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A DIRECT DISTANCE AND LUMINOSITY DETERMINATION FOR A SELF-LUMINOUS GIANT EXOPLANET: THE TRIGONOMETRIC PARALLAX TO 2MASSW J1207334−393254Ab

B. A. BILLER[1] AND L. M. CLOSE[1]

ABSTRACT

We present the first trigonometric parallax and distance for a young planetary mass object. A likely TW Hya cluster member, 2MASSW J1207334−393254Ab (hereafter 2M1207Ab), is an M8 brown dwarf with a mid-to-late L-type planetary mass companion. Recent observations of spectral variability have uncovered clear signs of disk accretion and outflow, constraining the age of the system to <10 Myr. Because of its late spectral type and the clearly youthful nature of the system, 2M1207b is very likely a planetary mass object. We have measured the first accurate distance and luminosity for a self-luminous planetary mass object. Our parallax measurements are accurate to <2 mas (1 σ) for 2M1207Ab. With 11 total epochs of data taken from 2006 January through 2007 April (475 images for 2M1207Ab), we determine a distance of 58.8 ± 7.0 pc ($17.0^{+2.3}_{-1.8}$ mas, 1.28 σ) to 2M1207Ab and a calculated luminosity of (0.68–2.2) × 10^{-5} $L_\odot$ for 2M1207b. Hence, 2M1207Ab is a clear member of the TW Hya cluster in terms of its distance, proper motions, and youthful nature. However, as previously noted by Mohanty and coworkers, 2M1207b's luminosity appears low compared to its temperature according to evolutionary models.

Subject headings: astrometry — planetary systems — stars: low-mass, brown dwarfs

Online material: color figure

1. INTRODUCTION

A very likely member of the ∼8 Myr TW Hydrae association (at distances of 35–70 pc; Mohanty et al. 2003; Mamajek 2005), 2MASSW J1207334−393254A (hereafter 2M1207A) is a young M8 brown dwarf with a late L companion (2M1207b; Chauvin et al. 2004; spectral type from Mohanty et al. 2007). Recent observations of spectral variability (Scholz & Jayawardhana 2006) have revealed accretion and jetlike features, constraining the age of the system to <10 Myr; with such a young age and low temperature, 2M1207b is very likely a planetary mass object.

Interestingly, previous distance estimates for this object have produced somewhat conflicting results. Using the measured K-band magnitudes and extrapolating a K-band absolute magnitude for an 8 Myr brown dwarf (from trends in Song et al. 2003), Chauvin et al. (2004) estimated a photometric distance of ∼70 pc at the outer edge of TW Hya from their extrapolated distance modulus. At this age and distance, the models of Baraffe et al. (2002) predict that the M8 dwarf should have a mass of 25 $M_{\rm Jup}$ and the companion should have a mass of ∼5 $M_{\rm Jup}$. Mamajek (2005) estimates a theoretical moving cluster distance to 2M1207 of 53 ± 6 pc and infers masses for 2M1207A and b (with an age of 8 Myr) of ∼21 and ∼3–4 $M_{\rm Jup}$ respectively. From precision *HST* proper motions, Song et al. (2006) also estimate a similar moving cluster distance −59 ± 7 pc and hence similar masses. However, using these closer distance estimates, 2M1207A becomes underluminous and falls nearer the locus of the (120 Myr) Pleiades on a color-magnitude diagram (Fig. 1), which is inconsistent with an object age of <10 Myr at ∼50 pc. Recently, Mamajek & Meyer (2007) have revised the estimated theoretical moving cluster distance to 2M1207 to 66 ± 5 pc. Thus, a direct distance measurement via parallax would help clarify this situation and would also constrain a number of important properties for this object. Since the youth (<10 Myr) and hence low-mass nature ($M < 13$ $M_{\rm Jup}$) of 2M1207b has recently been confirmed, we have also measured the first accurate luminosity for a self-luminous planetary mass object.

[1] Steward Observatory, University of Arizona, Tucson, AZ 85721; bbiller@as.arizona.edu.

2. OBSERVATIONS AND DATA REDUCTION

We have acquired 11 epochs of data stretching from 2006 January to 2007 April with ANDICAM at the SMARTS 1.3 m telescope on Cerro Tololo. Both 2M1207 and the standard object LHS 2397a (an M8 dwarf with an L7.5 brown dwarf companion with a well-known parallax of 62.3 ± 4.0 mas; Tinney 1996) were observed for 40 minutes over transit. Observations were repeated over multiple nights bracketing the new moon each month. Over the entire observing period, 475 I-band data frames with per frame exposure time of 300 s were acquired for 2M 1207, and 491 I-band data frames were acquired for LHS 2397a.

