A SURPRISING REVERSAL OF TEMPERATURES IN THE BROWN DWARF ECLIPSING BINARY 2MASS J05352184−0546085

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ABSTRACT

The newly discovered brown dwarf eclipsing binary 2MASS J05352184−0546085 provides a unique laboratory for testing the predictions of theoretical models of brown dwarf formation and evolution. The finding that the lower mass brown dwarf in this system is hotter than its higher mass companion represents a challenge to brown dwarf evolutionary models, none of which predict this behavior. Here we present updated determinations of the basic physical properties of 2M0535−05, bolstering the surprising reversal of temperatures with mass in this system. We compare these measurements with widely used brown dwarf evolutionary tracks, and find that the temperature reversal can be explained by some models if the components of 2M0535−05 are mildly non-coeval, possibly consistent with dynamical simulations of brown dwarf formation. Alternatively, a strong magnetic field on the higher mass brown dwarf might explain its anomalously low surface temperature, consistent with emerging evidence that convection is suppressed in magnetically active, low-mass stars. Finally, we discuss future observational and theoretical work needed to further characterize and understand this benchmark system.

Subject headings: binaries: eclipsing — stars: formation — stars: fundamental parameters — stars: individual (2MASS J05352184−0546085) — stars: low-mass, brown dwarfs

Online material: color figures, machine-readable table

1. INTRODUCTION

Born with masses between the least massive stars (∼0.072 M☉; Chabrier & Baraffe 2000) and the most massive planets (∼0.013 M☉; Burrows et al. 2001), brown dwarfs at once extend our understanding of the formation and evolution of both stars and planets. In the decade since the discovery of the first brown dwarfs (Nakajima et al. 1995; Rebolo et al. 1995), the study of star and planet formation has increasingly trained its attention on these objects that, while being neither star nor planet, may provide key insights to understanding the origins of both (Basri 2000).

Such an understanding must be founded on accurate measurements of fundamental physical properties—masses, radii, and luminosities. Unfortunately, the number of objects for which these properties can be measured directly is extremely small. Although rare, eclipsing binaries have long been employed as ideal laboratories for directly measuring fundamental stellar parameters (e.g., Andersen 1991). The power of eclipsing binaries lies in their provision of masses and radii with only the most basic of theoretical assumptions. With the addition of atmosphere models the ratio of effective temperatures can also be derived, and luminosities can then be determined directly through the Stefan-Boltzmann law without knowledge of distance. Finally, considering the two objects’ properties together permits study of the binary as twins at birth whose evolutionary histories differ because of their different masses.

Thus the recent discovery of a brown dwarf eclipsing binary system in the Orion Nebula Cluster, 2MASS J05352184−0546085 (hereafter 2M0535−05), offers a unique laboratory with which to directly and accurately test the predictions of theoretical models of brown dwarf formation and evolution (Stassun et al. 2006, hereafter Paper I). In Paper I, we presented a preliminary analysis of the orbit and of the mutual eclipses in 2M0535−05 to directly measure the masses and radii of both components, as well as the ratio of their effective temperatures. Our mass measurements reveal both objects in this young binary system to be substellar, with masses of $M_1 = 55 M_{\text{Jup}}$ and $M_2 = 35 M_{\text{Jup}}$, accurate to ∼10%. In addition, from the observed eclipse durations and orbital velocities we directly measured the radii of the brown dwarfs to be $R_1 = 0.67 R_{\odot}$ and $R_2 = 0.51 R_{\odot}$, accurate to ∼5% and representing the first direct measurements of brown dwarf radii. Such large radii are generally consistent with theoretical predictions of young brown dwarfs in the earliest stages of gravitational contraction.

Surprisingly, however, we reported in Paper I that the lower mass brown dwarf has an effective temperature that is slightly—but significantly—warmer than its higher mass companion. Such a reversal of temperatures with mass is not predicted by any theoretical model of coeval brown dwarfs. This finding has potentially important ramifications for theoretical brown dwarf evolutionary tracks, and thus for our understanding of brown dwarf formation more generally.

In this paper, we present supplementary light-curve and radial velocity measurements (§ 2) that we use to refine our determination of the basic physical properties of 2M0535−05 (§ 3). We verify the finding of a temperature reversal with mass in this system, and quantitatively compare the empirically determined physical parameters with those predicted by theoretical evolutionary tracks. We then briefly explore the implications of the temperature reversal in 2M0535−05 for theoretical models of brown dwarf formation and evolution (§ 4). Specifically, we consider whether the temperature reversal can be explained by dynamical brown dwarf formation scenarios and/or by the physical effects of strong surface fields on young brown dwarfs. We summarize our conclusions in § 5.

2. DATA AND METHODS

2.1. Spectroscopic Observations: Radial Velocities and Spectral Types

We observed 2M0535−05 with the Phoenix spectrograph on Gemini South on eight separate nights from 2002 December to

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The radial cross-correlating it with the standard from the previous step (e.g., ing the velocity shift of each sequentially later type standard by we applied velocity corrections in a stepwise fashion, determin-spectral type between this K4 standard and the late-M standards, introducing systematic velocity offsets due to large differences in standards were determined relative to the CORA VEL-ELODIE stan-dards were obtained of a grid of late-type spectral standards, with spec-neighbor the instrument wavelength zero point. In addition, observations were obtained of a grid of late-type spectral standards, with spectral types of M0--M9, selected from Mazeh et al. (2002) and Mohanty & Basri (2003). The standard-star observations are sum-marized in Table 1.

The observations were processed using Interactive Data Lan-guage procedures developed specifically for optimal extraction of Phoenix spectra. The background subtraction step includes logic to compensate for variations in the night sky lines due to grating motion or brightness variations between nods. A boot-strap procedure is used to determine a wavelength solution from ThNeAr calibration spectra obtained immediately before and after the science exposures. First an a priori wavelength disper-sion is determined by matching a Phoenix spectrum of a K giant with the KPNO FTS atlas of Arcturus (Hinkle et al. 1995). Next, a small wavelength shift (less than 1 km s\(^{-1}\)) is applied to match the mean wavelengths of the three strongest ThNeAr lines as a function of position along the slit. Finally, a multi-Gaussian fit is used to empirically determine the wavelengths of the remaining ThNeAr lines. The individual exposures from the different slit positions are combined and interpolated onto a uniform disper-sion and then continuum normalized using sixth-order polyno-mial fits to the high points in the spectra. Typical signal-to-noise ratios of the extracted spectra were \(\sim 15\) per resolution element for the nine observations of 2M0535--05 and \(\sim 50\) per resolution element for the standard stars.

Absolute heliocentric radial velocities of the late-type standards were determined relative to the CORAVEL-ELODIE standard star HD 50778 (see above). To minimize the possibility of introducing systematic velocity offsets due to large differences in spectral type between this K4 standard and the late-M standards, we applied velocity corrections in a stepwise fashion, determining the velocity shift of each sequentially later type standard by cross-correlating it with the standard from the previous step (e.g., M0 relative to K4, M1 relative to M0, and so on). The radial velocities reported below are thus formally on the CORAVEL-ELODIE system (Udry et al. 1999).

