

Discovery of two young brown dwarfs in an eclipsing binary system

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Brown dwarfs are considered to be ‘failed stars’ in the sense that they are born with masses between the least massive stars ($0.072 M_{\odot}$)¹ and the most massive planets ($\sim 0.013 M_{\odot}$)²; they therefore serve as a critical link in our understanding of the formation of both stars and planets³. Even the most fundamental physical properties of brown dwarfs remain, however, largely unconstrained by direct measurement. Here we report the discovery of a brown-dwarf eclipsing binary system, in the Orion Nebula star-forming region, from which we obtain direct measurements of mass and radius for these newly formed brown dwarfs. Our mass measurements establish both objects as brown dwarfs, with masses of $0.054 \pm 0.005 M_{\odot}$ and $0.034 \pm 0.003 M_{\odot}$. At the same time, with radii relative to the Sun’s of $0.669 \pm 0.034 R_{\odot}$ and $0.511 \pm 0.026 R_{\odot}$, these brown dwarfs are more akin to low-mass stars in size. Such large radii are generally consistent with theoretical predictions for young brown dwarfs in the earliest stages of gravitational contraction^{4,5}. Surprisingly, however, we find that the less-massive brown dwarf

is the hotter of the pair; this result is contrary to the predictions of all current theoretical models of coeval brown dwarfs.

Mass is the most fundamental property of a brown dwarf, as it determines all other physical characteristics and governs how brown dwarfs evolve with time. Theoretical brown-dwarf evolution models^{2,4,5} make specific, testable predictions of the relationship between a brown dwarf’s mass and its other physical properties, such as radius and temperature. Unfortunately, these predictions have yet to be empirically tested because the basic physical properties of brown dwarfs are extremely difficult to measure; the mass of only one brown dwarf has been measured with sufficient accuracy to make the brown-dwarf nature of the object definitive⁶, and in no case has a brown dwarf’s radius been measured directly. Astronomers have traditionally used stellar eclipsing binaries to measure the masses and radii of stars⁷, but until now no brown-dwarf eclipsing binaries were known. Here we have discovered the 2-Micron All-Sky Survey (2MASS) object J05352184–0546085 to be a previously unknown eclipsing binary in the Orion Nebula, and the first example of an

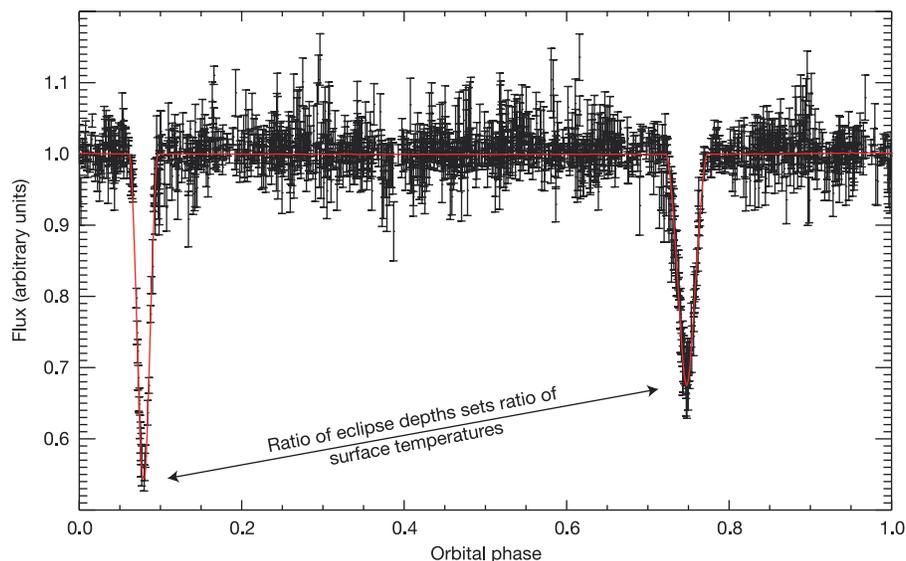


Figure 1 | Light curve of 2MASS J05352184–0546085 at $0.8 \mu\text{m}$. We repeatedly imaged 2MASS J05352184–0546085 with the 0.9-m telescope at Kitt Peak National Observatory and with the 0.9-m, 1.0-m and 1.3-m telescopes at the Cerro Tololo Inter-American Observatory, from December 1994 to March 2005. In total, 1,590 flux measurements were obtained on 280 separate nights and with an average cadence of 5–6 measurements per night. Error bars show ± 1 s.d.; the typical uncertainty is 2%. A time-series analysis reveals an unambiguous period of $P = 9.779621 \pm 0.000042$ days. The data are shown here folded on this period and phased relative to

periastron passage, as determined from the orbit solution (Fig. 2). The ratio of eclipse depths provides a direct measure of the ratio of surface temperatures, with the deeper eclipse corresponding to the eclipse of the hotter component. In this system, the deeper eclipse corresponds to the eclipse of the lower-mass component (see Fig. 2). A model fit to the light curve incorporating the final orbital and physical parameters of 2MASS J05352184–0546085 (Table 1, column 2) is also shown (solid red curve). The average residual relative to this model is 1.9%, and the reduced χ -squared of the fit is 0.85.