The M8 primary of 2M1207 has $I = 15.8$ (Scholz et al. 2005), so parallax can be determined in the visible. The L5-9.5 secondary of 2M1207 has $K = 16.9$ (Chauvin et al. 2004), is even fainter in the visible ($I > 19$), and lies within 0.8″ of its primary; thus, it is essentially invisible to the 1.3 m in the optical (and is not apparent in our images). Its presence does not affect our attainable astrometric precision. LHS 2397a is comparably bright as 2M1207 and was chosen as a standard object due to the fact that both are late M dwarf+mid- to late- L dwarf binaries (Freed et al. 2003). Our measurement of the parallax of LHS 2397a (previously found to be 62.3 ± 4.0 mas; Tinney 1996) serves as a test of our observational and data reduction procedures. Each target object was always placed at 82 pixels east and 148 pixels north of the center of the chip at pixel (330, 660). A number of bright stars lie right outside the LHS 2397a field; we chose to place our target objects in the upper left quadrant of the chip as opposed to the center of the chip in order to keep these bright stars and their saturation bleeds off of the CCD.

A dedicated parallax data analysis pipeline was used to reduce these data. This pipeline aligns each data frame to a master frame, removes cosmic rays, and performs PSF fitting photometry for 139 stars per frame using the DAOphot allstar task (Stetson 1987). The ANDICAM optical detector is a Fairchild 447 2048 × 2048 CCD and was used in 2 × 2 binning mode, yielding a nominal plate scale of 0.369 arcsec pixel^{-1} (ANDICAM Web site). Five bright stars in different parts of the field were used to calibrate x and y plate-scale changes on the CCD. The separations between
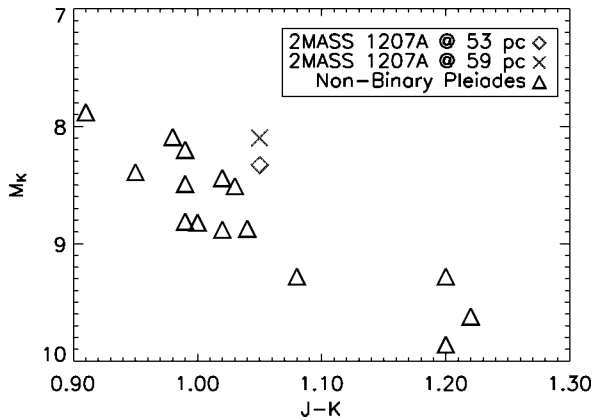
FIG. 1.—M_K vs. $J - K$ H-R diagram. Previous distance estimates for 2M1207A have led to a number of inconsistencies. J and K magnitudes are taken from the 2MASS survey. Triangle points are nonbinary Pleiades members from Martín et al. (2000). At the Mamajek (2005) moving cluster distance of 53 pc, 2M1207A falls very close to the locus of the Pleiades (120 Myr). This is inconsistent with the age of <10 Myr for this object unless this object is extincted by circumstellar dust. At a distance of 59 pc, 2M1207A is considerably above the locus of the Pleiades, consistent with an age of <10 Myr. [*See the electronic edition of the Journal for a color version of this figure.*]

the five plate-scale calibration stars were measured for each data frame and then normalized to the average value over all frames. These normalized values were used as frame-by-frame plate-scale corrections. We found plate-scale variations of less than 0.06% over the ~1.5 yr time baseline of our observations.

The position of 2M1207 and LHS 2397a in R.A. and decl. as a function of time is shown in Figure 2. Many reference stars as bright or brighter than the target are available in both the 2M1207 and LHS 2397a fields; thus, we have a good distribution of baselines around both objects from which to calculate parallax. The positions of 2M1207 and LHS 2397a were measured relative to 40 and 15 reference stars, respectively.