Radial velocities of the two components of 2M0535--05 were determined via the technique of broadening functions (BFs) de-scribed by Rucinski (1999). As discussed in that study, BFs are less prone than simple cross-correlation techniques to “peak pull-ling,” in which closely spaced correlation features in double-lined binaries can alter the positions of the correlation peak centroids, particularly when the velocity separation of the components is on the order of the spectral resolution. The BF analysis requires a radial velocity template spectrum that is well matched in spectral type to the target; we determined that the M6.5 star LHS 292 from our grid of standards was the best template for this purpose (see below).

In seven of the nine Phoenix spectra of 2M0535--05 the BFs show two clear peaks, an example of which is shown in Figure 1. For these seven observations, radial velocities and their uncer-tainties were determined using two-Gaussian fits to the BFs (e.g., Rucinski 1999). We designate the component producing the stronger peak in the BFs as the “primary” and the component producing the weaker peak in the BFs the “secondary” (as we show below, the primary component so defined is also the more massive of the pair). One of the remaining two observations was by chance taken during eclipse of the primary (orbital phase 0.75;

| Name | Spectral Type | Exposure Time (s) | Reference |
|------|--------------|------------------|-----------|
| GJ 328 | M0 | 180 | Mazeh et al. (2002) |
| GJ 382 | M1.5 | 180 | Mazeh et al. (2002) |
| GJ 447 | M4 | 120 | Mohanty & Basri (2003) |
| GJ 406 | M6 | 120 | Mohanty & Basri (2003) |
| LHS 292 | M6.5 | 3600 | Mazeh et al. (2002) |
| LHS 3003 | M7 | 900 | Mohanty & Basri (2003) |
| GJ 3655 | M8 | 3600 | Mohanty & Basri (2003) |
| BRIB 1507--0229 | M9 | 3600 | Mohanty & Basri (2003) |

2003 January (first reported in Paper I) and again on 2005 March 3 (newly reported here). All nine observations were obtained with the same instrument setup. Following Mazeh et al. (2002) we observed the wavelength range 1.5515--1.5585 \(\mu m\) (central wavelength 1.555 \(\mu m\); \(H\) band) at a resolving power of \(R \approx 30,000\) (slit size of 0.35\(^{\prime\prime}\)). Exposure times were varied between 1.0 and 3.3 hr by the queue observers based on sky conditions. The typi-cal exposure time was 2.6 hr (i.e., \(\sim 0.01\) orbital phase; see § 2.2), divided into six telescope nods in an ababa pattern for the pur-poses of sky subtraction and cosmic-ray rejection. An observation of the CORAVEL-ELODIE high-precision radial velocity standard HD 50778 (K4 III; Udry et al. 1999) was obtained imme-diately before or after each observation of 2M0535--05 to monitor the instrument wavelength zero point. In addition, observations show below, the primary component so defined is also the more massive of the pair). One of the remaining two observations was by chance taken during eclipse of the primary (orbital phase 0.75;
TABLE 2  
RADIAL VELOCITY MEASUREMENTS OF 2M0535–05

| HJD*  | Phase^b | RV^a  | σ_{RV}  | (O – C)^d |
|-------|---------|-------|---------|-----------|
| Primary |         |       |         |           |
| 2452623.74805 | 0.75  | 29.69 | 1.17   | −2.50     |
| 2452624.75701 | 0.85  | 48.53 | 1.73   | −0.41     |
| 2452625.72555 | 0.95  | 61.35 | 2.07   | 0.40      |
| 2452626.65154 | 0.04  | 42.14 | 2.97   | 0.43      |
| 2452649.72938 | 0.40  | 4.18  | 1.24   | 0.37      |
| 2452650.67281 | 0.50  | 5.07  | 2.00   | −3.21     |
| 2452655.74512 | 0.02  | 50.04 | 2.35   | 0.05      |
| 2452656.70824 | 0.12  | 22.58 | 1.28   | −0.84     |
| 2453432.57920 | 0.45  | 37.09 | 2.11   | 1.62      |
| Goodness of fit: | ...     | ...   | χ^2 = 0.7 | 
| Secondary |         |       |         |           |
| 2452623.74805 | 0.75  | 29.69 | 1.17   | −2.50     |
| 2452624.75701 | 0.85  | 48.53 | 1.73   | −0.41     |
| 2452625.72555 | 0.95  | 61.35 | 2.07   | 0.40      |
| 2452626.65154 | 0.04  | 42.14 | 2.97   | 0.43      |
| 2452649.72938 | 0.40  | 4.18  | 1.24   | 0.37      |
| 2452650.67281 | 0.50  | 5.07  | 2.00   | −3.21     |
| 2452655.74512 | 0.02  | 50.04 | 2.35   | 0.05      |
| 2452656.70824 | 0.12  | 22.58 | 1.28   | −0.84     |
| 2453432.57920 | 0.45  | 37.09 | 2.11   | 1.62      |
| Goodness of fit: | ...     | ...   | χ^2 = 1.2 | 

* Heliocentric Julian Date.
^b Orbital phase, relative to ephemeris of Table 5.
^c Heliocentric radial velocity.
^d Residual relative to WD solution (see text).

We found that the BF peaks of both components appeared strongest when we used LHS 292, an old M6.5 dwarf (see Table 1), as the radial velocity template in the BF analysis. The BF peaks were ~20% weaker when we used the M6 or M7 dwarfs as templates, and weaker still when we used earlier or later templates. This suggests that the spectral types of both components of 2M0535–05 are ~M6.5. Indeed, we found in Paper I (see Fig. 3 in that paper) that the isolated spectrum of the primary component of 2M0535–05 very closely matches that of LHS 292, and that the JHK colors of 2M0535–05 imply a spectral type in combined light of M6.5 ± 0.5 with negligible reddening. Taken together, the available evidence suggests that the components of 2M0535–05 have very similar spectral types of ~M6.5 ± 0.5, corresponding to T_eff ≈ 2700 K (Slesnick et al. 2004; Golimowski et al. 2004).

While our light-curve analysis below (§ 2.3) yields a T_eff ratio of ~1, reinforcing the conclusion that the components of 2M0535–05 are very similar in spectral type, we caution that our assignment of absolute spectral types is preliminary and subject to systematic uncertainty. The differences in spectral features seen in late-M standard stars are extremely subtle for dwarfs with spectral types M4–M8 (e.g., Bender et al. 2005; Prato et al. 2002), and the low S/N of our 2M0535–05 spectra prohibits a detailed analysis of spectral features. Moreover, the low surface gravities and strong magnetic fields of young, low-mass objects can bias classification of their spectra, in the sense that the true spectral types may be 1–2 subtypes later than inferred from comparison to old, high-gravity dwarfs (Mohanty & Basri 2003). Thus, for our purposes here, we emphasize that the spectral match between 2M0535–05 and the adopted radial velocity template is sufficiently good to permit precise radial velocity measurements, and that the spectral types of the components of 2M0535–05 are evidently very similar to one another.

