

A COMBINED SUBARU/VLT/MMT 1–5 μm STUDY OF PLANETS ORBITING HR 8799: IMPLICATIONS FOR ATMOSPHERIC PROPERTIES, MASSES, AND FORMATION

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ABSTRACT

We present new 1–1.25 μm (z and J band) Subaru/IRCS and 2 μm (K band) VLT/NaCo data for HR 8799 and a re-reduction of the 3–5 μm MMT/Clio data first presented by Hinz et al. Our VLT/NaCo data yield a detection of a fourth planet at a projected separation of ~ 15 AU—“HR 8799e.” We also report new, albeit weak detections of HR 8799b at 1.03 μm and 3.3 μm . Empirical comparisons to field brown dwarfs show that at least HR 8799b and HR 8799c, and possibly HR 8799d, have near-to-mid-IR colors/magnitudes significantly discrepant from the L/T dwarf sequence. Standard cloud deck atmosphere models appropriate for brown dwarfs provide only (marginally) statistically meaningful fits to HR 8799b and c for physically implausible small radii. Models with thicker cloud layers not present in brown dwarfs reproduce the planets’ spectral energy distributions far more accurately and without the need for rescaling the planets’ radii. Our preliminary modeling suggests that HR 8799b has $\log(g) = 4\text{--}4.5$, $T_{\text{eff}} = 900$ K, while HR 8799c, d, and (by inference) e have $\log(g) = 4\text{--}4.5$, $T_{\text{eff}} = 1000\text{--}1200$ K. Combining results from planet evolution models and new dynamical stability limits implies that the masses of HR 8799b, c, d, and e are 6–7 M_J , 7–10 M_J , 7–10 M_J , and 7–10 M_J . “Patchy” cloud prescriptions may provide even better fits to the data and may lower the estimated surface gravities and masses. Finally, contrary to some recent claims, forming the HR 8799 planets by core accretion is still plausible, although such systems are likely rare.

Key words: brown dwarfs – instrumentation: adaptive optics – planetary systems – stars: individual (HR 8799) – techniques: image processing

Online-only material: color figures

1. INTRODUCTION

The HR 8799 planetary system is the first directly imaged multiplanetary system (Marois et al. 2008). Along with Fomalhaut and β Pic, it is also the only imaged system with companion mass ratios and separations reasonably close to the giant planets in the solar system (Kalas et al. 2008; Lagrange et al. 2009, 2010).¹⁰ After the initial detection of HR 8799bcd, one or more planets were recovered in prior data sets (Lafreniere et al. 2009; Fukagawa et al. 2009; Metchev et al. 2009). Recently, Marois et al. (2011) imaged a fourth planet—HR 8799e—which we independently detected (see Section 2).

Mass estimates based on cooling models yield 5–11 M_J for HR 8799b and 7–13 M_J for the other planets (Marois et al. 2008, 2011). Dynamical constraints placed by HR 8799bcd imply that the companions likely have masses below the deuterium-burning limit (Spiegel et al. 2011) and are kept stable by resonant interactions (Fabrycky & Murray-Clay 2010; Moro-Martín et al. 2010). Including the fourth planet, Marois et al. (2011) argue that the planets most likely have masses at the low end of the range allowed by cooling models. With masses of $\approx 5\text{--}13 M_J$, the HR 8799 planets then bridge the gap between the solar

system’s gas giants/Jupiter-mass planets detected by radial-velocity surveys (e.g., Howard et al. 2010) and low-mass brown dwarf companions to nearby stars such as GJ 758B and PZ Tel (Thalmann et al. 2009; Currie et al. 2010; Biller et al. 2010).

Recent studies complicate our understanding of the relationship between brown dwarfs, the gas giants detected in RV surveys, and the HR 8799 planets. The planets’ masses are significantly larger than most planets detected by radial velocity and transit methods. Marois et al. (2008) noted that the planets appear slightly redder than the distribution of $H/H - K_s$ colors for old field brown dwarfs. The K -band spectrum of HR 8799b is not well matched by typical L- and T-type brown dwarf spectra (Bowler et al. 2010).

Comparisons between the HR 8799 planet photometry/spectroscopy and atmosphere models reveal additional difficulties in understanding their properties within the theoretical framework of standard, cloud deck models that track the field L/T dwarf sequence. In the discovery paper, Marois et al. (2008) briefly mention a discrepancy between temperatures derived from atmosphere models and those estimated from more simple, and presumably most accurate, cooling model estimates. More recently, Bowler et al. (2010) provide a detailed comparison between the HR 8799b spectra and 1.1–4.1 μm photometry and predictions from standard atmosphere models. They show that the “best-fit” temperatures derived from modeling are

¹⁰ Here, we consider IRXJ1609.1-210524b discovered by Lafreniere et al. (2008) to be a more complicated case as its mass ratio and separation are continuous with brown dwarf companions (see Section 5).

Table 1
Observations

| Telescope/Instrument | Filter | Date | Exposure Time (s) | Field Rotation (degrees) | Detections |
|----------------------|--------|-------------------|-------------------|--------------------------|--------------------|
| MMT/CLIO | L' | 2008 November 21 | 5460 | 83.88 | b, c, d |
| | M | 2008 November 21 | 9600 | 31.8 | – |
| | [3.3] | 2009 September 12 | 6780 | 128.53 | b ^a , c |
| Subaru/IRCS | z | 2009 August 15 | 4200 | 172 | b ^a |
| | J | 2009 August 15 | 1080 | 7.4 | b |
| VLT/NaCo | K_s | 2009 October 8 | 6185 | 63 | b, c, d, e |

Note. ^a Companion has a low signal-to-noise detection because it is intrinsically faint (photon-noise-dominated region).

inconsistent with cooling model estimates. They also explicitly show that the implied radii for best-fit models are well below the 1.1–1.3 R_J range allowed by standard cooling models (e.g., 0.3–0.5 R_J).

To interpret these modeling difficulties, Bowler et al. (2010) argue that a different atmospheric structure, namely, atmospheres with stronger cloud coverage, may better explain the HR 8799b spectral energy distribution (SED). Since atmospheric dust entrained in clouds absorbs more efficiently at shorter wavelengths, photometry for HR 8799b at wavelengths shortward of J band would provide a crucial test of the planet’s level of cloud coverage (cf. Burrows et al. 2006). The Bowler et al. (2010) study also found difficulty in reconciling their model fitting of detections from Marois et al. (2008) with 3–5 μm upper limits from Hinz et al. (2010). More sensitive photometry at these wavelengths would then provide better modeling constraints.

In this study, we investigate the atmospheres and dynamics of the HR 8799 planets using new observations obtained at the Subaru Telescope and Very Large Telescope (VLT) and a re-reduction of MMT data presented by Hinz et al. (2010). Combined with photometry presented by Marois et al. (2008), our data yield nine photometric points spanning 1–5 μm for a detailed comparison to the properties of field brown dwarfs. This wavelength range also provides a sensitive probe of the effects of surface gravity, temperature, (non)equilibrium chemistry, metallicity, and cloud coverage.

We compare the planets’ SEDs to atmosphere models exploring a phase space defined by these effects. By quantifying the model fits, we determine the range of parameter space that fails to characterize the planets’ SEDs and identify the subset of models that more accurately reproduce the data and may better represent their atmospheres’ physical properties. These results will then be used to more thoroughly and accurately probe the planets’ atmospheric properties in a companion paper (Madhusudhan et al. 2011).

Our study is structured as follows. Section 2 describes our observations, image processing, and detections for each data set. The first part of Section 3 compares the HR 8799 planet photometry to the L/T dwarf sequence and the IR properties of other very low mass objects ($M < 25 M_J$). The rest of Section 3 presents preliminary comparisons between the HR 8799 planet SEDs and planetary atmosphere models. Section 4 describes simple dynamical modeling of the system to identify the range of masses for dynamically stable orbits. Section 5 summarizes our results, discusses our work within the context of previous studies of HR 8799 and planet imaging in general, discusses how our results fit within the context of planet evolution models, and comments on the plausible formation mechanism(s) for the planets.

2. DATA

2.1. Observations

Our study combines data from three facilities—VLT/NaCo, Subaru/IRCS, and MMT/Clio—at six broadband filters centered on 1.03–4.8 μm . The VLT data are the most sensitive and were obtained to place limits on the presence of other candidate planets in the system. The Subaru data at 1.03–1.25 μm were taken to probe the effect of clouds on the planets’ atmospheres. Finally, we rereduced the 3–5 μm MMT/Clio data first presented by Hinz et al. (2010) using our reduction pipeline, which utilizes advanced image registration, point-spread function (PSF) removal, speckle suppression, and flux calibration routines (e.g., localized combination of images (LOCI); Lafreniere et al. 2007a) also used in Marois et al. (2008).

All of our data were taken in angular differential imaging (ADI) mode (Marois et al. 2006), where the instrument rotator is adjusted to stay at a fixed angle with respect to the (changing) parallactic angle, resulting in the field of view rotating with time. Combined with the Marois et al. data, we thus have data spanning nine photometric filters that is largely reduced self-consistently. Table 1 summarizes basic properties of our observations.

2.1.1. VLT/NaCo K_s -band Data

HR 8799 was imaged with VLT/NaCo on six separate nights in 2009 October as a part of a separate study of the HR 8799 planets (PI: Daniel Apai; D. Apai et al. 2011, in preparation). Once publically available, the science and calibration data were downloaded from the ESO VLT archive for October 8–11, nights over which the field rotation for the HR 8799 data was $>30^\circ$ – 45° , resulting in a small ($r \sim 0''.22$) inner working angle.

The data were taken with the 13.27 mas pixel scale, without coronagraphic masks, and in pupil tracking mode allowing for ADI. All data consist of co-added 0.345 s exposures totaling ~ 43 s a piece and are stored in the standard NaCo datacube format. In this paper, we focus specifically on the October 8 data, which had the highest quality and greatest amount of field rotation. D. Apai et al. (2011, in preparation) will later present a larger study combining all 2009 October data and Fall 2010 data.

2.1.2. Subaru/IRCS $z(Y)$ and $-band$ Data

HR 8799 was targeted for direct imaging on 2009 August 15 with the Subaru Telescope using the Infrared Camera and Spectrograph (IRCS; Tokunaga et al. 1998) and AO-188 adaptive optics system in natural guide star mode. The data were taken in the Mauna Kea J -band filter ($\sim 1.25 \mu\text{m}$) and the z filter centered on 1.033 μm , analogous to the better-known Y -band filter

(e.g., Hillenbrand et al. 2002).¹¹ During our observations, conditions were photometric with fair natural seeing ($\sim 0''.65\text{--}0''.75$). AO-188 yielded a corrected image with FWHM(PSF) $\sim 0''.06$ in z and $0''.064$ in J . For all observations, the native pixel scale is 20.57 mas pixel⁻¹; we used the $0''.8$ diameter, non-transmissive coronagraphic mask to block most of the primary starlight.

The z data were taken using 30 s exposures consisting of six co-added frames to avoid saturation at separations corresponding to HR 8799bcd for a total integration time of 4500 s. The J -band data consist of 25 s co-added exposures for a total integration time of 1080 s. The z data were observed through transit yielding a total field rotation of 172° . The J data were taken about an hour after transit resulting in very poor field rotation ($\sim 6^\circ.4$).

2.1.3. MMT/Clio 3–5 μm Data

MMT/Clio observations were previously described by Hinz et al. (2010). Briefly, HR 8799 was imaged in three separate observing runs—2008 November 21, 2009 January 10, and 2009 September 12—at the L' ($3.8\ \mu\text{m}$) and Barr M ($4.8\ \mu\text{m}$) and a shorter wavelength filter centered on $3.3\ \mu\text{m}$ methane absorption feature and extending from $3.12\ \mu\text{m}$ to $3.53\ \mu\text{m}$. We focus on the 2008 November and 2009 September runs, which had sufficient field rotation for ADI. The pixel scale for all Clio data is 48.57 mas pixel⁻¹.

The [3.3], L' , and M data were imaged for 6780 s, 5690 s, and 9600 s: the total field rotation for data in these three filters was $125^\circ.3$, 72° , and $31^\circ.8$. While observing conditions for the L' and M data were clear, the [3.3] μm data were taken through variable seeing in two sets between which the AO system failed to yield an acceptable correction.

2.2. Image Processing/Data Reduction

2.2.1. Basic Image Processing and Image Registration

For our Subaru/IRCS and VLT/NaCo data, we first performed standard dark subtraction, flat fielding, and bad pixel masking. While the NaCo data followed a four-point dither pattern which should wash out image distortion errors, the IRCS data were not dithered. Thus, each IRCS frame was corrected for image distortion using polynomial fits, resulting in a revised pixel scale of 20.53 mas pixel⁻¹.

For the MMT/Clio data we then performed sky subtraction. We constructed Clio sky frames from median-combined images obtained for each nod position and subtracted to remove the sky background. Final pixel values for each VLT/NaCo image were nominally constructed from the average pixel value drawn from each frame in the datacube. For regions within $1''$ of estimated stellar centroid, we determined the average pixel value after iteratively clipping 5σ outliers. For all data sets, bad pixels were identified as outliers within a moving-box median filter, flagged, and interpolated over.

Our image registration procedure closely follows that of Lafreniere et al. (2007b) and Marois et al. (2008). We first copied each image into a larger blank one, coarsely registering them using a priori knowledge about the center of the coronagraphic

mask (for IRCS) or a Gaussian fit to a convolved version of the image using the IDL function `gcntrd.pro`. For precise image registration, we center one image using a two-dimensional cross-correlation function relating it to a 180° rotation of itself. We then identify the fractional pixel offsets between the reference image and subsequent images yielding the highest correlation. The region of interest used to register IRCS images is focused on diffracted light from the secondary spider. For the Clio and NaCo images, we used the non-saturated portions of the stellar PSF, since the diffracted light from the spider is highly suppressed.

2.2.2. Localized Combination of Images (LOCI) Speckle Suppression Processing

Further data reduction follows the ADI/LOCI reduction procedure described by Lafreniere et al. (2007a) and Marois et al. (2008). We first subtract out the time-independent component of the stellar PSF, exploring two methods. In the first method, we median combine all images for a reference PSF which we subtract from each image, the simple ADI method used by Hinz et al. (2010). In the second method, we construct a two-dimensional radial profile for each image and subtract it to remove the smooth seeing halo.

