

**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 mags. Using follow-up *K*-band spectroscopy from Keck AO+NIRSPEC, we measure a spectral type of $L4.5 \pm 1.5$. This is the closest ultracool companion around a main sequence star found to date by direct imaging. We estimate the primary has an age of 1–3 Gyr. Assuming coevality, the companion is most likely substellar, with a mass of 55–78 M_{Jup} 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_{Jup} . 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 where 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.

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

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_{Jup} . In contrast, the same surveys find the incidence of more massive substellar companions (15–80 M_{Jup}) 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 1980’s and early 90’s (Campbell et al. 1988; Marcy & Benitz 1989; Walker et al. 1995). Their modest precisions (~ 300 m/s) were sufficient to detect brown dwarfs inside 3 AU, but only a single candidate was found.² Current high-precision (~ 3 m/s) radial velocity programs have identified about a dozen close companions with $M \sin i = 15 - 60 M_{Jup}$ (Mayor et al. 1997). However, the majority of these have been found by *Hipparcos* to be unresolved 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 et al. 2000; Liu 2001).

An unanswered observational question is whether the brown dwarf desert exists at $\gtrsim 3$ 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 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 ≈ 3 –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

²This object was the companion to HD 114762 with $M \sin i = 11 M_{Jup}$ (Latham et al. 1989). The primary star is likely seen pole-on so its companion was believed to be stellar (Cochran et al. 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 mis-aligned with the companion orbital axis (Patience et al. 2001). Hence, HD 114762B may in fact be a substellar companion.

systems. 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 the implications for understanding the planetary formation processes, 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 at any time in its history, its age and mass are degenerate for a given spectral type — young lower mass BDs can have same temperature as older higher mass BDs. By finding brown dwarf companions to main sequence stars, we can break this degeneracy by measuring the age of the primary and assuming 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 G1V. 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 24 June 2001 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 ± 0.08 mas pixel⁻¹. Conditions were non-photometric with variable transmission due to

patchy cloud cover. We obtained data in the K' -band filter (1.9–2.3 μm ; 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.³

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 22 Aug and 10 Dec 2001 UT. We used the slit-viewing camera of the facility near-IR spectrograph NIRSPEC (McLean et al. 1998) and a narrow-band $\text{Br}\gamma$ filter (2.155–2.175 μm). The camera has a pixel scale of 16.74 ± 0.05 mas pixel⁻¹. 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, though the astrometric measurements are actually done on the individual images. Figure 1 shows the Gemini AO discovery image.

To determine the separation and position angle 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 Aug 2001 data to measure a 2.16 μm flux ratio of 8.62 ± 0.07 mags.

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 of $0''.1$ – $0''.2$ 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

³We 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 02 August 1999 UT showed sources at $(d, \text{PA}) = (10''.0, 142^\circ)$, $(7''.9, 178^\circ)$, and $(5''.6, 256^\circ)$, all around 8–10 mags fainter than the primary. All three are detected in the Gemini AO image and are found to be background objects.

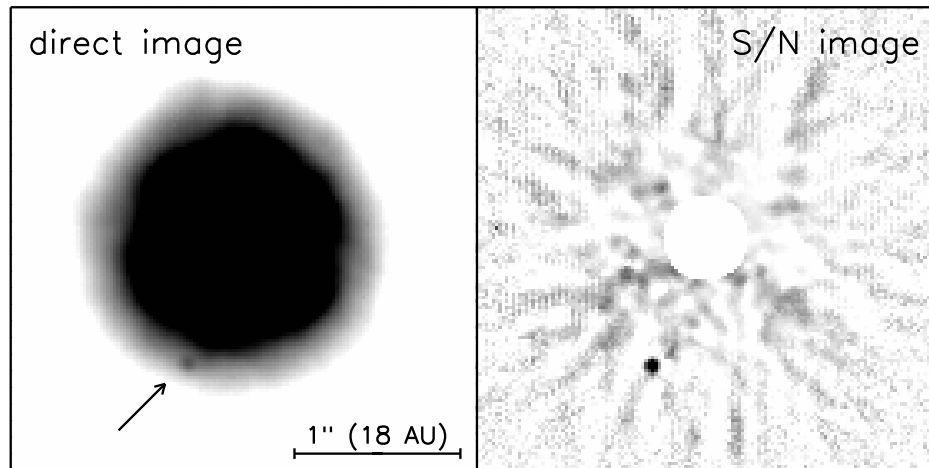


Fig. 1.— *Left*: K' -band discovery image of HR 7672B from Gemini-North AO. The companion is seen as a faint object in the halo of the primary. The orientation is as on the sky, North up and East left. *Right*: S/N image of the same data, constructed by unsharp masking the original data and then dividing 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.

centroid. We then averaged the results to get the separation and PA. We verified that these results are robust by (1) doing the measurements with several different 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, $(-394.07, -406.42) \pm (0.63, 0.64)$ mas/yr, allowing us to confirm if 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 PA would have changed significantly. The observed separation and PA are 7σ and 26σ 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 datasets alone indicate the companion is not a background object; since these both came from Keck AO+NIRSPEC using the Br γ filter, this eliminates any concern about systematic error due to using different instruments. Hence we conclude HR 7672B is physically associated with HR 7672.