Because the components of 2M0535–05 have such similar spectral types, the relative BF peak areas reflect the two components’ relative contributions to the total light of the system (e.g., Bayless & Orosz 2006). In particular, the primary component apparently contributes approximately 50% more flux than the secondary at 1.555 μm (see Fig. 1). This flux ratio provides an important additional constraint for removing degeneracies in the determination of physical parameters, as we discuss in § 2.3.

The component masses that we determine in § 2.3 follow directly from an orbit solution fit to the observed radial velocities, and thus the uncertainties in the derived masses (and in other properties that in turn depend on those masses) depend sensitively on uncertainties in the radial velocity measurements. The mean precisions of the radial velocity measurements from the BF analysis are formally 1.7 and 1.9 km s⁻¹ for the 2M0535–05 primary and secondary, respectively (see σ_{RV} column of Table 2). However, the accuracy of these measurements can potentially be degraded by various systematic effects. At the instrument level, the stability of the wavelength zero point is of particular concern. To assess this, we cross-correlated the first observation of the CORAVEL-ELODIE standard star HD 50778 against each subsequent observation of this star, providing a measure of the instrument stability over the course of our Phoenix observations. The resulting radial velocities of HD 50778 exhibit an rms

FIG. 2.—Radial velocity measurements of 2M0535–05. The individual radial velocity measurements from Table 2 are plotted (primary measurements shown with lighter lines, secondary measurements shown with darker lines), folded on the orbital period and phased to the time of periastron (see Table 5). The solid lines are WD models based on a simultaneous fit to the radial velocity measurements and the rectified I_c-band light curve (see Table 4 and Fig. 3). Distortions in the model curves near phases 0.075 and 0.75 are due to the brief occultations of the approaching and receding limbs of each component when it is eclipsed. Residuals are shown at bottom. [See the electronic edition of the Journal for a color version of this figure.]
scatter of 0.45 km s\(^{-1}\) on the nights that 2M0535–05 was observed, which is much smaller than the random errors in the individual measurements of 2M0535–05. Another possible source of systematic error is spectral-type mismatch between 2M0535–05 and the radial velocity template. However, as discussed above, the radial velocity template that we used in the BF analysis appears to match the spectral types of the 2M0535–05 components very well. Moreover, the components of 2M0535–05 have spectral types that are very similar to one another, so that any systematic effects due to spectral mismatch with the template should affect both components similarly, in which case only the center-of-mass velocity will be affected.

Finally, the observed radial velocities can be affected by spots on the surfaces of the brown dwarfs that cause phase-dependent distortions in the shapes of the spectral lines, and in fact we show in § 2.3.1 that spots are clearly present on one or both of the components in 2M0535–05. While the data suggest that this effect is small, we have not yet incorporated a physical spot model into our analysis and thus any spot signatures remain as potential systematic effects. In V1174 Ori, for example, a young eclipsing binary with photometric spot amplitudes similar to those observed in 2M0535–05, we found that the resulting radial velocity distortions were as large as \(-1\) km s\(^{-1}\) at certain orbital phases (Stassun et al. 2004b). Analyses of other spotted, low-mass eclipsing systems find similar effects; for example, GU Boo shows distortions of \(-0.5\) km s\(^{-1}\) (López-Morales & Ribas 2005) and YY Gem shows distortions of \(-1\) km s\(^{-1}\) (Torres & Ribas 2002). Any spot-induced radial velocity distortions in 2M0535–05 would need to be 2–3 times larger than in these systems to be comparable to the random measurement errors of \(-1.5\)–2 km s\(^{-1}\) (see, e.g., Neuhäuseler et al. 1998). Encouragingly, the residuals of the radial velocity measurements with respect to the final orbit solution of § 2.3 (\(x_i^2 = 0.7\) and 1.2 for the primary and secondary velocities, respectively; see Table 2) do not indicate that systematic effects dominate the radial velocity measurement errors.

### 2.2. Photometric Observations: Light Curves

We have continued to photometrically monitor 2M0535–05 intensively with the 1.0 m and 1.3 m telescopes at CTIO and, as of this writing, possess a total of 2404 \(I_C\)-band measurements spanning the time period 1994 December to 2006 April. The observing campaign to date is summarized in Table 3, and the individual measurements are provided in Table 4. We have excluded a small number of observations with photometric errors larger than 0.1 mag. Thus, photometric errors on the individual measurements have a range of 0.01–0.1 mag, with a mean error of 0.024 mag and a median error of 0.020 mag.

A period search based on the phase dispersion minimization (PDM) technique of Stellingwerf (1978) reveals an unambiguous period of \(P = 9.7795557 \pm 0.000019\) days. The PDM technique is well suited to periodic variability that is highly nonsinusoidal in nature, as is the case for most detached eclipsing binaries. This updated period is slightly shorter than, but not inconsistent with, the period reported in Paper I (see Table 5).

In Figure 3 we show the \(I_C\)-band light curve of 2M0535–05 folded on this period. Two distinct eclipses are clearly evident and cleanly separated in phase, as is typical of fully detached eclipsing binaries. One eclipse—the “primary eclipse” at orbital phase \(\phi = 0.075\)—is notably deeper than the other; this marks the time in the orbit when the hotter component is eclipsed, which, as discussed in Paper I and below in § 3.2, in this system is the lower mass component.

In addition, the time from primary to secondary eclipse is longer than from secondary to primary eclipse, indicating an eccentric orbit. More quantitatively, the two parameters that determine the shape and orientation of the orbit—the eccentricity, \(e\), and the argument of periastron, \(\omega\)—can be estimated from geometrical considerations relating the orbital period, the durations of the eclipses (6.8 and 10.1 hr, respectively), and their 6.5 day separation in time (e.g., Kallrath & Milone 1999), from which we estimate \(e \approx 0.35\) and \(\omega \approx 216^\circ\). These initial estimates of \(e\) and \(\omega\) agree well with the more precise values that we obtain from detailed light-curve modeling and analysis below (§ 2.3; Table 5).

In addition to the extensive \(I_C\)-band light curve measurements, we have also now obtained a set of near-infrared (\(HK\)) light curves. These are presented and analyzed in a subsequent paper (Y. Gómez Maqueo Chew et al. 2007, in preparation), but we note here that the same features observed in the \(I_C\)-band light curve are also seen at these other wavelengths.