Next, we perform the LOCI speckle suppression algorithm on the residual images, derotate the processed images, and median combine them for a final science image. We compared reductions for a range of LOCI input parameters— dr , N_δ , N_a , and $geom$ (see Lafreniere et al. 2007a for definitions)—to identify the set that maximized the signal to noise of the planets, using the set recommended by Lafreniere et al. (2007a) as a starting point. Our pipeline also produces the simple ADI reduction (Hinz et al. 2006, 2010) as a byproduct, useful for a separate, sensitive identification of HR 8799b, whose detection in some filters (e.g., z , [3.3], M) may be more severely limited by photon noise than by speckle noise.

2.3. Planet Detections and Astrometry

To identify detected planets in our images, we compute the standard deviation and signal-to-noise ratio (S/N) of pixel values in concentric annuli (Currie et al. 2010; Thalmann et al. 2009). As a check on our results, we compare our astrometry for candidate detections in a given filter with that obtained by us in other filters and from Marois et al. (2008, 2011) during the Fall 2008 and 2009 epochs. We claim a detection of a planet independent of other data sets if $S/N > 5$. For $S/N = 3\text{--}5$, the centroid of the candidate planet detection must be the same as that reported for the planet data where $S/N > 5$ within astrometric errors (typically 0.5 pixels). We centroid the planet using the IDL functions `gcntrd.pro` and `cntrd.pro` and adopt a minimum astrometric uncertainty of 0.5 pixels to account for image registration and centroiding/orientation errors. The rightmost column of Table 1 summarizes our planet detections and Table 2 lists their astrometry.

2.3.1. VLT/NaCo Detections

Figure 1 shows our reduced VLT/NaCo K_s -band image. HR 8799b and c are detected at better than 25σ , while HR 8799d is detected at 10σ . The planets are also free of deep, negative flux troughs at the same separation but slightly different position angles that results from LOCI being applied to data sets with poor field rotation or those where most exposures are taken well before or well after transit (e.g., Marois et al. 2010).

Additionally, our data show a detection of another point source located interior to and in the same quadrant as HR 8799d

¹¹ The zero-point wavelength for the z filter listed on the IRCS webpage is $1.033\ \mu\text{m}$ with a width of $0.073\ \mu\text{m}$. The Y -band filters for comparable cameras are slightly wider but otherwise quite similar: filters for Keck/NIRC (there called “Z”), UKIRT/WFCAM, and Gemini/NIRC have zero-point wavelengths of 1.032 , 1.031 , and $1.02\ \mu\text{m}$ and widths of 0.156 , 0.1 , and $0.1\ \mu\text{m}$, respectively. The IRCS z filter should not be confused with the Sloan z' filter, which covers shorter wavelengths.

Table 2
Astrometry (E ["], N ["] Position)

| Date | 2008 Nov 21 | 2009 Aug 15 | 2009 Sep 12 | 2009 Oct 8 |
|----------|------------------------------------|----------------------------------|-----------------------------------|--------------------------------------|
| Planet | | | | |
| HR 8799b | $1.532 \pm 0.02, 0.796 \pm 0.02$ | $1.536 \pm 0.01, 0.785 \pm 0.01$ | $1.538 \pm 0.03, 0.777 \pm 0.03$ | $1.532 \pm 0.007, 0.783 \pm 0.007$ |
| HR 8799c | $-0.654 \pm 0.02, 0.700 \pm 0.02$ | ... | $-0.634 \pm 0.03, 0.697 \pm 0.03$ | $-0.627 \pm 0.007, 0.716 \pm 0.007$ |
| HR 8799d | $-0.217 \pm 0.02, -0.608 \pm 0.02$ | ... | ... | $-0.241 \pm 0.007, -0.586 \pm 0.007$ |
| HR 8799e | ... | ... | ... | $-0.306 \pm 0.007, -0.217 \pm 0.007$ |

Note. The 2009 August 15 astrometry listed for HR 8799b comes from the J -band data because this data yields a higher signal-to-noise detection.

Table 3
Photometry

| Filter | z | J | H | CH_4s | CH_4l | K_s | [3.3] | L' | M |
|-----------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|----------|
| λ (μm) | 1.03 | 1.248 | 1.633 | 1.592 | 1.681 | 2.146 | 3.3 | 3.776 | 4.8 |
| Planet | | | | | | | | | |
| b | 18.24 ± 0.29 | 16.52 ± 0.14 | 14.87 ± 0.17 | 15.18 ± 0.17 | 14.89 ± 0.18 | 14.05 ± 0.08 | 13.96 ± 0.28 | 12.68 ± 0.12 | >11.37 |
| c | >16.48 | 14.65 ± 0.17 | 13.93 ± 0.17 | 14.25 ± 0.19 | 13.90 ± 0.19 | 13.13 ± 0.08 | 12.64 ± 0.20 | 11.83 ± 0.07 | >11.22 |
| d | >15.03 | 15.26 ± 0.43 | 13.86 ± 0.22 | 14.03 ± 0.30 | 14.57 ± 0.23 | 13.11 ± 0.12 | >11.63 | 11.50 ± 0.12 | >11.15 |
| e | | | | | | 12.89 ± 0.26 | | 11.61 ± 0.12 | |

Notes. Magnitudes listed are the *absolute magnitude* of the companions, assuming a distance of 39.4 pc. (1) H , CH_4s , CH_4l , and K -band photometry for HR 8799bcd taken from Marois et al. (2008). J -band photometry for HR 8799c and d also taken from Marois et al. (2008). L' -band ($3.8 \mu\text{m}$) photometry for HR 8799e taken from Marois et al. (2011). Photometry/upper limits at $3.3 \mu\text{m}$, L' band and M band ($4.8 \mu\text{m}$) for HR 8799bcd are taken from this work.

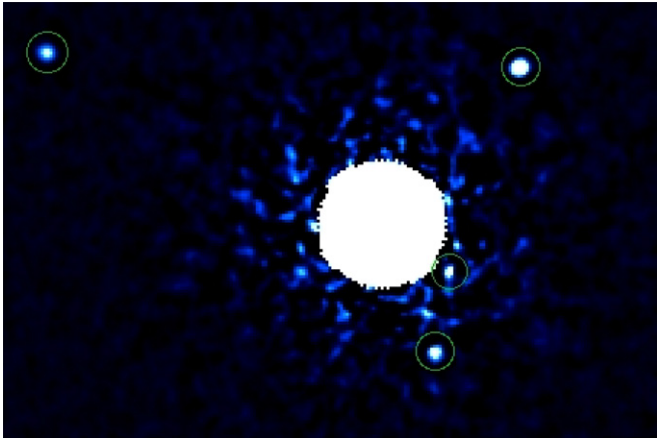


Figure 1. VLT/NaCo image of the HR 8799 planetary system. Previously detected planets—HR 8799b, c, and d—are easily visible at high signal to noise. At $\sim 0''.375$ separation, we detect an additional object consistent with being a fourth planet orbiting HR 8799—HR 8799e. This same object was independently detected by Marois et al. (2011) and confirmed to be a fourth planet. HR 8799e (and d, to a lesser extent) appears slightly smaller than b and c because of point-source self-subtraction inherent in LOCI processing.

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

consistent with a fourth planet—“HR 8799e.” Recently, Marois et al. (2011) announced a multiepoch detection of HR 8799e in K band and L' band using Keck/NIRC2. Their detection significance in K band using Keck/NIRC2 is slightly better than ours ($\sim 5\sigma$ versus our $\sim 4\sigma$). Our photometry using methods described in Section 2.4 yields an absolute magnitude of $m(K_s) = 12.89 \pm 0.26$, consistent with Marois et al.’s estimate of 12.93 ± 0.22 .

Figure 2 compares our astrometry. We measure a centroid position of $[E, N] = [-0''.306 \pm 0''.007, -0''.217 \pm 0''.007]$, implying a projected separation of $14.8 \text{ AU} \pm 0.4 \text{ AU}$. The average of the 2009 August and November positions from Marois et al. (2011) is $[-0.304, -0.203]$ with an intrinsic uncertainty $\sim 0''.01$. Our position is then consistent with theirs

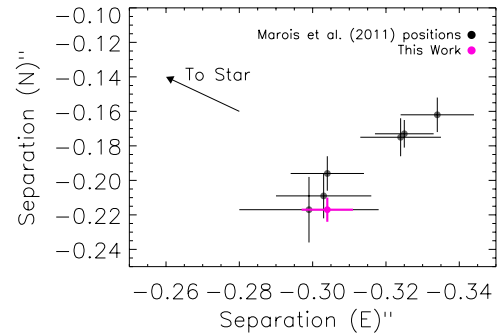


Figure 2. Astrometry for HR 8799e comparing positions from Marois et al. (2011) and from our work. The arrow identifies the direction to the HR 8799 primary. The two points from Marois et al. (2011) nearest to our 2009 October 8 measurement were taken in 2009 August and 2009 November, respectively. Our astrometry are consistent with those from Marois et al. (2011) within errors.

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

to within 1.4σ . Our implied projected physical separation is consistent with Marois et al.’s estimates from multiepoch data: $14.5 \text{ AU} \pm 0.5 \text{ AU}$.

2.3.2. Subaru/IRCS Detections

Figure 3 shows reduced images at J and z obtained with IRCS. In spite of poor field rotation severely limiting the performance of the ADI/LOCI processing and precluding detectability of objects within $\sim 1''$, we clearly detect the b planet in our J -band data at a $\sim 10\sigma$ significance (top panels). In spite of good seeing conditions, good field rotation, and a 70 minute integration time, we fail to detect any of the planets at a $>5\sigma$ significance in the z band (bottom panels). Our reduced image reveals a weak detection of HR 8799b with $S/N \sim 3.7$ (bottom right panel) and a centroid within 0.25 pixels of its centroid in the J -band data obtained 1 hr later with the same instrument. However, we do not detect HR 8799c or d in our z data. To verify that our low signal-to-noise detection of HR 8799b and nondetections for the other planets do not result from errors in derotation or a jump in

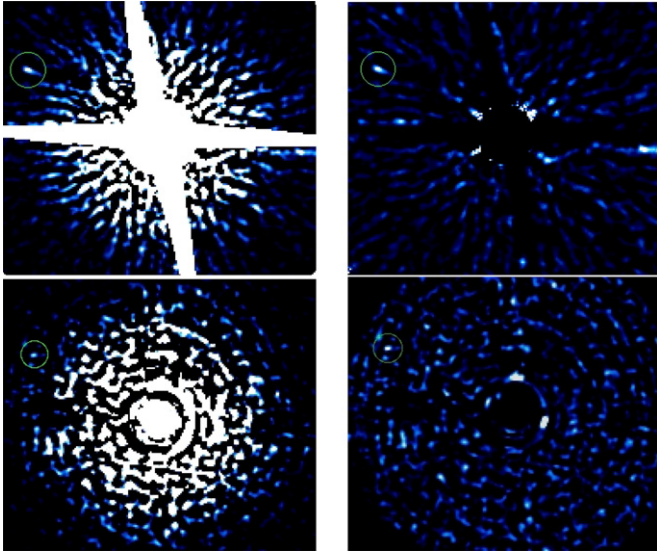


Figure 3. Subaru/IRCS images (left panels) and signal-to-noise maps (right panels) obtained at J band (top panels) and z band (bottom panels). The poor field rotation and short integration time in J limit our detection to HR 8799b. Despite over an hour of integration time in z band, we marginally detect HR 8799b but fail to detect the other planets.

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

parallactic angle near transit,¹² we introduced fake planets into each image with a flux equal to ~ 10 times the local noise of the final image, reran our reduction pipeline separately for frames before and after transit, and recovered their detections.

2.3.3. MMT/Clio Detections

Figures 4–6 show reduced images obtained with MMT/Clio in the L' , [3.3], and M filters. In the L' filter, we detect HR 8799bcd with signal to noise higher than that reported by Hinz et al. (2010) and comparable to that obtained in shorter Keck/NIRC2 exposures by Marois et al. (2008). In the [3.3] filter, we detect the c planet at $S/N > 5$. We marginally detect the b planet at $S/N \sim 3.8$. Hinz et al. (2010) formally report a nondetection for b at [3.3] as they adopt a 3σ threshold for detections, though they identify a cluster of pixels $\sim 2.8\sigma$ above the background consistent with b and roughly coincident with our MMT/Clio and VLT/NaCo detections.

Conversely, we do not detect HR 8799d in [3.3], while Hinz et al. (2010) report a low-significance detection. This disagreement is surprising since LOCI greatly improves the planet sensitivity at small separations such as that for the d planet (Lafreniere et al. 2007a). Furthermore, there is a 40 mas offset between the reported HR 8799d centroid from Hinz et al. and that from our 10σ VLT/NaCo detection obtained three weeks later. While their detection is likely instead residual speckle noise, our qualitative conclusion that HR 8799d is very faint at $3.3 \mu\text{m}$ is consistent with theirs. As with Hinz et al. (2010), we do not detect any of the planets at M band.

2.4. Photometry for Detections and Upper Limits for Nondetections

Photometry for each data set (Table 3) was performed with IDLPHOT with the aperture radius set to the $0.5 \times \text{FWHM}_{\text{image}}$. In all exposures, the stellar PSF core is either

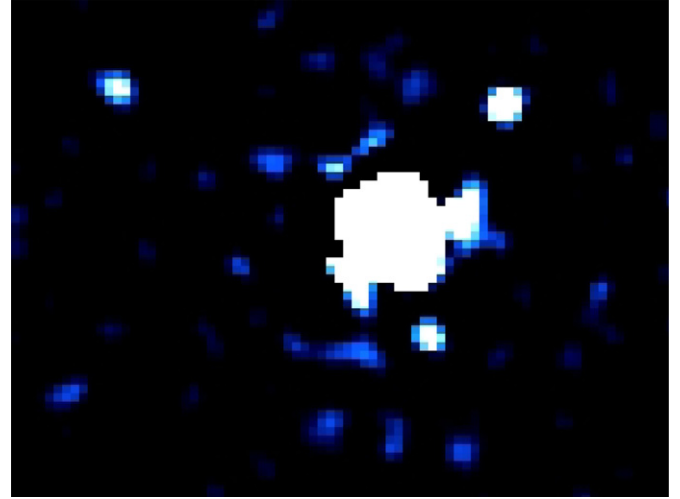


Figure 4. MMT/Clio image of the HR 8799 system at $L'/3.8 \mu\text{m}$. The three planets are clearly visible and all are detected at $S/N > 5$.

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

saturated or obscured. For initial photometric calibration, we obtained observations of the stellar primary viewed through a neutral density filter (MMT/Clio, VLT/NaCo) or observed standard stars immediately prior to and after our science exposures (Subaru/IRCS).

