. All three are detected in the Gemini AO image and are found to be background objects.

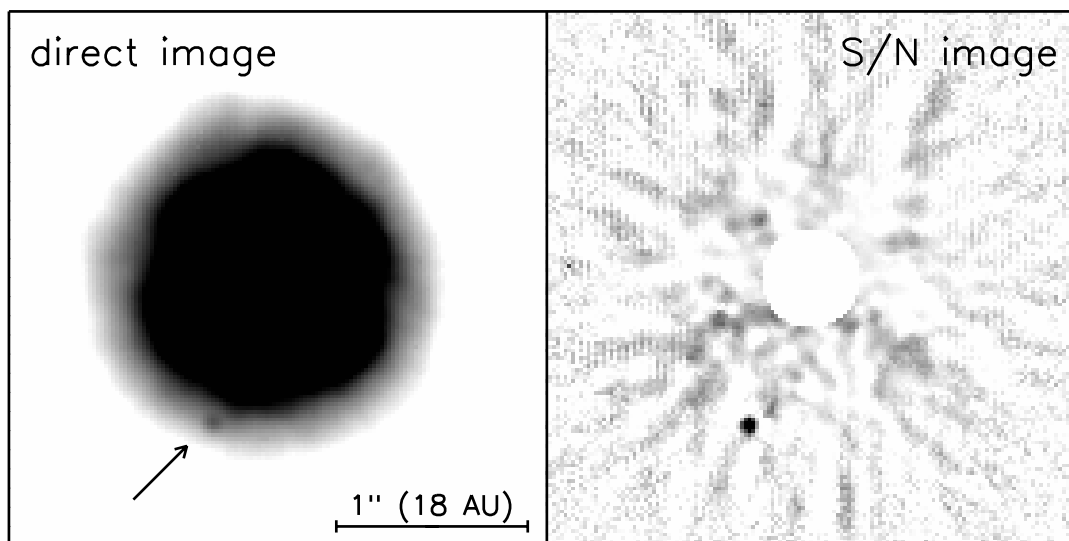


FIG. 1.—*Left*:  $K'$ -band discovery image of HR 7672B from Gemini-North AO. The companion is seen as a faint object in the halo of the primary. The orientation is as on the sky, north up and east left. *Right*: S/N image of the same data, constructed by unsharp masking the original data and then dividing by a radial profile whose amplitude follows the radial noise profile. The result is an image with uniform noise over the entire field; the companion is well detected. For both panels, the color stretch is linear.

0.64)  $\text{mas yr}^{-1}$ , allowing us to confirm whether the companion is physically associated relatively quickly. Nearly half a year passed between the first and third epochs of imaging, and Table 1 shows that if the object were a background object, its separation and P.A. would have changed significantly. The observed separation and P.A. are 7 and 26  $\sigma$  discrepant from being a background object, respectively. In fact, the first two epochs of imaging, spaced only 2 months apart, would have sufficed. Moreover, the second and third epoch data by themselves indicate the companion is not a background object; since these both came from the same instrument and filter, this eliminates any concern about systematic error from using different instruments. Hence we conclude that HR 7672B is physically associated with HR 7672.

## 2.2. Spectroscopy

We obtained a spectrum at Keck using NIRSPEC with the AO system via service observing. We obtained two 300 s exposures on 2001 August 31 UT in low-resolution mode with the NIRSPEC-7 blocking filter and the  $0''.072$  slit. The slit was oriented at the parallactic angle. (In contrast to seeing-limited near-IR observations, atmospheric dispersion with these nearly diffraction-limited images was not negligible.) The object was dithered on the slit between exposures. Conditions appeared to be photometric, and the AO-

produced images had  $0''.06$  FWHM as measured from the acquisition images taken with the slit-viewing camera. A nearby A0 V star was observed immediately afterward to calibrate the telluric and instrumental absorption profile. Images of an internal flat field and arc lamps were obtained when finished with the calibrator star. For comparison with the Gemini AO image, Figure 2 shows the  $K$ -band image of the system obtained from the NIRSPEC slit-viewing camera.

The spectra were reduced using custom IDL scripts. In NIRSPEC, the raw images on the detector are curved in both the spectral and spatial directions. After subtracting a dark frame and dividing by a flat field, the individual images were rectified using traces of the arc lamp lines and the object spectra. Since the primary is very bright, the light from the PSF halo and diffraction features fill much of the slit. We removed the telluric emission by fitting blank regions at the edges of the slit and subtracting the result from the entire image. To extract the companion spectrum, we then used a 3 pixel wide region. To remove the remaining primary light, at each wavelength we fitted for the contamination using pixels above and below the companion spectrum. This amounted to  $\approx 30\%$  of the light in the extraction aperture.

