DYNAMICAL MASS OF THE M8+M8 BINARY 2MASS
J22062280 — 2047058AB

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ABSTRACT
We present Keck laser guide star adaptive optics imaging of the M8+M8 binary 2MASS J2206 — 2047AB. Together with archival Hubble Space Telescope, Gemini-North, and Very Large Telescope data, our observations span 8.3 yr of the binary’s 35 yr orbital period, and we determine a total dynamical mass of $0.15+0.05−0.03\ M_\odot$, with the uncertainty dominated by the parallax error. Using the measured total mass and individual luminosities, the Tucson and Lyon evolutionary models both give an age for the system of 0.4$^{+0.6}_{−0.2}$ Gyr, which is consistent with its thin disk space motion derived from the Besançon Galactic structure model. Our mass measurement combined with the Tucson (Lyon) evolutionary models also yields precise effective temperatures, giving $2660^{+90}_{−100}$ K and $2640^{+90}_{−100}$ K ($2550^{+90}_{−100}$ K and $2530^{+90}_{−100}$ K) for components A and B, respectively. These temperatures are in good agreement with estimates for other M8 dwarfs (from the infrared flux method and the M8 mass benchmark LHS 2397A), but atmospheric model fitting of the integrated-light spectrum gives hotter temperatures of $2800 ± 100$ K for both components. This modest discrepancy can be explained by systematic errors in the atmospheric models or by a slight underestimation of the distance (and thus, mass and age) of the system. We also find that the observed near-infrared colors and magnitudes do not agree with those predicted by the Lyon Dusty models, given the known mass of the system.

Key words: binaries: close – binaries: general – infrared: stars – stars: low-mass, brown dwarfs – techniques: high angular resolution

Online-only material: color figures

1. INTRODUCTION

Direct mass measurements are a key underpinning of stellar astronomy, as the characteristics of stars depend more strongly on mass than any other property. However, there are only a handful of mass measurements available for the lowest mass stars ($M < 0.1\ M_\odot$), which largely comes from work conducted more than a decade ago (e.g., Henry & McCarthy 1993; Segransan et al. 2000). This is because such measurements were limited by the scarce number of low-mass objects known, until wide-field optical and infrared surveys enabled the discovery of hundreds more (e.g., Gizis et al. 2000) and high-resolution imaging campaigns identified dozens of visible binaries among these objects (e.g., Close et al. 2002; Bouy et al. 2003). Today, many of these binaries are finally yielding dynamical mass measurements after years of patient orbital monitoring (e.g., Seifahrt et al. 2008; Dupuy et al. 2009b).

2. OBSERVATIONS

2.1. Keck/NIRC2 LGS

The M8 dwarf 2MASS J22062280 — 2047058 (hereinafter 2MASS J2206 — 2047) was discovered in the Two Micron All Sky Survey (2MASS) by Gizis et al. (2000) and was revealed to be a binary by Close et al. (2002). Costa et al. (2006) measured a trigonometric parallax for the system of $37.5 ± 3.4$ mas, corresponding to a distance of $26.7^{+2.6}_{−2.1}$ pc. We present here a dynamical mass for 2MASS J2206 — 2047AB based on Keck laser guide star adaptive optics (LGS AO) imaging from our ongoing orbital monitoring program targeting ultracool binaries. Combining our Keck data with archival Hubble Space Telescope (HST), Very Large Telescope (VLT), and Gemini-North Telescope images, we measure a total mass of $0.15^{+0.05}_{−0.03}\ M_\odot$, with the dominant source of uncertainty being the $9.1\%$ error in the parallax, which translates into an asymmetric $+32_{−25}\%$ error in the mass. Despite the relatively large uncertainty in the mass, our measurement reveals significant discrepancies between the predictions of evolutionary and atmospheric models and the observed properties of 2MASS J2206 — 2047AB.

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quasi-static changes in the image of the LGS as seen by the wave front sensor were measured contemporaneously by a second, lower bandwidth wave front sensor monitoring 2MASS J2206 — 2047 AB in each epoch. The binary separation, position angle (P.A.), and flux ratio were determined using the same three-component Gaussian representation of the point-spread function (PSF) as described in Dupuy et al. (2009b). We used the astrometric calibration from Ghez et al. (2008), with a pixel scale of 9.963 ± 0.005 mas/pixel−1 and an orientation for the detector’s ±y-axis of +0.13 ± 0/02 east of north, and applied the distortion correction developed by B. Cameron (2007, private communication), which changed the results below the 1σ level.

To assess systematic errors in our PSF-fitting procedure, we also applied it to simulated Keck images of 2MASS J2206 — 2047AB that were created using images of PSF reference sources with similar FWHM and Strehl, summarized in Table 2. After being reduced in an identical fashion to the science images, the individual dithered images were shifted with interpolation and added to themselves to match the observed binary configuration at each epoch. These simulated images were then fitted in an identical manner to the science images, and the rms and mean of the truth-minus-fitted parameters determined the uncertainty and systematic offset.

For the 2008 May and December Keck Ks-band data, the simulations predicted insignificant systematic offsets (< 0.3σ) and rms errors that were somewhat smaller than the rms of individual science dithers. For these data sets, we adopted the science rms values for the errors in all binary parameters and did not apply the Monte Carlo offsets. For the 2008 September data (J, H, Ks, and L′ bands), our simulations yielded significant systematic offsets (as large as 2.4σ in L′ band) and errors that were consistent with or somewhat smaller than the rms of individual science dithers. Such offsets are expected, particularly in high-Strehl images with prominent Airy rings, as our multi-Gaussian PSF model is known to be an imperfect representation of the systematics.

Table 2

| Date (UT) | Time (UT) | Airmass | Filter | FWHM (mas) | Strehl Ratio |
|-----------|-----------|---------|--------|------------|--------------|
| 2008 May 29 | 14:55 | 1.375 | Ks | 54.7 ± 0.7 | 0.387 ± 0.017 |
| 2008 Sep 8 | 08:32 | 1.345 | J | 52 ± 3 | 0.050 ± 0.008 |
| 08:27 | 1.352 | H | 51 ± 3 | 0.145 ± 0.015 |
| 08:32 | 1.362 | Ks | 53.6 ± 1.1 | 0.368 ± 0.019 |
| 08:47 | 1.328 | L′ | 84 ± 2 | 0.67 ± 0.18 |
| 08:52 | 1.482 | Ks | 101 ± 6 | 0.047 ± 0.010 |
| 2008 Dec 1 | 05:29 | 1.482 | Ks | 101 ± 6 | 0.047 ± 0.010 |

Table 1

| Date (UT) | Time (UT) | Airmass | Filter | FWHM (mas) | Strehl Ratio |
|-----------|-----------|---------|--------|------------|--------------|
| 2008 May 29 | 13:17 | 1.162 | Ks | 55.5 ± 0.8 | 0.395 ± 0.020 |
| 2008 Sep 8 | 09:15 | 1.333 | J | 52 ± 3 | 0.054 ± 0.003 |
| 09:06 | 1.343 | H | 51 ± 2 | 0.145 ± 0.016 |
| 09:00 | 1.350 | Ks | 53.0 ± 0.9 | 0.348 ± 0.007 |
| 09:21 | 1.328 | L′ | 84 ± 2 | 0.42 ± 0.16 |
| 08:00 | 1.329 | Ks | 97 ± 12 | 0.049 ± 0.014 |

Note. (1) 2MASS J17502484 – 0016151; (2) 2MASS J22345725 – 2101071; (3) 2MASS J21402966+1625212.