Faint companions to stars observed in ADI and processed with LOCI lose flux due to field rotation and self-subtraction. To further calibrate our photometry, we introduce and measure the flux for faint point sources at random position angles over separations encompassing to the HR 8799 planets ($0''.25\text{--}2''$) in each registered frame, rerun our ADI/LOCI pipeline, compute the attenuated flux in the final, processed images, and correct for this attenuation. Figure 7 illustrates this flux loss, comparing the input and output flux for fake points sources for our MMT/Clio L' data. While images processed using a simple ADI reduction lose $\sim 20\%$ of their flux, self-subtraction is stronger with LOCI, especially at separations less than $0''.75$. The attenuation curves obtained for data in other filters do not differ qualitatively: LOCI always attenuates more flux than a simple ADI reduction and attenuation is significantly more severe at small separations.

To place limits on our nondetections, we compute 3σ upper limits where we correct our nominal sensitivity limits for point-source self-subtraction inherent in ADI/LOCI. The noise is defined in concentric annuli as before, since in most cases (for HR 8799c and d) radially dependent speckle noise dominates over radially independent photon noise. Despite using LOCI, our detection upper limit at $3.3 \mu\text{m}$ for HR 8799d is brighter than the magnitude listed by Hinz et al. (2010). Moreover, our upper limits for HR 8799bcd at M are consistently brighter than those reported by Hinz et al.

In both cases, the disagreement is likely explainable by our correction for point-source self-subtraction in deriving upper limits from the standard deviation of pixel values. Hinz et al. construct a reference PSF by median-combining all frames and then subtract this reference PSF from each image. For the $3.3 \mu\text{m}$ data, our reduction pipeline predicts that this processing should attenuate about half of the point-source flux at HR 8799d's position.¹³ For the M -band data, field rotation is poorer and thus self-subtraction with this reduction procedure is severe, reaching

¹² For an example of this phenomenon, see <http://www2.keck.hawaii.edu/inst/nirc2/vertAngJump.html>

¹³ While the total field rotation is large, $\sim 127^\circ$, the vast majority of the frames were taken over a time interval with only 30° of field rotation.

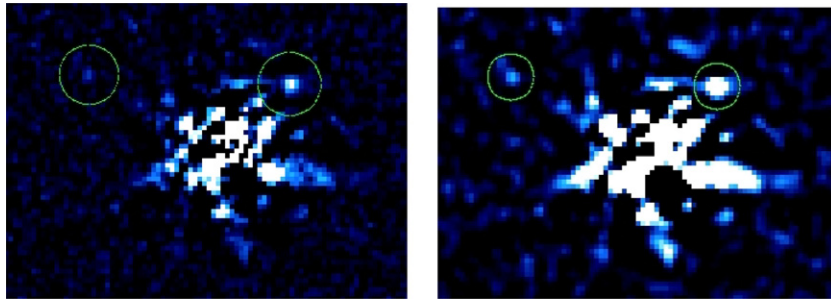


Figure 5. MMT/Clio image at $3.3\ \mu\text{m}$. Left panel: the image shown with a high dynamic range to more clearly show the detection of HR 8799c. Right panel: the image with a smaller dynamic range to better illustrate the marginal detection of HR 8799b.

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

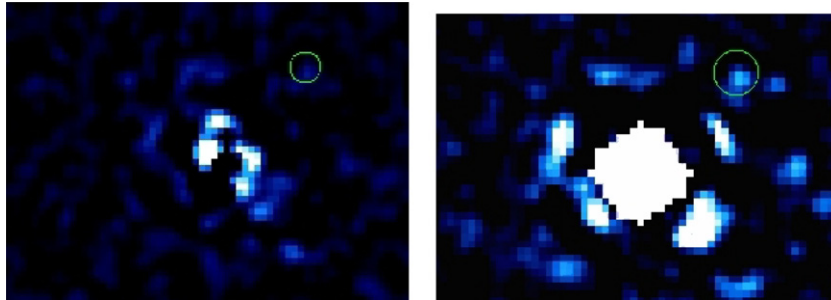


Figure 6. MMT/Clio image at $M'/4.8\ \mu\text{m}$ shown with slightly different procedures for PSF subtraction (left panel, simple ADI reduction; right panel, radial profile subtraction with LOCI reduction) and different dynamic ranges (left panel, high dynamic range; right panel, low dynamic range to show residual noise). The circle identifies the centroid position of HR 8799c in the L' image obtained on the same night. While a local peak appears near the position of HR 8799c, we do not identify any $>3\sigma$ peaks consistent with any of the planets in these images.

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

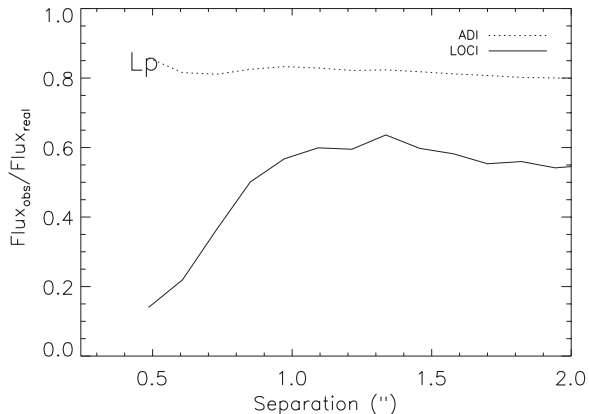


Figure 7. Plot of the point-source self-subtraction for LOCI as a function of separation for our MMT/Clio data for a simple ADI reduction and our LOCI reduction. LOCI attenuates more flux, especially interior to $0''.75$.

over 75% at the position of HR 8799d as nearly half the frames are obtained ~ 3 hr after transit and thus at essentially one position angle. Thus, the gain in sensitivity due to LOCI is reduced by self-subtraction, resulting in brighter 3σ upper limits.

3. PHOTOMETRIC ANALYSIS: CONSTRAINING THE ATMOSPHERIC PROPERTIES OF THE HR 8799 PLANETS

Combining our data with that from Marois et al. (2008) yields planet flux measurements at nine separate wavelengths from 1 to $5\ \mu\text{m}$. In this section, we use this rich multiwavelength sampling of HR 8799's planet SEDs to provide an empirical comparison

with other cool, substellar-mass objects and simple atmospheric modeling constraints on the planets' properties.

3.1. Near-to-Mid-IR Colors of the HR 8799 Planets

3.1.1. Methodology

To compare the near-to-mid-IR properties of the HR 8799 planets with those for other cool, substellar objects, we primarily use the sample of L/T dwarfs compiled by Leggett et al. (2010). The L/T dwarf sequence defined by the Leggett et al. sample allows us to determine how the HR 8799 planet SEDs deviate from those for brown dwarfs of similar temperatures. To explore how the HR 8799 planet SEDs compare to those for other planet-mass objects and very low mass brown dwarfs with $T_{\text{eff}} = 800\text{--}1800$ K, we include 2M 1207b ($5 M_J$), 1RXJ1609.1-210524 ($9 M_J$), AB Pic ($13.5 M_J$), and HD 203030b ($\sim 25 M_J$) (Chauvin et al. 2004, 2005; Lafreniere et al. 2010; Metchev & Hillenbrand 2006). Table 4 lists photometry for these objects.

We use color–magnitude diagrams constructed from the Y , J , H , K_s , and L' filters to determine whether the HR 8799 planets are similar to or under/overluminous compared to the Leggett L/T dwarf sequence. For simplicity and because there is no published response function for the IRCS z -band filter, we treat the IRCS z -band magnitudes/upper limits for the HR 8799 planets as synonymous with its Y -band magnitude.

To provide a physical point of reference for the L/T dwarf sequence and the HR 8799 color–magnitude positions, we overplot loci for standard, chemical equilibrium atmosphere models from Burrows et al. (2006). We specifically choose the Model E case, which assumes that the clouds are confined to a thin layer, where the thickness of the flat part of the

Table 4
Adopted Photometry for Other Planet-mass Objects and Low-mass Brown Dwarfs

| Companion | D (pc) | J | H | K | L' | References |
|-------------------|----------|------------------|-------------------|------------------|------------------|------------|
| 2M 1207b | 52.4 | 16.40 ± 0.2 | 14.49 ± 0.21 | 13.33 ± 0.11 | 11.68 ± 0.14 | 1,2 |
| 1RXJ1609.1-210524 | 140 | 12.17 ± 0.12 | 11.139 ± 0.07 | 10.44 ± 0.18 | 9.14 ± 0.3 | 3,4 |
| AB Pic b | 47.3 | 12.80 ± 0.10 | 11.31 ± 0.10 | 10.76 ± 0.08 | −99 | 5 |
| HD 203030b | 40.8 | 15.08 ± 0.55 | 13.80 ± 0.12 | 13.16 ± 0.10 | −99 | 6 |

Note. All magnitudes listed are absolute magnitudes.

References. (1) Chauvin et al. 2004; (2) Mohanty et al. 2007; (3) Lafreniere et al. 2008; (4) Ireland et al. 2011; (5) Chauvin et al. 2005; (6) Metchev & Hillenbrand 2006.

cloud encompasses the condensation points of different species with different temperature–pressure intercept points. Above and below the flat portion, the cloud shape function decays to the -6 and -10 power. Thus, above and below the flat portion, the clouds have scale heights $\sim 1/7$ th and $1/11$ th that of the gas. See Burrows et al. (2006) for more details.

3.1.2. Results

Figure 8 shows our color comparisons. At least three of the HR 8799 planets have $K_s/K_s - L'$ positions (upper left panel) roughly consistent with those for the Leggett L/T dwarf sequence and with 2M 1207b. HR 8799cde have positions overlapping with objects near the L/T dwarf boundary; HR 8799b has a similar $K_s - L'$ color but is underluminous compared to the three other companions and 2M 1207b by a factor of two. It is unclear how its position compares to those for field L/T dwarfs because the sequence is poorly sampled at HR 8799b's K_s -band magnitude.

The other three panels of Figure 8 clearly show that HR 8799c, d, and especially b have near-IR colors that depart from the L/T dwarf sequence. In $J/J - H$ and $J/J - K_s$, the L/T dwarf sequence turns toward blue colors by up to 1.5 mag starting at the L/T transition. While HR 8799c's position is roughly coincident with T0 dwarfs, HR 8799b and d follow an extension of the slope of the L dwarf sequence between $J/[J - H, K_s] = 11/[0.6, 1.2]$ and $15/[1.2, 2]$ toward fainter magnitudes and redder colors. HR 8799d's position coincides with that of HD 203030b, while HR 8799b is located closest to 2M 1207b. The $H/Y - H$ color–magnitude diagram shows that HR 8799c also is likely red/underluminous; HR 8799b is 2.5 mag too red in $Y - H$ for its H -band magnitude, indicating that it is underluminous compared to the L/T dwarf sequence at both Y and J .

Figure 8 overplots loci of standard Burrows et al. models for parameters covering a range expected for low-mass, cool brown dwarfs— $T_{\text{eff}} = 800\text{--}1800$ K, $\log(g) = 4\text{--}5$ —and two metallicities (solar and $3 \times$ solar).¹⁴ With the exception of some L/T dwarf transition objects, the dispersion in color–magnitude positions for L/T dwarfs is reproduced well by model atmosphere loci. This indicates that L/T dwarf atmospheres can be explained within the phase space encompassed by the models' assumed cloud structure and range in temperature, gravity, and metallicity (Burrows et al. 2006).

The HR 8799 planets, especially HR 8799b, are different. They consistently lie below the region enclosed by the standard model atmosphere loci, indicating that their near-IR luminosities are weaker compared to luminosities expected if their cloud

structure were represented well by the models. HR 8799b in particular probes a completely different range of parameter space, lying 0.75 mag or more redder than *any* standard atmosphere prediction regardless of temperature. Thus, Figure 8 suggests a strong contrast between the atmospheric properties of L/T dwarfs and the HR 8799 planets.

To summarize, all three HR 8799 planets—especially HR 8799b—have near-IR colors that cannot be easily understood within the field L/T dwarf sequence. They are consistently red and underluminous at Y and J , indicating that the $1\text{--}1.25 \mu\text{m}$ portion of their SEDs is suppressed in flux. The HR 8799 planets also lie well outside the loci of standard atmosphere models used to interpret the physical properties of L/T dwarfs. Thus, the HR 8799 planet atmospheres are not simply “scaled down” (in mass) versions of the atmospheres of field brown dwarfs defining the L/T dwarf sequence.

On the other hand, the planets' atmospheres show strong similarity to those for planetary-mass/low-mass brown dwarf companions to nearby stars. Specifically, HR 8799c and d have similar near-IR colors to HD 203030b, while HR 8799b consistently shows near-IR colors similar to 2M 1207b. The planetary-mass companions 1RXJ1609.1-210524b and AB Pic b are also redder in near-IR colors compared to the L/T dwarf sequence but not underluminous. Within the narrow context of our analysis, planetary-mass companions *in general* might not follow the L/T dwarf sequence.

3.2. Fiducial Model Atmosphere Fits to the HR 8799 Planet SEDs

Our color comparisons motivate a further investigation of the HR 8799 planet SEDs to better understand the source of the differences between their near-IR colors and those for field L/T dwarfs. To further explore the physical properties of the HR 8799 planets, we compare their photometry to atmospheric models. Because the color–magnitude comparisons indicate that standard model atmospheres provide poor fits to the planet data, we introduce a new set of models to explore additional phase space not covered by the standard models, specifically a different cloud structure:

The Burrows et al. (2006) Model A thick cloud layer prescription. Like the Model E case, this model defines a cloud base at the high temperature interception point with the shape function at higher temperatures/pressures decaying to the -10 power. However, the cloud density tracks the gas density at lower temperatures/pressures ($s_1 = 0$ in their terminology). Thus, clouds in this case are far more extended high in the atmosphere than in the standard Model E case.

As noted in Burrows et al. (2006), these models are qualitatively similar to the AMES-DUSTY models (Allard

¹⁴ We include the $3 \times$ solar models because they produce redder near-IR colors and the HR 8799 planets are red in the near-IR compared to the L/T dwarf sequence.