To calibrate for the relative throughput of the atmosphere and instrument, we divided the extracted spectra by the spectra of the A0 V calibrator star and then multiplied

TABLE 1  
HR 7672B ASTROMETRY

DATE (UT)	TELESCOPE	SEPARATION (mas)	P.A. (deg)	OBSERVED		IF BACKGROUND OBJECT	
				$\Delta$ Separation (mas)	$\Delta$ P.A. (deg)	$\Delta$ Separation (mas)	$\Delta$ P.A. (deg)
2001 Jun 24 .....	Gemini-N	$795 \pm 5$	$157.0 \pm 0.2$	...	...	...	...
2001 Aug 22 .....	Keck II	$786 \pm 6$	$157.9 \pm 0.5$	$-9 \pm 8$	$0.9 \pm 0.6$	$-31 \pm 5$	$-6.3 \pm 0.4$
2001 Dec 10.....	Keck II	$794 \pm 5$	$157.3 \pm 0.6$	$-1 \pm 7$	$0.3 \pm 0.7$	$-61 \pm 5$	$-19.2 \pm 0.3$

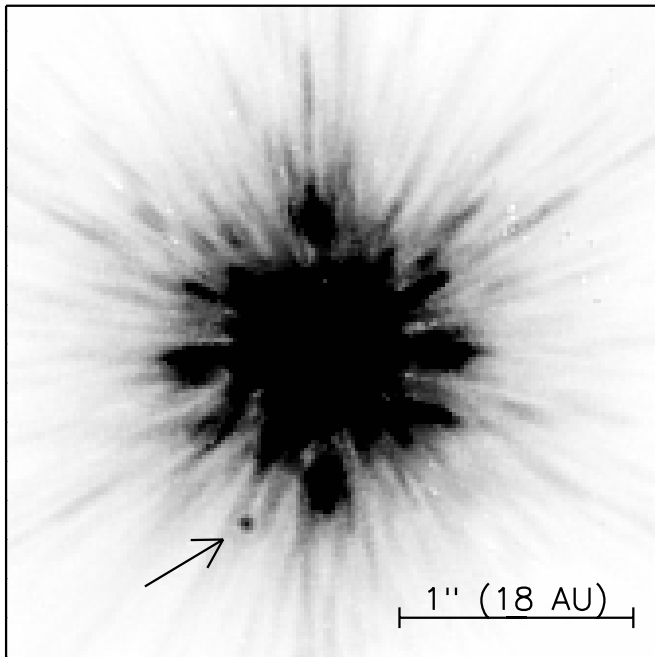


FIG. 2.—K-band image of HR 7672B obtained with Keck AO. The color scale is linear, and the image is the same size and orientation as in Fig. 1.

by a 9720 K blackbody to restore the true shape of the continuum. For this, we interpolated over the intrinsic Br $\gamma$  absorption in the calibrator star. Wavelength calibration was done with spectra of argon and neon lamps. The spectral resolution ( $\lambda/\Delta\lambda$ ) of the final spectra was 1400, as measured from the FWHM of the arc lines. The final spectrum is plotted in Figure 3, with the  $1\sigma$  uncertainties determined from the standard error of the two individual spectra.

### 3. RESULTS

#### 3.1. Temperature of HR 7672B

In order to determine the spectral type of HR 7672B, we compare its K-band spectrum with that of other very cool M- and L-type objects. We use published spectra for (non-subdwarf) M dwarfs from Leggett et al. (2000) and spectra from L dwarfs from Geballe et al. (2002), Leggett et al. (2001), and Reid et al. (2001a); hereafter, we refer to this compilation as the “calibration sample.” For the L dwarfs, we use the spectral types assigned by Geballe et al. (2002), which are based on several optical and near-IR spectral indices; for most objects, their spectral types agree well with previous typing based on optical spectroscopy alone. Qualitatively, the spectrum of HR 7672B shows strong blueward absorption indicative of H<sub>2</sub>O and a strong CO 2.3  $\mu$ m break. These are characteristic of very late type M dwarfs and L dwarfs. In addition, no absorption is seen in 2.2  $\mu$ m from Na I; this feature is seen in late M dwarfs (Jones et al. 1994; Leggett et al. 2000) but disappears in L dwarfs. These properties suggest that HR 7672B is an L dwarf.