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eclipsing binary comprising two brown dwarfs (a summary diagram of the salient features of 2MASS J05352184–0546085 is provided in the Supplementary Information).

The light curve of 2MASS J05352184–0546085 (Fig. 1) is characterized by two distinct, periodically recurring diminutions in flux that are well separated in phase, as is typical of eclipsing binaries in which the two components are fully detached (that is, not in contact). From radial velocity measurements of both components (Fig. 2) we obtain the binary mass ratio and derive a precise solution for all of the system parameters except the orbital inclination (Table 1, column 1). A combined analysis of the light curve and orbit solution^{8,9} then yields the inclination precisely and gives an accurate measurement of the total system mass (Table 1, column 2).

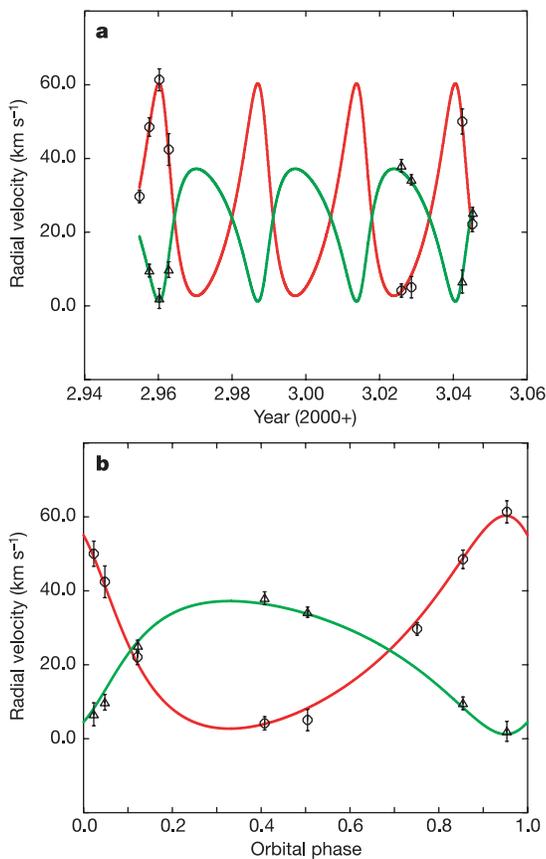


Figure 2 | Radial velocity measurements and orbit solution. We obtained high-resolution, near-infrared spectra of 2MASS J05352184–0546085 with the Phoenix spectrograph (resolving power of 30,000) at the 8-m Gemini South telescope on eight separate nights from December 2002 to January 2003. A cross-correlation analysis of the individual spectra against a radial-velocity standard star (see Fig. 3a) yields the radial velocities of the two components at eight distinct orbital phases. We tried several different radial-velocity standard stars with spectral types M1 to M9, and found that an M6.5 star produced the strongest cross-correlation signals for both components; the spectra of the two components are therefore probably similar to that of an M6.5 spectral type (see Fig. 3). Here the individual, heliocentric radial velocity measurements of the components of 2MASS J05352184–0546085 are shown, as functions of both time (a) and orbital phase (b). Orbital phase is measured with respect to the time of periastron passage (that is, closest approach of the two brown dwarfs to one another), as determined from the final orbit solution. Measurements of the primary are represented as triangles; the secondary as circles. Error bars show ± 1 s.d.; the typical uncertainty is 2 km s^{-1} . The final orbit solution (Table 1, column 2) was determined by simultaneously fitting the light-curve and radial-velocity measurements using a standard detached-eclipsing-binary model. This orbit solution is shown in a and b as solid curves, green for the more massive component, red for the less massive component. The reduced χ -squared of the fit is 1.0.