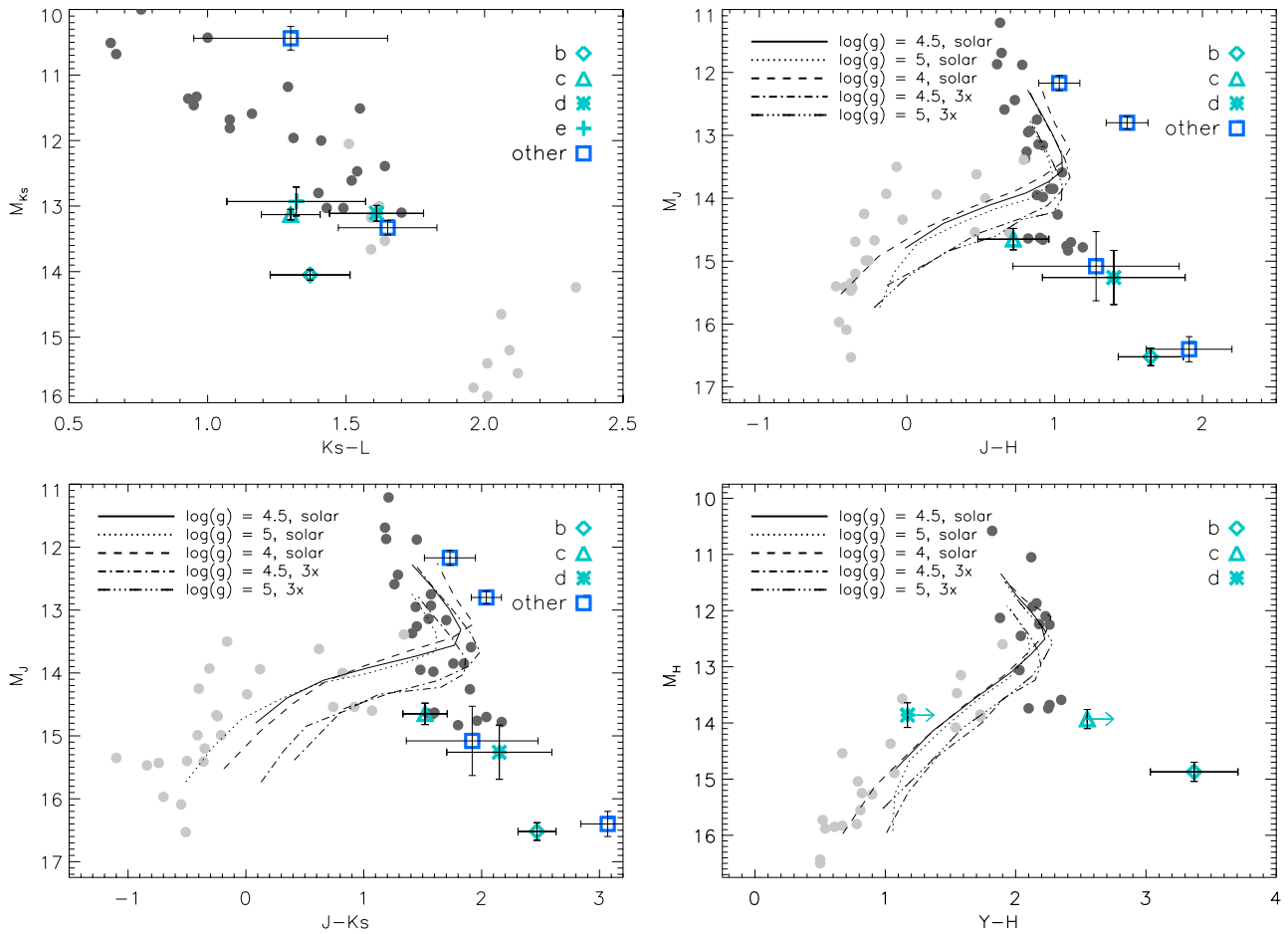


Figure 8. Color–magnitude diagrams comparing the HR 8799 planets with field L dwarfs (black dots) and T dwarfs (gray dots) and other planetary or very low mass brown dwarf companions (squares). In K_s/K_s-L' (top left panel), the planets follow the L/T dwarf sequence. In at least one of the diagrams including Y -, J -, and H -band data (top right panel; bottom panels), the planets are red/underluminous compared to the empirical L/T dwarf sequence and the synthetic L/T dwarf colors from Burrows et al. (2006) for a range of metallicities and gravities. The positions for other planetary-mass/low-mass brown dwarf companions also depart from the L/T dwarf sequence, especially 2M 1207b.

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

et al. 2001). However, they are bluer and brighter than AMES-DUSTY in the near IR because Allard et al. (2001) adopt the interstellar medium particle size distribution. The Model A case fails to reproduce the L/T dwarf sequence as it is consistently too red and underluminous in IR color–magnitude diagrams (Burrows et al. 2006). If the HR 8799 planets have thicker clouds than L/T-type brown dwarfs, these models—or some hybrid between them and the “E” models—should reproduce the planets’ SEDs far better than the Model “E” case alone.

Changing the cloud prescription radically alters the entire shape of the SED (Figure 9). The K - and L' -band fluxes are similar. However, the Model A/thick cloud prescription is underluminous over the Y and J passbands by an order of magnitude, underluminous at $1.65 \mu\text{m}$ by a factor of two but overluminous in the $3.3 \mu\text{m}$ region covering the trough produced by methane absorption in the Model E cloud prescription. Overall, the Model A SED is much flatter from 1 to $4 \mu\text{m}$. Additionally, the Model A prescription washes out the methane absorption feature at $1.65 \mu\text{m}$ used to identify the L/T dwarf transition (see also discussion in Burrows et al. 2006).

Both the standard models and thick cloud layer models use the formalism described in Burrows et al. (2006) for temperatures $T_{\text{eff}} = 700\text{--}1800 \text{ K}$, gravities with $\log(g) = 3.75\text{--}5$, and

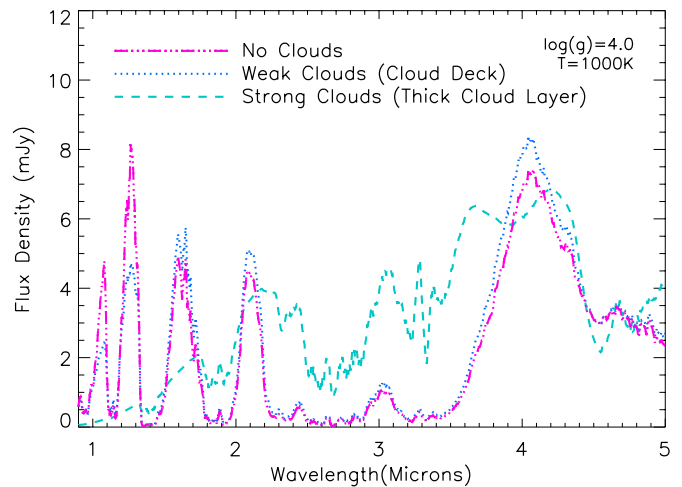


Figure 9. Comparing SEDs for different cloud prescriptions (no clouds, Model E, and Model A) at a given temperature and gravity.

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

solar/super-solar abundances of metals. For both models, we assume modal particle sizes of $60\text{--}100 \mu\text{m}$ and a particle size distribution appropriate for clouds (Deirmendjian 1964). For both models, we also assume radii from Burrows et al. (1997).

Table 5
Standard Model (Model E) Fitting Results

| Model Run | χ^2_{\min} | $\log(g), T_{\text{eff}}$ (for χ^2_{\min}) | C_k | $\Delta\chi^2$ | $\log(g), \log(T_{\text{eff}})$ ($\chi^2 < \Delta\chi^2$) |
|--|-----------------|--|-------|----------------|---|
| HR 8799b | | | | | |
| Model E solar, 3 \times | 279.0 | 4.5, 900 K | 1 | 291.85 | 4.5–5, 900–1000 K |
| Model E solar, 3 \times ($C_k = 0.9$ –1.1) | 264.5 | 4.5, 900 K | 0.91 | 286.4 | 4.5, 900 K; 5, 1000 K |
| Model E solar, 3 \times ($C_k = 0.2$ –2) | 36.6 | 4.5, 1400 | 0.34 | 58.5 | 4, 1400 K; 4.5, 1300–1500 K; 5, 1400 K |
| HR 8799c | | | | | |
| Model E solar, 3 \times | 120.8 | 5, 1200 K | 1 | 142.7 | 4.5, 1100 K; 5, 1200 K–1300 K |
| Model E solar, 3 \times ($C_k = 0.9$ –1.1) | 71.0 | 5.0, 1300 K | 0.9 | 92.5 | 5, 1300 K |
| Model E solar, 3 \times ($C_k = 0.2$ –2) | 17.6 | 4.5, 1400 | 0.54 | 39.5 | 4, 1300–1700 K; 4.5, 1300–1700 K; 5, 1400–1700 K |
| HR 8799d | | | | | |
| Model E solar, 3 \times | 17.0 | 4.5, 1100 K | 1 | 38.5 | 4.5, 1100 K; 5, 1200 K |
| Model E solar, 3 \times ($C_k = 0.9$ –1.1) | 17.0 | 4.5, 1100 K | 0.9 | 38.5 | 4.5, 1100–1200 K; 5, 1200–1300 K |
| Model E solar, 3 \times ($C_k = 0.2$ –2) | 10.91 | 4.5, 1300 K | 0.64 | 32.8 | 4, 1300–1600 K; 4.5, 900–1700 K; 5, 1200–1700 K |

Note. Where the metal-rich models are considered (first three rows for each planet), they always provide the smallest χ^2 value.

3.2.1. Fitting Method

Our atmosphere model fitting follows a simplified version of the fitting procedure employed by Bowler et al. (2010) to model the near-IR spectrum and photometry for HR 8799b. Nominally, we quantify the model fits with the χ^2 statistic,

$$\chi^2 = \sum_{i=0}^n (f_{\text{data},i} - F_{\text{model},i})^2 / \sigma_{\text{data},i}^2. \quad (1)$$

We weight each data point equally. To account for variability in emission and absolute calibration uncertainties, we set a 0.1 mag floor to σ for each data point (see Robitaille et al. 2007). Because of incomplete line lists near the 1.6 μm CH₄ band, we do not compare the models to data at the CH₄ filter (see Bowler et al. 2010; Saumon et al. 2007; Leggett et al. 2007). However, we confirmed that this choice has no consequential bearing on our results.

The z , [3.3], and M photometry include many nondetections. We quantitatively incorporate nondetections in the following way. For model predictions consistent with the 3σ upper limits estimated for each nondetection, we treat the model as perfectly consistent with the data and do not penalize the χ^2 value. For model predictions inconsistent with the 3σ upper limits, we do not automatically discard the model. Rather, we penalize the χ^2 value by determining the flux ratio between the model prediction and the 3σ upper limit. Specifically, a model prediction two and four times brighter than the 3σ upper limit will contribute 12 (3×4) and 48 (3×16) to the final χ^2 value, respectively.

We fit atmosphere models in two cases. First, to provide a straightforward comparison between our data and the luminosity and colors predicted from atmosphere models, we keep the radii fixed to the Burrows et al. (1997) dwarf radii. Second, we vary the radius and identify the scaling factor, $C_k = (R_{\text{scaled}}/R_{\text{nominal}})$, that minimizes χ^2 for a particular model:

$$C_k^2 = \frac{\sum_{i=0}^n f_{\text{data},i} F_{\text{model},i} / \sigma_{\text{data},i}^2}{\sum_{i=0}^n F_{\text{model},i}^2 / \sigma_{\text{data},i}^2}. \quad (2)$$

We nominally only allow the radius to vary by $\pm 10\%$ from the assumed Burrows et al. (1997) values to encompass the range of radii for 5–20 M_J objects at 30–300 Myr (~ 1.1 –1.3 R_J).

We determine which models are *formally* consistent with the data by comparing the resulting χ^2 value to that identifying the 3σ and 5σ confidence limits. For the first case, where the planet radius is fixed, the appropriate χ^2 limits are 21.85 and 41.80 for eight data points and seven degrees of freedom. For the second case—a variable planet radius—the limits are 20.1 and 39.4 for eight data points and six degrees of freedom.

To select the *best-fit* models, we follow Bowler et al. (2010) by identifying the model with the smallest χ^2 and computing the $\Delta\chi^2$ limit for a 3σ confidence limit. “Best-fit” models satisfy $\chi_{\text{model}}^2 - \chi_{\text{best}}^2 < \chi_{99,73\%}^2$. We do this separately for the Model A and E cloud prescriptions.

3.2.2. Results for Standard Cloud Deck Models

Table 5 summarizes our entire fitting results for models with the standard cloud deck prescription. Figure 10 displays some of these fitting results with the planet radii fixed to the Burrows et al. (1997) values. The top left panel shows the distribution of χ^2 values for HR 8799b; the top right panel compares the HR 8799b SED to the “best-fit” model.

For each planet, the models with the lowest χ^2 values have temperatures within 100 K of those derived from cooling models: $T_{\text{eff}} = 900$ K, 1200 K, and 1100 K for HR 8799b, c, and d (see Marois et al. 2008). Models with a 3 \times solar abundance of metals have marginally smaller χ^2 values. Adopting the $\Delta\chi^2$ criterion, $\chi_{\min}^2 + \chi_{99,73\%}^2$, the minimum χ^2 values for modeling b, c, and d are 300.9, 133.2, and 38.9. The ranges of temperatures and gravities fulfilling this criterion are $T_{\text{eff}} = 900$ –1000 K, 1100–1300 K, 1000–1300 K and $\log(g) = 4.5$ –5, 4.5–5, and 4–5 for the b, c, and d planets.