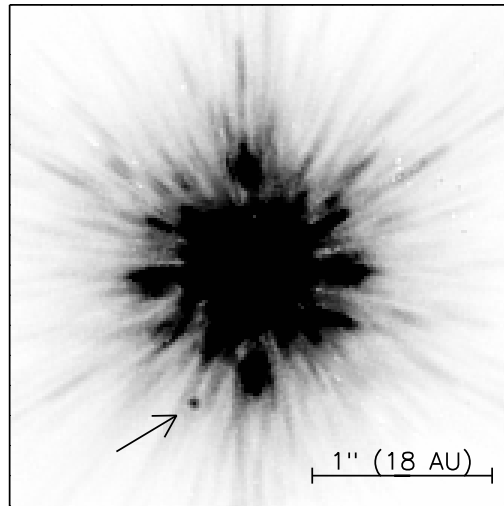


Fig. 2.— *K*-band image of HR 7672B obtained with Keck AO. The color scale is linear, and the image is the same size and orientation as in Figure 1.

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 31 Aug 2001 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 A0V 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 direction. 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 fit for the contamination using pixels above and below the companion spectrum. This amounted to $\approx 30\%$ of the light in the extraction aperture.

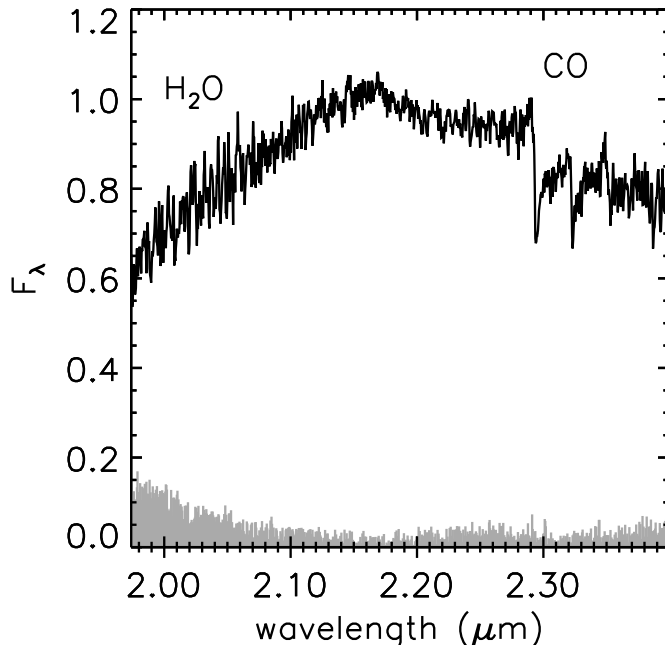


Fig. 3.— *K*-band spectrum for HR 7672B obtained with Keck AO+NIRSPEC. The spectrum has been scaled to an arbitrary constant. The lines at the bottom are the 1σ errors as determined from the scatter in the individually extracted spectra. The companion shows strong H₂O absorption on the blue side and strong CO absorption in the red.

To calibrate for the relative throughput of the atmosphere and instrument, we divided the extracted spectra by the spectra of the A0V calibrator star and then multiplied by a 9720 K blackbody to restore the true shape of the continuum. For this, we interpolated over the intrinsic Br γ 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 1σ 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. (2001), Leggett et al. (2001), and Reid et al. (2001a); hereinafter, we refer to this compilation as the “calibration sample.” For the L dwarfs, we use the spectral types assigned by Geballe et al. (2001), 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 H₂O and a strong CO 2.3 μm break. These are characteristic of very late-type M dwarfs and L dwarfs. In addition, no absorption is seen in 2.2 μm 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 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 could be due to heterogeneity in time variability, photospheric dust properties, and/or surface gravities. Hence, a qualitative (eyeball) 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 which measure H₂O absorption on the blue side of the bandpass (H₂O-C from Burgasser et al., and H₂O(2.0) from Geballe et al.), an index which tracks the slope of the 2.1–2.3 μm continuum (CH₄(2.2) from Geballe et al.)⁴, and a CO bandhead index of our own construction (R_{CO} = the ratio of 2.30–2.32 μm flux to 2.26–2.28 μm 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 H₂O absorption suggests a spectral type later than L2, while the continuum CH₄ 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 μm) absolute magnitude:

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

where *subclass* = −1 for M9V, 0 for L0V, 1 for L1V, etc. The scatter about the fit is ≈1 subtype. HR 7672 has a *V*-band magnitude of 5.80 mag, a distance of 17.7 pc, and a spectral type of G1V. Using *V* − *K* colors for dwarfs from Bessell & Brett (1988), this means 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 μm flux ratio of 8.6 mags. We use synthetic photometry of the calibration sample to find that $(K_S - [\text{Br}\gamma]) \approx 0.05 - 0.10$ mags for L dwarfs, so the companion has $M_{K_S} = 11.8 \pm 0.1$ mags, 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.

⁴This index is primarily designed to track the depth of 2.2 μm absorption in T dwarfs due to CH₄. However, it is also a reasonable diagnostic for L dwarfs, as discussed by Geballe et al.

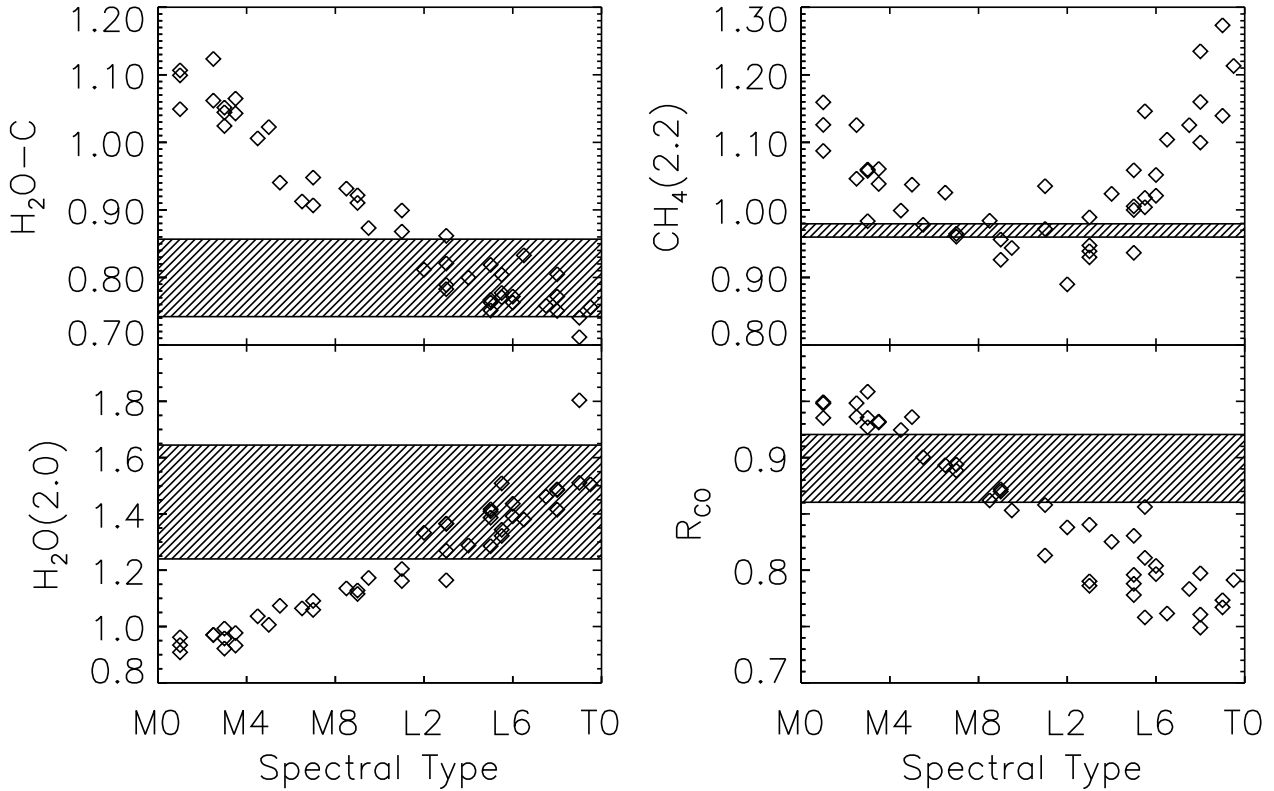


Fig. 4.— Spectral classification of HR 7672B based on molecular spectral indices for very cool atmospheres (see § 3 for references). The diamonds are objects from the literature with known spectral types. The hatched bands represent the HR 7672B measurements. The indices on the left trace the increasing H_2O absorption at the blue edge of the bandpass; these indicate 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.