#### 2.3. Analysis

As in Paper I, we have performed a simultaneous analysis of the Phoenix radial velocities and the \(I_C\)-band light curve using...
### TABLE 5
**Orbital and Physical Parameters of 2M0535—05**

| Parameter                        | Paper I                  | Unrectified<sup>a</sup> | Rectified<sup>a</sup> |
|----------------------------------|--------------------------|--------------------------|------------------------|
| Orbital period, \( P \) (days)   | 9.779621 ± 0.000042      | 9.779556 ± 0.000019<sup>b</sup> |
| Time of periastron, \( T_0 \) (Besselian year) | 2001.863650 ± 0.000095 | 2001.863903 ± 0.000160 | 2001.863765 ± 0.000071 |
| Eccentricity, \( e \)           | 0.3225 ± 0.0060          | 0.3354 ± 0.0049         | 0.3276 ± 0.0033        |
| Orientation of periastron, \( \omega \) (deg) | 215.4 ± 1.1             | 219.2 ± 1.4             | 217.0 ± 0.9            |
| Semimajor axis, \( a \sin i \) (AU) | 0.0398 ± 0.0010         | 0.0406 ± 0.0016         | 0.0406 ± 0.0010        |
| Center-of-mass velocity, \( \gamma \) (km s\(^{-1}\)) | 24.1 ± 0.4              | 24.1 ± 0.4              | 24.1 ± 0.4             |
| Mass ratio, \( q = M_2/M_1 \)   | 0.622 ± 0.022           | 0.631 ± 0.015           |
| Total mass, \( (M_1 + M_2 \sin^3 i) \) | 0.0880 ± 0.0076         | 0.0932 ± 0.0111         | 0.0932 ± 0.0073        |
| Inclination, \( i \) (deg)      | 88.8 ± 0.2              | 89.4 ± 0.3              |
| Primary semi-amplitude, \( K_1 \) (km s\(^{-1}\)) | ...                     | 18.37 ± 1.01            | 18.49 ± 0.67           |
| Secondary semi-amplitude, \( K_2 \) (km s\(^{-1}\)) | ...                     | 29.55 ± 1.24            | 29.30 ± 0.81           |
| Primary mass, \( M_1 \) (\(M_\odot\)) | 0.0541 ± 0.0046         | 0.0575 ± 0.0069         | 0.0572 ± 0.0045        |
| Secondary mass, \( M_2 \) (\(M_\odot\)) | 0.0340 ± 0.0027         | 0.0358 ± 0.0043         | 0.0360 ± 0.0028        |
| Primary radius, \( R_1 \) (\(R_\odot\)) | 0.669 ± 0.034           | 0.673 ± 0.037           | 0.675 ± 0.023          |
| Secondary radius, \( R_2 \) (\(R_\odot\)) | 0.511 ± 0.026           | 0.485 ± 0.029           | 0.486 ± 0.018          |
| Primary gravity, \( \log g_1 \) | ...                     | 3.62 ± 0.14             | 3.62 ± 0.10            |
| Secondary gravity, \( \log g_2 \) | ...                     | 3.54 ± 0.14             | 3.54 ± 0.09            |
| Effective temperature ratio, \( T_2/T_1 \) | ...                     | 1.054 ± 0.006           | 1.062 ± 0.006          | 1.064 ± 0.004          |

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<sup>a</sup> WD solutions based on fits to the unrectified and rectified \( I_c \)-band light curve (see § 2.3).

<sup>b</sup> Uncertainty in the period is from a phase dispersion minimization (Stellingwerf 1978) analysis on the \( I_c \)-band light curve (see § 2.2); the period is held fixed in the WD fit and its uncertainty propagated into the uncertainties of derived quantities.

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**Fig. 3.** - \( I_c \)-band light curve of 2M0535—05. The individual photometric measurements from Table 4 are plotted, rectified using sinusoidal fits to the out-of-eclipse portions of the light curve (see § 2.3), folded on the orbital period and phased to the time of periastron (see Table 5). The solid line is a WD model based on a simultaneous fit to the rectified \( I_c \)-band light curve and the Phoenix radial velocities (see Table 2). Residuals are shown at bottom. Insets show detail around primary and secondary eclipses, which in this system correspond to the eclipses of the secondary and primary components, respectively. The rms residual is 0.02 mag, comparable to the mean photometric error. The reduced \( \chi^2 \) of the fit is 1.035. [See the electronic edition of the Journal for a color version of this figure.]
the eclipsing-binary algorithms of Wilson & Devinney (1971, updated 2005; hereafter WD) as implemented in the PHOEBE code of Prsa & Zwitter (2005). WD has become standard in the modeling and analysis of all manner of eclipsing binary systems, having grown in sophistication over the past 35 years to include, e.g., phase-dependent projection effects in eccentric orbits, radial velocity perturbations arising from proximity and eclipse effects, apsidal motion, and reflection and limb-darkening effects. In its most advanced implementation, the code can also treat the effects of surface spots, model atmospheres, and asynchronous rotation, including any attendant gravity brightening and radial velocity perturbations arising from nonsphericity and from phase-dependent variations in the shapes of the components.

For the present study, we add information from the out-of-eclipse variations in the light curve to model asynchronous rotation of the components and as a first step toward accounting for the presence of surface spots (§ 2.3.1). As part of our ongoing study of 2M0535−05, we plan to incorporate progressively more advanced treatments, including a full investigation of surface spots and inclusion of state-of-the-art brown dwarf model atmospheres. Here, as in Paper I, we use simple blackbody spectra in our light-curve models. While brown dwarf spectra are known to exhibit strong departures from simple blackbodies, we show below that this effect is unlikely to significantly alter our principal findings; in particular, the reversal of temperatures with mass that this effect is unlikely to significantly alter our principal findings; in particular, the reversal of temperatures with mass and mass and mass that this effect is unlikely to significantly alter our principal findings; in particular, the reversal of temperatures with mass and mass.

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2.3.1. Spot-related Variations in the Light Curve

To begin, we ran an initial WD fit to the light-curve and radial velocity data (Tables 2 and 4) using as initial values the system’s orbital and physical parameters from Paper I, together with the updated orbital period from this study (§ 2.2). The best-fit parameters and their formal uncertainties are summarized in Table 5. The reduced χ² of this fit is large (χ² = 3.10), and the rms of the residuals relative to this fit (0.033 mag) is accordingly larger than expected given the typical error on the photometric measurements (§ 2.2). This suggests an additional source of variability in the light curve—spots, for example—not included in the model.

Surface spots are most commonly manifested as low-amplitude, periodic, roughly sinusoidal variations superposed on the eclipse light curve (e.g., Stassun et al. 2004b). We searched for such low-amplitude, periodic variations in the light curve of 2M0535−05 by applying a Lomb-Scargle periodogram (Scargle 1982) analysis to those portions of the light-curve data obtained outside of eclipse. We performed this periodogram analysis separately on each epoch of light-curve data (see Table 3), as spot-related variations often show evolution in amplitude and phase with time (Stassun et al. 1999, 2004b; Torres & Ribas 2002).

We find statistically significant periodic signals in all but the first two epochs, these earlier epochs possessing relatively few measurements. While the amplitudes of these periodic signals vary slightly from epoch to epoch, they are always small (∆m ≤ 0.06 mag, peak to peak). Importantly, the periods of these signals are consistent across epochs, with a value of P_{spot} ≈ 3.3 days. Spot-related variability observed in other eclipsing binaries is similarly characterized by photometric amplitudes of a few percent and periods that are constant over many epochs (e.g., Ribas 2003), most likely reflecting the rotation period of one or both binary components. The implication here is that at least one of the brown dwarfs in 2M0535−05 is nearly always spotted and rotates with P_rot ≈ 3.3 days.