Figure 1. HST, Gemini, VLT, and Keck images of 2MASS J2206 — 2047AB shown chronologically by column. All images are shown on the same scale, 1′/0 on a side, using a square-root stretch for the grayscale images. We do not rotate the HST data so that north is up in order to preserve the somewhat undersampled nature of the WFPC2 data. The Airy ring of the Keck PSF is visible in some Keck images. Contours are drawn at 0.76, 0.37, 0.18, 0.085, and 0.040 of the peak pixel. The lowest contour is not drawn for the Gemini, VLT, and 2008 December Keck images. The lowest two contours are not drawn for the Keck L′-band images.

2.2. HST/WFPC2-PCI

Bouy et al. (2003) reported binary parameters for 2MASS J2206 — 2047AB based on their HST discovery images; how-
we determined the binary separation, P.A., and flux ratio. The data in a similar fashion to our previous work (Liu et al. 2008; TinyTim (Krist 1995) to generate PSF models which were fit to for deriving astrometry because (1) the smaller PSF enables these comprise two 30 s exposures in the F814W bandpass and for each binary in their sample, and accurate uncertainties are Bouy et al. (2003) did not derive individual measurement errors ever, we have chosen to re-analyze this data because in our previous work we have found that our PSF-fitting technique can yield somewhat more precise astrometry (Liu et al. 2008). Also, Bouy et al. (2003) did not derive individual measurement errors for binary in their sample, and accurate uncertainties are critical for orbit fitting. We retrieved the HST archival images of 2MASS J2206 − 2047AB obtained with the WFPC2 Planetary Camera (PC1) on UT 2000 August 13 (GO-8581, PI: Reid). These comprise two 30 s exposures in the F814W bandpass and one 500 s F1042M exposure. We only used the F814W images for deriving astrometry because (1) the smaller PSF enables better deblending of this tight binary and (2) a pair of images offers better cosmic ray rejection than a single image. We used TinyTim (Krist 1995) to generate PSF models which were fit to the data in a similar fashion to our previous work (Liu et al. 2008; Dupuy et al. 2009a). From our PSF fitting of the two images, we determined the binary separation, P.A., and flux ratio. To determine uncertainties and potential systematic offsets for our measurements, we simulated images of 2MASS J2206 − 2047AB using images of single ultracool objects from other HST/WFPC2 programs (GO-8563, PI: Kirkpatrick; GO-8581, PI: Reid; and GO-8146, PI: Reid). We only used objects with an equivalent or higher signal-to-noise ratio (S/N) compared to the science data so that we could degrade the S/N of the single images to match the science data. We also restricted ourselves to observations consisting of two or more images to allow robust rejection of cosmic rays. We only shifted images by an integer number of pixels to preserve the somewhat undersampled nature of the WFPC2 data. However, we were able to reproduce the binary configuration of 2MASS J2206 − 2047AB to within 0.2 pixels of the actual (Δx, Δy) separation of (+3.2, −1.6) pixels by carefully selecting appropriate pairs of input PSFs whose sub-pixel positions were determined in advance by single TinyTim PSF fitting. We fitted the simulated binary images with TinyTim PSFs in the same way as the science data. The resulting rms scatter of the truth-minus-fitted parameters gave their errors, and the mean gave their systematic offsets. For both the separation and P.A., the offsets were small compared to the errors (−0.5 ± 1.8 mas and −0.1 ± 1.1), but we found an offset in the flux ratio that was large compared to its rms error (−0.10 ± 0.02 mag). Since these errors in deblending the binary are due to small imperfections in the PSF model, it is natural that they would have the largest impact on the flux ratio, not positional measurements, since the cores of the PSFs are well separated for this binary. In fact, because this binary has a flux ratio near unity, the systematic offset we found “flips” the binary, changing the component that is identified as the primary, and this flip brings the astrometry into agreement with the astrometry from other epochs. We applied the systematic offsets from our simulations to the binary parameters, resulting in a separation of 161.1 ± 1.8 mas, a P.A. of 57°5 ± 1°1, and a flux ratio of 0.06 ± 0.02 mag (Table 3). We can compare these parameters to those derived by Bouy et al. (2003), who found a separation (163.0 ± 2.8 mas) and P.A. (57.5 ± 0.3) consistent with our measurements. Our separation uncertainty is slightly smaller, and our P.A. uncertainty is larger. From their Figure 2, it is clear that our separation and P.A. errors are actually consistent with their analysis, and the apparent discrepancy between our errors only arises because they condense their detailed study of binary parameter uncertainties to a single number for the separation error and two numbers for the P.A. error (0.3 above separations of 150 mas; 1.2 below 150 mas). For example, our P.A. error of 1°1 is intermediate between their two values, which is reasonable for a binary with a separation very close to their cutoff between the two regimes. However, the flux ratio of 0.36 ± 0.07 mag derived by Bouy et al. (2003) is inconsistent with ours at 4σ. Because the measurement of the flux ratio is most sensitive to imperfections in the PSF model, it is natural that our different PSF-fitting methods would disagree most on this parameter. We note that they apply a large 0.17 mag systematic offset to their flux ratio, which again is a single number condensed from more detailed analysis (see their Figure 3). This offset could account for 2.3σ of the discrepancy, which would bring our two flux ratios into reasonable agreement. The F814W flux ratio does not enter substantially into the following analysis, and so the discrepancy between our value and that of Bouy et al. (2003) has no impact on our results. 2.3. Gemini/Hokupa’a 2MASS J2206 − 2047AB was imaged on UT 2001 September 22 by the Hokupa’a curvature AO system at the Gemini-North Telescope on Mauna Kea, Hawaii. Analysis of these data has previously been presented by Close et al. (2002); however, we have conducted our own analysis in an attempt to reduce the astrometric errors. We retrieved these raw data from the Gemini science archive and registered, sky-subtracted, and performed cosmic ray rejection on the images. Figure 1 shows a typical image of one of the 15 K′ band 10 s exposures, which were used to derive the astrometry for 2MASS J2206 − 2047AB. We used the same analytic PSF-fitting routine as for the Keck data to fit the Gemini images of 2MASS J2206 − 2047AB. Adopting an instrument pixel scale of 19.98 ± 0.08 mas pixel−1.