Among L dwarfs, there are noticeable variations in the published K-band spectra for a given subtype. The origins of these variations are unknown, but they could be due to heterogeneity in time variability, photospheric dust properties, and/or surface gravities. Hence, a qualitative (eyeball)

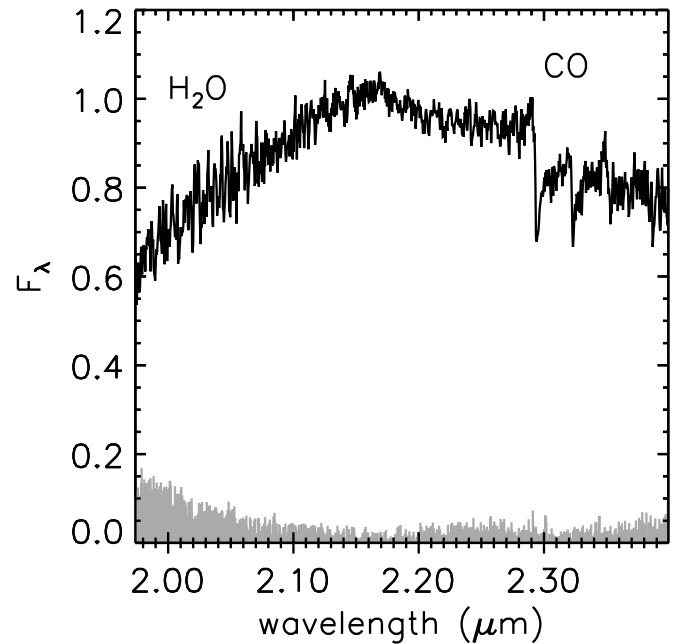


FIG. 3.—K-band spectrum for HR 7672B obtained with Keck AO+NIR-SPEC. The spectrum has been scaled to an arbitrary constant. The lines at the bottom are the  $1\sigma$  errors as determined from the scatter in the individually extracted spectra. The companion shows strong H<sub>2</sub>O absorption on the blue side and strong CO absorption in the red.

comparison between HR 7672B and the published spectra does not yield a clear and unique match. To quantitatively assign a spectral type, we compute several spectral indices: two indices that measure H<sub>2</sub>O absorption on the blue side of the bandpass [H<sub>2</sub>O-C from Burgasser et al. and H<sub>2</sub>O(2.0) from Geballe et al.], an index that tracks the slope of the 2.1–2.3  $\mu$ m continuum [CH<sub>4</sub>(2.2) from Geballe et al.],<sup>4</sup> and a CO bandhead index of our own construction ( $R_{CO}$  is the ratio of 2.30–2.32  $\mu$ m flux to 2.26–2.28  $\mu$ m flux). We degrade our NIRSPEC spectra to a spectral resolution comparable to the published spectra before measuring the indices. To estimate our measurement errors, especially given the possibility that there is some residual contamination in our spectra from the light of the primary, we measure the two extracted spectra individually and plot the resulting range.

The results are shown in Figure 4. The strength of the H<sub>2</sub>O absorption suggests a spectral type later than L2, while the continuum CH<sub>4</sub> indices point to a type no cooler than L6. The CO index is discrepant; the strength of the absorption is weaker than most L dwarfs, and is more typical of mid/late M dwarfs. To disentangle this uncertainty, we also use the absolute K-band magnitude of HR 7672B to estimate the spectral type. Kirkpatrick et al. (2000) have compiled a sample of 24 nearby late M and L dwarfs with measured parallaxes to generate a calibration for spectral type with  $K_S$ -band (2.0–2.3  $\mu$ m) absolute magnitude

$$M_{K_S} = 10.450 + 0.127(\text{subclass}) + 0.023(\text{subclass})^2, \quad (1)$$

where subclass =  $-1$  for M9 V,  $0$  for L0 V,  $1$  for L1 V, etc. The scatter about the fit is  $\approx 1$  subtype. HR 7672 has a  $V$ -

<sup>4</sup> This index is primarily designed to track the depth of 2.2  $\mu$ m absorption in T dwarfs due to CH<sub>4</sub>. However, it is also a reasonable diagnostic for L dwarfs, as discussed by Geballe et al.