We adopt a final spectral type of $\text{L}4.5 \pm 1.5$. This is based on the intersection of the results from the spectral indices, which suggest L2 to L6, and the K -band absolute magnitude, which points to L4 to L6. The spectral typing (and hence the mass estimate) could be improved in the future by obtaining spectra in the H -band and J -band; the latter would require good seeing conditions given the currently available AO systems on >8 -m telescopes. To convert to effective temperature, we use the scale produced by Burgasser et al. (2001), which is intermediate between those proposed by Kirkpatrick et al. (1999b, 2000) and Basri et al. (2000). This choice gives $T_{\text{eff}} = 1510 - 1850$ 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 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 this data to determine the minimum possible companion mass strictly from dynamics. The primary’s radial acceleration is related to the companion mass by

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

where d is the distance to the primary from Earth, ρ is the observed angular separation of the companion, and \dot{v}_r is the radial acceleration (Torres 1999). $F(i, e, \omega, \phi)$ is a function which depends on the orbital parameters (inclination i , eccentricity e , longitude of periastron ω , and orbital phase ϕ) and has a minimum value of $\sqrt{27}/2$. From the original Lick radial velocity survey, Cumming et al. (1999) reported a long-term radial velocity trend (acceleration) of -24 ± 0.6 m s⁻¹ yr⁻¹ over 11.4 yrs. This gives a minimum companion mass of $66 \pm 2 M_{Jup}$ (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 re-normalize the PDF.) Applying this technique to HR 7672B, we find a maximum companion mass of $0.11 M_{\odot}$ at the 68% confidence limit (1σ), 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 ρ , namely $66 M_{Jup}$.

The approach of Torres (Eqn. 2) makes use of the instantaneous radial velocity slope, \dot{v}_r . However we have radial velocity measurements from the last 13 years. This duration places a

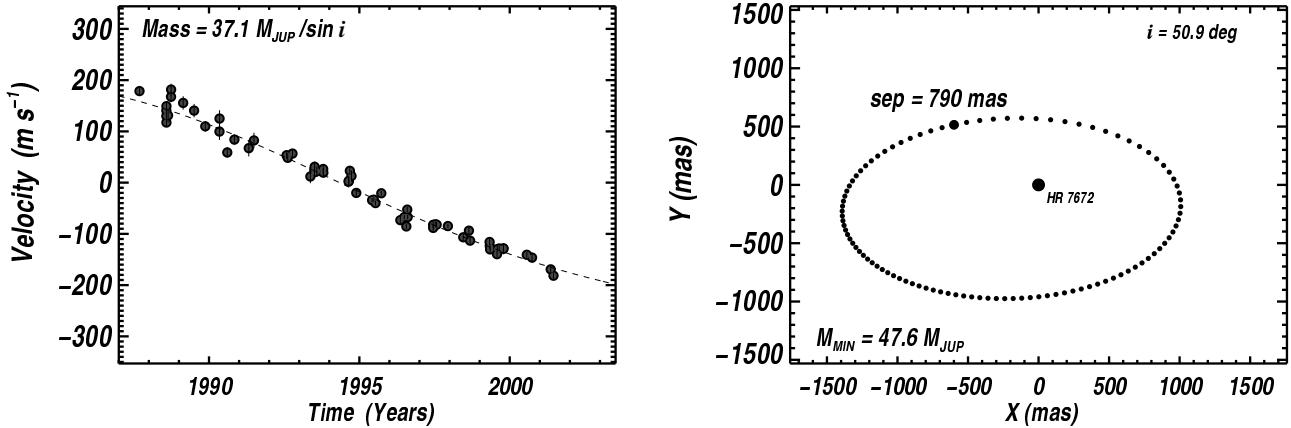


Fig. 5.— One plausible orbit for HR 7672B, of the many possible ones, which is consistent with the radial velocity and AO data. This orbit implies a minimum mass for the companion of $48 M_{Jup}$ and has a period of 100 yr, eccentricity of 0.3, and inclination of 51° . *Left*: Measured velocities (dots) and the velocity curve of the plausible orbit (dashes). *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.

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 than 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 years. Such orbits imply a 25% lower mass for the companion, as given by Eqn. 2. This difference can be seen in the plotted velocities (Figure 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 $48 M_{Jup}$ with a 100 yr orbital period, a semi-major axis of 21 AU, an eccentricity of 0.3, and an inclination of 51° . 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 $48 M_{Jup}$. Therefore we conclude that HR 7672B has a mass of at least $48 M_{Jup}$.