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Table 3
Best-fit Binary Parameters for 2MASS J2206 − 2047AB

| Epoch (UT)  | Instrument      | Filter | ρ (mas)       | P.A. (deg) | Δw (mag) |
|------------|-----------------|--------|---------------|------------|----------|
| 2000 Aug 13| HST/WFPC2-PC1a  | F814W  | 161.1 ± 1.8   | 57.5 ± 1.1 | 0.06 ± 0.02 |
| 2001 Sep 22| Gemini/Hokupa’a | K′     | 167.7 ± 1.0   | 68.2 ± 0.5 | 0.04 ± 0.02 |
| 2003 Jul 11| VLT/NACOa      | H      | 164.2 ± 0.3   | 89.2 ± 0.2 | 0.05 ± 0.05 |
| 2006 Jun 28| VLT/NACOa      | K5     | 131.3 ± 0.2   | 130.38 ± 0.16 | 0.077 ± 0.017 |
| 2008 May 29| Keck/NIRC2a    | K5     | 119.32 ± 0.14 | 170.07 ± 0.11 | 0.067 ± 0.010 |
| 2008 Sep 8 | Keck/NIRC2c    | J      | 120.5 ± 0.3   | 175.94 ± 0.11 | 0.06 ± 0.02 |
|            | Keck/NIRC2c    | H      | 120.2 ± 0.3   | 176.05 ± 0.10 | 0.065 ± 0.017 |
|            | Keck/NIRC2c    | K5     | 120.4 ± 0.4   | 175.89 ± 0.11 | 0.06 ± 0.02 |
|            | Keck/NIRC2c    | L′     | 121.1 ± 0.5   | 176.1 ± 0.4  | 0.004 ± 0.016 |
| 2008 Dec 1 | Keck/NIRC2c    | K5     | 121.4 ± 1.0   | 180.9 ± 0.8  | 0.06 ± 0.06 |

Note. a Used in the orbit fit.
Figure 2. Probability distributions of all orbital parameters derived from the MCMC analysis: semimajor axis ($a$), orbital period ($P$), eccentricity ($e$), inclination ($i$), epoch of periastron ($T_0$), P.A. of the ascending node ($\Omega$), and argument of periastron ($\omega$). Each histogram is shaded to indicate the 68.3% and 95.4% confidence regions, which correspond to 1σ and 2σ for a normal distribution, and the solid vertical lines represent the median values. Note that $T_0$ is shown in days since UT 2005 March 11 00:00 for clarity.

(F. Rigaut 2001, private communication), we found a separation of 167.7 ± 1.0 mas, where the uncertainty is the standard deviation of measurements from individual dithered images. This is in good agreement with the 168 ± 7 mas separation reported by Close et al. (2002). The improvement in the separation error may be attributed to the fact that Close et al. (2002) used the scatter among $J$, $H$, and $K'$-band images, whereas we have restricted our measurement to the bandpass with highest quality images ($K'$ band). We found a $K'$-band flux ratio of 0.04 ± 0.02 mag, which is consistent (at 1.1σ) with the flux ratio of 0.08 ± 0.03 mag derived by Close et al. (2002).

Unfortunately, we are not able to derive the correct value for the binary P.A. from the archive images. As reported by Close et al. (2002), the image rotator was turned off for these observations so that the pupil is aligned with the detector. Thus, there is an arbitrary rotation in the images, which is not recorded in the FITS headers, and this rotation changes during each data set. We were able to remove this changing rotation by subtracting the parallactic angle from the binary P.A. measured in the individual dithers, and the rms scatter among the resulting P.A. measurements was 0.4°. Adding in quadrature the 0.3° error in the absolute orientation of Hokupa’a/QUIRC that was adopted by Close et al. (2002) results in a P.A. error of 0.5°, which is identical to their P.A. uncertainty.

Given the good agreement between our derived parameters and those derived by Close et al. (2002), we adopt our own separation measurement because of the smaller uncertainty but the Close et al. (2002) P.A. measurement because of our inability to reconstruct the orientation of the archival images.
3. RESULTS

3.1. Orbit Determination and Dynamical Mass

Our observations together with archival data span 8.3 yr of the orbit of 2MASS J2206 − 2047AB. We used a Markov Chain Monte Carlo (MCMC) approach, described in detail by Liu et al. (2008), to determine the probability distributions of all orbital parameters. All the chains had lengths of $2 \times 10^8$ steps, and the correlation length of our most correlated chain, as defined by Tegmark et al. (2004), was $5.4 \times 10^4$ for the orbital period. This gives an effective length of the chain of $3.7 \times 10^3$, which in turn gives statistical uncertainties in the parameter errors of about $1/\sqrt{3.7 \times 10^3} = 1.6\%$, i.e., negligible. Figure 2 shows the resulting MCMC probability distributions, and the best-fit parameters and their confidence limits are given in Table 4. The single best-fit orbit has a reduced $\chi^2$ of 1.07 (7 degrees of freedom) and is shown in Figures 3 and 4.

Applying Kepler’s Third Law ($M_{\text{tot}} = a^3/P^2$) to the period and semimajor axis distributions gives the posterior probability distribution for the total mass of 2MASS J2206 − 2047AB, which has a median of 0.152 $M_\odot$, a standard deviation of 0.003 $M_\odot$, and 68.3(95.4)% confidence limits of 0.150−0.156 $M_\odot$ (Figure 5). In Figure 6, it is evident that the tight correlation between the two parameters $P$ and $a$ is responsible for the very precise total mass (2%), despite the fact that the parameters are not independently determined as precisely (16% and 12%, respectively). The MCMC probability distribution of the total mass does not include the uncertainty in the parallax (9.1%), which by simple propagation of errors would contribute an additional $1.1\%$ uncertainty in the mass. We account for this additional error by randomly drawing a normally distributed parallax value for each step in the chain. The resulting mass distribution is asymmetric, and our final determination of the total mass is 0.152$^{+0.05}_{-0.03}$ $M_\odot$ at 68.3(95.4)% confidence.