The individual masses follow directly from the total system mass and the binary mass ratio. At $M_1 = 0.0541 \pm 0.0046 M_\odot$ the more massive component—the ‘primary’—is four standard deviations below the $0.072 M_\odot$ threshold for a star, and at $M_2 = 0.0340 \pm 0.0027 M_\odot$ the lower-mass ‘secondary’ is even further below this threshold; both components are thus proved to be brown dwarfs. In addition, from the observed eclipse durations and orbital velocities we directly and accurately measure the radii of the brown dwarfs to be $R_1 = 0.669 \pm 0.034 R_\odot$ and $R_2 = 0.511 \pm 0.026 R_\odot$, representing the first direct measurements of brown-dwarf radii.

The relative depths of the eclipses (Fig. 1) yield the ratio of the brown dwarfs’ surface fluxes at $0.8 \mu\text{m}$, from which we determine the ratio of their surface temperatures to be $T_2/T_1 = 1.054 \pm 0.006$. Remarkably, the lower-mass secondary has a surface temperature that is slightly—but significantly—warmer than the primary. This follows directly from the fact that the deeper eclipse occurs when the secondary is eclipsed, which implies that it has the higher surface flux. Brown dwarf spectra deviate significantly from an ideal black-body, potentially affecting the eclipse depths. Examining up-to-date synthetic models of brown-dwarf spectra¹⁰ at temperatures appropriate to 2MASS J05352184–0546085 (Fig. 3), we find that the ratio of fluxes at $0.8 \mu\text{m}$ is consistent with that predicted from simple blackbodies to within 3%, which implies a ratio of temperatures that agrees with the blackbody value to within 0.5%, consistent with the uncertainty quoted above. Spots have been found on many brown dwarfs¹¹ and are likely to be present in 2MASS J05352184–0546085 as well. However, the effect of spots on the temperature ratio is likely to be minor^{12,13}.

The spectrum of the primary (Fig. 3a), as well as the observed near-infrared colours (Fig. 3b), both indicate a spectral type for the primary of $M6.5 \pm 0.5$ (ref. 14). This suggests a surface temperature of $T_1 = 2,650 \pm 100 \text{ K}$ (refs 12, 15) which, from the temperature ratio, then implies $T_2 = 2,790 \pm 105 \text{ K}$. The temperature scale of young brown dwarfs is uncertain, so the assignment of absolute temperatures to 2MASS J05352184–0546085 is subject to systematic uncertainties of $\sim 300 \text{ K}$ in addition to the formal spectral-typing errors quoted¹⁶. We emphasize that it is the ratio of surface temperatures that is most accurately determined from our analysis (Fig. 1).

The distance to 2MASS J05352184–0546085 can be determined by comparing its total luminosity with its observed apparent magnitude of $m_K = 13.58 \pm 0.02$ (ref. 17), and adopting a bolometric correction¹⁵ appropriate for the observed surface temperatures. The luminosity of each brown dwarf is calculated directly from its radius and surface temperature via the Stefan-Boltzmann relation, $L = 4\pi R^2 \sigma T^4$. The distance so determined is 435 ± 55 parsecs. Extinction by as much as 0.75 visual magnitudes may be present (Fig. 3), in which case the distance is 420 ± 55 parsecs. This distance is consistent with the distance to the Orion Nebula of 480 ± 80 parsecs (ref. 18). In addition, the centre-of-mass velocity (Table 1) is within 1 km s^{-1} of the systemic radial velocity ($25 \pm 1.5 \text{ km s}^{-1}$) of members in the Orion Nebula star-forming region^{13,19}. The Orion Nebula star cluster is extremely young, with an age that has been estimated to be just 1^{+2}_{-1} million years^{20,21}. 2MASS J05352184–0546085 is thus probably also very young, probably having formed within the past few million years. The near-infrared colours of 2MASS J05352184–0546085 (Fig. 3) limit the amount of remnant material available to the brown dwarfs for accretion. The observed masses are therefore unlikely to change significantly over time, and these brown dwarfs will probably forever remain brown dwarfs.

Models^{2,4,5} predict that very young brown dwarfs still in the early stages of gravitational contraction should be significantly larger and warmer than their more evolved counterparts, and that is in fact what we see in 2MASS J05352184–0546085. At an age of ~ 1 Myr, these brown dwarfs are $\sim 500\%$ larger, and $\sim 1,500 \text{ K}$ warmer, than older brown dwarfs, which are predicted to have radii of $\sim 0.1 R_\odot$ and surface temperatures of $\sim 1,000 \text{ K}$ at 1 Gyr. The recently measured