However, the fits are quantitatively very poor for HR 8799c and (especially) b. As shown by Figure 10 (top left panel), the minimum χ^2 value for HR 8799b is a factor of ~ 5.5 times higher than the formal 5σ confidence limit. The minimum χ^2 value for HR 8799c is twice as large. The large χ^2 difference between that for “best-fit” models and the formal 5σ confidence

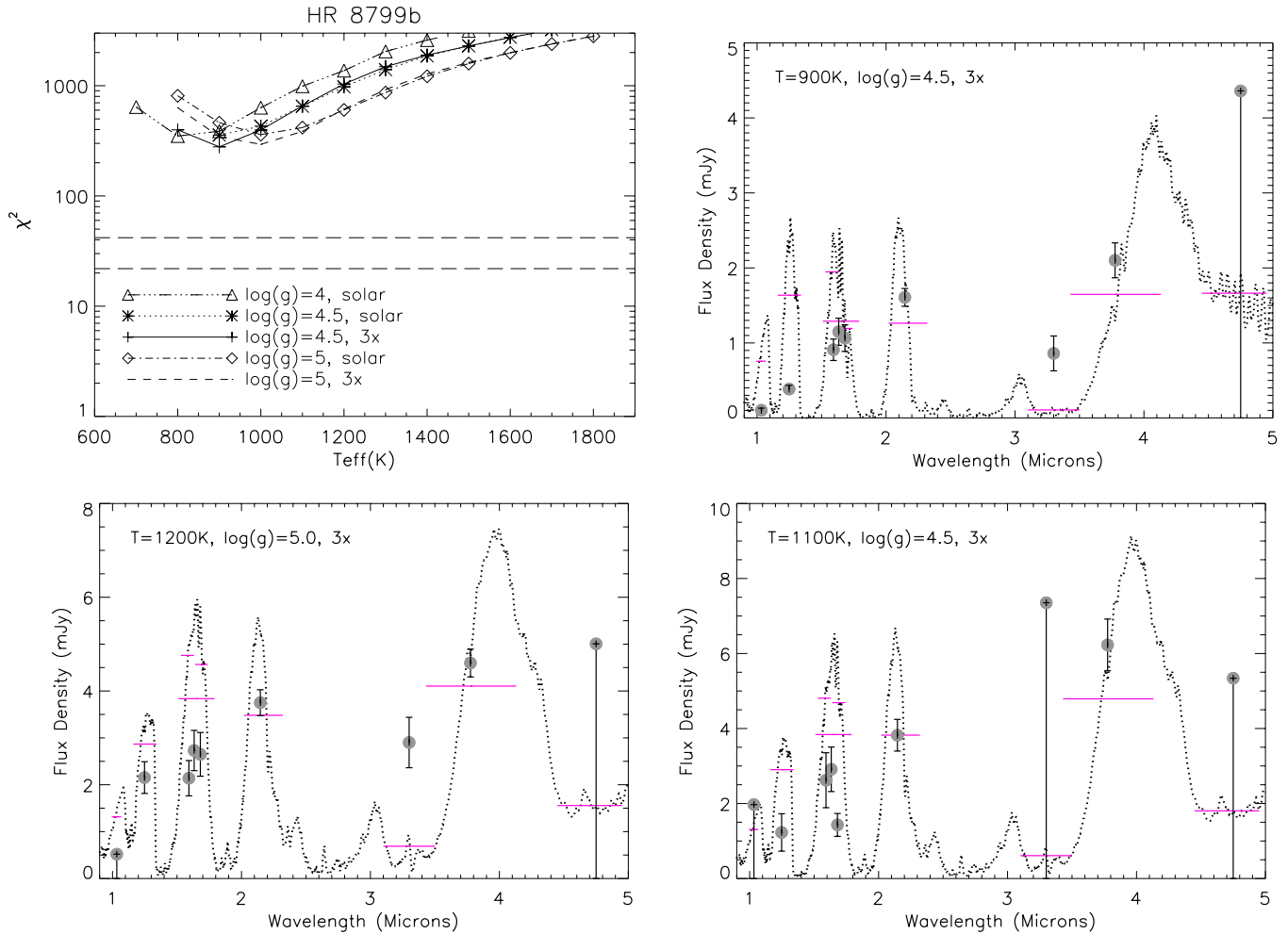


Figure 10. Fitting results for the standard cloud deck models assuming the Burrows et al. (1997) radii. The top left panel shows the distribution of χ^2 vs. T_{eff} for model fits to HR 8799b with a range of surface gravity and metallicity. The top right panel compares the HR 8799b planet SED to the model with the smallest χ^2 value. The bottom panels compare the HR 8799c (left) and HR 8799d (right) SEDs to the best-fit models for these data. In the SED comparisons, the horizontal magenta lines identify the flux of the model in the photometric filters convolved over the filter function. The width of the magenta line corresponds to the width of the filter.

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

limit suggests that the models do not provide meaningful fits to the data. Fits to the HR 8799d SED are not quite as poor but include only one model with $\chi^2 < \chi_{99.73\%}^2$. Allowing the planetary radii to vary over the range plausible for 5–20 M_J objects does not qualitatively improve the model fits for the b and c planets (Table 5).

The top right-hand panel and lower panels of Figure 10 illustrate how the models fail to reproduce the SEDs of HR 8799bcd. For example, for HR 8799b the “best-fit” model provides a good estimate of its K_s -band and L' -band fluxes and is consistent with its upper limit at M band. At $[3.3]$, however, the model predicts too deep of a trough due to methane absorption, underpredicting the flux by a factor of ~ 3 –4. Most strikingly, the model overpredicts the flux at Y and J band by *over an order of magnitude*. The model overestimates the H band and CH_4 s flux by a factor of ~ 2 . Compared to the best-fitting models, HR 8799c also has too strong of a $3.3 \mu\text{m}$ flux and too low of a Y -band upper limit.

For modeling results discussed in Figure 10, the scaling factors for the radii are almost always $C_k = 0.9$ for temperatures greater than those predicted from cooling models and 1.1 for lower temperatures. To see which radii formally yield the smallest χ^2 values, we allow the radius to vary between 0.2

and 2 times the Burrows et al. (1997) values. The resulting trend of χ^2 versus T_{eff} for all planets changes, as the minima are systematically pushed toward higher T_{eff} ($T_{\text{eff}} = 1300$ – 1400 K). However, radius scale factors for the best-fit models imply that the planets are unphysically small – $R_{b,c,d} \sim 0.4, 0.6$, and $0.7 R_J$.

In summary, atmosphere models with standard, cloud deck prescriptions appropriate for brown dwarfs only provide statistically meaningful fits to HR 8799b and c for unrealistically small radii (see also Bowler et al. 2010 for HR 8799b). Assuming radii characteristic of planet-mass objects, we fail to find a single model that provides a statistically meaningful fit to the HR 8799b and c data indicating that such models provide a poor description of the planets’ atmospheres (see also Marois et al. 2008; Janson et al. 2010; Hinz et al. 2010). These results are independent of surface gravity for $\log(g) = 4$ –5 and whether the planets have solar or $3\times$ solar metallicity. These results then motivate us to see if models with different cloud prescriptions fare better in reproducing the SEDs of HR 8799bcd.

3.2.3. Results for Thick Cloud Layer Models

Figure 11 shows and Table 6 summarizes our fitting results for the thick cloud layer models. Best-fit models for the HR

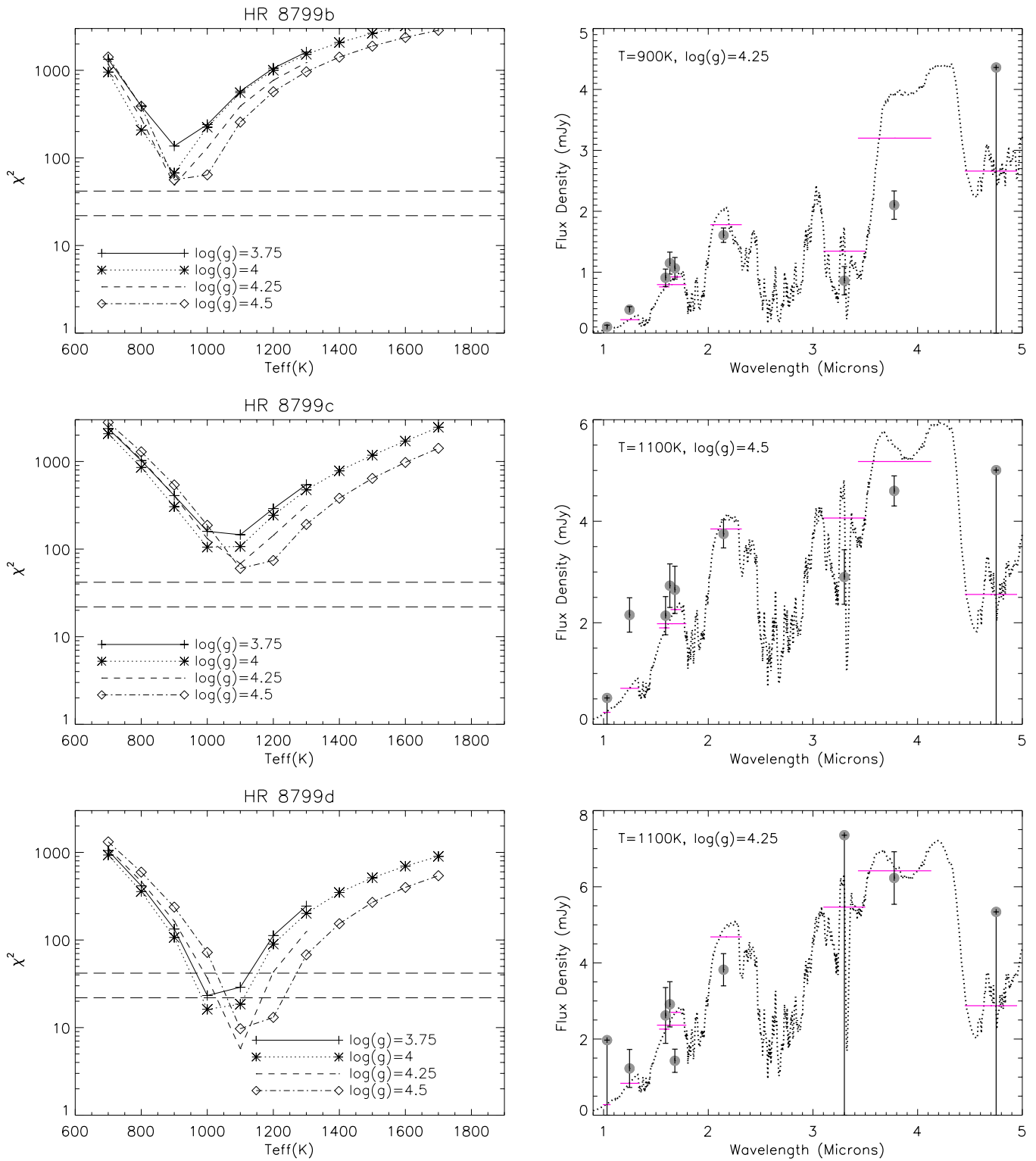


Figure 11. Fitting results for the Model A, thick cloud layer prescription with a modal particle size of $60\ \mu\text{m}$. The left-hand panels show the χ^2 distributions for each planet while the right-hand panels compare the planet SEDs to the best-fit models in each case. Compared to the Model E, standard cloud deck fits, these models yielded smaller χ^2 minima and better fits to the data.

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

8799 planets cover a similar range in T_{eff} as the standard model fits and cooling model predictions. For HR 8799b, the best-fit model assumes $T_{\text{eff}} = 900\ \text{K}$ and $\log(g) = 4.25$; the ranges of best-fit models cover $\log(g) = 4\text{--}4.5$ and $T_{\text{eff}} = 900\text{--}1000\ \text{K}$. The range in $\log(g)$ for HR 8799c and d are similar to that for b

($\log(g) = 4.25\text{--}4.5$ and $4\text{--}4.5$), whereas their temperatures are slightly higher (1100–1200 K and 1000–1200 K).

As illustrated by Figure 11, models with thick cloud layers provide *far* better fits to the SEDs of *all three* planets. Quantitatively, the χ^2 minima shrink by factors of six, two,

Table 6
Thick-cloud Model (Model A) and “Patchy” Cloud Approximation Fitting Results

| Model Run | χ^2_{\min} | $\log(g), T_{\text{eff}}$ (for χ^2_{\min}) | C_k | $\Delta\chi^2$ | $\log(g), \log(T_{\text{eff}})$ ($\chi^2 < \Delta\chi^2$) |
|---|-----------------|--|-------|----------------|--|
| HR 8799b | | | | | |
| Model A solar | 48.9 | 4.25, 900 K | 1 | 70.8 | 4, 900 K; 4.25, 900 K; 4.5, 900–1000 K |
| Model A solar ($C_k = 0.9$ –1.1) | 27.6 | 4.5, 1000 K | 0.9 | 47.7 | 4, 900 K; 4.25, 900 K; 4.5, 900–1000 K |
| Model A/E solar (60% thick clouds) | 91.5 | 4, 900 K | 1 | 111.6 | 4, 800 K |
| Model A/E solar (60% thick clouds, $C_k = 0.9$ –1.1) | 85.5 | 4, 900 K | 1 | 105.6 | 4, 800–900 K |
| Model A/E solar (90% thick clouds) | 51.4 | 4, 900 K | 1 | 71.5 | 4, 800–900 K |
| Model A/E solar (90% thick clouds, $C_k = 0.9$ –1.1) | 20.6 | 4, 900 K | 1 | 40.7 | 4, 800–900 K |
| HR 8799c | | | | | |
| Model A solar | 60.7 | 4.5, 1100 K | 1 | 82.6 | 4.25, 1100 K; 4.25, 1100 K 4.5, 1100 K–1200 K |
| Model A solar ($C_k = 0.9$ –1.1) | 43.5 | 4.5 1200 K | 0.9 | 63.6 | 4.25, 1100 K; 4.5, 1100–1200 K |
| Model A solar (60% thick clouds) | 14.1 | 4, 1000 K | 1 | 34.5 | 4, 1000 K |
| Model A solar (60% thick clouds, $C_k = 0.9$ –1.1) | 14.0 | 4, 1000 K | 1 | 34.1 | 4, 1000–1100 K |
| Model A solar (90% thick clouds) | 51.6 | 4, 1000 K | 1 | 71.7 | 4, 1000 K |
| Model A solar (90% thick clouds, $C_k = 0.9$ –1.1) | 48.0 | 4, 1100 K | 1 | 68.1 | 4, 1000–1100 K |
| HR 8799d | | | | | |
| Model A solar | 5.7 | 4.25, 1100 K | 1 | 25.8 | 3.75, 1000 K; 4, 1000–1100 K 4.25, 1100 K; 4.5, 1100–1200 K |
| Model A solar ($C_k = 0.9$ –1.1) | 5.3 | 4.5, 1200 K | 0.98 | 27.2 | 3.75–4, 1000–1100 K; 4.25, 1000–1200 K 4.5, 1100–1200 K |
| Model A solar (60% thick clouds) | 7.4 | 4, 1000 K | 1 | 27.5 | 4, 1000–1100 K |
| Model A solar (60% thick clouds, $C_k = 0.9$ –1.1) | 2.8 | 4, 1000 K | 1 | 22.9 | 4, 1000–1100 K |
| Model A solar (90% thick clouds) | 8.8 | 4, 1000 K | 1 | 28.9 | 4, 1000–1100 K |
| Model A solar (90% thick clouds, $C_k = 0.9$ –1.1) | 3.1 | 4, 1000 K | 1 | 23.2 | 4, 1000–1100 K |

and five for HR 8799b, c, and d compared to those for Model E fits. For HR 8799b and c, the minima approach the formal 5σ confidence limit. For HR 8799d, multiple models have χ^2 minima less than the formal 3σ confidence limit.