As an independent verification of our MCMC results, we also fit the orbit of 2MASS J2206 − 2047AB using the linearized least-squares routine ORBIT (described in Forveille et al. 1999). All of the orbital parameters are consistent between the ORBIT and MCMC results, and the resulting total mass and $\chi^2$ were identical. Using ORBIT, we tested whether varying the input astrometry and corresponding uncertainties affected the orbital solution. We tried a variety of permutations: using the published

![Figure 3](image-url)
found a spectral type of M8.0 ± 0.5. Without resolved spectroscopy of the binary, we cannot directly determine the spectral types of the two components; however, our resolved photometry shows that they are nearly identical. To quantify the potential difference in spectral types, we compiled 2MASS photometry for the single M8.0, M8.5, and M9.0 objects with parallaxes from Monet et al. (1992) and Dahn et al. (2002). Between the spectral types M8.0 and M8.5, we found a difference in absolute magnitude of $\Delta M_J = 0.67 \pm 0.19$ mag, $\Delta M_H = 0.68 \pm 0.20$ mag, and $\Delta M_K = 0.64 \pm 0.22$ mag, where the uncertainty is the rms of objects in each bin added in quadrature. Between spectral types M8.0 and M9.0, we found only slightly larger magnitude differences. Our best measurement of the flux ratio of 2MASS J2206 − 2047AB in each of these bands is $\Delta J = 0.06 \pm 0.02$ mag, $\Delta H = 0.065 \pm 0.017$ mag, $\Delta K = 0.067 \pm 0.010$ mag. Thus, we find that the $J$, $H$, and $K_s$-band photometry is inconsistent with the two components of 2MASS.

Figure 4. Measurements of the projected separation (left) and P.A. (right) of 2MASS J2206 − 2047AB. The best-fit orbit is shown as a solid line. The bottom panels show the observed minus predicted measurements with observational error bars.

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

Figure 5. Probability distribution of the total mass of 2MASS J2206 − 2047AB resulting from our MCMC analysis. The histogram is shaded to indicate the 68.3%, 95.4%, and 99.7% confidence regions, which correspond to 1\(\sigma\), 2\(\sigma\), and 3\(\sigma\) for a normal distribution. The dashed line represents the median value of 0.152 $M_\odot$. The standard deviation of the distribution is 0.003 $M_\odot$. The dotted unshaded curve shows the final mass distribution after accounting for the additional +32 $\%$ error due to the uncertainty in the parallax. The asymmetry in this curve is due to the asymmetric distance errors resulting from symmetric parallax errors. The confidence limits for both distributions are given in Table 4.

Figure 6. Steps in the MCMC chain show a high level of correlation between the orbital period and semimajor axis. This correlation enables the total mass to be determined more precisely than from simple propagation of errors for these two parameters ($M_{\text{tot}} = a^3/P^2$). Lines are drawn demarcating the 3\(\sigma\) range for the total mass of 2MASS J2206 − 2047AB without accounting for the distance uncertainty (0.143–0.163 $M_\odot$).
their photometric errors, we found LHS 2397aAB, and 2MASS J0746+2000AB) and weighting by single M1–L1 objects (i.e., excluding the binaries LHS 333AB, dwarfs and early L dwarfs from Golimowski et al. (2004), which there is no published value for the bolometric luminosity of M0 and L0, and the rms about the fit was 0.07 mag. From this relation, we estimated a \( K - L' \) color for 2MASS J2206 − 2047 of 0.53 ± 0.07 mag, resulting in an \( L' \)-band magnitude of 10.73 ± 0.08 mag.\(^5\)

To derive the integrated-light bolometric luminosity, we numerically integrated our SpeX spectrum and the \( L' \)-band photometric point at 3.8 \( \mu \)m, interpolating between the gaps in the data, neglecting flux at shorter wavelengths, and extrapolating beyond \( L' \) band assuming a blackbody. We determined the luminosity error in a Monte Carlo fashion by adding randomly drawn noise to our data over many trials and computing the rms of the resulting luminosities. We accounted both for the noise in the spectrum and the errors in the 2MASS photometry used to flux-calibrate it. Before accounting for the error in the distance, we found a total bolometric luminosity of \( \log(L_{\text{bol}}/L_\odot) = -2.982 \pm 0.006 \) dex. After accounting for this error, the symmetric parallax uncertainty results in slightly asymmetric luminosity errors, giving \( \log(L_{\text{bol}}/L_\odot) = -2.982^{+0.08}_{-0.07} \) dex. Using the flux ratio to apportion this luminosity to the two binary components results in individual luminosities of \(-3.27^{+0.08}_{-0.07} \) and \(-3.30^{+0.08}_{-0.07} \) dex. In the following analysis, we correctly account for the covariance between these quantities (via the flux ratio), enabling more precise determinations of relative quantities (such as \( \Delta T_{\text{eff}} \)) due to the more precise luminosity ratio \( \Delta \log(L_{\text{bol}}) = 0.027 \pm 0.004 \) dex.

3.4. Atmospheric Model Fitting: \( T_{\text{eff}}, \log(g), \) and \( R \)

Because the two components of 2MASS J2206 − 2047AB have essentially identical fluxes and colors, we can determine the effective temperatures and surface gravities of both by fitting atmospheric models to its integrated-light spectrum.\(^6\) We used the PHOENIX-Gaia (Brott & Hauschildt 2005) and the Ames-Dusty (Allard et al. 2001) solar-metallicity atmospheric models to fit our IRTF/SpeX SXD spectrum of 2MASS J2206 − 2047. The PHOENIX-Gaia models include updated line lists compared to the Ames-Dusty models, but they do not include the effects of dust. The treatment of dust in the Ames-Dusty models is an extreme limiting case (no dust settling), but models with a more sophisticated treatment of dust are not yet publicly available. For the PHOENIX-Gaia models, we used grids of synthetic spectra ranging in \( T_{\text{eff}} \) from 2000 to 3500 K (\( \Delta T_{\text{eff}} = 100 \) K) and \( \log(g) \) from 3.5 to 5.5 (\( \Delta \log(g) = 0.5 \)). For the Ames-Dusty models, we used grids of synthetic spectra ranging in \( T_{\text{eff}} \) from 1500 to 3400 K (\( \Delta T_{\text{eff}} = 100 \) K) and \( \log(g) \) from 4.0 to 6.0 (\( \Delta \log(g) = 0.5 \)).

Our fitting procedure utilized a Monte Carlo approach based on that of Cushing et al. (2008) and Bowler et al. (2009). To account for the heterogeneous resolution of our SXD spectrum, we Gaussian-smoothed synthetic spectra in separate spectral ranges corresponding to the different SXD orders. When fitting our near-infrared spectrum (0.81–2.42 \( \mu \)m), we excluded a small region from 1.82–1.88 \( \mu \)m not covered by the instrument. We flux-calibrated our observed spectrum using 2MASS \( J, H, \) and \( K_\text{s} \) photometry. For each Monte Carlo trial, we applied small flux shifts to the observed spectrum corresponding to the spectroscopic (SpeX) and photometric (2MASS) measurement errors and then found the best-fitting model by minimizing the \( \chi^2 \) statistic. This process was repeated 10\(^3\) times, after which

\[
K_{\text{MKO}} - L' = 0.111 + 0.0526 \times \text{SpT},
\]

where \( K - L' \) is in mag, spectral type (SpT) is defined such that M0 = 0 and L0 = 10, and the rms about the fit was 0.07 mag. In Section 4.3, we use the measured total mass and luminosity ratio to derive from evolutionary models an effective temperature difference of 27 ± 5 K between the two components. Since the model grid steps are 100 K, a single-temperature fit to the integrated-light spectrum is valid.