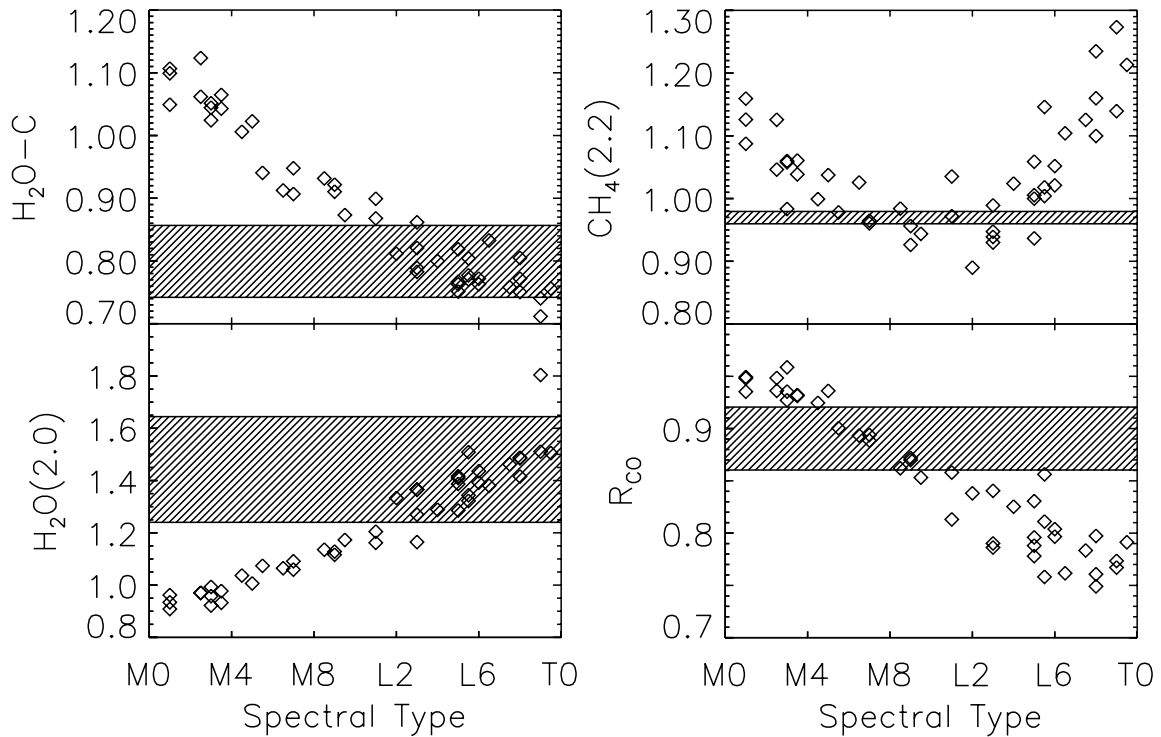


FIG. 4.—Spectral classification of HR 7672B based on molecular spectral indices for very cool atmospheres (see § 3 for references). The diamonds are objects from the literature with known spectral types. The hatched bands represent the HR 7672B measurements. The indices on the left trace the increasing  $\text{H}_2\text{O}$  absorption at the blue edge of the bandpass; these indicate that HR 7672B has spectral type of L2 or later. The ones on the right track the shape of the continuum and the depth of CO absorption; these suggest a type no later than L6. The CO absorption appears to be anomalously weak.

band magnitude of 5.80 mag, a distance of 17.7 pc, and a spectral type of G1 V. Using  $V-K$  colors for dwarfs from Bessell & Brett (1988), this means that the primary has  $M_K = 3.1$  mag. For G stars, we use synthetic photometry of spectra from Pickles (1998) to determine that there is a negligible difference between the  $K$  and  $K_S$ -band magnitudes. For HR 7672B, we measure a  $2.16 \mu\text{m}$  flux ratio of 8.6 mag. We use synthetic photometry of the calibration sample to find that  $(K_S - [\text{Br}\gamma]) \approx 0.05\text{--}0.10$  mag for L dwarfs, so the companion has  $M_{K_S} = 11.8 \pm 0.1$  mag, which gives a spectral type of L5.5. Given the relatively small L dwarf sample and the scatter about the fit, spectral types between L4 and L6 could be accommodated.

We adopt a final spectral type of L4.5 with an uncertainty of  $\pm 1.5$  subclasses. This is based on the intersection of the results from the spectral indices, which suggest L2–L6, and the  $K$ -band absolute magnitude, which points to L4–L6. The spectral typing (and hence the mass estimate) could be improved in the future by obtaining spectra in the  $H$  and  $J$  bands; the latter would require good seeing conditions given the currently available AO systems on 8–10 m telescopes. To convert to effective temperature, we use the scale produced by Burgasser et al. (2002), which is intermediate between those proposed by Kirkpatrick et al. (1999b), Kirkpatrick et al. (2000), and Basri et al. (2000). This choice gives  $T_{\text{eff}} = 1510\text{--}1850$  K for HR 7672B.

### 3.2. Mass of HR 7672B

#### 3.2.1. From Spectroscopy

Not all L dwarfs are brown dwarfs (i.e., substellar). Current evidence suggests that the substellar boundary occurs around spectral types of L2–L4 (Kirkpatrick et al. 1999b;

Basri 2000). With a spectral type of  $L4.5 \pm 1.5$ , HR 7672B lies at or below this boundary. A useful point of comparison is GD 165B, which has a spectral type of L4 and an age estimate of 1.2–5.5 Gyr from its primary star. A detailed analysis by Kirkpatrick et al. (1999a) finds that GD 165B is probably a brown dwarf. Detecting lithium absorption in HR 7672B would be an unambiguous sign that the companion is substellar. However, given its small separation and large brightness difference ( $\Delta I \approx 13.5$  mag), this is unlikely to be feasible any time soon.