3.2.3. From Age of the Primary

We can also estimate the companion mass by determining the age of the primary. Assuming 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 anti-correlation 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, ≈ 100 Myr.
2. Rotation period: The rotation of solar-type stars is believed to increase as they age in a power-law fashion, $P_{rot} \sim t^\alpha$. The value for α has been suggested to be 0.5 (Skumanich 1972) or $1/e$ (Walter & Berry 1991). Messina et al. (2001) measure a photometric period of 13.95 d for HR 7672, which we adopt as the stellar rotation period. Taking the Sun as a reference point ($P_{rot} = 26$ days and $t = 4.6$ Gyr) gives an age of 0.9–1.4 Gyr. Lachaume et al. (1999) also have 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. Hempelmann et al. (1995) measured $\log(L_X/L_{bol}) = -5.54$ from ROSAT data. Gaidos (1998) provides an age calibration based on scaling relations for stellar activity:

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

where t is the age in Gyr and α is the same as given above. We have adopted the zeropoint 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 $\log(R'_{HK}) = -4.79$ 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 $R_5 = 10^5 R'_{HK}$. This gives an age of 2.6 Gyr.

5. Kinematics: Older stars tend to have higher space velocities due to 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 just inside the young disk population defined by Leggett (1992).⁵ Eggen (1989) has approximated the division between old and young disk at ~ 1.5 Gyr.

⁵Note that the Gliese & Jahreiss catalog and Leggett use the opposite sign conventions for U .

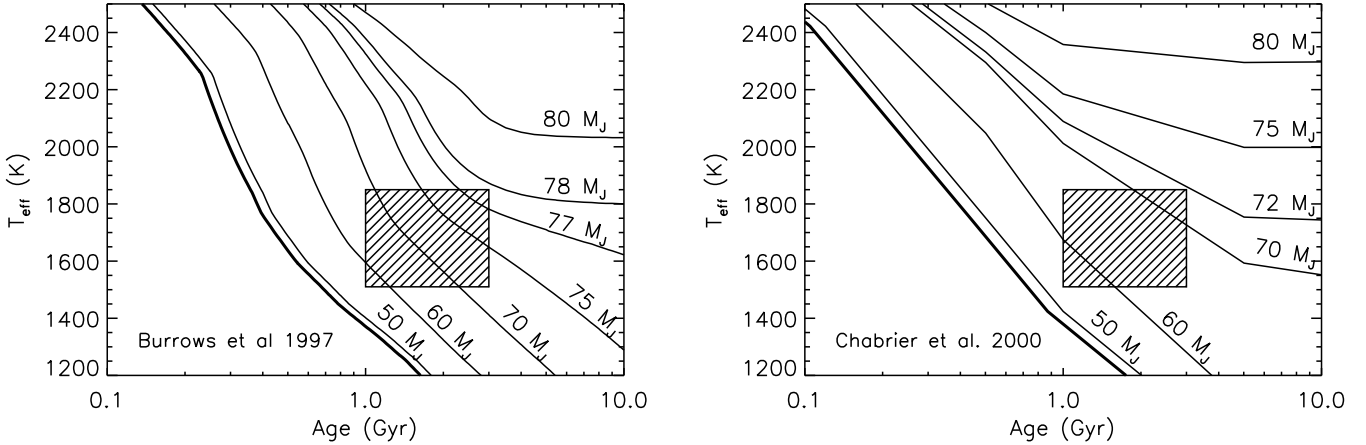


Fig. 6.— Mass determination for HR 7672B based on theoretical models from Burrows et al. (1997) and Chabrier et al. (2000). The hatched region indicates the observational constraints, a combination of the age of the primary and the spectral type of the companion. The inferred mass ranges from 55 to 78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

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 ~ 600 Myr on the age of the primary. Also, the abundance is more than early-type G stars in the ~ 4.5 Gyr open cluster M67 (Jones et al. 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 it is a young disk star, while the lithium abundance points to an age greater than Hyades stars. The star’s rotation period, Ca H+K emission, and X-ray emission suggest ages of 1–3 Gyr, which we adopt as a conservative age range for the primary.