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\(^5\) We converted the 2MASS \( K_\text{s} \)-band integrated-light photometry to the MKO photometric system using synthetic photometry of our SpeX spectrum: \( K_{\text{MKO}} - K_{\text{2MASS}} = -0.051 \) mag.

\(^6\) In Section 4.3, we use the measured total mass and luminosity ratio to derive from evolutionary models an effective temperature difference of 27 ± 5 K between the two components. Since the model grid steps are 100 K, a single-temperature fit to the integrated-light spectrum is valid.
we tallied the fraction of times each model yielded the best fit ($f_{MC}$). Fractions near 1.0 indicate that only a single model fit the data well. The results of our fitting procedure are given in Table 5, and the best-fit spectra for each set of models are shown in Figures 8 and 9.

Both sets of models gave best-fit effective temperatures of 2800 K, but the best-fit PHOENIX-Gaia model had a lower surface gravity ($\log g = 4.5$) than the Ames-Dusty model ($\log g = 6.0$; the grid maximum). Although the $f_{MC}$ value for the best-fit PHOENIX-Gaia model was only 0.46, the next best-fit model ($f_{MC} = 0.27$) had a temperature and gravity different by only one grid step ($T_{\text{eff}} = 2700$ K, $\log g = 4.0$). We also fitted the observed spectrum separately over individual bandpasses ($Y$, $J$, $H$, and $K$), and these fits yielded similar results to the entire spectrum, typically within 100 K and 0.5 dex (i.e., one model grid step). Thus, we adopt errors of $\pm 100$ K and $\pm 0.5$ dex on the best-fit parameters in order to account for the impact of the measurement errors on the fit as well as uncertainties in modeling a limited spectral range.

In addition to the effective temperature and surface gravity, the radius can be derived from atmospheric model fitting when the distance is known. This is because the scaling factor used to shift the synthetic spectrum to the observed flux-calibrated spectrum is a free parameter equal to $R^2/d^2$. Accounting for the flux ratio between the two components, the error in the

![Figure 8](image-url)  
*Figure 8. Integrated-light near-infrared spectrum of 2MASS J2206 − 2047 (black) shown with the best-fitting PHOENIX-Gaia models (red) for the entire spectrum (top) and for individual spectral ranges ($Y$, $J$, $H$, and $K$ bands). The top panel inset (upper right) shows $\chi^2$ contours of 1.02, 1.1, 1.3, 1.5, 1.7, 2.0, 2.3, and 3.3 times the minimum $\chi^2$ for model atmospheres compared to the entire spectrum. The model fit is well constrained in $T_{\text{eff}}$ and less so in $\log g$. (A color version of this figure is available in the online journal.)*

### Table 5

| Spectral Range | $T_{\text{eff}}$ (K) | $\log g$ | $f_{MC}$
|----------------|----------------------|----------|-----------
| All (0.81–2.42 μm) | 2800 | 4.5 | 0.46 |
| 2700 | 4.0 | 0.27 |
| 3400 | 3.5$^b$ | 0.19 |
| $Y$ (0.95–1.12 μm) | 2900 | 5.0 | 1.00 |
| 2900 | 5.5$^b$ | 0.99 |
| $J$ (1.10–1.34 μm) | 2900 | 5.0 | 1.00 |
| 2900 | 5.5$^b$ | 0.99 |
| $H$ (1.40–1.80 μm) | 2900 | 5.5$^b$ | 1.00 |
| 3000 | 5.5$^b$ | 1.00 |
| $K$ (1.90–2.40 μm) | 2800 | 5.0 | 0.46 |
| 2900 | 5.5 | 0.99 |
| 2800 | 5.5 | 0.99 |
| 3000 | 5.5 | 0.99 |
| 3000 | 5.5 | 0.99 |

### Notes.

$^a$ Fraction of Monte Carlo trials in which the model gave the best fit.

$^b$ The best-fit value is at the edge of the model grid.

distance, and the rms scatter in this scaling factor over the 10$^3$ trials, we found identical radii of $0.096 \pm 0.009 R_\odot$ from the
PHOENIX-Gaia models and $0.095 \pm 0.009 \, R_\odot$ from the Ames-Dusty models.\footnote{Because more than one PHOENIX-Gaia model fit the data well (see Table 5), we used only the best-fitting model’s scaling factors when deriving radii.}

### 3.5. Age Constraints from Kinematics and Activity

In this section, we consider whether the space motion or activity of 2MASS J2206 − 2047 can provide useful constraints on the age of the system. There are three values of its radial velocity in the literature: (1) $16.3 \pm 2.7 \, \text{km s}^{-1}$ derived by Reid et al. (2002) from cross-correlation of the optical spectrum with radial velocity standards; (2) $8.0 \pm 2.0 \, \text{km s}^{-1}$ also from Reid et al. (2002) but derived from the central wavelength of the Hα emission line; and (3) $10.8 \pm 1.3 \, \text{km s}^{-1}$ derived by Guenther & Wuchterl (2003) using the central wavelengths of unspecified spectral lines. Reid et al. (2002) attributed the discrepancy between their two radial velocities to the fact that 2MASS J2206 − 2047 is a fast rotator ($v \sin i = 22 \, \text{km s}^{-1}$) with an asymmetric Hα profile, confusing their estimate of the Hα centroid. 2MASS J2206 − 2047’s binarity was unknown to Reid et al. (2002), and we note that this could be partially responsible for the discrepancy. For example, if one component dominated the Hα emission, the Hα centroid would be offset from the cross-correlation velocity (which likely represents the average velocity of the two components) by $1.8 \, \text{km s}^{-1}$, assuming a mass ratio of unity. However, this alone is insufficient to account for the $8.3 \, \text{km s}^{-1}$ discrepancy observed.