Table 1 | Orbital and physical parameters of 2MASS J05352184–0546085

	Fit to radial-velocity data only	Fit to radial-velocity and light-curve data simultaneously
Time of periastron passage	2001.86334 ± 0.00024	2001.863650 ± 0.000095
Eccentricity, e	0.307 ± 0.024	0.3225 ± 0.0060
Orientation of periastron, ω	211.8 ± 3.9°	215.4 ± 1.1°
Semi-major axis, $asini$	0.0401 ± 0.0015 AU	0.0398 ± 0.0010 AU
Centre-of-mass velocity, γ	23.9 ± 0.5 km s ⁻¹	24.1 ± 0.4 km s ⁻¹
Mass ratio, $q \equiv M_2/M_1$	0.642 ± 0.043	0.625 ± 0.018
Total mass, $(M_1 + M_2)\sin^3 i$	0.0897 ± 0.0086 M_\odot	0.0880 ± 0.0066 M_\odot
Inclination, i		88.8 ± 0.1°
Primary mass, M_1		0.0541 ± 0.0046 M_\odot
Secondary mass, M_2		0.0340 ± 0.0027 M_\odot
Primary radius, R_1		0.669 ± 0.034 R_\odot
Secondary radius, R_2		0.511 ± 0.026 R_\odot
Surface temperature ratio, T_2/T_1		1.054 ± 0.006

The orbital and physical parameters of 2MASS J05352184–0546085 were determined in step-wise fashion, beginning with estimates of basic orbital parameters from the light curve. The orbital period, P , is determined directly from time-series analysis of the light curve. From geometrical considerations relating the orbital period, the relative durations of the eclipses, and their separations in time, we estimate the orbital eccentricity e and the orientation of periastron ω to be $e \approx 0.35$ and $\omega \approx 216^\circ$. With P fixed, we obtain a preliminary orbit solution by fitting the radial-velocity measurements alone, using these e and ω estimates as initial guesses. This preliminary orbit solution (column 1) yields the binary mass ratio and the total mass multiplied by $\sin^3 i$, where i is the unknown inclination of the orbital plane relative to the plane of the sky. 'Primary' and 'secondary' refer to the higher- and lower-mass brown dwarf, respectively. The preliminary orbit solution was refined, and the physical parameters of the brown dwarfs measured, by simultaneously fitting the light-curve and radial-velocity data using a standard detached-eclipsing-binary model^{8,9}. This final orbit solution (column 2) yields the orbital and physical parameters with no $\sin i$ ambiguity; i is very nearly 90° , as expected for an eclipsing geometry. From the eclipse durations and their relative depths, we also obtain the radii of the brown dwarfs and the ratio of their surface temperatures. Surprisingly, the secondary brown dwarf is warmer than the primary; this result is highly statistically significant. Uncertainties in the parameters represent standard 1σ formal errors from the covariance matrix of the fit. AU, astronomical units.

radius ($R = 0.12R_\odot$) of the old and low-mass ($M = 0.09M_\odot$) star in OGLE-TR-122 (ref. 22) confirms that objects with near-brown-dwarf masses do indeed have planet-like radii when they are old. Together, these observations verify the basic theoretical prediction that brown dwarfs begin their lives in a 'star-like' state—large and warm—and evolve to a more planet-like state as they contract under gravity.

At the same time, our finding that the higher-mass brown dwarf of 2MASS J05352184–0546085 is cooler than its companion is puzzling because all theoretical models predict that a brown dwarf of a given mass will at all times be warmer than a lower-mass brown dwarf of the same age. Thus, perhaps the brown dwarfs in 2MASS J05352184–0546085 are not the same age; perhaps they did not form together as a