Assuming the system is coeval, we estimate the mass of HR 7672B using theoretical models (Figure 6). With an implied range of 55–78 M_{Jup} , 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_{Jup} with the models to find a lower limit of ~ 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 multi-band 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

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 $L4.5\pm 1.5$. This alone suggests the companion is substellar, or right at the substellar boundary. A variety of data indicate 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 55–78 M_{Jup} , 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_{Jup} on the companion mass strictly from dynamical considerations. At a separation of only $0''.79$ (14 AU), this is the closest ultracool (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 semi-major axis which is 0.5–2 times that of the observed separation. Hence the semi-major axis of HR 7672B is likely to be 7–28 AU, meaning an orbital period of 20–150 yrs. Orbital motion could be detectable in a few years. This raises the possibility of determining its orbital eccentricity, perhaps a important clue into 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_{Jup} at separations of 0.1–4 AU, respectively. Hence, we know 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 co-exists 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 which 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 semi-major axis of 3 AU and with a mass between 17.2 M_{Jup} (from the radial velocities) and 42 M_{Jup} (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 ones for extrasolar planets, remain an open question. Current semantic convention designates planets as object below $\sim 15 M_{Jup}$, 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 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., $\sim 5\text{--}30$ 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 et al. 1996; Ward 1997; Trilling et al. 1998), since the $\lesssim 4$ AU 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 ~ 15 AU. This suggests they are immune to the migration process(es) which 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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REFERENCES

- Baliunas, S. L., Donahue, R. A., Soon, W. H., Horne, J. H., Frazer, J., Woodard-Eklund, L., Bradford, M., Rao, L. M., Wilson, O. C., Zhang, Q., Bennett, W., Briggs, J., Carroll, S. M., Duncan, D. K., Figueroa, D., Lanning, H. H., Misch, T., Mueller, J., Noyes, R. W., Poppe, D., Porter, A. C., Robinson, C. R., Russell, J., Shelton, J. C., Soyumer, T., Vaughan, A. H., & Whitney, J. H. 1995, *ApJ*, 438, 269
- Basri, G. 2000, *ARA&A*, 38, 485
- Basri, G., Mohanty, S., Allard, F., Hauschildt, P. H., Delfosse, X., Martín, E. L., Forveille, T., & Goldman, B. 2000, *ApJ*, 538, 363
- Bauman, B. J., Gavel, D. T., Waltjen, K. E., Freeze, G. J., Keahi, K. A., Kuklo, T. C., Lopes, S. K., Newman, M. J., & Olivier, S. S. 1999, in *Proc. SPIE Vol. 3762*, p. 194-200, *Adaptive Optics Systems and Technology*, Robert K. Tyson; Robert Q. Fugate; Eds., Vol. 3762, 194–200
- Bessell, M. S. & Brett, J. M. 1988, *PASP*, 100, 1134
- Bodenheimer, P. 1998, in *ASP Conf. Ser. 134: Brown Dwarfs and Extrasolar Planets*, 115
- Boss, A. P. 1998, *ApJ*, 503, 923
- Bouvier, J., Stauffer, J. R., Martin, E. L., Barrado y Navascues, D., Wallace, B., & Bejar, V. J. S. 1998, *A&A*, 336, 490
- Bryden, G., Różyczka, M., Lin, D. N. C., & Bodenheimer, P. 2000, *ApJ*, 540, 1091
- Burgasser, A. J., Kirkpatrick, J. D., Cutri, R. M., McCallon, H., Kopan, G., Gizis, J. E., Liebert, J., Reid, I. N., Brown, M. E., Monet, D. G., Dahn, C. C., Beichman, C. A., & Skrutskie, M. F. 2000, *ApJ*, 531, L57
- Burgasser, A. J. et al. 2001, *ApJ*, in press (astro-ph/0108452)
- Burrows, A., Marley, M., Hubbard, W. B., Lunine, J. I., Guillot, T., Saumon, D., Freedman, R., Sudarsky, D., & Sharp, C. 1997, *ApJ*, 491, 856
- Campbell, B., Walker, G. A. H., & Yang, S. 1988, *ApJ*, 331, 902
- Cayrel de Strobel, G. 1996, *A&A Rev.*, 7, 243
- Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, *ApJ*, 542, 464
- Cochran, W. D., Hatzes, A. P., & Hancock, T. J. 1991, *ApJ*, 380, L35
- Cumming, A., Marcy, G. W., & Butler, R. P. 1999, *ApJ*, 526, 890
- Donahue, R. A. 1993, PhD thesis, New Mexico State University