We used the cross-correlation radial velocity ($16.3 \pm 2.7 \, \text{km s}^{-1}$) from Reid et al. (2002) and the parallax and proper motion from Costa et al. (2006) to derive the heliocentric velocity of 2MASS J2206 − 2047: $(U, V, W) = (+7.8 \pm 1.6, +1.7 \pm 1.1, -15.0 \pm 2.1) \, \text{km s}^{-1}$. We adopted the sign convention for $U$ that is positive toward the Galactic center and accounted for the errors in the parallax, proper motion, and radial velocity in a Monte Carlo fashion. For comparison, we compiled all objects of spectral type M7 or later that have the radial velocities, parallaxes, and proper motions necessary for computing space motions (described in detail in Section 3.4 of Dupuy et al. 2009b). 2MASS J2206 − 2047 is only $1.3 \, \sigma$ away from the mean of this population’s space motion ellipsoid (Figure 10). Thus, its space motion is not significantly different from other ultracool dwarfs, implying an age consistent with the population of ultracool dwarfs as a whole. Several authors have attempted to estimate the age of this population, typically comparing the distribution of tangential velocities ($V_{\text{tan}}$, which requires only a proper motion and distance determination) to the well-studied nearby populations of FGKM stars. The resulting age for the population of ultracool dwarfs estimated in this way
has been found to be 2–4 Gyr (Dahn et al. 2002; Faherty et al. 2009). We have also assessed 2MASS J2206 − 2047’s membership in the Galactic populations of the thin disk (1–10 Gyr; e.g., Wood & Oswalt 1998) and thick disk (~10 Gyr; e.g., Ibukiyama & Arimoto 2002) using the Besançon model of the Galaxy (Robin et al. 2003). Our method is described in Section 3.4 of our study of LHS 2397a (Dupuy et al. 2009b); and for 2MASS J2206 − 2047, we found a membership probability of ~99.9% for the thin disk. Finally, the fact that 2MASS J2206 − 2047 is chromospherically active (log (L_{Hα}/L_{bol}) = −4.59, −4.54; Gizis et al. 2000 and Reid et al. 2002, respectively) could also potentially provide an age constraint, as the activity of M dwarfs changes with age. West et al. (2008) showed that the fraction of active M dwarfs as a function the vertical distance above the Galactic plane (z) provides a constraint on the activity lifetime of M dwarfs, given a model of how thick disk heating pumps up z over time. West et al. (2008) found that the activity lifetime increases monotonically with M dwarf spectral type, and the latest type for which they were able to determine a robust lifetime was M7 (8.0±1.5 Gyr). This provides a weak constraint on the age of 2MASS J2206 − 2047, as its activity is therefore expected to last for at least ≥8 Gyr.

4. TESTS OF MODELS

Our measured total mass of 2MASS J2206 − 2047AB enables strong tests of theoretical models, and in the following analysis we consider two independent sets of evolutionary models: the Tucson models (Burrows et al. 1997) and the Lyon Dusty models (Chabrier et al. 2000). Our approach follows previous work for 2MASS J1534 − 2952AB (Liu et al. 2008), HD 130948BC (Dupuy et al. 2009a), and LHS 2397aAB (Dupuy et al. 2009b).

Figure 10. Heliocentric space velocity of 2MASS J2206 − 2047 (star) shown alongside other ultracool dwarfs: > M7 dwarfs (squares), L dwarfs (circles), and T dwarfs (triangles). The 2σ ellipsoids of the thin disk (solid line) and thick disk (dotted line) as predicted by the Besançon galaxy model (Robin et al. 2003) are also shown for comparison. The space velocity of 2MASS J2206 − 2047 is consistent with other ultracool dwarfs, and we derive a mean 2σ thickness of 1.3 km s⁻¹ for the thin disk membership probability. (A color version of this figure is available in the online journal.)
4.1. Model-inferred Age

As described in detail by Liu et al. (2008) and Dupuy et al. (2009a), the total mass of a binary along with its individual component luminosities can be used to estimate the age of the system from evolutionary models. This age estimate can be surprisingly precise when both components are likely to be substellar since their luminosities depend very sensitively on age. However, with spectral types of M8.0 ± 0.5, both components of 2MASS J2206 − 2047AB are likely to be stars unless the system is quite young.

We derived an age of 0.4+0.9−0.6 Gyr from both the Tucson and Lyon models (Figure 11). Because the median total mass is 0.15 \( M_\odot \), which is roughly the limit at which both components would be brown dwarfs, the median age derived from models is correspondingly young. However, the 1σ uncertainty in the total mass reaches 0.20 \( M_\odot \), in which case both components would be main-sequence stars. In this case, since stars do not dim over time as brown dwarfs do, the luminosities of both components do not strongly constrain the age of the system. Thus, while the lower bound of our uncertainty on the model-derived age corresponds to the age a pair of brown dwarfs would need to match the observed luminosities and total mass, the upper limit is essentially unconstrained. Our limit of 10 Gyr comes from the fact that the evolutionary models are computed only up to this age. In our analysis, which uses a Monte Carlo approach to compute model-derived properties, we found that about 30% of the time the randomly drawn observed luminosities were too low to match the randomly drawn total mass. In other words, models would never predict that such massive objects (>0.09 \( M_\odot \) stars) could be as faint as the components of 2MASS J2206 − 2047AB, and in such cases we assigned an age of 10 Gyr.

4.2. Individual Masses

Given the near unity flux ratio of 2MASS J2206 − 2047AB, we expect the mass ratio to also be very close to unity. We used evolutionary models to estimate the mass ratio of 2MASS J2206 − 2047AB (\( q = M_B/M_A \)) by constraining the model-derived individual masses of 2MASS J2206 − 2047A and 2MASS J2206 − 2047B to add up to the observed total mass, while still matching their observed luminosities. The Tucson models gave \( q = 0.981^{+0.012}_{-0.007} \), while the Lyon models gave a consistent value of 0.983±0.008. The resulting individual masses (Table 7) are essentially identical to those resulting from an assumed mass ratio of unity, with the exception of the upper confidence limits. This is due to the effect described in Section 4.1 where about 30% of the randomly drawn total masses and individual luminosities were inconsistent with any models. In these cases, we assigned the highest individual masses for which the luminosities were consistent with the models. In Section 5.1, we consider the issue of plausible individual masses in more detail.

4.3. Temperatures and Surface Gravities

Without radius measurements for 2MASS J2206 − 2047A and 2MASS J2206 − 2047B, we cannot directly determine their
effective temperatures or surface gravities. In Section 3.4, we derived these properties by fitting atmospheric model spectra to the integrated-light spectrum, and have also used evolutionary models to estimate these properties in the same fashion as our model-derived age and individual masses. The Tucson models give effective temperatures for 2MASS J2206 − 2047 A and 2MASS J2206 − 2047 B of 2660 ± 90 K and 2640 ± 90 K, and surface gravities of 5.26 ± 0.12 and 5.26 ± 0.17 (cgs). The Lyon models give systematically lower but formally consistent temperatures of 2550 ± 100 K and 2530 ± 100 K and surface gravities of 5.17 ± 0.18 and 5.17 ± 0.12 (cgs). (Note that the upper confidence limits are likely affected by the same truncation within our Monte Carlo method as discussed in Section 4.2 for the individual masses.)

The differences between the two sets of models are due to the fact that the Tucson models predict radii that are 9% smaller than predicted by Lyon models (Table 7).