With a rotation period that is shorter than the orbital period by a factor of (almost exactly) 3, the rotational and orbital angular velocities of 2M0535−05 have evidently not yet become pseudo-synchronized with one another (where the rotational angular velocity is synchronized to the orbital angular velocity at periastron; Hut 1981), which for the eccentricity of 2M0535−05 would give P_rot/P_{orb} ≈ 1/2. Instead, the rotation of at least one component in 2M0535−05 is supersynchronous. Such supersynchronicity is probably not surprising given the extreme youth of 2M0535−05 (see below) and that young brown dwarfs tend to be rapid rotators (Mohanty & Basri 2003); tidal effects have likely not yet had sufficient time to synchronize the system (e.g., Meibom & Mathieu 2005).

A more detailed discussion of rotation in 2M0535−05 is beyond the scope of this paper. For our present purposes, we proceed to adopt the observed P_rot = 3.3 days in our final WD fit as a constraint on the oblateness of both 2M0535−05 components. In addition, we rectify the I’C-band light curve by subtracting a sinusoid of P = 3.3 days, with the amplitude and phase determined separately for each epoch of data, as described above. The aim of this rectification procedure is to “remove” the spot signal from the light curve and to thereby allow the WD model to achieve goodness of fit without introducing additional spot-fitting parameters that are poorly constrained at present. We caution, however, that this procedure is not equivalent to modeling the spots physically. The inclusion of additional light curves at multiple wavelengths into our analyses (Y. Gómez Maqueo Chew et al. 2007, in preparation) will ultimately be required to constrain the physical properties of the spots and to permit full modeling of their effects on the observed light curves and radial velocities. Bearing these caveats in mind, we proceed with our analysis below using the rectified I’C-band light curve, and revisit the possible influence of spots in § 3.2.

2.3.2. Determination of Physical Parameters

The final WD solution was determined by simultaneously fitting the Phoenix radial velocities and the I’C-band light curve, rectified as described above. The resulting orbital and physical parameters of 2M0535−05 are summarized in Table 5, the fit to the radial velocities shown in Figure 2, the fit to the light curve displayed in Figure 3, and the system geometry illustrated in Figure 4. With the light curve rectified, the WD fit is now excellent; the rms of the residuals is 0.021 mag, comparable to the typical error on the photometric measurements (§ 2.2), and the goodness of fit is correspondingly very good, χ² = 1.035.

A comparison of the orbital and physical properties of 2M0535−05 derived from the rectified and unrectified light curves (Table 5) reveals mostly minor, statistically insignificant differences in the fit parameters. However, a few parameters do show differences that are larger than their formal uncertainties. For example, both e and ω differ by ~2 σ (although these parameters are strongly correlated with one another, so their uncertainties are not independent), suggesting that the rectification procedure is not entirely free of small, systematic couplings to some parameters. Thus, while a physical treatment of spots in the WD model will ultimately be required to achieve full accuracy in the determination of some parameters, the effects of spots on the most fundamental physical parameters that we derive for 2M0535−05—the orbital parameters, in particular, and thus the component masses and radii—are probably insignificant. Moreover, if other parameters remain susceptible to spot-modeling effects, these effects are evidently very subtle.
We note that there exists an alternative WD solution to the one presented in Table 5, with nearly identical best-fit parameters except that the component radii are reversed. Formally, the goodness of fit of this alternative solution is inferior, with $\chi^2 = 1.062$, but it is nonetheless acceptable. This particular type of degeneracy is a general feature of eclipsing-binary solutions (see, e.g., Stassun et al. 2004b; López-Morales & Ribas 2005). Since only the component radii are significantly different in the two solutions, the degeneracy can be broken by adding the additional constraint of the luminosity ratio, which is generally very different in the two solutions. In this case, the preferred solution from Table 5 gives an $H$-band luminosity ratio of $L_1/L_2 = 1.63 \pm 0.13$, whereas the alternative solution gives $L_1/L_2 = 0.69 \pm 0.06$. The luminosity ratio predicted by the alternative solution—in which the secondary is both warmer and larger, and thus more luminous, than the primary—is clearly inconsistent with the ratio inferred from the observed spectra, which imply $L_1/L_2 \sim 1.5$ in the $H$ band (see Fig. 1).

3. RESULTS

3.1. Masses and Radii

With masses of $M_1 = 0.0569 \pm 0.0046 \, M_\odot$ and $M_2 = 0.0358 \pm 0.0028 \, M_\odot$, the components of 2M0535–05 are proven to be bona fide brown dwarfs. Moreover, with radii of $R_1 = 0.674 \pm 0.023 \, R_\odot$ and $R_2 = 0.485 \pm 0.018 \, R_\odot$, these brown dwarfs are more comparable in their physical dimensions to young, low-mass stars than to old brown dwarfs, consistent with their being very young (see below). Importantly, these mass and radius measurements are distance independent. Moreover, systematic errors do not appear to dominate over random measurement uncertainties (§ 2.1). Thus the masses and radii of 2M0535–05 reported here are accurate to 8% and 3%, respectively. In § 3.4 we make use of these measurements for an initial examination of the predictions of theoretical brown dwarf evolutionary models.

3.2. Reversal of Temperatures

The physical properties that we have determined for the brown dwarfs in 2M0535–05 are surprising in at least one important respect: the less-massive secondary is hotter than the primary. Specifically, we find $T_{\text{eff}, 2}/T_{\text{eff}, 1} = 1.064 \pm 0.004$ (Table 5), which follows from the relative depths of the eclipses and bolometric corrections from the model atmospheres (blackbodies in this case), with small corrections for differences in occulted areas that occur due to the mildly eccentric orbit (Fig. 4). This finding is highly statistically significant. Such a reversal of temperatures with mass is not predicted by any theoretical model for coeval brown dwarfs—in which temperature increases monotonically with mass—and thus merits closer scrutiny. Here we consider the possible effects of non-blackbody atmospheres and surface spots.

Brown dwarf spectra deviate significantly from an ideal blackbody, due primarily to the strong wavelength dependence of molecular opacity. The corresponding redistribution of flux into or out of any specific wavelength depends on temperature, potentially affecting the ratio of eclipse depths. However, the primary and secondary of 2M0535–05 have very similar effective temperatures (§ 2.1), so both components should have similar deviations from a blackbody.

To check this quantitatively, we have examined up-to-date synthetic models of brown dwarf spectra for temperatures appropriate to the components of 2M0535–05. In particular, we use the solar-metallicity COND atmosphere models of Allard et al. (2001). As the masses and radii of 2M0535–05 imply $\log g \approx 3.5$ for both components, we use the COND models with this $\log g$ value also. The COND models incorporate recent opacities, including $\sim 500$ million molecular lines, as well as dust formation and condensation at very low temperatures. (For a more detailed discussion of these models, and their applicability to young brown dwarfs in particular, we point the reader to the extensive discussion in Mohanty & Basri [2003]). The results of our analysis are summarized in Figure 5. We find that while dramatic departures from simple blackbodies are clearly present in the model spectra, the ratio of surface brightnesses in the $I$ band is consistent with that predicted from simple blackbodies to within 2%, which implies a $T_{\text{eff}}$ ratio that is consistent with the blackbody value to within 0.5%.