The right-hand panels of Figure 11 illustrate why the thick cloud layer models are more accurate. For HR 8799b, the best-fit models predict a flat, rising SED from 1 to $1.5\ \mu\text{m}$, consistent with the planet’s weak Y - and J -band emission. The best-fit models also predict stronger $3.3\ \mu\text{m}$ emission than in the standard model case and in better agreement with HR 8799b’s measured [3.3] flux. While the best-fit model for HR 8799c underpredicts its J -band flux while overpredicting its [3.3] and L' -band flux, the discrepancies are weaker than in the standard cloud model case. With the exception of the CH_4 filter data, which was not incorporated into our fitting, the best-fit thick cloud model ($\log(g) = 4.25$, $T_{\text{eff}} = 1100\ \text{K}$) for HR 8799d accurately reproduces the planet’s flux at every data point.

Allowing the planet radii to vary by $\pm 10\%$ slightly improves the model fits. More importantly, results in more models with χ^2 values below the formal 3σ and 5σ confidence limits (Figure 12). For these models, the HR 8799b’s ranges of best-fit models have $\log(g) = 4.25$ – 4.5 , $T_{\text{eff}} = 900$ – $1000\ \text{K}$, and

$C_k = 0.9$ – 1.02 ; HR 8799c’s have $\log(g) = 4.25$ – 4.5 , $T_{\text{eff}} = 1100$ – $1200\ \text{K}$, and $C_k = 0.9$ – 0.975 ; and HR 8799d’s have $\log(g) = 3.75$ – 4.5 , $T_{\text{eff}} = 1000$ – $1200\ \text{K}$, and $C_k = 0.9$ – 1.09 . As before, the scaling factor for each model is correlated with the model’s temperature compared to the cooling model estimates.

3.3. Estimates for “Patchy”/Partly Cloudy Models

The two models used to fit our data define limiting cases for the cloud structure in planet atmospheres. The Model A thick cloud layer prescription fits the data for each planet far better. However, intermediate cases—with far thicker clouds than the Model E case but slightly thinner than Model A or a “patchy” cloud coverage—may be more physically realistic. The two processes may be tied together: Ackerman & Marley (2001) show that clouds may become patchy as they sediment below photospheric pressures. Near-IR photometric variability detected from the T2.5 brown dwarf SIMP J013656.5+093347 is consistent with grain free, cloudless regions and grain-bearing cloudy regions rotating in and out of view (Artigau et al. 2009). Cloud patchiness may also be important for defining the

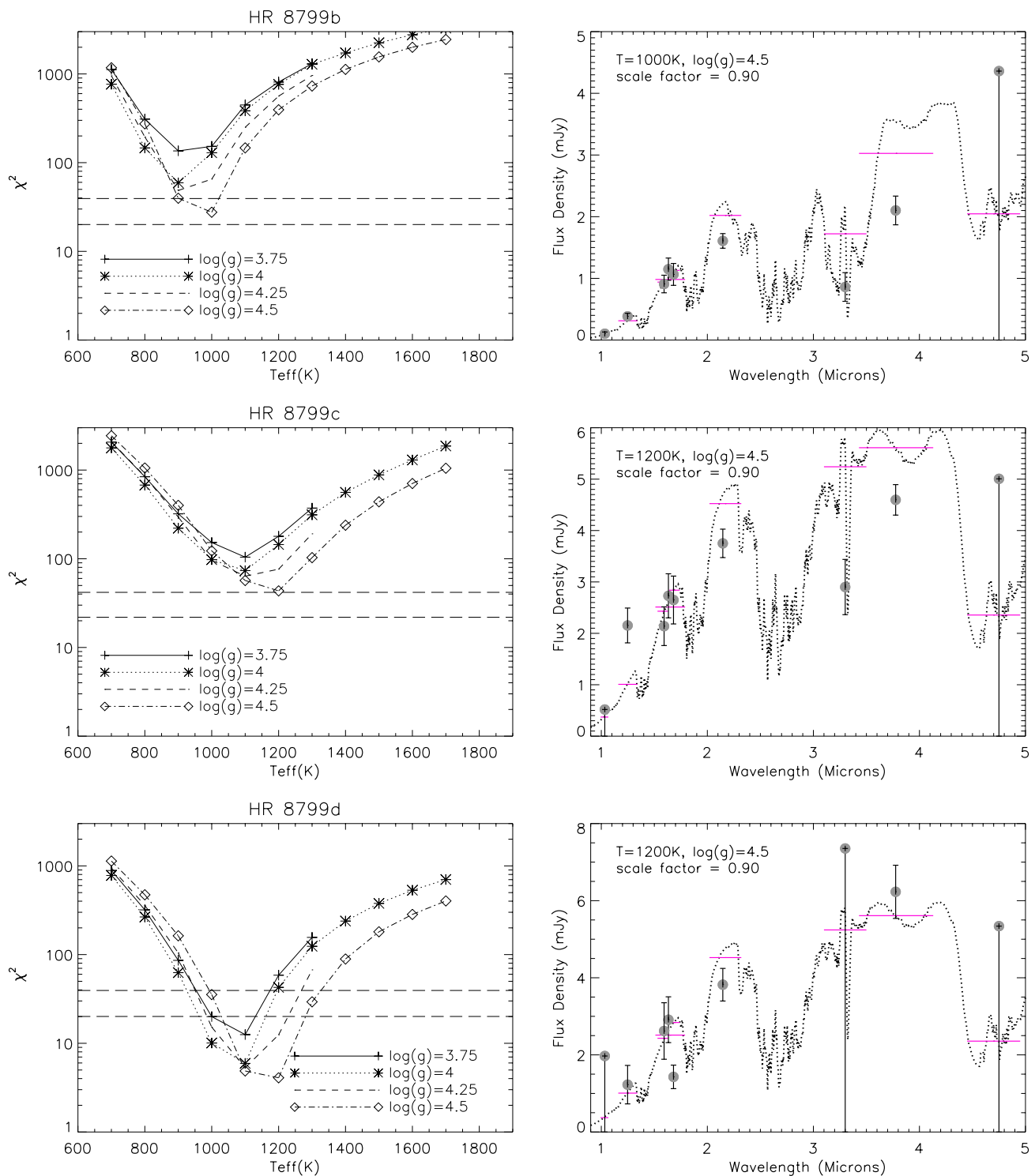


Figure 12. Same as Figure 11 except allowing the planet radius to depart by $\pm 10\%$ from the Burrows et al. (1997) values. (A color version of this figure is available in the online journal.)

L/T dwarf transition (e.g., Marley et al. 2010, and references therein).

We leave a detailed construction of such models to a future paper (Madhusudhan et al. 2011) but here we qualitatively explore how intermediate cases may affect the predicted planet spectrum (see also Marley et al. 2010). Similar to Burgasser et al. (2002), we follow a highly simplified, crude approach by combining weighted sums of Model A and E cloud prescriptions to approximate an atmosphere whose cloud thickness varies over

the seeing disk of the planet.¹⁵ For simplicity, we compare two parameterizations: a “partly cloudy” approximation where we weight the thick cloud model by 60% and a “mostly cloudy”

¹⁵ Technically, this is not physically realistic as the temperature–pressure profiles for cloud layer and cloud deck regions would be discontinuous. On the other hand, for a given T_{eff} self-consistent models with intermediate cloudiness Marley et al. (2010) have color–magnitude positions intermediate between the two extremes, broadly consistent with simple parameterizations (e.g., Burgasser et al. 2002).

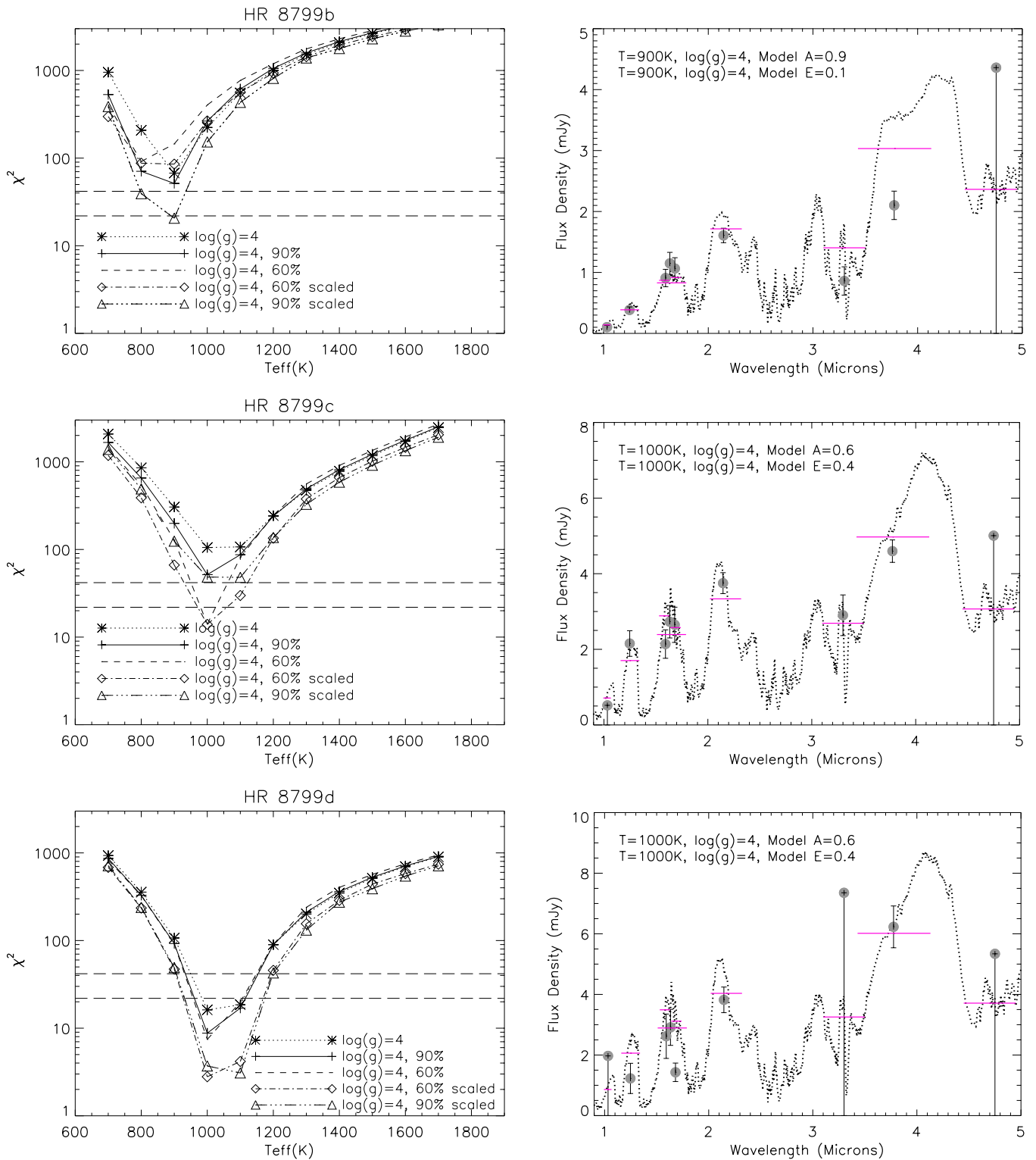


Figure 13. Fitting results for our simple approximation of a “patchy” cloud atmosphere. The displayed best-fit SEDs have $C_k = 0.9, 1,$ and 1.1 for the top-right, middle-right, and lower-right panels, respectively. (A color version of this figure is available in the online journal.)

approximation where we weight 90% of the surface by the Model A case.

Figure 13 shows modeling results for these two cases compared against the thick cloud layer results for $\log(g) = 4$ and 4.5 . Our approximations yield smaller χ^2 minima for HR 8799b and c; models with partly/mostly cloudy approximations have the

smallest χ^2 . The best-fit model for HR 8799b has $T_{\text{eff}} = 900$ K, consistent with the thick cloud layer model, while temperatures for HR 8799c and d are lower by 100 K.

While our approach is entirely ad hoc, it indicates that slightly weakening clouds compared to the limiting Model A case may provide better fits, at least for low surface gravity models

($\log(g) = 4$). Madhusudhan et al. (2011) present a set of new atmosphere models with a range of cloud coverages intermediate between the Model A and E cases to explore how varying the cloud strength between these two extremes affects fits to the data.

4. DYNAMICAL STABILITY ANALYSIS

As shown by Fabrycky & Murray-Clay (2010) and Moro-Martín et al. (2010), stability analysis of the HR 8799 system constrains the planet masses independently of planet cooling and atmospheric modeling. Here, we investigate the plausible mass range of companions imposed by dynamical stability. Later, we will combine the results of these simulations with the implied mass range from atmospheric modeling to identify planet masses consistent with both atmospheric modeling and dynamical stability analysis.

4.1. Procedure

Using the Swifter N -body code, an updated version of the Swift package (Duncan et al. 1998), we integrate the equations of motion for the HR 8799 planets. We adopt the Burlirsh–Stoer method to treat close encounters. For all simulations, we use an accuracy parameter of 10^{-12} and dynamically evolve the system until one or more planets are ejected or until 100 Myr is reached.

We expand the analysis of Marois et al. (2011) who searched for stable orbital configurations for two sets of planet masses incorporating HR 8799e—5, 7, 7, and 7 M_J ; 7, 10, 10, 10 M_J for b, c, d, and e. We assume a single-2:1 resonance between c and d for the former and a double-2:1 resonance for d–c and c–b pairs for the latter. We hereafter refer to these sets of initial conditions as Cases A and B. To expand upon the Marois et al. (2011) investigation, we considered a wider range of masses for HR 8799bcde – 10, 13, 13, and 13 M_J —with the same double resonance configuration as Case B. We refer to this set of initial conditions as Case C. In all cases, we simply require the system to be stable for 30 Myr—the minimum age of HR 8799—to be consistent with the data.

We do two sets of 8000 simulations for each case. In the first set, we allow HR 8799e to vary in separation from 13.1 AU to 15.7 AU. This allows us to identify general trends in the time to instability versus separation for HR 8799e. In the second set, we more finely sample initial orbital properties for the planets assuming a range of 14–15 AU for HR 8799e to better identify stable solutions.

4.2. Results

Figure 14 illustrates our simulation results. The top panel displays the time to instability for Case A. The bottom left and bottom right panels show the same plot for Cases B and C, respectively. The first set of simulations allowing HR 8799e to range from 13.1 AU to 15.7 AU is shown as orange lines; the second set is shown as black lines.