Compared to the effective temperature of 2800 ± 100 K derived from spectral synthesis fitting, the Tucson models are consistent (at 1.0σ − 1.2σ), but the Lyon model temperatures are 1.9σ − 2.0σ lower. This is illustrated in Figure 12, which shows the atmospheric model-derived temperatures in comparison to the evolutionary tracks on the Hertzsprung–Russell (H–R) diagram. As a result of this temperature discrepancy, the Tucson and Lyon model-predicted radii are larger than derived from the atmospheric model scaling factors by 14% and 24%, respectively. These could be brought into better agreement if the system was older than the median model-derived age of 0.4 Gyr, as evolutionary models would predict smaller radii and thus higher effective temperatures (corresponding to the 2σ lower upper limits in Table 7 for radii/temperatures). Finally, atmospheric model fitting did not yield consistent surface gravity estimates: the dust-free PHOENIX-Gaia models gave log (g) = 4.5, and the Ames-Dusty models gave log (g) = 6.0 (the maximum allowed by the model grid). These are, respectively, lower and higher than the evolutionary model-derived surface gravities of log (g) = 5.0–5.4.

**4.3.1. Comparison to Field Dwarfs**

The model-derived effective temperatures for both components of 2MASS J2206 − 2047AB can be compared to those that have been determined for other objects of similar spectral type. Temperatures have been estimated in a number of ways, always relying to some degree on models due to the lack of direct radius measurements, and we summarize such estimates for late-M dwarfs in order from most to least model dependent.

1. **Spectral synthesis.** Fitting atmospheric models over a very narrow spectral range (2.297–2.310 μm; R = 42000), Jones et al. (2005) found effective temperatures of 2900 K for the two M7–M9 dwarfs in their study. Using a broader spectral range (0.7–2.5 μm; R = 600–3000), Leggett et al. (2001) found much cooler temperatures of 2100–2300 K for the five M7–M9 dwarfs in their study. Comparing our atmospheric model derived temperature of 2800 ± 100 K to these determinations, it is consistent with the former but inconsistent with the latter by more than 400 K. We investigated this discrepancy by using a similar spectral fitting approach as Leggett et al. (2001), which excludes the 1.5–1.7 μm portion of the spectrum, weights the spectral regions 0.7–1.4 μm and 2.0–2.5 μm by a factor of 5 higher than the rest of the spectrum, and finally selects the best-

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9 Since at least one component of 2MASS J2206 − 2047AB is chromospherically active, it may be possible to estimate one or both radii using the technique employed by Berger et al. (2009) who measured the rotation period of 2MASSW J0746425 + 20032A from its chromospheric radio emission and combined this with its vsin(i) and orbital inclination (i) to derive its radius. This method assumes that the orbital and rotation axes are aligned. With a vsin(i) of 22 km s⁻¹ (Reid et al. 2002), the active component(s) of 2MASS J2206 − 2047AB is expected to have a rotation period of about 280 minutes.
fitting spectrum by eye. When we employed this procedure, we found an effective temperature of 2500 K for 2MASS J2206 − 2047, which is consistent with the Leggett et al. (2001) measurements of M7–M9 dwarfs (assuming 100 K uncertainties in both determinations).

2. Model radii. For objects with Lbol measurements, the nearly flat mass–radius relationship predicted by theoretical models for very low mass stars and brown dwarfs may be utilized to estimate Teff. Adopting an age range of 0.1–10 Gyr, Leggett et al. (2001) derived effective temperatures of 1850–2650 K for the five M7–M9 dwarfs in their sample with Lbol measurements, and this broad range is consistent with our model-derived effective temperatures.

3. Mass benchmarks. Objects in binaries with measured individual luminosities and a dynamical total mass enable more precise model-derived temperatures and gravities. This is the method we have used to determine the effective temperatures of both components of 2MASS J2206 − 2047AB; and Dupuy et al. (2009b) have previously used an identical method to determine the temperature and surface gravity of LHS 2397A (M8.0 ± 0.5): the Tucson models gave 2580 ± 30 K and 5.381 ±0.009 (cgs), and the Lyon models gave 2470 ± 30 K and 5.307 ±0.006 (cgs). These temperatures are consistent with those derived for 2MASS J2206 − 2047AB from evolutionary models, though LHS 2397A is predicted to be 80 K cooler due to its slightly lower Lbol. Although an indirect comparison, we note that our atmospheric model temperature of 2800 ± 100 K is about 200–300 K higher than the evolutionary model derived temperature of LHS 2397A. The evolutionary model-derived surface gravities of 2MASS J2206 − 2047AB are lower than LHS 2397A and formally inconsistent; however, this is easily explained by the higher mass of LHS 2397A (e.g., Tucson models give 0.0839±0.0007 M⊙).

4. Infrared flux method. The infrared flux method is a nearly model-independent way of estimating effective temperature that relies on a monochromatic flux measurement in the Rayleigh–Jeans tail of an spectral energy distribution (SED) as well as a bolometric flux measurement (Blackwell & Shallis 1977). Gautier et al. (2007) used their 24 μm Spitzer/MIPS photometry to determine effective temperatures for nine M7.5–M8.5 dwarfs by this method, finding temperatures of 2400–2730 K.10 These effective temperatures are in excellent agreement with the evolutionary model-derived temperatures for nine M7.5–M8.5 dwarfs by this method, though LHS 2397A and LHS 2397B are 0.0848 ±0.008 (cgs). These temperatures are in excellent agreement with the evolutionary model-derived effective temperature of LHS 2397A. The evolutionary model-derived temperature of LHS 2397A is 9.26 ± 0.04; Delfosse et al. (2000) and Ségransan et al. (2000). In contrast, the objects closest in K-band brightness to 2MASS J2206 − 2047AB are GJ 1245C (0.074 ±0.013 M⊙, MK = 9.99 ± 0.04; Henry et al. 1999) and LHS 2397A (0.0848 ± 0.0011 M⊙,12 MK = 10.06 ± 0.07; Dupuy et al. 2009b). Thus, it is more likely that the components of 2MASS J2206 − 2047AB have individual masses in this range; in which case, the total mass would be well below the formally allowed value of 0.20 M⊙.

5. DISCUSSION

5.1. Additional Constraints on the Mass

We have directly measured the total mass of 2MASS J2206 − 2047AB to be 0.15±0.03 M⊙. However, the entire range of formally allowed masses is not consistent with some of its other properties. For example, at the 1σ upper limit in Mtot, both components of 2MASS J2206 − 2047AB would be 0.10 M⊙ stars, but they would then be 0.7 mag fainter at K band than the faintest object of comparable mass (Gl 234B: 0.1034 ± 0.0035 M⊙, MK = 9.26 ± 0.04; Delfosse et al. 2000; Séguransan et al. 2000). In contrast, the objects closest in K-band brightness to 2MASS J2206 − 2047AB are GJ 1245C (0.074 ±0.013 M⊙, MK = 9.99 ± 0.04; Henry et al. 1999) and LHS 2397A (0.0848 ± 0.0011 M⊙,12 MK = 10.06 ± 0.07; Dupuy et al. 2009b). Thus, it is more likely that the components of 2MASS J2206 − 2047AB have individual masses in this range; in which case, the total mass would be well below the formally allowed value of 0.20 M⊙.