As an additional check, we calculated the $T_{\text{eff}}$ values of the components of 2M0535–05 independently at 1.25, 1.65, and 2.2 $\mu$m. We use the ratio of surface fluxes at 0.8 $\mu$m (measured directly from the ratio of eclipse depths in the $I_{\text{C}}$-band light curve; § 2.3) and the radii (measured directly from the eclipse durations and the orbital velocities; Table 5), together with an assumed distance to the Orion Nebula Cluster of 450 pc, empirical bolometric corrections from the literature (Golimowski et al. 2004), and the observed $JHK$ magnitudes at these wavelengths from Carpenter et al. (2001): $K = 13.58 \pm 0.02$, $J - H = 0.640 \pm 0.015$, and $H - K = 0.385 \pm 0.015$. We derive temperatures of $T_1 = 2730$ K and $T_2 = 2875$ K (1.25 $\mu$m), $T_1 = 2675$ K and $T_2 = 2860$ K (1.65 $\mu$m), and $T_1 = 2680$ K and $T_2 = 2795$ K (2.2 $\mu$m). In all cases, the derived $T_{\text{eff}}$ values are consistent with a spectral type of $\sim$M6.5, and in all cases the reversal of temperatures persists.

4 At the temperatures of the components of 2M0535–05, the DUSTY atmosphere models of these authors are very similar and would work equally well for our purposes. See also Mohanty & Basri (2003).
Another potential contributor to non-blackbody spectra is the presence of hot or cold spots (akin to solar plage or sunspots) on the brown dwarfs, leading to spectra that derive from a combination of temperatures. Cool spots have now been found to be present on many brown dwarfs (e.g., Scholz & Eisloeffel 2005) and may thus be expected on one or both brown dwarfs in 2M0535$^\circ$/C05 as well. Indeed, we find a clear periodic signal in the out-of-eclipse portions of the $I_C$-band light curve, with a period of $P_{\text{spot}}/C25$3 days and a semimagnitude of $/C240.03$ mag ($x2.3.1$); almost certainly this is a rotationally modulated spot signal.

Such spot signals are commonly observed in the light curves of close eclipsing binaries, although modeling these effects is often a largely cosmetic exercise with little effect on the resulting stellar properties. For example, in our analysis of the young eclipsing binary V1174 Ori (Stassun et al. 2004b), we successfully reproduced the observed out-of-eclipse light-curve variations by including spots in the light-curve model, but the derived system parameters were altered only negligibly as a result (see also Torres & Ribas 2002; Ribas 2003; Lopez-Morales & Ribas 2005).

On the other hand, accurate modeling of spot effects can be crucially important for the proper interpretation of certain systems. W UMa stars of the so-called “W type” are a particularly good case in point. A defining characteristic of these systems is that the deeper eclipse corresponds to the occultation of the physically smaller and lower mass secondary, similar to what is observed in 2M0535$^\circ$/C05. One interpretation advanced early on by Rucinski (1974) is that the secondary is hotter than the primary (typically by $\sim$5%), perhaps due to thermal effects arising from mass and energy transfer in these contact systems. However, an alternate interpretation (e.g., Eaton et al. 1980) is that cool spots on the primary, if preferentially located along the eclipsed latitude and more-or-less uniformly distributed in longitude, can have the effect of lowering the surface brightness of the eclipsed regions on the primary during transit by the secondary, thus making the eclipse of the primary shallower. Such a model is generally very delicate in the details, and requires careful arrangement of the putative spots in order that they produce only mild ($\lesssim0.05$ mag) out-of-eclipse variations in the light curve; the inferred spot configurations can resemble a “leopard print” pattern in some cases (e.g., Linnell 1991).

We are now experimenting with more sophisticated light-curve models that include the effects of spots. In the meantime, we emphasize here that the ratio of eclipsed surface brightnesses implied by our current light-curve model is robust; the higher mass primary really does radiate less per unit area than the secondary. Thus, in what follows, we continue to explore the implications of a temperature reversal in 2M0535$^\circ$/C05.

3.3. Physical Association with the Orion Nebula

Star-forming Region: Evidence for Youth

Strong evidence for the physical association of 2M0535$^\circ$/C05 with the Orion Nebula Cluster, and hence of its youth, is provided by its center-of-mass velocity. The observed value of...
\[ \gamma = 24.1 \pm 0.4 \text{ km s}^{-1} \text{ (Table 5)} \] is within 1 \text{ km s}^{-1} of the systemic radial velocity (25 \pm 1.5 \text{ km s}^{-1}) of kinematic members of this active star-forming region (Stassun et al. 1999; Sicilia-Aguilar et al. 2005).

In addition, we can derive a distance to 2M0535−05 by comparing the total system luminosity to its observed flux. To calculate the luminosity, we use the directly measured radii (Table 5) together with the effective temperatures and apply the Stefan-Boltzmann relation, \[ L = 4\pi R^2 \sigma T_{\text{eff}}^4. \] The adopted spectral type of M6.5 ± 0.5 for the 2M0535−05 primary (§ 2.1) implies \[ T_{\text{eff},1} = 2715 \pm 100 \text{ K based on recent calibrations of the } T_{\text{eff}} \text{ scale for brown dwarfs (Mohanty \\& Basri 2003; Slesnick et al. 2004; Golimowski et al. 2004), although as mentioned earlier, systematic uncertainties in the } T_{\text{eff}} \text{ scale may be as large as } \approx 200 \text{ K. From the measured temperature ratio of } T_{\text{eff},2}/T_{\text{eff},1} = 1.064 \pm 0.004 \text{ (Table 5), we obtain } T_{\text{eff},2} = 2820 \pm 105 \text{ K. This then gives component luminosities of } L_1 = 0.0223 \pm 0.0034 L_\odot \text{ and } L_2 = 0.0148 \pm 0.0023 L_\odot, \text{ and a total system luminosity of } L = 0.0372 \pm 0.0060 L_\odot. \text{ Adapting an apparent magnitude of } m_K = 13.58 \pm 0.02 \text{ (Carpenter et al. 2001) and bolometric corrections appropriate for the observed } T_{\text{eff}} \text{ values (Golimowski et al. 2004) yields a derived distance to 2M0535−05 of } 456 \pm 34 \text{ pc, assuming no extinction. This distance determination is consistent with the distance to the Orion Nebula of } 480 \pm 80 \text{ pc (Genzel \\& Stutzki 1989).}

The Orion Nebula Cluster is extremely young, with an age that has been estimated to be just \[ t \approx 1^{+2}_{-1} \text{ Myr (Palla \\& Stahler 1999; Hillenbrand 1997). With a center-of-mass velocity and distance that are both consistent with membership in this cluster, 2M0535−05 is probably also very young, likely having formed within the past few Myr. In addition, as discussed in Paper I, the JHK colors of 2M0535−05 place an upper limit on the extinction of \[ A_V < 0.75, \] and thus limit the amount of remnant material available to the brown dwarfs for ongoing accretion. Given the eclipsing nature of the system, any disk material would necessarily be seen edge-on and would thus produce a large amount of extinction and reddening. Thus, while the colors of 2M0535−05 are formally consistent with a small amount of interstellar extinction and/or a small amount of remnant disk material, the currently observed masses are unlikely to change significantly over time. These brown dwarfs will likely forever remain brown dwarfs.

