arXiv:1004.0539v1 [astro-ph.GA] 4 Apr 2010

DISCOVERY OF A PLANETARY-MASS COMPANION TO A BROWN DWARF IN TAURUS[1]

K. Todorov[2], K. L. Luhman[2,3], and K. K. McLeod[4]
Draft version April 6, 2010

ABSTRACT

We have performed a survey for substellar companions to young brown dwarfs in the Taurus star-forming region using the Wide Field Planetary Camera 2 on board the *Hubble Space Telescope*. In these data, we have discovered a candidate companion at a projected separation of $0\overset{''}{.}105$ from one of the brown dwarfs, corresponding to 15 AU at the distance of Taurus. To determine if this object is a companion, we have obtained images of the pair at a second epoch with the adaptive optics system at Gemini Observatory. The astrometry from the *Hubble* and Gemini data indicates that the two objects share similar proper motions and thus are likely companions. We estimate a mass of 5–$10~M_{\rm Jup}$ for the secondary based on a comparison of its bolometric luminosity to the predictions of theoretical evolutionary models. This object demonstrates that planetary-mass companions to brown dwarfs can form on a timescale of $\tau \lesssim 1$ Myr. Companion formation on such a rapid timescale is more likely to occur via gravitational instability in a disk or fragmentation of a cloud core than through core accretion. The Gemini images also reveal a possible substellar companion ($\rho = 0\overset{''}{.}23$) to a young low-mass star that is $12\overset{''}{.}4$ from the brown dwarf targeted by *Hubble*. If these four objects comprise a quadruple system, then its hierarchical configuration would suggest that the fragmentation of molecular cloud cores can produce companions below $10~M_{\rm Jup}$.

Subject headings: protoplanetary disks — stars: formation — brown dwarfs — binaries: visual — stars: pre-main sequence

1. INTRODUCTION

Most of the known planets outside of the solar system have been detected through radial velocity measurements, and thus reside close to their parent stars ($a \lesssim 5$ AU, Marcy et al. 2005; Udry et al. 2007). Meanwhile, a small number of companions with masses below $10~M_{\rm Jup}$ have been detected at large separations through high-resolution imaging ($a \sim 30$–300 AU, Chauvin et al. 2004; Lafrenière et al. 2008; Kalas et al. 2008; Marois et al. 2008). The available data tend to favor core accretion as the mechanism responsible for the close-in giant planets (Santos et al. 2004; Fischer & Valenti 2005), but gravitational instability in disks and fragmentation of molecular cloud cores are plausible (perhaps likely) alternatives for producing the wide companions (Lodato et al. 2005; Dodson-Robinson et al. 2009). The formation models for wide planetary-mass companions are particularly in need of observational tests.

Companions are expected to form much more quickly through disk instability and cloud core fragmentation than core accretion ($\tau \sim 0.1$ Myr vs. $\tau \sim 5$–10 Myr, Boss 1998, 2006; Burkert & Bodenheimer 1993; Pollack et al. 1996). Thus, measurements of the frequency of planetary companions at very young ages can help identify the dominant mode for the formation of these objects. To provide data of this kind, we have performed a search for substellar companions to 32 young brown dwarfs in the Taurus star-forming region ($\tau \sim 1$ Myr, $d \sim 140$ pc) using high-resolution images obtained with the *Hubble Space Telescope*. In this Letter, we present the discovery of a companion that has a mass of 5–$10~M_{\rm Jup}$ and a projected separation of 15 AU from one of the brown dwarfs in this survey.

2. BACKGROUND

The brown dwarf for which we have detected a substellar companion is 2MASS J04414489+2301513 (henceforth 2M J044144). It is a member of the Taurus star-forming region and it has a spectral type of M8.5 (Luhman 2006), which corresponds to a mass of $\sim 20~M_{\rm Jup}$ for an age of 1 Myr (Chabrier et al. 2000; Luhman et al. 2003). 2M J044144 exhibits mid-IR excess emission and strong Hα emission, indicating the presence of a circumstellar disk and active accretion, respectively (Luhman 2006; Luhman et al. 2010). Kraus & Hillenbrand (2007) identified a possible wide stellar companion at a separation of $12\overset{''}{.}4$ ($a = 1700$ AU at 140 pc). This candidate companion, 2MASS J04414565+2301580 (henceforth 2M J044145), has been spectroscopically confirmed as a young low-mass star, and hence a likely member of Taurus (M3-M4.5, Luhman et al. 2009; Kraus & Hillenbrand 2009).