To correct for a slightly variable x and y "pincushion" distortion (first derivative of the x and y plate scale) on the chip, we measured the apparent motion on the sky for the five stars nearest 2M1207 on the chip. These stars are faint and likely significantly behind 2M1207 and thus presumed background, so the motion observed for these should calibrate the local distortion of the chip near our target. Two of these stars showed apparent space motions of their own and were thus discarded. The motions from the remaining three stars were then averaged together to create a first derivative plate-scale correction curve. This correction curve was then subtracted from the measured parallax curve for 2M1207. A similar correction was also performed for the LHS 2397a data.

To determine the trigonometric parallax to 2M1207 and LHS

2397a, we fit (least-squares fit) our measured parallax data to a parallax and proper motion model for each data set. Precise *HST* proper motions for 2M1207 of $\mu_\alpha = -60.2 \pm 4.9$ and $\mu_\delta = -25.0 \pm 4.9$ mas yr^{-1} were adopted from Song et al. (2006). Proper motions for LHS 2397a of $\mu_\alpha = -508.0 \pm 20.0$ and $\mu_\delta = -80.0 \pm 20.0$ mas yr^{-1} were adopted from Salim & Gould (2003). Fits were performed both holding proper motion fixed and also fitting to proper motion; for both 2M1207 and LHS 2397a we retrieve the published proper motions to within the published errors. We find that the error in published proper motion is negligible compared to per frame measurement errors. The error in each nightly parallax measurement was calculated from the rms of measurements taken over that night. Measurements from late 2006 (2006.9–2007.1 epoch) were discarded since these data were taken off transit and thus suffer considerably from differential color refraction (see, e.g., Dahn et al. 2002).

In order to estimate the error in our trigonometric parallax measurement, a Monte Carlo ensemble of 10,000 data sets was simulated by multiplying our measured position errors by a random number distribution pulled from a Gaussian distribution, then adding that random error to the measured position. An error-free trigonometric parallax model was then fitted and χ^2 minimized to each of these simulated observations. The adopted distance is the mean of this 10,000 simulated observation distribution of fits, and the adopted error is 1.28 times the standard deviation of this distribution, corresponding to an 80% confidence interval. Histograms of the distributions of observation fits are presented in Figure 3.

We estimate a correction from relative to absolute parallax of 1.2 ± 0.9 mas, based on I-band photometry of 40 reference stars for 2M1207 and 15 reference stars for LHS 2397a. This correction was obtained by adopting an average spectral type of M0 for our relatively faint field reference stars ($I = 15–18$ mag), calculating photometric parallaxes for each reference star, and then employing the median photometric parallax of the reference stars as the estimated correction.

3. RESULTS AND DISCUSSION

For 2M1207Ab, we acquired a best-fit relative parallax of $15.8^{+2.1}_{-1.6}$ mas, corresponding to an absolute parallax of $17.0^{+2.3}_{-1.8}$ mas and a best-fit distance of 58.8 ± 7.0 pc (all 1.28 σ errors). For our standard LHS 2397a, we acquired a best-fit relative parallax of $66.7^{+5.2}_{-4.6}$ mas, corresponding to an absolute parallax of $67.9^{+5.3}_{-4.7}$ mas (similar to the previous result of 62.6 ± 4.0 mas; Tinney 1996) and a best-fit distance of 14.7 ± 1.0 pc. Fewer reference stars were available for the LHS 2397a standard object
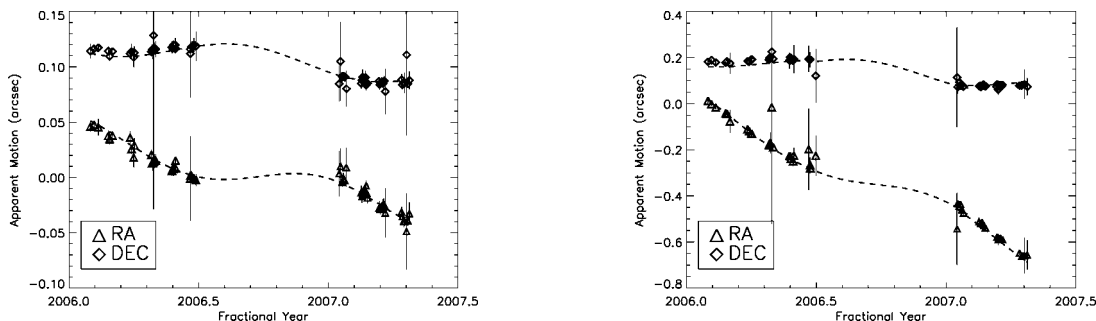