### 3.4. Comparison to Theoretical Brown Dwarf Evolutionary Tracks

While we expect that our ongoing analysis of 2M0535−05 will further improve the accuracy of the measured system parameters, the present accuracy is sufficient to permit an initial examination of theoretical brown dwarf evolutionary models. Here we consider two of the more widely used sets of tracks: those of Baraffe et al. (1998) and those of D’Antona \\& Mazzitelli (1997, updated 1998). These models differ in their treatment of brown dwarf atmospheres and of energy transport (convection) in brown dwarf interiors, as well as in the choice of initial conditions (for a more in-depth discussion of differences in these models, see Siess et al. 2000; Baraffe et al. 2002).

Figure 6 compares the observed radii, effective temperatures, and luminosities of 2M0535−05 with the values theoretically predicted by these models for brown dwarfs with masses of \[ M_1 = 0.0569 \pm 0.0046 M_\odot \text{ and } M_2 = 0.0358 \pm 0.0028 M_\odot \text{ (Table 5).} \]

We note first that, generally speaking, the agreement between the observed and theoretically predicted properties of 2M0535−05 is quite good. The models predict that these very young brown dwarfs should, at an age of \approx 1 \text{ Myr, be significantly larger, warmer, and more luminous than their older counterparts—and that is in fact what we see. Indeed, between 1 and 100 \text{ Myr, a brown dwarf with a mass of } 0.057 M_\odot \text{ (the mass of the 2M0535−05 primary) is predicted to shrink by } 50\%, \text{ cool by several hundred K (or, equivalently, go from an M spectral class to an L spectral class), and dim by } 1.5 \text{ orders of magnitude (Fig. 6). The recently measured radius } R = 0.12 R_\odot \text{ of the old and low-mass } M = 0.09 M_\odot \text{ star in the eclipsing binary system OGLE-TR-122 (Pont et al. 2005) confirms that stars with near-brown-dwarf masses have very small radii } (\approx 1 R_J) \text{ when they are old. Thus, the fact that 2M0535−05 comprises young brown dwarfs that are both large and luminous—and even simply that they are of M spectral class, as predicted—is a testament to the generally good predictive power of current theoretical models of brown dwarfs.}

At a more detailed level, the models of D’Antona \\& Mazzitelli (1997) predict radii and luminosities that are more consistent with the observed values. The difference is most pronounced in the radii; the Baraffe et al. (1998) models underpredict both radii by \approx 10\%. This finding of underpredicted model radii is similar in sense and magnitude to that found from recent efforts to derive the physical properties of low-mass stars and brown dwarfs through detailed modeling of their spectra (Mohanty et al. 2004a, 2004b). In addition, while both sets of models perform reasonably well with respect to the observed luminosities, the agreement is somewhat better for the D’Antona \\& Mazzitelli (1997) models; it appears possible that more accurate measurements will reveal an underprediction of luminosity by the Baraffe et al. (1998) models for the lower mass secondary.

But perhaps more importantly, the reversal of temperatures in 2M0535−05 remains puzzling; the relationship between effective temperature and mass is predicted by both sets of models to be monotonic for brown dwarfs of the same age. However, this expectation disappears for two brown dwarfs of differing age. The observed effective temperatures can be seen as consistent with the D’Antona \\& Mazzitelli (1997) models if the primary is taken as being modestly younger than the secondary (\[ \Delta t \approx 0.5 \text{ Myr.} \] Indeed, the temperatures, radii, and luminosities of 2M0535−05 all remain in marginally good agreement with these models for such an age difference, at a mean age of 1 \text{ Myr (Fig. 7), if we also adjust the observed } T_{\text{eff}} \text{ scale cooler by } 70 \text{ K. Such a shift is well within the current systematic uncertainty of the brown dwarf } T_{\text{eff}} \text{ scale (§ 2.1). Thus, a question raised by our findings is whether current brown dwarf formation theory can accommodate a scenario in which two brown dwarfs—that are part of the same, very young, binary system—can have sufficiently different ages to allow for reversed temperatures as we have observed in 2M0535−05.

### 4. DISCUSSION

#### 4.1. 2M0535−05 as a Case Study in Dynamical Brown Dwarf Formation?

In truth, we have very little understanding about how binaries with components as close as those in 2M0535−05 are formed (see, e.g., Bonnell 2001; Tohline 2002). 2M0535−05 is, after PPI 15 in the Pleiades (Basri \\& Martin 1999), the shortest-period brown dwarf binary system yet discovered. With a few exceptions (e.g., Tohline \\& Durisen 2001), fission seems to be ruled out. In situ mechanisms involving dynamic cloud fragmentation and disk fragmentation have not yet proven successful in creating such close binaries, but remain to be fully developed. In particular,
Fig. 6.—Comparisons of observations with theoretical models of young brown dwarfs. The measured radii, effective temperatures, and luminosities of 2M0535−05 (symbols with error bars) are compared to the values predicted by two sets of theoretical models (Baraffe et al. 1998; D’Antona & Mazzitelli 1997) of young brown dwarfs. Solid curves show the predicted evolution from 0.1 to 100 Myr for brown dwarfs with masses equal to those measured for the primary (lighter curves) and secondary (darker curves) brown dwarfs in 2M0535−05. (The theoretical calculations of Baraffe et al. [1998] do not extend to ages less than 1 Myr.) Dashed curves bracketing the solid curves represent the 1 σ measurement uncertainties in those masses. Observed and predicted values are generally in good agreement, particularly with the D’Antona & Mazzitelli (1997) models. Note that the effective temperature of the primary is predicted by both sets of models to be warmer than that of the secondary at any particular age, but that the D’Antona & Mazzitelli (1997) models allow the primary to be cooler than the secondary if it is sufficiently younger (see also Fig. 7). [See the electronic edition of the Journal for a color version of this figure.]
the role of orbital migration in the presence of a massive circumbinary disk needs to be considered. Certainly, if the two brown dwarfs formed together as a close binary, we have essentially no a priori expectations for whether they should be observed to be coeval to within 0.5 Myr.

Alternatively, recent theoretical work (Reipurth & Clarke 2001), as well as detailed numerical simulations (Bate et al. 2002a, 2002b; Bate & Bonnell 2005), suggest that dynamical interactions may be integral to the formation of brown dwarfs. The argument is essentially that strong gravitational interactions in multiple-body...
encounters provide a feasible mechanism for disrupting the accretion process and thereby preventing the accumulation of mass by objects that would otherwise have become stars. This hypothesis remains under debate (e.g., Maxted & Jeffries 2005). Still, it is tempting to speculate that the components of 2M0535−05 did not form together as a binary, but rather formed separately—with the primary forming later—and then were later married through a dynamical interaction. In such a scenario, it is possible that the resulting binary system—comprising two objects that were not originally formed together—may exhibit seemingly peculiar characteristics, such as the observed reversal of effective temperatures, that in fact reveal the non-coeval nature of the system.