3. OBSERVATIONS

3.1. *WFPC2 Images*

We selected 2M J044144 as one of the targets for a survey of late-type members of Taurus with the Wide Field Planetary Camera (WFPC2) on board the *Hubble Space Telescope*. The targets were imaged through the F791W

---

[2] Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802; kot104@astro.psu.edu.
[3] Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, University Park, PA 16802.
[4] Whitin Observatory, Wellesley College, Wellesley, MA.

and F850LP filters with the PC camera within WFPC2, which contained a 800×800 CCD ($0\rlap{.}''046$ pixel^{-1}). In each filter, we obtained two images at each position in a two-point diagonal dither pattern. For 2M J044144, the exposure times of the individual images were 260 and 160 s for F791W and F850LP, respectively. The observations of 2M J044144 were performed during one orbit on 2008 August 20.

We reduced the WFPC2 images using the MultiDrizzle software (Koekemoer et al. 2002). To facilitate the detection of low-mass companions, we applied point spread function (PSF) subtraction to each brown dwarf in our survey using techniques described by Luhman et al. (2005). This process revealed a possible companion to 2M J044144, which we refer to as 2M J044144 B. The images of this pair in F850LP before and after PSF subtraction are shown in Figure 1. We fit PSFs to both the primary and candidate companion to measure their flux ratios and astrometric positions in the two filters. In addition to PSF subtraction of the primaries, we identified all point sources appearing in the WFPC2 images and measured aperture photometry for them. In the case of 2M J044144, the PSF of the candidate companion was subtracted prior to the photometric measurement of the primary. The photometry for companion was computed by combining the aperture photometry of the primary with the flux ratios produced by the PSF fits. The errors in the photometry for the primary are dominated by the uncertainty in the correction for charge transfer efficiency while the errors in the measurements for the companion have a comparable contribution from the process of PSF fitting. The astrometric offsets and photometry for the two objects are presented in Tables 1 and 2, respectively. Additional details concerning the observations and data analysis will be provided in a forthcoming paper that presents the entire survey.

3.2. *NIRI+ALTAIR Images*

To constrain the relative proper motions of 2M J044144 and its candidate companion, we obtained images of the pair at a second epoch using NIRI (Hodapp et al. 2003) in conjunction with the ALTAIR adaptive optics system at the Gemini North telescope. NIRI was configured with the f/32 camera, which provided a plate scale of $0\rlap{.}''0214$ pixel^{-1} and a field of view of $22'' \times 22''$. Because natural guide stars were unavailable, ALTAIR was operated in the laser guide star mode. The tip/tilt correction was performed with 2M J044145, which is the possible wide companion to 2M J044144 that was described in § 2. We imaged 2M J044144 through the H and K' filters using individual exposure times of 1 and 20 s. For each exposure time and filter, one image was taken at each position in a 3×3 dither pattern. After one set of dithered images was collected for all of the combinations of exposure time and filter, the entire sequence of observations was repeated. To provide a PSF for fitting the primary and candidate companion, we also observed 2MASS 04383110+2310107. It was selected as the PSF star because it was similar to the science target in its sky position and the optical brightness, separation, and position angle of its tip/tilt star.

The individual images were divided by flat field exposures taken with the Gemini Facility Calibration Unit. The resulting images in a given dither sequence were registered and combined, producing two final images of 2M J044144 for each combination of exposure time (1 and 20 s) and filter (H and K'). All of the combined images of 2M J044144 and the PSF star exhibited FWHM$\sim 0\rlap{.}''09$, which is similar to the image quality from WFPC2. To measure the relative positions and flux ratios of the components of 2M J044144, we performed PSF fitting with the four long exposures in the same manner as done for the WFPC2 data. In Figure 1, we present one of the two long K'-band exposures before and after PSF subtraction alongside the WFPC2 images. We also show a wider area of this NIRI image that encompasses the tip/tilt star, 2M J044145, which is resolved into a pair of objects that are separated by $0\rlap{.}''23$. We applied PSF fitting to the components of this pair as well to measure their flux ratios. This was done with the short exposures since the primary is saturated in the 20 s data.

Our measurements of the astrometric offsets between 2M J044144 A and B are listed in Table 1. We have adopted the average values produced by PSF fitting of the four long exposures. We have derived photometry for the components of 2M J044144 and 2M J044145 by combining the flux ratios from the PSF fitting with the unresolved H and K_s data from the Point Source Catalog of the Two-Micron All-Sky Survey (2MASS, Skrutskie et al. 2006). We have assumed that the flux ratios at K_s are the equal to the ratios that we have measured at K'.