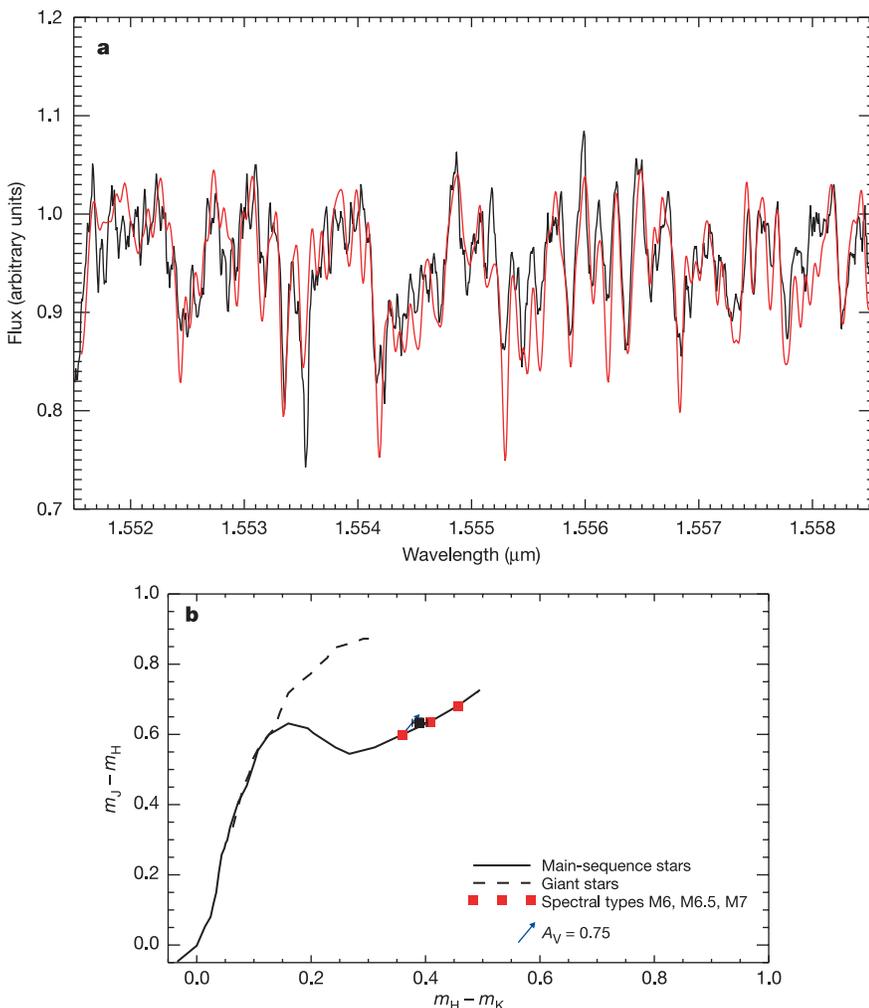


Figure 3 | Near-infrared spectrum and colours of 2MASS J05352184–0546085. **a**, The spectrum at $1.555 \mu\text{m}$ of the primary brown dwarf, obtained by averaging the eight individual spectra after shifting them to the velocity of the primary, is shown (black). For comparison, the spectrum of the best-fitting standard star—LHS 292, an old M6.5 dwarf—is also shown (red). On the basis of this very good spectral match, we adopt this standard star for the purposes of the radial-velocity analysis (Fig. 2). **b**, The near-infrared colours (J, H, Ks magnitudes, corresponding to wavelengths of 1.2, 1.6 and $2.2 \mu\text{m}$) of 2MASS J05352184–0546085 (black symbol with error bars), are compared to standard colours of field dwarfs and giants¹⁴. The colours of 2MASS J05352184–0546085 are the mean of 30 observations from the time-series 2MASS measurements of ref. 17 and converted to the CIT photometric system as described in the 2MASS documentation. Error bars represent the uncertainty of the mean (s.e.m.) of the 30 measurements. Red symbols mark the mean colours of main-sequence spectral types M6, M6.5 and M7 (from left to right). The observed colours are consistent with no extinction, though also consistent with a spectral type of M6 seen through an extinction of $A_V = 0.75$ (blue arrow), which is not uncommon for objects in this region²⁰. We thus adopt a spectral type for the primary of $M6.5 \pm 0.5$, though systematic uncertainties may be as large as about one spectral subtype. That the colours of 2MASS J05352184–0546085 in combined light so closely match the spectral type assigned to the primary on the basis of its spectrum in **a** confirms that both brown dwarfs have very similar spectral types.

binary, but rather formed separately and were later married through a dynamical interaction. Indeed, recent theoretical work²³ and detailed numerical simulations^{24,25} suggest that dynamical interactions may be integral to the formation of brown dwarfs, but this hypothesis remains under debate²⁶. Alternatively, the theoretical model ages may simply be in error. Indeed, the model ages of low-mass stars and brown dwarfs have never been independently calibrated; instead, the models currently adopt arbitrary starting points for their calculations. 2MASS J05352184–0546085 may thus provide an empirical calibration of the initial conditions for newly formed brown dwarfs. 2MASS J05352184–0546085 may also indicate the need for additional physical ingredients in the models. For example, the presence of strong magnetic fields on one or both brown dwarfs could be affecting energy transport, thereby altering their physical structure. Interestingly, recent work has suggested that the radii of young brown dwarfs may be larger than predicted^{27–30}. Additional theoretical work will be needed to ascertain whether these ideas are plausible. In any event, the reversal of temperature with mass in 2MASS J05352184–0546085 is an unexpected result that demands explanation.

More generally, the discovery of 2MASS J05352184–0546085 represents the first direct, accurate measurement to our knowledge of the fundamental physical properties of young brown dwarfs. Detailed analyses of this unusual system promise to yield meaningful tests of the predictions of theoretical models for young brown dwarfs, and to provide rare empirical insight into the nature and origins of these ‘failed stars’.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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