There are at least two specific scenarios involving multiple-body interactions that might pertain to the origin of 2M0535−05. One involves a low-mass binary pair that interacts with a more massive third body from elsewhere in the cluster. Simulations show that if the binary is not simply broken apart by the encounter, the lower mass member of the binary is ejected and replaced by the massive incoming object (Bate et al. 2002a). The resulting binary would then likely consist of non-coeval members. A serious concern with this scenario in the context of 2M0535−05 is that it is unlikely in three-body encounters within clusters that the most massive object would have a mass of only 0.06 $M_\odot$.

Thus, a second scenario is that several objects formed in the fragmentation of a small molecular core, forming an unstable multiple system. The consequent rapid dynamical evolution of the system may have both terminated accretion and formed a hard binary (Bate et al. 2002b). In such a fragmentation scenario the relative core-collapse times and evolutionary zero points might easily vary by 0.5 Myr, of order the age difference needed to explain the temperature reversal of 2M0535−05 in the context of some evolutionary models (Fig. 7).

The position of 2M0535−05 might be taken as further evidence that dynamics have been important in its history. With a projected separation of 2.8 pc from the center of the Orion Nebula, 2M0535−05 is situated more than 10 core radii from the center of the Orion Nebula Cluster (Hillenbrand & Hartmann 1998); perhaps the pair was ejected from the cluster center during a dynamical encounter. The one-dimensional velocity dispersion in the cluster is $\sim 2$ km s$^{-1}$ (van Altena et al. 1988; Hillenbrand & Hartmann 1998; Stassun et al. 1999; Sicilia-Aguilar et al. 2005), so to reach its current position in 1 Myr, if ejected from the cluster core, 2M0535−05 would need a somewhat higher-than-usual velocity of $\sim 3$ km s$^{-1}$ in the plane of the sky. However, the measured center-of-mass radial velocity of 2M0535−05 does not deviate significantly from the cluster velocity. An alternative interpretation for the position of 2M0535−05 at the outskirts of the cluster may be that it is not a member of the Cluster proper, but rather a member of the more widely distributed population of young stars in the region surrounding the Orion Nebula (Warren & Hesser 1978). The binary’s proper motion is the critical measurement needed to establish whether 2M0535−05 was ejected from the cluster center.

4.2. Missing Physics in Theoretical Brown Dwarf Evolutionary Tracks?

An alternative explanation is that the evolutionary tracks are deficient with respect to some critical physical ingredient(s). For example, the presence of strong magnetic fields on one or both brown dwarfs in 2M0535−05 could be affecting energy transport and thereby altering their physical structure.

Indeed, recent analyses of several young, low-mass eclipsing binaries (e.g., Stassun et al. 2004b; Covino et al. 2004; Torres et al. 2006) indicate systematic discrepancies in the models. In particular, the observed effective temperatures are cooler than expected, and the observed radii larger than expected. These discrepancies are especially pronounced among the most magnetically active stars (as traced by X-ray emission and other proxies). One possible interpretation is that strong magnetic fields inhibit energy transport in these otherwise fully convective stars, resulting in a decrease of the surface temperature and a corresponding increase in radius so as to radiate the same total flux (Montalbán & D’Antona 2006). Such an interpretation would be consistent with, and would help explain, the emerging observational evidence for suppressed convection in young, low-mass stars (e.g., Stassun et al. 2004b; Mathieu et al. 2007; Torres et al. 2006 and references therein).

Thus, the temperature reversal in 2M0535−05 might be taken as evidence for a strong magnetic field on the higher mass primary that is causing a sufficient decrease in its surface temperature to make it effectively cooler than the lower mass secondary. By inference, the secondary would be interpreted as being less magnetically active. The observational evidence is strong for magnetic activity in young, low-mass stars and brown dwarfs of early- and mid-M type (e.g., Mohanty et al. 2002; Stassun et al. 2004a; Preibisch et al. 2005). Moreover, the evidence in fact shows a marked decline in magnetic activity at very late M types (e.g., Gizis et al. 2000; Mohanty et al. 2002), suggesting that brown dwarfs with roughly the mass of the 2M0535−05 secondary and below are not capable of generating strong fields. The idea of a magnetically active primary would also be consistent with the primary being heavily spotted (see § 3.2).

If we are to explain the anomalously low effective temperature of the 2M0535−05 primary in this way, we should then also expect its radius to be larger than theoretically predicted, as the one effect goes hand in hand with the other (Montalbán & D’Antona 2006). As discussed above (§ 3.4), whether the 2M0535−05 radii agree with theoretical predictions depends on one’s choice of model. The Baraffe et al. (1998) tracks do indeed suggest oversized radii in 2M0535−05 (for both components), although this may simply reflect the truncation of those tracks at 1 Myr. On the other hand, the D’Antona & Mazzitelli (1997) tracks agree with the observed radii very well (Fig. 6), with no need to invoke missing physics.

5. SUMMARY AND CONCLUSIONS

2M0535−05 is the first known eclipsing binary system comprising two brown dwarfs. Satisfying both kinematic and distance requirements for physical association with the young (~1 Myr) Orion Nebula Cluster, 2M0535−05 provides the only direct, accurate measurements of the fundamental physical properties of newly formed substellar objects. The masses that we measure are accurate to ~10%, the radii accurate to ~5%, the ratio of effective temperatures accurate to ~1%, and all are distance independent. As such, 2M0535−05 represents an important benchmark for theoretical models of brown dwarf formation and evolution.

Encouragingly, we find that current brown dwarf evolutionary tracks are, broadly speaking, successful in predicting the fundamental physical properties of these young brown dwarfs. More quantitatively, of the two sets of theoretical models considered here, we find that the models of D’Antona & Mazzitelli (1997) yield mass-radius and mass-luminosity relationships that best agree with the empirically determined ones. The models of Baraffe et al. (1998) predict radii and luminosities that are 1.5–2 $\sigma$ smaller than the observed values.

However, the reversal of component effective temperatures with mass in 2M0535−05 is unexpected and unexplained. We have considered here two possible interpretations of this intriguing result. The first is that the components of 2M0535−05 are mildly non-coeval, with the higher mass primary being ~0.5 Myr younger
than the secondary. The models of D’Antona & Mazzitelli (1997) are in fact consistent with the observed temperature reversal for such an age difference. A second hypothesis is that strong magnetic activity on the primary is inhibiting convection and thereby lowering its surface temperature.

Neither of these interpretations is wholly satisfying, and neither is obviously discreditable. Binary formation theory is largely silent on the subject of coevality at the level of ~0.5 Myr, and theorists have long warned the star formation community about the limited applicability of evolutionary track chronometry at such early ages (the model zero points being arbitrary in most cases). In addition, while the observational evidence is strong that young brown dwarfs can be magnetically active, the effects of magnetic fields on brown dwarf structure and evolution have yet to be consistently modeled or fully understood.

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Note added in proof.—G. Chabrier et al. (A&A, submitted [2007]) have calculated new models that appear capable of reproducing the observed radii and temperatures in 2M0535–05. They suggest that strong surface magnetic fields and spots can lead to reduced convective efficiency and reduced heat flux, which in turn produces a lower effective temperature for the primary component and a larger radius for the secondary component. See also § 4.2 above.