#### 3.2.2. From Radial Velocities

HR 7672 was included in the original Lick radial velocity survey and was found to have a long-term radial velocity trend (acceleration). We can use these data to determine the minimum possible companion mass strictly from dynamics. The primary’s radial acceleration is related to the companion mass by

$$M_{\text{comp}} = 5.34 \times 10^{-6} M_{\odot} \left( \frac{d}{\text{pc}} \frac{\rho}{\text{arcsec}} \right)^2 \times \left| \frac{\dot{v}_r}{\text{m s}^{-1} \text{ yr}^{-1}} \right| F(i, e, \omega, \phi), \quad (2)$$

where  $d$  is the distance to the primary from Earth,  $\rho$  is the observed angular separation of the companion, and  $\dot{v}_r$  is the radial acceleration (Torres 1999). The function  $F(i, e, \omega, \phi)$  is a function that depends on the orbital parameters (inclination  $i$ , eccentricity  $e$ , longitude of periastron  $\omega$ , and orbital phase  $\phi$ ) and has a minimum value of  $\sqrt{27}/2$ . From the original Lick radial velocity survey, Cumming, Marcy, & Butler (1999) reported a long-term radial velocity trend (acceleration) of  $-24 \pm 0.6 \text{ m s}^{-1} \text{ yr}^{-1}$  over 11.4 yr. This

gives a minimum companion mass of  $66 \pm 2 M_J$  (but see below).

As discussed by Torres (1999), it is possible to evaluate the companion mass in a statistical fashion given the observed acceleration and angular separation at a single epoch. Basically, the approach is to generate a Monte Carlo realization of  $F(i, e, \omega, \phi)$  by choosing randomly distributed values for the orbital parameters. The resulting probability distribution function (PDF) can be used to set statistical upper limits on the companion mass. (Note that the PDF has a long tail at high masses, which arises from highly improbable orbits. We adopt an upper mass cutoff of  $1 M_\odot$  based on physical plausibility and then renormalize the PDF.) Applying this technique to HR 7672B, we find a maximum companion mass of  $0.11 M_\odot$  at the 68% confidence limit ( $1 \sigma$ ), a relatively weak constraint. Note that the most probable companion mass from this approach is the same as the minimum possible mass based on the observed  $\dot{v}_r$  and  $\rho$ , namely  $66 M_J$ .

The approach of Torres (eq. [2]) makes use of the instantaneous radial velocity slope,  $\dot{v}_r$ . However we have radial velocity measurements from the last 13 yr. This duration places a better constraint on the orbit, given the difficulty of accurately measuring the instantaneous slope. In particular, the velocity slope at the current epoch may be slightly different from the average slope during the entire monitoring, which is what is listed in Cumming et al. (1999).

To find the most accurate minimum companion mass, we constructed a family of orbits that fit both the radial velocity data and the observed separation of  $0''.79$ . Note that with only two observables, namely, the separation and velocity slope, no unique orbit can be established. Nonetheless, we searched the orbital parameters for the lowest possible companion mass consistent with the data. For these minimum mass orbits, the instantaneous slope in the radial velocities was typically 25% less than the average during the past 13 yr. Such orbits imply a 25% lower mass for the companion, as given by equation (2). This difference can be seen in the plotted velocities (Fig. 5), as the most recent data indicate a slight flattening in the velocities.

One such minimum mass orbit is shown in Figure 5. The companion has mass of  $48 M_J$  with a 100 yr orbital period, a

semimajor axis of 21 AU, an eccentricity of 0.3, and an inclination of  $51^\circ$ . This hypothetical orbit fits the measured radial velocities of the primary within errors, and it would place the companion at a separation of  $0''.79$  at the current epoch, as observed. No orbits are consistent with a companion mass less than  $48 M_J$ . Therefore, we conclude that HR 7672B has a mass of at least  $48 M_J$ .

### 3.2.3. From Age of the Primary

We can also estimate the companion mass by determining the age of the primary. Assuming that the system is coeval, we can then use the measured temperature of HR 7672B with theoretical models to estimate its mass. Main-sequence G stars can be age-dated using a variety of indicators, many of which are based on the anticorrelation of stellar activity with age. None of these indicators are perfectly correlated with the age of the star (for reasons which remain to be understood), but all follow general trends.

1. *Absolute V-band magnitude.*—With  $M_V = 4.56$ , the primary is on the main sequence, which sets an age greater than the zero-age main sequence,  $\approx 100$  Myr.