4. ANALYSIS

4.1. *Evidence of Binarity*

To investigate whether 2M J044144 B is a companion to 2M J044144 A, we begin by plotting a color-magnitude diagram in Figure 2 from photometry at F791W and F850LP for all unsaturated sources in our entire WFPC2 survey of 32 brown dwarfs in Taurus. Four of the substellar primaries are absent from the diagram because they are saturated in one of the filters. The faintest primary is 2MASS J04373705+2331080, which is the coolest known member of Taurus (L0, Luhman et al. 2009). As shown in Figure 2, 2M J044144 B appears near the bottom of the sequence of the known members of Taurus, indicating that it has the appropriate magnitudes and color for a low-mass companion. Given the spectral types of the known members, these data suggest a spectral type of M9.5-L0 for 2M J044144 B. In addition, the line connecting the primary and secondary is parallel to the cluster sequence, which is consistent with the coevality that is expected for the components of a binary system.

We can use the data in Figure 2 to estimate the probability that our companion survey would detect a field star that has the photometric properties of a low-mass Taurus member. We assume that the sequence of Taurus members becomes vertical at the faintest magnitudes in Figure 2 ($m_{791} > 22$), which is supported by the location of the coolest known member and the fact that the $I - Z$ colors of field dwarfs do not increase significantly from M8 to mid-L (Steele & Howells 2000; Dahn et al. 2002; Dobbie et al. 2002). In that case, ~ 7 objects in Figure 2 (in addition to the known brown dwarfs) have colors and magnitudes that are consistent with membership in Taurus. Therefore, the surface density of field stars that could be mistaken for Taurus members is ~ 7

divided by the total area of the WFPC2 images, which is 160 arcmin^2. The probability of a field star of this kind appearing within 0″1 of any of the 32 primaries in our survey is $\sim 10^{-5}$.

The two epochs of astrometry from WFPC2 and NIRI provide an additional constraint on the companionship of 2M J044144 B. We first consider whether the astrometry for 2M J044144 B is consistent with the negligible motion expected for the vast majority of background stars. Accurate measurements of the proper motion for the primary are not available. Therefore, we adopt for the primary the average proper motion of the nearest group of Taurus members ($\mu_\alpha, \mu_\delta = +6.7, -17.7$ mas yr^{-1}, Luhman et al. 2009). Combining this proper motion with the astrometry from the first epoch, we find that the separation and position angle of the candidate companion would have become 0″089 and 111.5° in the second epoch if it had no proper motion, which is inconsistent with our measurements in Table 1.

According to the data in Table 1, 2M J044144 A and B maintained the same relative positions to within ~ 10 mas over a period of 1.15 years, indicating that their proper motions agree at a level of ~ 9 mas yr^{-1} in each direction. Only a small fraction of field stars are expected to have proper motions that are similar to that of 2M J044144 A. For instance, using multi-epoch *Hubble* images of Chamaeleon I that are comparable in depth to our WFPC2 data in Taurus, we find that $\sim 0.3\%$ of field stars have proper motions that are consistent with those of cluster members at the level of the uncertainties in the relative proper motions of 2M J044144 A and B. If we adopt this value for Taurus, which is similar to Chamaeleon I in its distance and the magnitude of its proper motion, then the probability of a field star exhibiting WFPC2 photometry that is indicative of a Taurus member, a separation of $\rho \leq 0″1$ from one of our 32 primaries, and a proper motion similar to that of Taurus is $\sim 3 \times 10^{-8}$. Therefore, we conclude that 2M J044144 B is a companion to 2M J044144 A.

The possible wide companion 2M J044145 appears within one of the WFC arrays, but it is too heavily saturated for the detection of its candidate companion. As a result, we cannot place constraints on the proper motions of those two objects relative to each other.