FIG. 2.—R.A. and decl. measured relative motion curves (before absolute parallax correction) for 2M1207A (*left*) and LHS 2397a (*right*). The dashed lines represent the 15.8 mas/63 pc relative parallax best-fit model for 2M1207A and the 66.7 mas/15 pc relative parallax best-fit model for LHS 2397a. Correcting for absolute parallax, we find an absolute parallax of $17.0^{+2.3}_{-1.8}$ mas and a best-fit distance of 58.8 ± 7.0 pc (all 1.28 σ errors) for 2M1207A and an absolute parallax of $67.9^{+5.3}_{-4.7}$ mas (similar to the previous result of 62.6 ± 4.0 mas; Tinney 1996) and a best-fit distance of 14.7 ± 1.0 pc for our standard LHS 2397a.
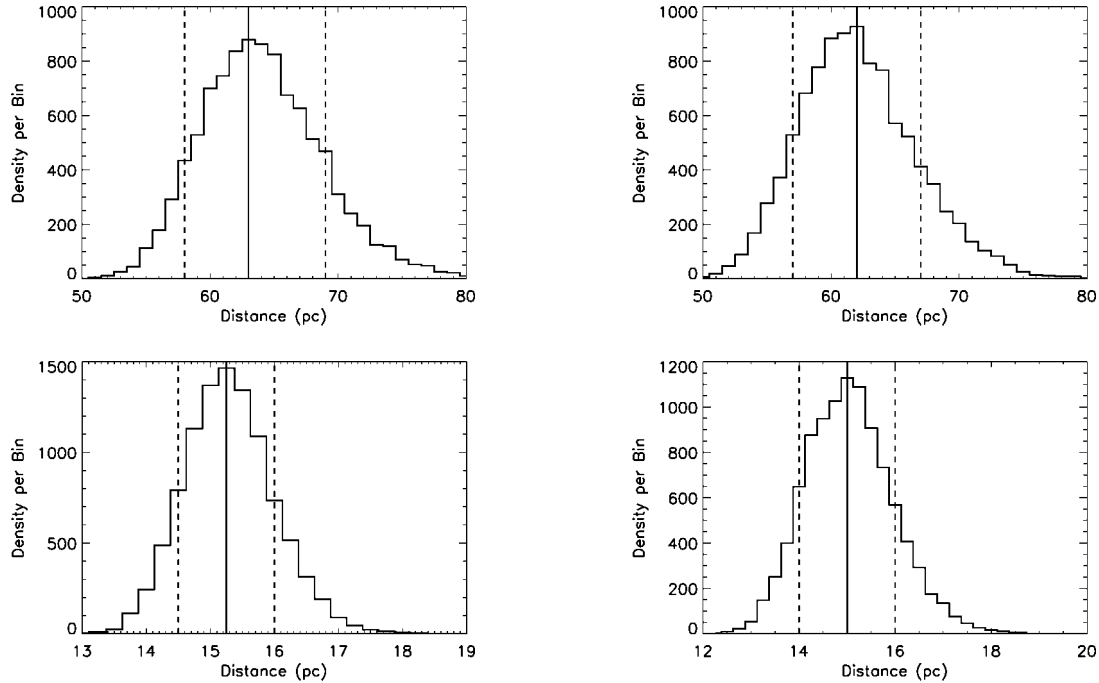
FIG. 3.—Histograms of the distributions of Monte Carlo simulation observation fits before absolute parallax correction. *Top left*: Fits to the R.A. component of 2M1207. *Top right*: Fits to the decl. component of 2M1207. *Bottom left*: Fits to the R.A. component of LHS 2397a. *Bottom right*: Fits to the decl. component of LHS 2397a. The solid line marks the mean of each distribution, and the dashed lines mark 1 σ from the mean.

than for 2M1207, leading to a lower precision result. Parallax results are presented in Table 1. Absolute magnitudes derived using our measured distance are presented in Table 2.