2. *Rotation period.*—The rotation of solar-type stars is believed to increase as they age in a power-law fashion,  $P_{\text{rot}} \sim t^\alpha$ . The value for  $\alpha$  has been suggested to be 0.5 (Skumanich 1972) or  $1/e$  (Walter & Berry 1991). Messina, Rodoná, & Guinan (2001) measure a photometric period of 13.95 days for HR 7672, which we adopt as the stellar rotation period. Taking the Sun as a reference point ( $P_{\text{rot}} = 26$  days and  $t = 4.6$  Gyr) gives an age of 0.9–1.4 Gyr. Lachaume et al. (1999) have also provided a calibration of this relation using a sample from the *Hipparcos* catalog:

$$\log(t) = 2.667 \log(P) - 0.944(B - V) - 0.309[\text{Fe}/\text{H}] + 6.530, \quad (3)$$

where  $t$  is the age in Gyr and  $P$  is the period in days. For HR 7672,  $B - V = 0.60$  (Baliunas et al. 1995) and  $[\text{Fe}/\text{H}] = -0.07$  (Gorgas et al. 1999), so we find an age of 1.1 Gyr.

3. *X-ray emission.*—Related to the decline in stellar rotation, the X-ray emission of solar analogs declines with age.

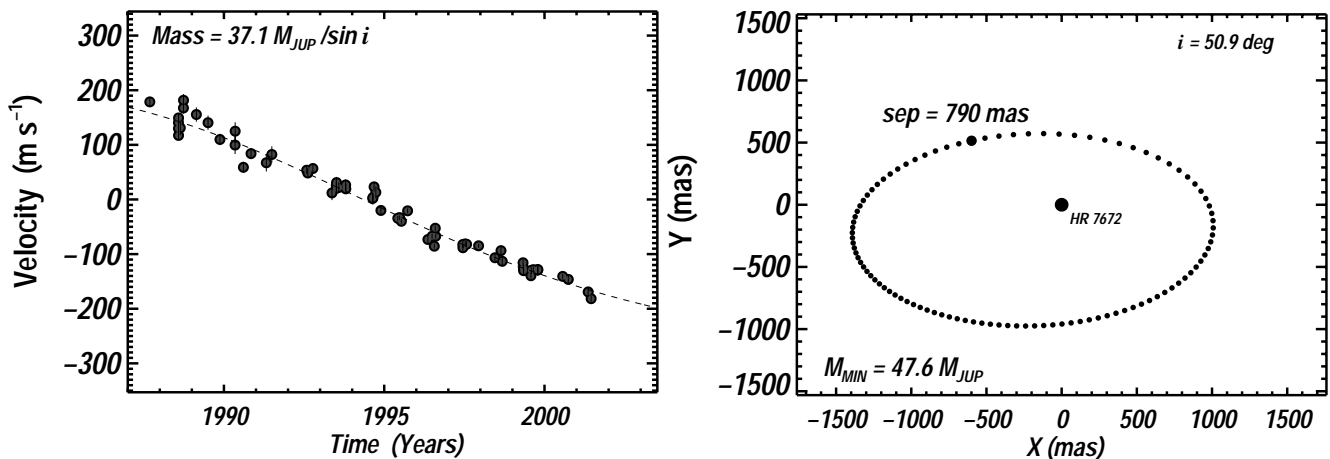


Fig. 5.—One plausible orbit for HR 7672B, of the many possible ones, which is consistent with the radial velocity and AO data. This orbit implies a minimum mass for the companion of  $48 M_J$  and has a period of 100 yr, eccentricity of 0.3, and inclination of  $51^\circ$ . *Left*: Measured velocities (dots) and the velocity curve of the plausible orbit (dashed line). *Right*: The same orbit but showing the motion of the companion in the plane of the sky relative to the primary, yielding a separation of  $0''.79$  at the current epoch, as observed. Orientation on the sky is arbitrary.

Hempelmann et al. (1995) measured  $\log(L_X/L_{\text{bol}}) = -5.54$  from *ROSAT* data. Gaidos (1998) provides an age calibration based on scaling relations for stellar activity,

$$\log(L_X/L_{\text{bol}}) = -6.38 - 2.6\alpha \log(t/4.6) + \log[1 + 0.4(1 - t/4.6)], \quad (4)$$

where  $t$  is the age in Gyr and  $\alpha$  is the same as given above. We have adopted the zero point of  $-6.38$  from Maggio et al. (1987). This gives an age of 0.8–1.3 Gyr.

4. *Ca H+K emission*.—Chromospheric activity also decreases with age. From Keck spectroscopy in 1997, we measured  $\log(R'_{\text{HK}}) = -4.79$  for the primary. As cited by Kirkpatrick et al. (2001), Donahue (1993, 1998) provide an age calibration for this index:

$$\log(t) = 10.725 - 1.334R_5 + 0.4085R_5^2 - 0.0522R_5^3, \quad (5)$$

where  $R_5 = 10^5 R'_{\text{HK}}$ . This gives an age of 2.6 Gyr.