4.2. *Physical Properties of Companion*

We can estimate the bolometric luminosity of 2M J044144 B if we apply a bolometric correction to its photometry at K_s. In previous studies of young brown dwarfs, we have adopted bolometric corrections derived for field dwarfs, but doing so may not be perfectly valid for 2M J044144 B since some of the IR colors of young objects later than M9 differ from those of dwarfs (Cruz et al. 2009; Luhman et al. 2009). To determine an appropriate value of BC$_K$ for 2M J044144 B, we have estimated bolometric luminosities for young brown dwarfs from M9.5–L0 for which relatively complete spectral energy distributions have been measured, consisting of the Taurus member KPNO 4 (M9.5, Briceño et al. 2002) and the young field dwarfs 2MASS J01415823−4633574 and 2MASS J02411151−0326587 (L0, Kirkpatrick et al. 2006; Cruz et al. 2009). We have excluded from this sample brown dwarfs that exhibit disk emission in their mid-IR data or that have extinctions of $A_V > 1$. For

each object, we constructed a spectral energy distribution using a 0.8-2.5 μm spectrum from the NASA Infrared Telescope Facility that was flux calibrated with 2MASS photometry, 3.2-9.2 μm photometry from the *Spitzer Space Telescope* (Luhman et al. 2009, 2010), a linear interpolation of the fluxes between 2.5 μm and 3.2 μm, and a Rayleigh-Jeans distribution longward of 9.2 μm. By integrating the flux in each distribution and combining the resulting luminosity with the K_s photometry, we arrive at BC$_K$ = 3.42, 3.39, and 3.41 for KPNO 4, 2MASS J01415823−4633574, and 2MASS J02411151−0326587, respectively. These bolometric corrections are larger than those of dwarfs by ~ 0.2 mag (Golimowski et al. 2004). Based on these measurements, we adopt BC$_K$ = 3.4 for 2M J044144 B.

The $J - H$ color from 2MASS and the 0.8-1.8 μm spectrum from Luhman (2006) for 2M J044144 A+B indicate $A_V \sim 0$ when they are compared to average intrinsic colors and spectra of young brown dwarfs (Luhman et al. 2010). In the K band, the spectroscopy and 2MASS photometry of the system and our resolved photometry for the primary are slightly redder than a stellar photosphere with the spectral type of the primary, which is probably caused by emission from a circumstellar disk based on the excess emission detected at longer wavelengths (Luhman et al. 2010). Therefore, we have not applied an extinction correction to the photometry for 2M J044144 B. When we combine K_s = 14.94, BC$_K$ = 3.4, $M_{bol\odot}$ = 4.75, and the average distance of Taurus ($d = 140$ pc, Wichmann et al. 1998; Torres et al. 2009), we derive log $L_{bol} = -3.14$ for 2M J044144 B.

In Figure 3, we estimate a mass from the luminosity of 2M J044144 B by comparing it to the values predicted by theoretical evolutionary models for an age of 1 Myr, which is the average age for members of Taurus and the isochronal age of the primary (Luhman et al. 2009). Given the uncertainties in its age (few Myr) and luminosity (± 0.12 dex), 2M J044144 B could have a mass between 5 and 10 M_{Jup} according to the models of Chabrier et al. (2000) and Burrows et al. (1997). For comparison, we include in Figure 3 the luminosities of other resolved companions that appear to have masses below ~ 15 M_{Jup} and that are younger than 10 Myr, which consist of 2M1207-3932 B (Chauvin et al. 2004), DH Tau B (Itoh et al. 2005), CHXR 73 B (Luhman et al. 2006), CT Cha B (Schmidt et al. 2008), and IRXS1609 B (Lafrenière et al. 2008).

5. DISCUSSION

The first planetary-mass companion to be detected through direct imaging was 2MASS J12073346-3932539 B (a = 40 AU, $M \sim 4$ M_{Jup}, Chauvin et al. 2004; Biller & Close 2007; Gizis et al. 2007; Ducourant et al. 2008), which is bound to a young brown dwarf in the TW Hya association ($\tau \sim 8$ Myr, $M \sim 25$ M_{Jup}, Gizis 2002). The new companion that we have presented, 2M J044144 B, is a younger analog of 2MASS J12073346-3932539 B, thus demonstrating that wide planetary-mass companions to brown dwarfs can form on a timescale of $\tau \lesssim 1$ Myr. This result is consistent with the rapid formation expected from both gravitational instability in disks and fragmentation of cloud cores. The latter is more likely to have produced these two secondaries given their relatively large masses com-

pared to the primaries (Lodato et al. 2005). Indeed, if 2M J044144 A and B are members of a quadruple system, then its hierarchical configuration further suggests that 2M J044144 B formed by cloud core fragmentation. Additional data are needed to determine more definitively whether 2M J044144 A/B and 2M J044145 A/B comprise a quadruple system.