The 1σ lower limit of Mtot = 0.12 M⊙ corresponds to a pair of 0.06 M⊙ brown dwarfs, and masses at or below this value are also disfavored. Reid et al. (2002) found an upper limit of 0.05 Å for lithium absorption at 6807 Å in the integrated-light spectrum of 2MASS J2206 − 2047, indicating that both components have depleted their initial lithium. As discussed by Chabrier et al. (1996), lithium can only be depleted in objects more massive than ≳0.06 M⊙. Moreover, even more massive objects require a finite amount of time to become lithium depleted: according to Chabrier et al. (1996), a 0.070 M⊙ object takes 0.2 Gyr to destroy 99% of its initial lithium, with lower mass objects taking longer. Given the constraint of the individual luminosities of 2MASS J2206 − 2047AB, the low-mass tail of the Mtot distribution corresponds to young ages. At the median mass of 0.15 M⊙, the model-derived age is 0.4 Gyr; and at the 1σ lower bound of 0.12 M⊙, the age is 0.2 Gyr. Below this 1σ limit, the components of 2MASS J2206 − 2047AB would be inconsistent with the lithium non-detection: (1) they would have had insufficient time to destroy their initial lithium, and/or (2) they should be low enough mass that they would never destroy any lithium. Thus, regardless of the precise location of the lithium-fusing boundary, the formally allowed low-mass tail of the Mtot distribution is not physically plausible.

5.2. Direct Measurement of the Mass Ratio

Since the components of 2MASS J2206 − 2047AB are nearly identical, testing models using our measured total mass is straightforward. However, future measurements may constrain the binary’s mass ratio directly. Given that the flux ratio is so near unity, the mass ratio would not be feasible to measure

10 This range excludes the M8+L7 binary LHS 2397A as the companion flux likely contaminates the MIPS measurement (see discussion in Section 4.3.1 of Dupuy et al. 2009b).
11 The models give JHK photometry on the CIT system, and we converted our photometry to this system using the relations of Carpenter (2001).
12 Note that the mass of LHS 2397A is derived from a total dynamical mass and evolutionary models.
from astrometric monitoring of the photocenter since the center of light would be imperceptibly different from the center of mass. Thus, the mass ratio must be determined through radial velocity monitoring. This is also challenging as the binary is currently approaching $\Delta V = 0$ km s$^{-1}$ and will not reach the next peak in the radial velocity curve for $P/4 \approx 9$ yr, in 2018. Until then, the radial velocities of the two components will remain below 1.4 km s$^{-1}$. Since the velocity of each component must be measured to 7% in order to determine the mass ratio to 10%, radial velocity measurements with a precision better than 0.1 km s$^{-1}$ are needed. This is just at the limit of state-of-the-art techniques using current instrumentation (Blake et al. 2007) but should be well within reach of future near-infrared spectrographs with precision goals of 1 m s$^{-1}$ (Jones et al. 2008).

6. CONCLUSIONS

We have determined the orbit of the M8+M8 binary 2MASS J2206−2047AB using relative astrometry spanning 8.3 yr of its 35.5 yr orbit. The astrometry and corresponding errors used to derive this orbit were thoroughly examined through Monte Carlo simulations, using PSF reference sources for the AO images. The resulting best-fit orbit has a reduced $\chi^2$ of 1.07 and total mass of $1.5^{+0.05}_{-0.03} M_\odot$. Because the orbit only contributes 2% to the mass error, the uncertainty in the dynamical mass is dominated by the 9.1% error in the parallax, which translates into an asymmetric +32%−22% mass error. Although this mass is sufficiently precise to perform interesting model tests, a more precise parallax would provide even stronger tests and would remove the large ambiguity in the characterization of the system (i.e., whether it is composed of young brown dwarfs or old stars).

We have used evolutionary models to derive the properties of 2MASS J2206−2047AB using Monte Carlo methods developed in previous studies (e.g., Liu et al. 2008; Dupuy et al. 2009a). Both the Tucson and Lyon Dusty models give an age of $0.4^{+0.6}_{-0.3}$ Gyr for the system. The median age is somewhat young because the median total mass is somewhat low given the individual luminosities; however, the 1σ upper bound extends to the maximum allowed age (10 Gyr). This model-derived age is consistent with 2MASS J2206−2047’s space motion and its chromospheric activity.

We also derived the near-infrared colors of both components of 2MASS J2206−2047AB from the Lyon models and compared them to our observations. We found that the model $J−H$ and $J−K$ colors were significantly (0.2–0.3 mag) bluer than observed, while the model $H−K$ colors were in good agreement, suggestive of an important opacity source missing at $J$ band in the Dusty models (or else systematic errors that cancel out for $H−K$). In any case, our observations show that masses and/or ages derived from the Dusty evolutionary models on the color–magnitude diagram will be in error for objects such as 2MASS J2206−2047AB.

Our effective temperature determinations from evolutionary models are in very good agreement with $T_{\text{eff}}$ determinations for other M7.5–M8.5 dwarfs: (1) from the infrared flux method (Gautier et al. 2007), and (2) from a similar mass benchmark system including the M8 dwarf LHS 2397A (Dupuy et al. 2009b). We also derived effective temperatures for both components from atmospheric model fitting of the integrated-light spectrum, which is made possible by their essentially identical fluxes and colors. We found that these temperatures ($2800 \pm 100$ K) are warmer than predicted by evolutionary models and are most discrepant (2σ) with the Lyon Dusty models (n.b., the surface boundary condition for the Lyon evolutionary models is determined by the same Dusty atmospheric models as we used for spectral synthesis fitting). This modest discrepancy may be caused by systematic errors in the atmospheric models, which use a maximal limiting case in the treatment of dust and incomplete line lists. Alternatively, the discrepancy could be explained if the system were somewhat older than the median age of 0.4 Gyr inferred from its luminosity and mass, as this would cause evolutionary model radii to be smaller and the derived effective temperatures warmer. In such a scenario, the true mass would be in the high-mass tail of the $M_{\text{bol}}$ distribution,
corresponding to a larger distance to the system, which can be tested directly with an improved parallax measurement.

Stars at the bottom of the main sequence experience much of the same atmospheric physics as the warmest brown dwarfs and extrasolar planets because of the presence of dust in their photospheres. The characterization of such objects largely relies on theoretical models that must accurately describe the behavior of this dust as well as the opacity due to millions of molecular transitions (e.g., Barber et al. 2006). Dynamical behavior of this dust as well as the opacity due to millions relies on theoretical models that must accurately describe the photospheres. The characterization of such objects largely has the same atmospheric physics as the warmest brown dwarfs tested directly with an improved parallax measurement. The future holds many more such benchmarks as ongoing orbital monitoring efforts have only begun to yield new dynamical masses from the large samples of ultracool dwarfs discovered by wide-field surveys nearly a decade ago.

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