5. *Kinematics*.—Older stars tend to have higher space velocities because of an accumulated history of dynamical interactions. The Gliese & Jahreiss (1991) catalog lists  $U = +40$ ,  $V = -19$ ,  $W = +9$  km s $^{-1}$  for HR 7672. This lies outside the young disk population defined by Leggett (1992).<sup>5</sup> Eggen (1989) has approximated the division between old and young disk stars at  $\sim 1.5$  Gyr.

6. *Lithium absorption*.—Li is steadily burned in main-sequence stars with convective envelopes. Soderblom (1985) measured a lithium abundance of  $N(\text{Li}) = 2.15$ . This is weaker than Hyades stars of the same spectral type (Thorburn et al. 1993; Soderblom et al. 1993), which sets a lower limit of  $\sim 600$  Myr on the age of the primary. Also, the abundance is more than early-type G stars in the  $\sim 4.5$  Gyr open cluster M67 (Jones, Fischer, & Soderblom 1999).

To summarize, HR 7672 exhibits a higher level of chromospheric activity than the Sun, pointing to a younger age. The primary's kinematics suggest that it is an old disk star, while the lithium abundance points to an age greater than Hyades stars. The star's rotation period, Ca H+K emission,

<sup>5</sup> Note that the Gliese & Jahreiss catalog and Leggett use the opposite sign conventions for  $U$ .

and X-ray emission suggest ages of 1–3 Gyr, which we adopt as a conservative age range for the primary.

Assuming that the system is coeval, we estimate the mass of HR 7672B using theoretical models (Fig. 6). With an implied range of 55–78  $M_J$ , the companion most likely lies below the minimum H-burning mass. (Note that we can also reverse the comparison and use the radial velocity limit of 48  $M_J$  with the models to find a lower limit of  $\sim 0.3$ –0.7 Gyr on the age of the primary, consistent with the observational properties described above.) This mass estimate could be improved in the future by obtaining multiband near-IR spectra to improve the spectral typing.

#### 4. CONCLUSIONS

We have found a common proper motion companion to the nearby solar analog HR 7672 using AO imaging from the Gemini and Keck telescopes. IR spectra from Keck AO+NIRSPEC find that the companion has a very cool atmosphere, and its faint  $K$ -band magnitude also points to a very late-type object: we estimate a spectral type of L4.5 with an uncertainty of  $\pm 1.5$  subclasses. This alone suggests that the companion is substellar, or right at the substellar boundary. A variety of data indicate that the primary star is younger than the Sun but older than the Hyades, with a likely age around 1–3 Gyr. Using theoretical models for cooling of very low mass objects, the inferred companion mass ranges from 55 to 78  $M_J$ , under the assumption that the two components are coeval. The primary has a long-term radial velocity acceleration, and we combine the radial velocity and AO data to set a lower limit of 48  $M_J$  on the companion mass strictly from dynamical considerations. At a separation of only  $0''.79$  (14 AU), this is the closest ultra-cool (L or T dwarf) companion to a main-sequence star found to date by direct imaging, in both angular and physical separation (see compilation in Reid et al. 2001b).

For a random distribution of orbital eccentricities,  $\approx 85\%$  of orbits have a true semimajor axis that is 0.5–2 times that of the observed separation. Hence, the semimajor axis of HR 7672B is likely to be 7–28 AU, meaning an orbital period of 20–150 yr. Orbital motion could be detectable in a few years. This raises the possibility of determining its orbi-