Our results show that the HR 8799 companions must have masses below the deuterium-burning limit *based on dynamics alone*. Case C configurations are typically only stable for 0.01 Myr and *never* stable for more than 10–20 Myr. Because HR 8799 is a main sequence star, it cannot be as young as 10–20 Myr. Therefore, companion masses for HR 8799cde \geq 13 M_J and a mass for HR 8799b \geq 10 M_J can be ruled out.

Lower planet masses are strongly preferred on dynamical grounds, consistent with the results of Marois et al. (2011). Only seven Case B configurations are stable for \sim 30 Myr, nearly all of which require separations for HR 8799e more than 1σ

different from the position implied by our astrometry. Only two are stable for 100 Myr, and these likewise require anomalously small separations. On the other hand, 60 Case A configurations are stable for 30 Myr. Three are stable for 100 Myr, one of which places HR 8799e at a separation consistent with our astrometry. Our dynamical stability results are in rough agreement with Marois et al.’s (2011) results. They find 12 solutions out of 10^5 possible solutions stable for more than 100 Myr, where HR 8799e varies between 14.35 AU and 14.56 AU. We find that 3 out of 1.6×10^4 solutions are stable for 100 Myr over this semimajor axis range.

In summary, we can rule out companion masses greater than 10 M_J for HR 8799b and 13 M_J for the others. The companions cannot be brown dwarfs. Systems with masses of 5 M_J for HR 8799b and 7 M_J for the others are characteristically far more stable than systems with larger masses. We fail to find any stable configuration with 7, 10, 10, and 10 M_J for HR 8799bcde’s masses that place HR 8799e at a position consistent with our astrometry. While our investigation is not exhaustive, it implies that masses of less than 7 M_J for HR 8799b and less than 10 M_J for the others are most plausible.

5. DISCUSSION

Our primary result in this paper is that the atmospheres of at least two and potentially all of the HR 8799 planets do not easily fit within the empirical IR color sequence for L/T-type brown dwarfs of similar temperatures, nor can they be fit well by standard atmosphere models used to infer the properties of brown dwarfs. Adopting realistic assumptions about planet radii, all atmosphere model fits to data for HR 8799b and c are far poorer than any meaningful threshold identifying models consistent with the data. The models primarily fail by underpredicting the 3.3 μm flux and badly overpredicting flux at 1–1.3 μm .

Our analysis suggests that having “thicker” clouds—ones with larger vertical extents—is key to reproducing the planets’ SEDs. Compared to cloud structures assumed in standard L/T dwarf atmosphere models, these clouds are more optically thick at a given T_{eff} , so they are visible (in the photosphere) at a lower T_{eff} even though the cloud base is located far below at much higher pressures. Adopting a thick cloud layer prescription, we succeed in identifying models for each planet that quantitatively are good-fitting models. Moreover, the temperatures of these models are consistent with simpler, presumably more accurate cooling model estimates.

5.1. Comparisons with Previous Studies of HR 8799

The most direct comparison to this work is the recent analysis of the HR 8799b K -band spectrum and 1.1–4.1 μm photometry from Bowler et al. (2010) whose modeling formalism we largely follow. Bowler et al. (2010) also find difficulties in using standard atmosphere models to fit HR 8799b’s SED and interpret its properties (see also Marois et al. 2008). Likewise, they find that temperatures inferred from standard atmosphere models disagree with cooling model predictions and that the former require unphysically small radii.

Our results indicate that including Y/z -band data only exacerbates the already serious disagreement between standard cloud deck model predictions and the planet’s SED. Our analysis confirms Bowler et al.’s (2010) inference that HR 8799b’s atmosphere is exceptionally dusty compared to field brown dwarfs. Our results extend this inference, indicating that HR 8799c and,

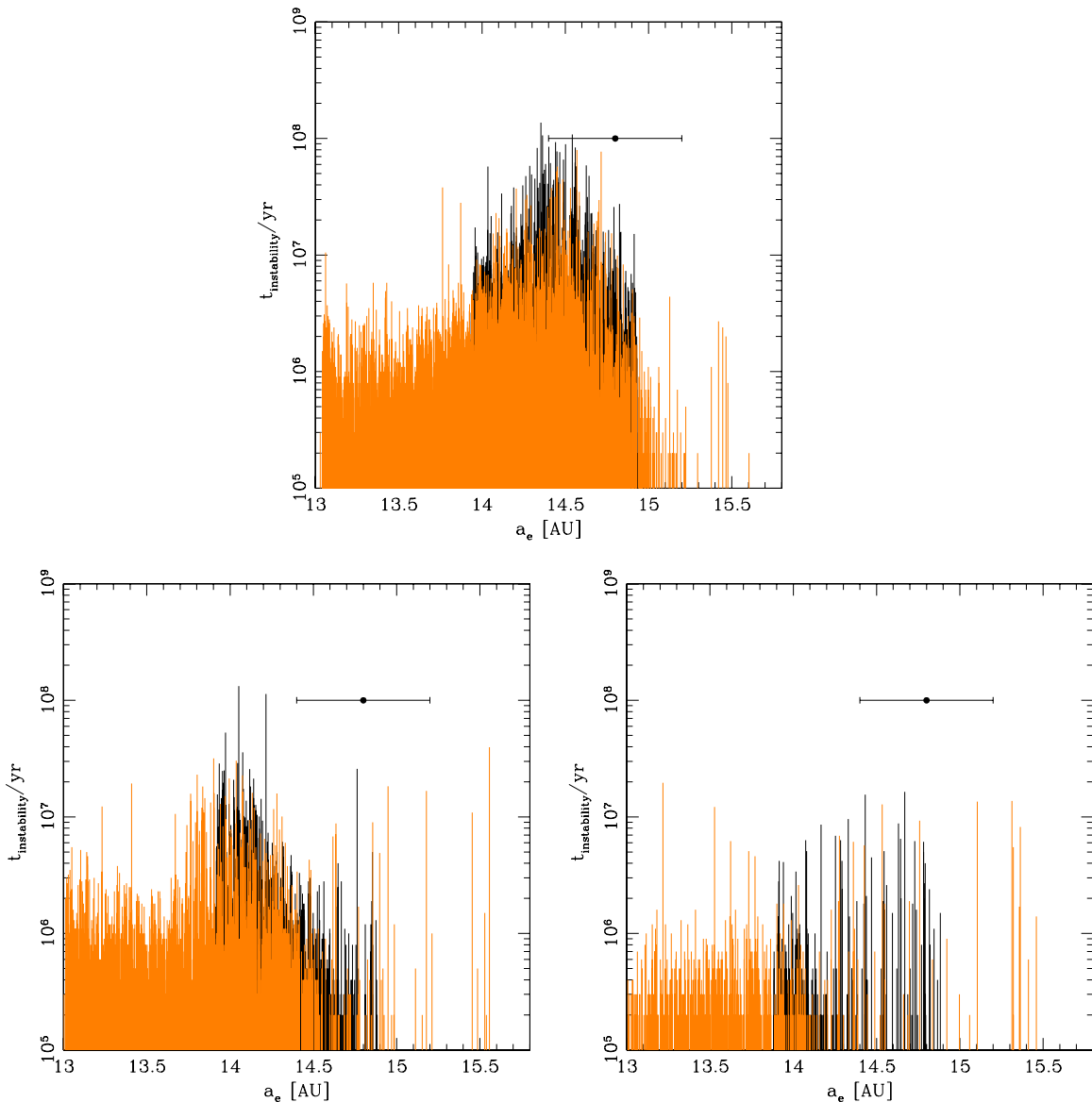


Figure 14. Time to dynamical instability vs. semimajor axis of HR 8799e for three separate sets of masses and orbital resonances. In all plots, the orange lines denote our set of simulations allowing HR 8799e to vary between 13.1 AU and 15.7 AU, while the black lines denote our simulations that restrict HR 8799e to be between 14 and 15 AU while more finely sampling the range of other orbital parameters (e.g., mean anomaly, longitude of periastron). The horizontal dot with error bars identifies the 1σ range of projected separations for HR 8799e from our work. In Case A (top panel), HR 8799bcde have masses of 5, 7, 7, and 7 M_J . Case B (bottom left) corresponds to planet masses of 7, 10, 10, and 10 M_J and Case C (bottom right) correspond to 10, 13, 13, and 13 M_J . The density of the bars appears anomalously low for Case C because many simulations have instability times less than 10^5 yr.

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

plausibly, HR 8799d are also dusty compared to field brown dwarfs.

Janson et al. (2010) noted that while standard atmosphere models—the COND models in their case—can reproduce the mean brightness of HR 8799c’s L' -band spectrum they incorrectly predict the spectral slope from $3.9\ \mu\text{m}$ to $4.5\ \mu\text{m}$. They cite greater atmospheric dust absorption and, especially, non-equilibrium carbon chemistry as features that may bring the models into better agreement. Hinz et al. (2010) argue that incorporating non-equilibrium chemistry is necessary to reproduce the mid-IR photometry of HR 8799bcd since the chemical equilibrium models they use Saumon et al. (2006) predict M -band fluxes larger than the upper limits they report.

Non-equilibrium carbon chemistry has little effect on the near-IR portion of the SED (e.g., Hubeny & Burrows 2007). Thus, our analysis indicates that thicker clouds—and, by im-

plication, stronger atmospheric dust absorption—are far more important than non-equilibrium chemistry in reproducing the HR 8799 planet $1\text{--}5\ \mu\text{m}$ SEDs. Nevertheless, the HR 8799 planet atmospheres are plausibly not in local chemical equilibrium. Since departures from chemical equilibrium alter the spectral structure at $4\text{--}5\ \mu\text{m}$, non-equilibrium chemistry incorporated into thick or “patchy” cloud models may yield better fits to $1\text{--}5\ \mu\text{m}$ photometry and mid-IR spectroscopy of the planets. Higher signal-to-noise L' -band spectra and detections/more stringent upper limits at M will better identify evidence of non-equilibrium chemistry in the planets’ atmospheres.

5.2. Comparisons with Planet Evolution Models and Implied Masses

Within the context of the Burrows et al. (1997) planet cooling models, a particular combination of $\log(g)$ and T_{eff} defines

an object with a mass M and age t . Taking the gravity and temperature range implied by our modeling at face value, we can then identify the mass and age range implied. Our modeling efforts succeed in yielding planets with physically realistic radii. However, if our range of $\log(g)$ and T_{eff} were to imply wildly discrepant masses compared to cooling model estimates and dynamical stability requirements or widely varying ages our analysis would have solved one problem only to create comparably serious ones.

Here, we combine all modeling results to identify the range of best-fit parameters and implied parameters—mass and age—from atmosphere models that we consider.

We then determine whether the atmospheric and dynamical modeling constraints are consistent and, if so, what mass and age range they imply.

1. *HR 8799b*. The minimum χ^2 value for HR 8799b for thick cloud models is 27.6 if we allow the radius to vary by up to 10% from the Burrows et al. (1997) values and 48.9 if we do not. For the “patchy” cloud approximation, the corresponding χ^2 minima are 20.6 and 51.4. Considering the best-fit models passing the $\Delta\chi^2$ threshold in each case, this range covers $\log(g) = 4\text{--}4.5$ and $T_{\text{eff}} = 800\text{--}1000$ K. Thus, our modeling yields $\log(g) = 4\text{--}4.5$, $T_{\text{eff}} = 800\text{--}1000$ K. Using the Burrows et al. (1997) evolutionary models, this implies a mass and age range of $M, t = 5 M_J, 30$ Myr to $15 M_J, 300$ Myr.
2. *HR 8799c, d, and e*. The minimum χ^2 values here for thick cloud models are 43.5 and 60.7 for c and 5.7 and 5.3 with and without radius rescaling. For the “patchy” cloud approximation, the corresponding χ^2 minima are 14–14.1 for c and 2.8–7.4 for d. For HR 8799c, the range of models passing the $\Delta\chi^2$ threshold for the thick and patchy cloud prescriptions cover $\log(g) = 4\text{--}4.5$ and $T_{\text{eff}} = 1000\text{--}1200$ K. This yields a mass/age range of $7 M_J, 30$ Myr to $15\text{--}17.5 M_J$ at $150\text{--}300$ Myr. For HR 8799d, the range is $\log(g) = 3.75\text{--}4.5$, $T_{\text{eff}} = 1000\text{--}1200$ K, yielding $5 M_J$ at 10 Myr to $15\text{--}17.5 M_J$ at $150\text{--}300$ Myr. Since HR 8799e likely has a bolometric luminosity and $K - L$ colors comparable to HR 8799c and d, its range of masses is plausibly consistent with those derived for HR 8799c and d.

Dynamical constraints require that HR 8799b is less than $7 M_J$ and HR 8799cde are less than $10 M_J$ (Section 4 of this work; Marois et al. 2011). The $5 M_J$ mass estimate for HR 8799d can be ruled out because the primary star is on the main sequence and thus cannot be 10 Myr old. Coupled with the range in surface gravities and temperatures, the implied ranges in masses are then $6\text{--}7 M_J$ for HR 8799b, $7\text{--}10 M_J$ for HR 8799c, and $7\text{--}10 M_J$ for HR 8799 d. If HR 8799e’s atmospheric properties mirror those of c and d, its plausible range of masses is also $7\text{--}10 M_J$. Conversely, for these ranges of masses, the surface gravities of HR 8799bcde should be no greater than $\log(g) \approx 4.25$.

These estimates are consistent with cooling model estimates from Marois et al. (2008, 2011). For the lower end of the mass ranges, the system age corresponding to these models is ≈ 30 Myr and puts HR 8799’s age on the low end of the $30\text{--}160$ Myr range quoted by Marois et al. (2008). The (disfavored) high end of the mass range corresponds to ~ 100 Myr old objects.

Despite our success in arriving at self-consistent answers for the planets’ masses and ages, we strongly caution against overinterpreting these results. Our results do not *prove* that, above the cloud base, the vertical density/pressure profile of

clouds follows that of the gas as a whole (e.g., $s_1 = 0$), as opposed to being truncated at higher pressures. Neither do our results prove that other models with slightly different assumptions about the clouds, grain particles, atmospheric chemistry, etc., provide better fits to the data. In particular, slight modifications to our models may improve the fit at L' band, the data point responsible for much of the χ^2 contribution for HR 8799b. Even within the context of our adopted physical models, our sampling in temperature and gravity is also too coarse to precisely estimate best-fit atmosphere parameters.