Adopting an apparent J magnitude of 13.00 ± 0.03 (Mohanty et al. 2007) and $BC_J = 2.0$ for an M8 (Dahn et al. 2002), we estimate a total luminosity for 2M1207A of $2.7 \times 10^{-3} L_{\odot}$. Adopting an apparent J magnitude of 20.00 ± 0.02 (Mohanty et al. 2007) and $BC_J = 1.5$ for a late L dwarf (Dahn et al. 2002), we estimate a total luminosity for 2M1207b of $6.8 \times 10^{-6} L_{\odot}$. We repeated this calculation in the Ks band: adopting $m_{Ks} = 11.95 \pm 0.03$ (Chauvin et al. 2004) and $BC_K = 3.2$ (Golimowski et al. 2004) for 2M1207A and converting m_{Ks} to m_K using the transformations from Carpenter (2001), we estimate a total luminosity of $2.4 \times 10^{-3} L_{\odot}$, consistent with the J-band estimate. However, adopting $m_{Ks} = 16.93 \pm 0.11$ (Chauvin et al. 2004) and $BC_K = 3.3$–3.4 (Golimowski et al. 2004) for 2M1207b and converting m_{Ks} to m_K using the transformations from Stephens & Leggett (2004), we estimate a total luminosity of $(2.0$–$2.2) \times 10^{-5} L_{\odot}$, 3 times brighter than the J-band estimate. The culprit here is likely the bolometric corrections used, which, while appropriate for older field objects are not entirely appropriate for this very young, very cool object. Accordingly, we do not assign error bars to our luminosity estimates because of the uncertainties in the bolometric corrections. 2M1207b is somewhat redder $(J - K)$ than field objects of the same spectral types. Thus, BC_K is especially suspect, since the K-band flux of 2M1207b represents a larger portion of its total bolometric flux than

is true for comparable spectral type field objects. Estimated luminosities are presented in Table 2.

We estimated mass and effective temperatures for 2M1207Ab using only our derived absolute magnitudes and the DUSTY models of Chabrier et al. (2000) and Baraffe et al. (2002). Adopting an isochronal age for the TWA Hydra cluster of $\sim 8^{+4}_{-3}$ Myr (Song et al. 2003; Zuckerman & Song 2004; Chauvin et al. 2004), we compared the absolute J, H, K_s, and L' colors (after converting from 2MASS to CIT magnitudes) to the 5 and 10 Myr isochrones. 2M1207A is consistent in color and luminosity with the 20–30 M_{Jup} models. 2M1207b is roughly consistent in luminosity with the 3–7 M_{Jup} models (early T spectral types); however, it possesses much redder colors than these models, consistent with mid-to-late-L dwarfs (6–10 M_{Jup} models). This color/luminosity mismatch has been previously noted by Mohanty et al. (2007), among others; 2M1207b possesses a mid- to late- L spectrum and colors, but is underluminous for its age, possessing the luminosity expected of an early T, yet no methane absorption is observed. From spectral fitting, $T_{eff} \sim 1600$ K for 2M1207b (Mohanty et al. 2007), yet we derive an incorrect model T_{eff} of only 1260–1430 K. Put in other words, according to the models, 2M1207b is 10 times too faint for its spectral type and age. A comparison of model to observed properties is presented in Table 3.

At a distance of ~ 50 pc, both 2M1207A and b are somewhat underluminous for their respective spectral types (see Fig. 1). Increasing the distance to 59 pc and adopting $T_{eff} = 2550 \pm 150$ pc (Mohanty et al. 2007) and age $= 5$–10 Myr solves the underluminosity issue for 2M1207A, which becomes consistent with the 30 M_{Jup}, 10 Myr DUSTY models to within 0.2 mag. However, adopting $T_{eff} = 1600 \pm 100$ K (Mohanty et al. 2007) and age $= 5$–10 Myr, at a distance of 59 pc, 2M1207b is still underluminous compared to the models by 2–3 mag in JHK_sL'. Thus, our increase in distance does not resolve the issue of 2M1207b's underluminosity.

A number of reasons for the lower than expected luminosity

TABLE 1
PARALLAX RESULTS

Target	R.A.	Decl.	π(rel) (mas)	π(abs) (mas)	Distance (pc)
2M1207Ab	12 07 33.4	−39 32 54.0	$15.8^{+2.1}_{-1.6}$	$17.0^{+2.3}_{-1.8}$	58.8 ± 7.0
LHS 2397a	11 21 49.2	−13 13 08.4	$66.7^{+4.8}_{-4.2}$	$67.9^{+5.3}_{-4.7}$	14.7 ± 1.0