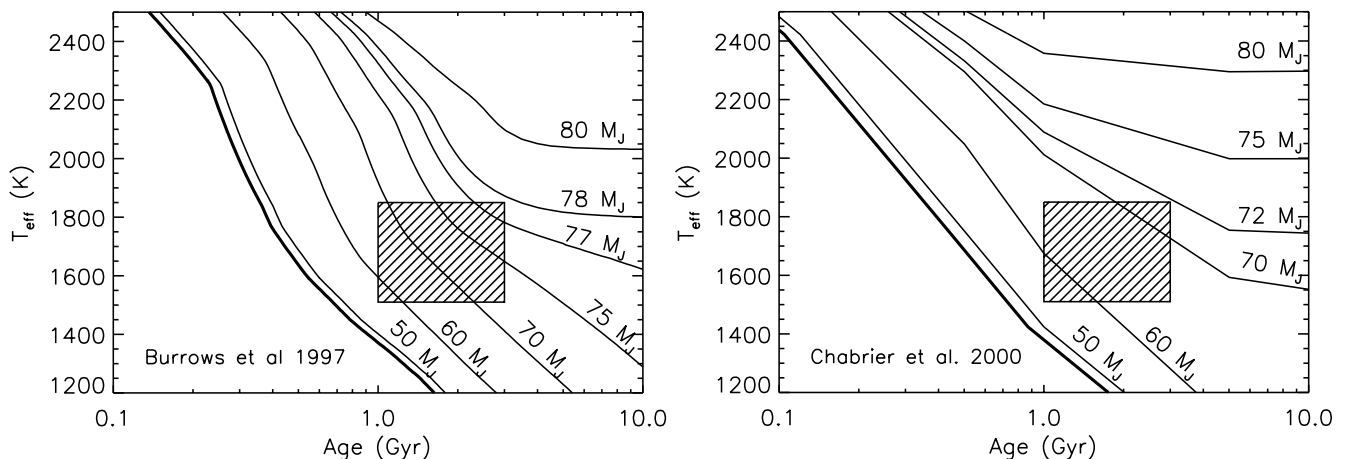


FIG. 6.—Mass determination for HR 7672B based on theoretical models from Burrows et al. (1997) and Chabrier et al. (2000). The hatched region indicates the observational constraints, a combination of the age of the primary and the spectral type of the companion. The inferred mass ranges from 55 to 78  $M_J$ . The heavy line represents the model-independent lower limit of 48  $M_J$  from the radial velocity and AO data.

tal eccentricity, perhaps an important clue to its formation history. Furthermore, the combination of AO imaging with continued radial velocity monitoring can be used to better constrain the companion mass in advance of observing a full orbital period.

The formation and presence of close brown dwarf companions might inhibit the formation of circumstellar disks, and hence planets. Using radial velocity data, Cumming et al. (1999) set upper limits on any planetary companion of 0.1–10  $M_J$  at separations of 0.1–4 AU, respectively. Hence, we know that the HR 7672 system does not have any Jovian mass planets in its inner regions. However, we know from the case of GL 86 that at least one brown dwarf coexists with an extrasolar planet (Els et al. 2001). The existence of HR 7672B and GL 86B indicates that brown dwarfs can form at separations comparable to circumstellar disks. (These objects are most likely substellar, or right at the substellar boundary. In the discussion that follows, we assume for the sake of argument that these are brown dwarfs.) A third possible example is the brown dwarf companion orbiting HD 168443 (Marcy et al. 2001), at a semimajor axis of 3 AU and with a mass between 17.2  $M_J$  (from the radial velocities) and 42  $M_J$  (from limits on any astrometric wobble). This system also illustrates the gradual convergence of radial velocities and AO imaging, closing the mass gap for discovery of planets and brown dwarfs by indirect and direct means.

Formation scenarios for HR 7672B, and their connection with those for extrasolar planets, remain an open question. Current semantic convention designates planets as object below  $\sim 15 M_J$ , with this border motivated either by the deuterium-burning limit for substellar objects or simply by the observed steep decline in frequency of such objects in radial velocity surveys (Marcy et al. 2001); more massive objects are considered brown dwarfs. HR 7672B would certainly be considered in the brown dwarf regime based on its estimated mass. Reipurth & Clarke (2001) have suggested that brown dwarfs form as stellar embryos in small newborn multiple systems: they grow in mass by accretion of infalling gas, but their growth is prematurely truncated by ejection due to dynamical interactions. The discovery of HR 7672B is at variance with this scenario, since the ejection model discounts the existence of close-separation brown dwarfs around solar-type stars.

An additional criterion to distinguish planets from brown dwarfs under consideration is whether the object forms “as planets do,” presumably in a circumstellar disk, or instead as an isolated object. In this regard, objects like HR 7672B and GL 86B are interesting in that they reside in the zone of giant planet formation, i.e.,  $\sim 5$ –30 AU, where we know giant planets exist in our own solar system and theoretical models can most easily form them. Giant planets are thought to form at these radii via gas accretion onto a rocky core. Subsequent dynamical processes may cause them to migrate to smaller radii (Lin, Bodenheimer, & Richardson 1996; Ward 1997; Trilling et al. 1998), since the  $\lesssim 4$  AU giant planets found by radial velocity surveys are not thought to have formed in situ.

However, brown dwarfs are believed to be too massive to form by the same core accretion scenario as giant planets. Instead, they may have originated, e.g., by fragmentation during initial cloud collapse (Bodenheimer 1998), by instabilities in a very massive disk (Boss 1998; Bryden et al. 2000; Pickett et al. 2000), or by collisions between protoplanetary disks (Lin et al. 1998). Furthermore, brown dwarf companions are not found at small separations, but we now have strong evidence that they exist at  $\sim 15$  AU. This suggests that they are immune to the migration process(es) that affect massive planets. The discovery of brown dwarfs in the zone of giant planet formation implies that a diversity of physical processes act to populate the outer regions of exoplanetary systems.

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