On the other hand, our analysis provides compelling evidence for thick clouds, motivates future modeling work to test how different assumptions about thick clouds affect model fits to planetary atmospheres, and encourages further observations of substellar objects to test these models. Madhusudhan et al. (2011) will develop and better assess model fits for varying cloud strengths and more precisely and accurately determine temperatures and gravities for the HR 8799 planets and other planetary-mass objects.

5.3. Constraints on the Formation of the HR 8799 Planetary System

The planets’ large masses and wide orbits make them a particularly interesting probe of planet formation. The favored theory invoked to explain the formation of gas giant planets is *core accretion* (e.g., Mizuno 1980; Pollack et al. 1996; Kenyon & Bromley 2009; Chambers et al. 2010), where cores that have grown to $\approx 5\text{--}10 M_{\oplus}$ rapidly accrete much more massive gaseous envelopes. Alternatively, planets could form by disk instability (Boss 1997, and later papers), where the protoplanetary disk is massive and gravitationally unstable, forming multiple self-gravitating clumps of gas that coalesce into bound, planet-mass objects.

HR 8799’s planets are often described as confounding either planet formation model (e.g., Marois et al. 2011) or being clear examples of disk instability-formed planets, as claimed by Dodson-Robinson et al. (2009). They find that cores at distances characterizing the HR 8799 planets cannot reach $\sim 10 M_{\oplus}$ in mass to undergo runaway gas accretion *even under the most favorable conditions*. They claim that planet–planet scattering cannot create stable, wide-orbit systems like HR 8799’s. They conclude that massive, wide-separation gas giants like HR 8799bcd form by disk instability and “can certainly rule out core accretion.”

Critical to Dodson-Robinson et al.’s conclusion is their treatment of the core growth rate. The growth rate strongly depends upon the planetesimal approach velocity, which they fix at $v_a = \Omega R_{\text{hill}}$. They claim this velocity yields an “optimistically high” growth rate. Their formalism implicitly assumes that planetesimals have an isotropic velocity dispersion ($v_a \sim v_z$), which is valid as long as the scale height of planetesimals accreted by cores (v_z/Ω) is larger than the core’s impact parameter, $R_{\text{core}}\sqrt{1+\theta}$ (Rafikov 2004), where θ is the Safronov number. However, if the planetesimals are dynamically cold such that $v_z \leq \sqrt{p}\Omega R_{\text{hill}}$ (where $p = R_{\text{core}}/R_{\text{hill}}$), this condition is violated (Dones & Tremaine 1993; Rafikov 2004). The core can then accrete the entire vertical column of planetesimals at a vastly higher rate since accretion is now essentially two dimensional (Rafikov 2004).

As a result, Dodson-Robinson et al. (2009) catastrophically underestimate the maximum growth rate by a factor of $p^{-1/2}$, or up to 114, 85, and 68 at the positions of HR 8799b, c, and d (cf. Equations (78), (80), and (82) in Rafikov 2004; see

also Rafikov 2011).¹⁶ Detailed numerical simulations confirm that this rapid growth phase can be reached if collisional fragmentation and gas drag are properly treated (Kenyon & Bromley 2009). The Dodson-Robinson et al. planet–planet scattering simulations also were conducted assuming gas free, planetesimal-free conditions and assumed that planets could not further grow after scattering. However, gas drag and dynamical friction from planetesimals are critically important as they promote orbit circularization and stability (e.g., Goldreich et al. 2004; Ford & Chiang 2007).¹⁷ Cores with masses sufficient for rapid gas accretion can circularize after being scattered to the outer disk (Bromley & Kenyon 2011; S. Kenyon 2010, private communication). Simulations by E. Thommes et al. (2011, in preparation) show that the HR 8799 planet cores could acquire most of their gas *after* scattering.

The mass ratio and semimajor axis distribution of wide planets and low-mass brown dwarfs may help constrain the formation mechanism for HR 8799’s planets (Kratter et al. 2010). Core accretion preferentially forms planets with smaller masses and orbital separations, while disk instability has difficulty producing lower-mass gas giants and forming them close to the star (e.g., Rafikov 2005; Kratter et al. 2010). Therefore, if HR 8799bcde formed by core accretion (disk instability), they should comprise the high-mass extrema (low-mass tail) of a population continuous with radial-velocity-detected planets (brown dwarf companions). Using our new results for the masses of the HR 8799 planets, we update Kratter et al.’s plot comparing planet and brown dwarf distributions. We also add the planet-mass companions to IRXJS1609.1-210524, and 2M J044144b (Todorov et al. 2010; 5–10 M_J , 15 AU); the planet/brown dwarf companion to GSC 06214-00210B (14 M_J , ~300 AU; Ireland et al. 2011); and the low-mass brown dwarf companion GJ 758B (25–40 M_J , 44 AU; Currie et al. 2010).

As shown by Figure 15, the revised masses for the HR 8799 planets and the addition of HR 8799e expand the space between them and brown dwarf companions (asterisks). Visually, they join with the distribution of closer-separation planets plausibly formed by core accretion. The other new companions (red triangles) are continuous with brown dwarfs that may form by disk fragmentation.

While core accretion—especially when coupled with planet–planet scattering—may form the HR 8799 planetary system, HR 8799-like systems are still plausibly uncommon. The Gemini Deep Planetary Survey of 85 nearby, young (mostly solar-mass) stars was typically sensitive to 2 M_J planets at 40–200 AU yet failed to detect any (Lafreniere et al. 2007b). Similarly, nondetections from the deep ($M < 1 M_J$) survey from Kasper et al. (2007) showed that the giant planet populations detected at small separations ($a \lesssim 4$ AU) by RV surveys cannot extend to separations larger than ~30 AU. More massive stars like HR 8799 likely have more massive disks, which aid gas giant planet formation. However, their disks also dissipate much more rapidly (Currie et al. 2009): even if critical core masses are

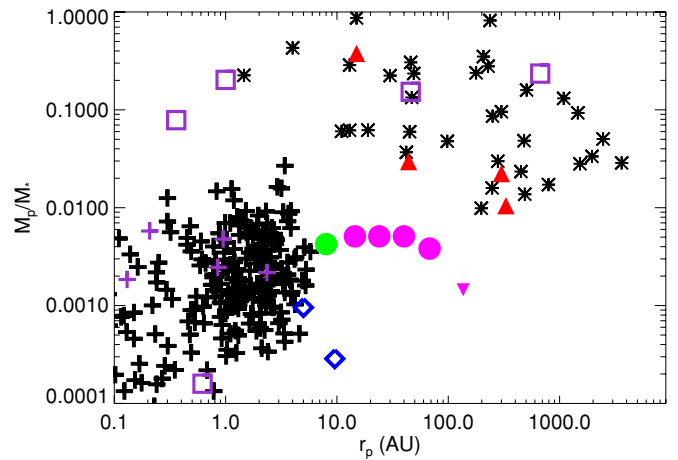


Figure 15. Updated version of the mass ratio vs. orbital separation plot from Kratter et al. (2010) incorporating our revised masses for HR 8799bcd (magenta dots). We also include HR 8799e, assigned a mass of 7 M_J from Marois et al. (2011), and displayed as the leftmost magenta dot. The β Pic planet is specifically identified as a green dot (Lagrange et al. 2010). Fomalhaut b is a downward-pointing magenta triangle (Kalas et al. 2008; Chiang et al. 2009). Substellar companions discovered after or not included in the Kratter et al. (2010) publication—IRXJS1609.1-210524, GJ 758B, 2M J044144b, and GSC 06214-00210B—are plotted as red triangles. Black crosses, purple crosses, and purple squares denote radial velocity, transit, and microlensing-detected planets around stars with three mass bins: $M_* \geq 0.4 M_\odot$, $M_\odot = 0.1\text{--}0.4 M_\odot$, and $M_* < 0.1 M_\odot$. For direct comparisons and simplicity, we plot the same population of exoplanets *not* detected by direct imaging as that used by Kratter et al. (2010; e.g., we do not include planets discovered by RV or transits since the publication of this paper). Black asterisks denote the sample of substellar companions listed in Zuckerman & Song (2009). Jupiter and Saturn are plotted as blue diamonds.

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

reached, the leftover mass of gas may be small. Moreover, rapid core growth results from being able to fragment and then dynamical cool the surrounding planetesimal population. The current state-of-the-art simulations show that this requires Pluto-mass cores to start with (e.g., Kenyon & Bromley 2009), yet the formation time for Pluto-mass objects at wide separations may be long (e.g., Rafikov 2011). Thus, forming HR 8799-like systems by core accretion is difficult, though *not* impossible, and probably happens infrequently.

5.4. Implications for the Atmospheres of Other Substellar Companions: A Possible Fundamental Difference Between Planetary-mass Objects and $M > 15\text{--}20 M_J$ Brown Dwarfs

In some ways, the difficulty in reproducing the IR SEDs of the HR 8799 planets mirrors difficulties in modeling other planetary-mass objects detected prior to HR 8799bcde. In particular, 2M 1207b also appears discrepant compared to standard atmosphere models as noted in Mohanty et al. (2007) and discussed in this work. Like HR 8799b, 2M 1207b is noticeably underluminous (~2.5 mag) in the near-IR (Mohanty et al. 2007, this work).

To explain 2M 1207b’s properties, Mohanty et al. (2007) propose that the object is occulted by an edge-on disk with large, gray dust grains. Alternatively, Mamajek & Meyer (2007) propose that 2M 1207b’s properties can be explained as resulting from a recent protoplanet–protoplanet collision. Comparing high-resolution spectra of 2M 1207b to the DUSTY atmosphere models from Allard et al. (2001), Patience et al. (2010) identify a problem similar to that noted for modeling HR 8799b from Bowler et al. (2010) and this work. Namely, allowing the object

¹⁶ At first glance, Equation (17) in Rafikov (2011) appears to imply that the limiting distance for core accretion in shear-dominated growth is comparable to Dodson-Robinson et al.’s estimate (44 AU versus their 20–35 AU). However, Rafikov’s result of 44 AU is valid for a Minimum Mass Solar Nebula case (Hayashi 1981). Adopting initial assumptions more comparable to those that Dodson-Robinson et al. assume—e.g., a disk more massive than the Minimum Mass Solar Nebula or a longer-lived one with $\tau_{\text{disk}} = 5$ Myr instead of 3 Myr—implies that gas giants can in some cases form by core accretion at separations comparable to HR 8799c and b.

¹⁷ In fairness, they clearly acknowledge that their study does not consider planet–planet scattering in a gaseous disk, which may result in a more favorable outcome for core accretion.

radius to freely vary yields best-fit radii far smaller ($\approx 0.5 R_J$) than is physically plausible (cf. Burrows et al. 1997). Patience et al. (2010) also conclude that extinction from an edge-on disk comprised of gray dust grains is also a viable scenario.

For the same reasons—underluminosity/red colors—a disk origin also has been proposed to explain the IR SED of HR 8799b and (to a lesser extent) c and d (Marois et al. 2008). However, Marois et al. (2008) consider the chance alignment of an edge-on circumplanetary disk to be unlikely, especially given that the system is viewed nearly face on. Even more unlikely is the chance that circumplanetary disks or recent protoplanet collisions explain the near-IR properties of two to four separate planets in two systems with very different ages and primary star properties.

Given the success in better reproducing HR 8799bcd’s SEDs with thick cloud models and the similarity between HR 8799b and 2M 1207b, it is more plausible that the latter’s near-IR spectrum is likewise explained by thick clouds. If this is generally true of planetary-mass objects, thicker clouds may constitute the primary difference between the atmospheres of massive planets and brown dwarfs, at least over the gravity and temperature range enclosed by the HR 8799 planets and 2M 1207b (e.g., $\log(g) = 3.75\text{--}4.5$, $T_{\text{eff}} = 900\text{--}1600$ K). Since thicker clouds affect the color–magnitude positions of substellar objects it is quite possible the Model A “thick cloud” sequence extending to HR 8799b and 2M 1207b from the nominal L/T dwarf boundary continues on to even cooler temperatures (e.g., $T_{\text{eff}} \sim 700\text{--}900$ K). Since thick clouds present reshape the spectral structure at $\sim 1.6 \mu\text{m}$ (e.g., in the methane band), they may also affect the L/T dwarf transition, which is already known to be dependent upon surface gravity (e.g., Metchev & Hillenbrand 2006; Luhman et al. 2007).

5.5. Future Work

Our study motivates the development of a suite of new atmosphere models with clouds intermediate in thickness between the Model E cloud deck and Model A thick cloud layer prescriptions. Adopting these models as fiducial models, we can revisit the (secondary) effects of surface gravity, metallicity, and non-equilibrium chemistry on the atmospheres of planetary-mass objects, complementing similar investigations for brown dwarfs (Allard et al. 2001; Marley et al. 2002; Burrows et al. 2006; Hubeny & Burrows 2007). These models will be developed and applied to HR 8799bcde and other planetary-mass objects in upcoming papers (Madhusudhan et al. 2011) and may provide a useful comparison to planet parameters derived from cooling models (e.g., Burrows et al. 1997; Baraffe et al. 2003; Fortney et al. 2007, 2008).

New observations at $1\text{--}5 \mu\text{m}$ will provide better constraints on the HR 8799 planet atmospheres. In addition to more sensitive data at *Y* band and [3.3], Figure 9 (lower left panel) implies that thick cloud atmospheres may have *far* stronger emission at $\sim 2.3 \mu\text{m}$ and $3.0 \mu\text{m}$ than standard models predict. This wavelength range can be probed for at least HR 8799bcd by current ground-based facilities such as VLT/NaCo, Keck/NIRC2, and MMT/Clio. Integral field spectrographs on *Gemini Planet Imager* (*GPI*; MacIntosh et al. 2008) and *SPHERE* (Beuzit et al. 2008) will sample the $1\text{--}2.5 \mu\text{m}$ SED region with exceptional sensitivity and thus provide a detailed comparison between observed and predicted atmospheric properties of all planets.

Finally, ongoing collaborations such as the IDPS survey (C. Marois et al. 2011, in preparation) and *Gemini/NICI* (Liu et al. 2010) will better probe the frequency of wide,

massive ($\sim 5\text{--}13 M_J$, >30 AU) around nearby stars. *GPI* and *SPHERE* will probe $1\text{--}5 M_J$ planets at even smaller separations (e.g., $5\text{--}30$ AU). These surveys will produce a far more complete census of Jupiter-mass planets to better determine their ubiquity and constrain how the formation of planets like HR 8799’s compare to that expected for lower-mass planets at smaller separations and wide-separation, low-mass brown dwarfs.

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