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

TABLE 2
PROPERTIES OF 2M1207Ab

Target	M_J[a]	M_H[b]	M_{Ks}[b]	M_L[b]	Luminosity (L_{obs})
2M1207A ……	$9.15^{+0.28}_{-0.24}$	$8.54^{+0.28}_{-0.24}$	$8.10^{+0.28}_{-0.24}$	$7.53^{+0.29}_{-0.24}$	$(2.4–2.7) \times 10^{-3}$
2M1207b ……	$16.15^{+0.34}_{-0.31}$	$14.24^{+0.35}_{-0.32}$	$13.08^{+0.30}_{-0.26}$	$11.43^{+0.31}_{-0.28}$	$(0.68–2.2) \times 10^{-5}$

[a] Apparent magnitude from Mohanty et al. (2007).
[b] Apparent magnitude from Chauvin et al. (2004).

of 2M1207b have been suggested. Mohanty et al. (2007) suggest that an edge-on disk around 2M1207b produces ∼2.5 mag of gray extinction (over JHK_sL') and, hence, the observed low luminosity. Mamajek and Meyer (2007) suggest that 2M1207b may be a hot protoplanet collision remnant. In addition, while equally unlikely, 2M1207b may not be coeval with 2M1207A and may indeed be an older, smaller, and hence less luminous captured L dwarf (or rather, 2M1207A was captured by an old ∼60 M_{Jup} L dwarf). Indeed, the measured colors, absolute magnitudes (JHK_sL'), and luminosity of 2M1207b are consistent with that of a 10 Gyr, 67 M_{Jup} object with L spectral type and $T_{eff} = 1500$.

The culprit could simply be the initial conditions of the evolutionary models used to derive physical properties. Marley et al. (2007) have noted that the "hot-start" evolutionary models for planets and brown dwarfs such as those from both the Lyon and Tucson groups (Baraffe et al. 2003; Burrows et al. 2003) possess very high initial entropies and predict considerably brighter luminosities for young high-mass planets than those models that start with lower entropy initial conditions (which may be more appropriate for planets which form via core accretion). For 4–10 M_{Jup} objects, the Marley et al. (2007) models converge with the standard evolutionary models by 100 Myr. While 2M1207b most likely formed via fragmentation from a cloud core rather than core accretion or gravitational collapse within 2M1207A's small disk, the initial entropy conditions of its formation might

have been considerably lower than those utilized by standard evolutionary models, producing a lower luminosity for each spectral type than expected at very young ages. In particular, inside a binary system, the initial entropy conditions may have been different, presumably lower, for a forming 8 M_{Jup} object interacting with a 30 M_{Jup} "primary" than for a 8 M_{Jup} object forming individually. Mohanty et al. (2007) claim that the models are not the culprit for 2M1207b's underluminous nature, comparing it with the young, low-mass brown dwarf AB Pic B, whose colors, T_{eff}, and luminosity agree well with the models. However, AB Pic is somewhat older than 2M1207Ab (30 vs. <10 Myr) and has a much wider separation between components (250 vs. 50 AU), so it may have already converged to the standard evolutionary model tracks.

4. CONCLUSIONS

We measured a distance of 58.8 ± 7.0 pc ($17.0^{+2.3}_{-1.8}$ mas) to 2M1207Ab and a luminosity of $(0.68–2.2) \times 10^{-5}$ $L_\odot$ for 2M1207b, making 2M1207Ab a clear member of the TW Hya cluster. While 2M1207A now agrees well with evolutionary models, 2M1207b is still 2–3 mag underluminous in JHK_sL' for its suggested T_{eff} of 1600 ± 100 K (Mohanty et al. 2007) and age of ∼8^{+4}_{-3} Myr (for the TW Hya cluster; Song et al. 2003).

TABLE 3
COMPARISON OF MEASURED TO MODEL PROPERTIES (5–10 Myr DUSTY MODELS)

Target	$T_{eff\,obs}$[a] (K)	$T_{eff\,mod}$[b] (K)	Mass from L_{obs} (M_{Jup})	Mass from $T_{eff\,obs}$[a] (M_{Jup})
2M1207A ……	2550 ± 150	2500–2700	20–30	20–30
2M1207b ……	1600 ± 100	1260–1430	3–7	6–10

[a] From Mohanty et al. (2007).
[b] T_{eff} derived from age and luminosity (L_{obs}).

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Note added in proof.—J. E. Gizis et al. (elsewhere in this issue of the *Letters*) independently (and effectively simultaneously) have derived a distance from trigonometric parallax of $54^{+3.2}_{-2.8}$ pc to 2M1207A.