THE FIRST DISCOVERY OF A WIDE BINARY BROWN DWARF

K. L. LUHMAN
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; kluhman@cfa.harvard.edu

ABSTRACT
I present observations of a new faint double, 2MASS J11011926–7732383AB, toward the Chamaeleon I star-forming region. From optical and near-infrared images of the pair, I measure a separation of $1\arcmin$44 and extract $RIHJK_s$ photometry of the components ($I_\alpha = 17.21$, $\Delta J = 1.07$, $K_s,\alpha = 11.97$, $\Delta K_s = 0.84$). I use resolved optical spectroscopy to derive spectral types of M7.25 and M8.25 for the A and B components, respectively. Based on the strengths of gravity-sensitive features in these data, such as the Na i and K i absorption lines, I conclude that these objects are young members of Chamaeleon I rather than field stars. The probability that this pair is composed of unrelated late-type members of Chamaeleon I is low enough ($\sim 5 \times 10^{-5}$) to definitively establish it as a binary system. After estimating extinctions, effective temperatures, and bolometric luminosities for the binary components, I place them on the H-R diagram and infer their masses with the evolutionary models of Chabrier and Baraffe, arriving at substellar values of 0.05 and 0.025 $M_\odot$. The projected angular separation of this system corresponds to 240 AU at the distance of Chamaeleon I, making it the first known binary brown dwarf with a separation greater than 20 AU. This demonstration that brown dwarfs can form in fragile, easily disrupted configurations is direct evidence that the formation of brown dwarfs does not require ejection from multiple systems or other dynamical effects. It remains possible that ejection plays a role in the formation of some brown dwarfs, but it is not an essential component according to these observations.

Subject headings: binaries: visual — infrared: stars — stars: evolution — stars: formation — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION
Over the past decade, hundreds of free-floating brown dwarfs have been discovered in the field and in young clusters (Basri 2000), but their origin remains a mystery. In recent numerical hydrodynamical simulations of the fragmentation of molecular cloud cores, self-gravitating objects can form with initial masses of only $\sim 1M_{\text{Jup}}$, but these fragments continue to accrete matter from their surrounding core, usually to the point of eventually reaching stellar masses (Boss 2001; Bate et al. 2003). As a result, the formation of brown dwarfs appears difficult to achieve in these models. One possible solution has been proposed by Reipurth & Clarke (2001) and Boss (2001) and investigated further by Bate et al. (2002) and Kroupa & Bouvier (2003). In this scenario, dynamical interactions within a small cluster of protostellar sources leads to the ejection of one of the embryos, which prematurely halts accretion from the core’s reservoir of infalling material and results in the formation of a brown dwarf.

Models for the origin of brown dwarfs can be tested through measurements of the multiplicity of substellar objects. Significant progress in this area has been made through extensive direct imaging of primaries in the field with masses near and below the hydrogen burning mass limit (Koerner et al. 1999; Martin et al. 1999; Reid et al. 2001b; Close et al. 2002a, 2002b, 2003; Bouy et al. 2003; Burgasser et al. 2003; Freed et al. 2003; Gizis et al. 2003). In the data from these surveys, binary brown dwarfs occur at a rate of $\sim 15\%$ for separations of $a > 1$ AU and exhibit maximum separations of $a \approx 20$ AU. Ejection models predict a somewhat lower binary fraction ($\sim5\%$) but a similar maximum separation ($a \approx 10$ AU) (Bate et al. 2002). Burgasser et al. (2003) concluded that the observed maximum separation is not a reflection of disruption of wider binaries by interactions with stars or molecular clouds, which is supported by the absence of wide binaries among substellar primaries in less evolved populations in open clusters (Martin et al. 1998, 2000, 2003) and in star-forming regions (Neuhäuser et al. 2002; Bouy et al. 2004). Instead, Burgasser et al. (2003) suggested that wide low-mass binaries do not form or are disrupted at a very early stage.

I report the discovery of the first known separated binary brown dwarf, which was found serendipitously during observations of candidate young brown dwarfs in the Chamaeleon I star-forming region. I present optical and near-IR images and optical spectroscopy of the components of the pair (§2), assess the membership of the two objects in Chamaeleon I (§3.1) and in a binary system (§3.2), place them on the Hertzsprung-Russell (H-R) diagram (§3.3), estimate their masses from theoretical evolutionary models (§3.4), and discuss the implications of this new binary system for theories of brown dwarf formation (§4).