- Donahue, R. A. 1998, in ASP Conf. Ser. 154: Cool Stars, Stellar Systems, and the Sun, Vol. 10, 1235
- Eggen, O. J. 1989, PASP, 101, 366
- Els, S. G., Sterzik, M. F., Marchis, F., Pantin, E., Endl, M., & Kurster, M. 2001, A&A, in press
- Fischer, D. A., Marcy, G. W., Butler, R. P., Vogt, S. S., Frink, S., & Apps, K. 2001, ApJ, 551, 1107
- Gaidos, E. J. 1998, PASP, 110, 1259
- Geballe, T. et al. 2001, ApJ, in press (astro-ph/0108443)
- Gizis, J. E., Kirkpatrick, J. D., Burgasser, A., Reid, I. N., Monet, D. G., Liebert, J., & Wilson, J. C. 2001, ApJ, 551, L163
- Gliese, W. & Jahreiss, H. 1991, in Nearby Stars, Preliminary 3rd Version (1991), 0
- Gorgas, J., Cardiel, N., Pedraz, S., & González, J. J. 1999, A&AS, 139, 29
- Graves, J. E., Northcott, M. J., Roddier, F. J., Roddier, C. A., & Close, L. M. 1998, Proc. SPIE, 3353, 34
- Halbwachs, J. L., Arenou, F., Mayor, M., Udry, S., & Queloz, D. 2000, A&A, 355, 581
- Hempelmann, A., Schmitt, J. H. M. M., Schultz, M., Ruediger, G., & Stepien, K. 1995, A&A, 294, 515
- Jones, B. F., Fischer, D., & Soderblom, D. R. 1999, AJ, 117, 330
- Jones, H. R. A., Longmore, A. J., Jameson, R. F., & Mountain, C. M. 1994, MNRAS, 267, 413
- Kirkpatrick, J. D., Allard, F., Bida, T., Zuckerman, B., Becklin, E. E., Chabrier, G., & Baraffe, I. 1999a, ApJ, 519, 834
- Kirkpatrick, J. D., Dahn, C. C., Monet, D. G., Reid, I. N., Gizis, J. E., Liebert, J., & Burgasser, A. J. 2001, AJ, 121, 3235
- Kirkpatrick, J. D., Reid, I. N., Liebert, J., Cutri, R. M., Nelson, B., Beichman, C. A., Dahn, C. C., Monet, D. G., Gizis, J. E., & Skrutskie, M. F. 1999b, ApJ, 519, 802
- Kirkpatrick, J. D., Reid, I. N., Liebert, J., Gizis, J. E., Burgasser, A. J., Monet, D. G., Dahn, C. C., Nelson, B., & Williams, R. J. 2000, AJ, 120, 447
- Lachaume, R., Dominik, C., Lanz, T., & Habing, H. J. 1999, A&A, 348, 897
- Latham, D. W., Stefanik, R. P., Mazeh, T., Mayor, M., & Burki, G. 1989, Nature, 339, 38

- Leggett, S. K. 1992, *ApJS*, 82, 351
- Leggett, S. K., Allard, F., Dahn, C., Hauschildt, P. H., Kerr, T. H., & Rayner, J. 2000, *ApJ*, 535, 965
- Leggett, S. K., Allard, F., Geballe, T. R., Hauschildt, P. H., & Schweitzer, A. 2001, *ApJ*, 548, 908
- Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, *Nature*, 380, 606
- Lin, D. N. C., Laughlin, G., Bodenheimer, P., & Rozyczka, M. 1998, *Science*, 281, 2025
- Liu, M. C. 2001, in *Twelfth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ASP. Conf. Series, in press
- Lloyd, J. P., Liu, M. C., Macintosh, B. A., Sevenson, S. A., Deich, W. T., & Graham, J. R. 2000a, in *Proc. SPIE Vol. 4008, p. 814-821, Optical and IR Telescope Instrumentation and Detectors*, Masanori Iye; Alan F. Moorwood; Eds., Vol. 4008, 814–821
- Lloyd, J. P., Liu, M. C., et al. 2000b, in *Proceedings of IAU Symposium 202, "Planetary Systems in the Universe: Observation, Formation and Evolution"*, ed. A. Penny, P. Artymowicz, A.-M. Lagrange, & S. Russell, in press (astro-ph/0103027)
- Luhman, K. L., Rieke, G. H., Young, E. T., Cotera, A. S., Chen, H., Rieke, M. J., Schneider, G., & Thompson, R. I. 2000, *ApJ*, 540, 1016
- Maggio, A., Sciortino, S., Vaiana, G. S., Majer, P., Bookbinder, J., Golub, L., Harnden, F. R., & Rosner, R. 1987, *ApJ*, 315, 687
- Marcy, G. W. & Benitz, K. J. 1989, *ApJ*, 344, 441
- Marcy, G. W., Butler, R. P., Vogt, S. S., Liu, M. C., Laughlin, G., Apps, K., Graham, J. R., Lloyd, J., Luhman, K. L., & Jayawardhana, R. 2001, *ApJ*, 555, 418
- Mayor, M., Queloz, D., Udry, S., & Halbwachs, J. 1997, in *IAU Colloq. 161: Astronomical and Biochemical Origins and the Search for Life in the Universe*, 313
- McLean, I. S., Becklin, E. E., Bendiksen, O., Brims, G., Canfield, J., Figer, D. F., Graham, J. R., Hare, J., Lacayanga, F., Larkin, J. E., Larson, S. B., Levenson, N., Magnone, N., Teplitz, H., & Wong, W. 1998, in *Proc. SPIE Vol. 3354, p. 566-578, Infrared Astronomical Instrumentation*, Albert M. Fowler; Ed., Vol. 3354, 566–578
- Messina, S., Rodonò, M., & Guinan, E. F. 2001, *A&A*, 366, 215
- Najita, J. R., Tiede, G. P., & Carr, J. S. 2000, *ApJ*, 541, 977
- Ochsenbein, F., Bauer, P., & Marcout, J. 2000, *A&AS*, 143, 23
- Patience, J. et al. 2001, *ApJ*, submitted