2. OBSERVATIONS
During spectroscopy of candidate young brown dwarfs in Chamaeleon I on 2004 January 10 with the Inamori Magellan Areal Camera and Spectrograph (IMACS) on the Magellan I telescope at Las Campanas Observatory, I found that one of the candidates, 2MASS J11011926–7732383 (hereafter 2M 1101–7732), appeared as a $\sim 1''$ double on the telescope acquisition camera. I obtained an optical spectrum of the brighter component, found it to be indicative of a young late-type object, and thus proceeded to perform the following observations to study the pair in more detail.
2.1. Photometry

Optical images of 2M 1101-7732AB were obtained with IMACS on the Magellan I telescope on the night of 2004 January 11. The instrument contained eight 2048 × 4096 CCDs separated by ∼10" and arranged in a 4 × 2 mosaic. The plate scale was 0.202 pixel^{-1}. One and two 60 s exposures were acquired of the target through I and R filters, respectively. I obtained near-IR images of 2M 1101-7732AB with Persson’s Auxiliary Nasmyth Infrared Camera (PANIC) on the Magellan I telescope on the night of 2004 April 7. The instrument contained eight 2048 × 1024 HgCdTe Hawaii array with a plate scale of 0.126 pixel^{-1}. For each of the filters I, H, and Ks, one exposure of the target was taken at each position in a 3 × 3 dither pattern with either sizes of 5". The individual exposure times were 3, 4, and 4 s for the three filters, respectively.

After the data at each filter were dark-subtracted, flat-fielded, and combined, the final optical and IR images exhibited FWHM = 0.85 and 0.45 for point sources, respectively. I extracted photometry of the two components of 2M 1101-7732AB with the task PHOT under the IRAF package APPHOT using radii of three and four pixels in the optical and IR images. The optical photometry was calibrated in the Cousins I system by combining data for standards across a range of colors (Landolt 1992) with the appropriate aperture and airmass corrections. The IR photometry was calibrated with measurements from the 2MASS Point Source Catalog for the nine 2MASS sources surrounding 2M 1101-7732AB in these images. Plate solutions were derived from coordinates measured in the 2MASS Point Source Catalog for stars that appeared in the images and were not saturated (excluding 2M 1101-7732AB, which is unresolved in 2MASS data). Because the optical images encompass a larger area and thus contain more 2MASS sources than the IR data, the absolute astrometry of 2M 1101-7732AB is better determined in the optical images. Meanwhile, the higher resolution of the IR data provides greater precision in measurements of the relative coordinates of A and B. Therefore, the astrometry of A was measured from the I-band image, and the offset of B from A was taken as the average value measured in the J, H, and Ks images. The absolute and relative uncertainties in the coordinates are ±0.1 and ±0.02, respectively. The astrometric and photometric measurements of 2M 1101-7732AB are listed in Table 1. A second set of images at Ks (FWHM = 0.39) were obtained on 2004 April 9, which produced photometry at Ks and relative coordinates of A and B that agreed with those in Table 1 to within 0.02 mag and 0.01. The magnitudes measured here for A+B are brighter than those from the 2MASS Point Source Catalog by 0.1, 0.05, and 0.07 mag at J, H, and Ks, respectively. The images of 2M 1101-7732AB at I and Ks are shown in Figure 1.

2.2. Spectroscopy

I performed optical spectroscopy on 2M 1101-7732AB with IMACS on the Magellan I telescope on the night of 2004 April 8. The spectrograph was operated with the 200 l mm^{-1} grism, OG570 blocking filter, and 1′0 long slit (FWHM = 8 Å). One 30 minute exposure was obtained of 2M 1101-7732AB with the slit placed along the axis connecting the components, corresponding to a position angle of 30°. In the resulting images, the components exhibited FWHM = 1", and

![Figure 1](image-url)
thus were sufficiently resolved from each other for the extraction of separate spectra. On a coordinate system where the primary is at the origin and the secondary is at $+1^\circ 44$, the spectra of the primary and secondary were extracted from apertures of $-1^\circ 6$ to $+0^\circ 6$ and $+0^\circ 8$ to $+2^\circ 4$, respectively. To correct for contamination by the primary in the latter aperture, the same aperture on the opposite side of the primary ($-1^\circ 6$ to $+0^\circ 6$) was used for background subtraction. Because the slit was not aligned at the parallactic angle, these data are subject to differential slit loss with wavelength. To correct for this effect, the spectra were multiplied by a spectral function such that the primary’s spectrum matched the data for the primary from 2004 January 10, which was acquired with the slit at the parallactic angle. The spectra of 2M 1101–7732 A and B are shown in Figure 2 after smoothing to a resolution of 10 Å. For comparison, I include spectra of the field dwarf vB 8 and the field giant YY Cha. The first spectrum was obtained with the same instrument configuration (except with a $0^\circ 9$ slit) on 2004 April 27, and the second spectrum was measured by Luhman (2004a).

3. ANALYSIS

3.1. Evidence of Membership in Chamaeleon I

I now use the photometry and spectroscopy from the previous section to assess membership in Chamaeleon I and measure spectral types for the components of 2M 1101–7732AB by applying the methods described in my previous studies of young populations (Luhman 1999, 2004a; Luhman et al. 2003a, 2003b). The spectra of 2M 1101–7732 A and B exhibit evidence of youth, and thus membership in Chamaeleon I, in the form of $K_i$ and $Na_i$ line strengths that are intermediate between those of field dwarfs and giants (Martín et al. 1996; Luhman 1999), as illustrated in Figure 2 by the comparison to vB 8 (M7 V) and YY Cha (M7.75 III; Luhman 2004a). Other features in these spectra are also distinctive from field objects and clearly indicative of pre–main-sequence surface gravities, such as the CaH band at 7000 Å and the shape of the spectrum across 8200 Å. Indeed, the spectra for 2M 1101–7732 A and B agree well with those of other known late-type members of star-forming regions. In the diagram of $H$ versus $K_s$, the separation of 2M 1101–7732 from the dwarf sequence is indicative of some combination of reddening, excess emission from circumstellar material, and departure of the intrinsic colors from dwarf values, each of which is evidence of the youth, and thus the membership in Chamaeleon I, of these sources.
further evidence of membership in Chamaeleon I. Through a comparison to averages of dwarfs and giants (Luhman 1999) and to previously observed young late-type objects (Briceno et al. 2002; Luhman 2004a), I measure spectral types of M7.25 and M8.25 for 2M 1101—7732 A and B.

3.2. Evidence of Binarity

Because of the low stellar density of the Chamaeleon I star-forming region, it is unlikely that unrelated members will be seen in projection near each other. This applies particularly to the vicinity of 2M 1101—7732AB, which is a sparsely populated area of the cloud, as shown in Figure 4. The nearest known member to 2M 1101—7732AB is at a distance of 4’. According to the results of the survey in which 2M 1101—7732AB was discovered, the area of 2 deg² encompassing Chamaeleon I contains ~20 young brown dwarfs down to the mass of 2M 1101—7732B. The probability that two of these brown dwarfs have a projected separation of $a < 1^\circ 44$ is $5 \times 10^{-5}$. Based on this low probability, I conclude that 2M 1101—7732 A and B comprise a bound binary system rather than two unrelated members of Chamaeleon I. To test the binarity of this pair through common proper motions, such measurements would need to have extremely high precision, since unrelated members of the cluster share the same motion to within ~2 km s⁻¹, or ~0.00025 yr⁻¹.

3.3. Extinctions, Temperatures, and Luminosities

Extinctions for 2M 1101—7732 A and B have been estimated from the spectra in the manner described by Luhman (2004a). The resulting values of $A_J = 0.45$ and 0 (≤0.2) are consistent with the extinctions implied by the color excesses of $E(R-I) = 0.2$ and 0.1 produced when the observed colors are combined with estimates of intrinsic values of $R-I$ for young late-type objects (Luhman et al. 2003b). When the observed near-IR colors of A are dereddened by $A_J = 0.45$, there remain small excesses of $E(J-H) = 0.06$ and $E(H-K_s) = 0.11$ relative to dwarf values. The IR colors of B exhibit larger excesses of $E(J-H) = 0.12$ and $E(H-K_s) = 0.18$. These excesses could result from circumstellar material or from deviations of the intrinsic colors from the average dwarf values. The fact that these excesses remain when computed relative to other late-type members of Chamaeleon I instead of field dwarfs, as illustrated in Figure 3, tends to support the former possibility. The spectral types of 2M 1101—7732 A and B are converted to effective temperatures with the temperature scale that was designed by Luhman et al. (2003b) to be compatible with the models of Baraffe et al. (1998) and Chabrier et al. (2000). Bolometric luminosities are estimated by combining dereddened $J$-band measurements, a distance of 168 pc (Whittet et al. 1997; Wichmann et al. 1998; Bertout et al. 1999), and bolometric corrections (BC) described in Luhman (1999) and from Reid et al. (2001a). The combined uncertainties in $A_J$, $J$, and $BC_J$ ($\sigma \approx 0.2, 0.03, 0.1$) correspond to errors of ±0.09 in the relative values of log $L_{bol}$. When an uncertainty in the distance is included ($\sigma \approx 10$ pc), the total uncertainties are ±0.1. The extinctions, effective temperatures, and bolometric luminosities for 2M 1101—7732 A and B are listed in Table 1.