- Pickett, B. K., Durisen, R. H., Cassen, P., & Mejia, A. C. 2000, *ApJ*, 540, L95
- Pickles, A. J. 1998, *PASP*, 110, 863
- Pourbaix, D. & Arenou, F. 2001, *A&A*, 372, 935
- Reid, I. N., Burgasser, A. J., Cruz, K. L., Kirkpatrick, J. D., & Gizis, J. E. 2001a, *AJ*, 121, 1710
- Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. W. 2001b, *AJ*, 121, 489
- Reid, I. N., Kirkpatrick, J. D., Liebert, J., Burrows, A., Gizis, J. E., Burgasser, A., Dahn, C. C., Monet, D., Cutri, R., Beichman, C. A., & Skrutskie, M. 1999, *ApJ*, 521, 613
- Reipurth, B. & Clarke, C. 2001, *AJ*, 122, 432
- Skumanich, A. 1972, *ApJ*, 171, 565
- Soderblom, D. R. 1985, *PASP*, 97, 54
- Soderblom, D. R., Jones, B. F., Balachandran, S., Stauffer, J. R., Duncan, D. K., Fedele, S. B., & Hudon, J. D. 1993, *AJ*, 106, 1059
- Thorburn, J. A., Hobbs, L. M., Deliyannis, C. P., & Pinsonneault, M. H. 1993, *ApJ*, 415, 150
- Torres, G. 1999, *PASP*, 111, 169
- Trilling, D. E., Benz, W., Guillot, T., Lunine, J. I., Hubbard, W. B., & Burrows, A. 1998, *ApJ*, 500, 428
- Wainscoat, R. J. & Cowie, L. L. 1992, *AJ*, 103, 332
- Walker, G. A. H., Walker, A. R., Irwin, A. W., Larson, A. M., Yang, S. L. S., & Richardson, D. C. 1995, *Icarus*, 116, 359
- Walter, F. M. & Berry, D. C. 1991, in *The Sun in Time*, ed. C. P. Sonett, M. S. Giampapa, & M. S. Matthews (Tucson: University of Arizona Press), 653
- Ward, W. R. 1997, *ApJ*, 482, L211
- Wilson, J. C., Kirkpatrick, J. D., Gizis, J. E., Skrutskie, M. F., Monet, D. G., & Houck, J. R. 2001, *ApJ*, in press (astro-ph/0108424)
- Wizinowich, P., Acton, D. S., Shelton, C., Stomski, P., Gathright, J., Ho, K., Lupton, W., Tsubota, K., Lai, O., Max, C., Brase, J., An, J., Avicola, K., Olivier, S., Gavel, D., Macintosh, B., Ghez, A., & Larkin, J. 2000, *PASP*, 112, 315
- Zucker, S. & Mazeh, T. 2001, *ApJ*, in press (astro-ph/0107124)

Table 1. HR 7672B Astrometry

Date (UT)	Telescope	sep (mas)	PA (°)	observed		if background object	
				Δ sep (mas)	Δ PA (°)	Δ sep (mas)	Δ PA (°)
2001 Jun 24	Gemini-N	795 ± 5	157.0 ± 0.2
2001 Aug 22	Keck II	786 ± 6	157.9 ± 0.5	-9 ± 8	0.9 ± 0.6	-31 ± 5	-6.3 ± 0.4
2001 Dec 10	Keck II	794 ± 5	157.3 ± 0.6	-1 ± 7	0.3 ± 0.7	-61 ± 5	-19.2 ± 0.3