3.4. Ages and Masses

The temperatures and luminosities derived in the previous section can be interpreted in terms of ages and masses via theoretical evolutionary models. For this analysis, I select the models of Baraffe et al. (1998) and Chabrier et al. (2000), because they provide the best agreement with observational constraints (Luhman et al. 2003b). The adopted temperature scale was designed to produce coevality for the components of the young quadruple GG Tau and the same ages for the stellar and substellar members of Taurus and IC 348 with these evolutionary models (Luhman et al. 2003b). As shown in the H-R diagram in Figure 5, the components of
2M 1101–7732AB exhibit nearly perfect coevality as well, providing strong support for the validity of this combination of temperature scale and models. The coevality of 2M 1101–7732AB is additional evidence that these sources comprise a true binary system. The H-R diagram in Figure 5 implies masses of $0.05 \pm 0.01$ and $0.025 \pm 0.005 \, M_{\odot}$ for A and B, respectively, both of which are below the hydrogen-burning mass limit. The projected separation of $1^{\prime}44$ of these brown dwarfs corresponds to 240 AU at the distance of Chamaeleon I. Thus, 2M 1101–7732AB is the first known binary brown dwarf with a separation greater than $\sim 20$ AU.

4. DISCUSSION

Based on the absence of wide binary brown dwarfs in multiplicity surveys of the field and young clusters, Burgasser et al. (2003) suggested that wide systems do not form or are disrupted at ages of 1–10 Myr. The discovery of 2M 1101–7732AB now demonstrates that wide binary brown dwarfs indeed do exist. Because this system was found serendipitously and not through a systematic companion search, it cannot be combined with previous multiplicity surveys of brown dwarfs in star-forming regions (e.g., Neuhäuser et al. 2002) to compute a frequency of wide binary brown dwarfs. Even if such an estimate were possible, a single detection would not provide sufficient statistical significance to determine if the frequency of wide systems differs in star-forming regions and the field. However, the discovery of additional wide binary brown dwarfs in star-forming regions would indicate a clear difference from the field, where none have been found with 2MASS among the $\sim 300$ known L and T dwarfs.

The discovery of a wide binary brown dwarf has important implications for understanding the origin of brown dwarfs. Previous constraints on the formation mechanism of substellar objects, particularly the embryo ejection hypothesis, have been somewhat inconclusive. Detections of IR excesses and emission lines toward young objects near and below the hydrogen burning limit have indicated the presence of circumstellar disks (Comerón et al. 1998; 2000; Luhman 1999; Muench et al. 2001; Klein et al. 2003), accretion (Muzerolle et al. 1998; 2003; J. Muzerolle et al. 2004, in preparation; Jayawardhana et al. 2003; White & Basri 2003; Luhman et al. 2003a; Barrado y Navascués & Martín 2003), and outflows (Fernández & Comerón 2001; Muzerolle et al. 2003; Luhman 2004b), which have been taken as evidence that brown dwarfs and stars might share a common formation history. However, given that all of these signatures probe activity near the brown dwarfs, they do not exclude the ejection model, which predicts that only the outer portions of brown dwarf disks (>20 AU) are removed during ejection (Bate et al. 2003). Meanwhile, the similarity between stars and brown dwarfs in their distributions of velocities (Joergens & Güenther 2001) and spatial positions (Briceno et al. 2002; Luhman et al. 2003b; Luhman 2004b) contradicts the predictions of some ejection models (Reipurth & Clarke 2001) but not others (Bate et al. 2003). Finally, as pointed out in § 1, the binary fraction and maximum separation observed in previous surveys of field brown dwarfs are roughly consistent with the ejection hypothesis (Reipurth & Clarke 2001; Bate et al. 2002) but can be explained through other means as well (Burgasser et al. 2003).

In contrast to these previous results, 2M 1101–7732AB provides arguably the most definitive insight to date into the formation of brown dwarfs. The existence of a 240 AU binary brown dwarf is clearly inconsistent with the ejection models, which predict a maximum separation of $\sim 10$ AU for substellar binaries. Any process that is capable of removing an embryo from its parent core, envelope, and outer disk would easily disrupt a loosely bound pair of such embryos. As a result, ejection or other dynamical processes could not have played a role in the formation of the brown dwarfs in 2M 1101–7732AB. Although some brown dwarfs may form through ejection, it is not an essential component of the birth of substellar objects. Instead, it appears that brown dwarfs can arise from standard, unperturbed cloud fragmentation.

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