REFERENCES

Biller, B. A., & Close, L. M. 2007, ApJ, 669, L41
Boss, A. P. 1998, ApJ, 503, 923
Boss, A. P. 2006, ApJ, 637, L137
Briceño, C., Luhman, K. L., Hartmann, L., Stauffer, J. R., & Kirkpatrick, J. D. 2002, ApJ, 580, 317
Burkert, A., & Bodenheimer, P. 1993, MNRAS, 264, 798
Burrows, A., et al. 1997, ApJ, 491, 856
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Chauvin, G., et al. 2004, A&A, 425, L29
Cruz, K. L., Kirkpatrick, J. D., & Burgasser, A. J. 2009, AJ, 137, 3345
Dahn, C. C., et al. 2002, AJ, 124, 1170
Dobbie, P. D., Kenyon, F., Jameson, R. F., & Hodgkin, S. T. 2002, MNRAS, 331, 445
Dodson-Robinson, S. E., Veras, D., Ford, E. B., & Beichman, C. A. 2009, ApJ, 707, 79
Ducourant, C., Teixeira, R., Chauvin, G., Daigne, G., Le Campion, J.-F., Song, I., & Zuckerman, B. 2008, A&A, 477, L1
Fischer, D. A., & Valenti, J. 2005, ApJ, 622, 1102
Gizis, J. E. 2002, ApJ, 575, 484
Gizis, J. E., Jao, W.-C., Subasavage, J. P., & Henry, T. J. 2007, ApJ, 669, L45
Golimowski, D. A., et al. 2004, AJ, 127, 3516
Hodapp, K. W., et al. 2003, PASP, 115, 1388
Itoh, Y., et al. 2005, ApJ, 620, 984
Kalas, P., et al. 2008, Science, 322, 1345
Kirkpatrick, J. D., et al. 2006, ApJ, 639, 1120

Koekemoer, A. M., Fruchter, A. S., Hook, R. N., & Hack, W. 2002, in The 2002 HST Calibration Workshop: Hubble after the Installation of the ACS and the NICMOS Cooling System, ed. S. Arribas, A. Koekemoer, & B. Whitmore, 337
Kraus, A. L., & Hillenbrand, L. A. 2007, ApJ, 662, 413
Kraus, A. L., & Hillenbrand, L. A. 2009, ApJ, 703, 1511
Lafrenière, D., Jayawardhana, R., & van Kerkwijk, M. H. 2008, ApJ, 689, L153
Lodato, G., Delgado-Donate, E., & Clarke, C. J. 2005, MNRAS, 364, L91
Luhman, K. L. 2006, ApJ, 645, 676
Luhman, K. L., Allen, P. R., Espaillat, C., Hartmann, L., & Calvet, N. 2010, ApJS, 186, 111
Luhman, K. L., Mamajek, E. E., Cruz, K. L., & Allen, P. R. 2009, ApJ, 703, 399
Luhman, K. L., McLeod, K. K., & Goldenson, N. 2005, ApJ, 623, 1141
Luhman, K. L., et al. 2003, ApJ, 593, 1093
Luhman, K. L., et al. 2006, ApJ, 649, 894
Marcy, G., et al. 2005, Progress of Theoretical Physics Supplement, 158, 24
Marois, C., et al. 2008, Science, 322, 1348
Pollack, J. B., et al. 1996, Icarus, 124, 62
Santos, N. C., Israelian, G., & Mayor, M. 2004, A&A, 415, 1153
Schmidt, T. O. B., et al. 2008, A&A, 491, 311
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Steele, I. A., & Howells, L. 2000, MNRAS, 313, 43
Torres, R. M., Loinard, L., Mioduszewski, A. J., & Rodríguez, L. F. 2009, ApJ, 698, 242
Udry, S., Fischer, D., & Queloz, D. 2007, Protostars and Planets V, B. Reipurth, D. Jewitt,and K. Keil (eds.), University of Arizona Press, Tucson, 685
Wichmann, R., Bastian, U., Krautter, J., Jankovics, I., & Ruciński, S. M. 1998, MNRAS, 301, L39

TABLE 1
Astrometry for 2MASS J04414489+2301513 B

Instrument	ρ (arcsec)	P.A. (deg)	Date
WFPC2	0.105±0.004	120.4±2.2	2008 Aug 20
NIRI+ALTAIR	0.108±0.005	121.0±2.6	2009 Oct 13

TABLE 2
Photometry for 2MASS J04414489+2301513 and 2MASS J04414565+2301580

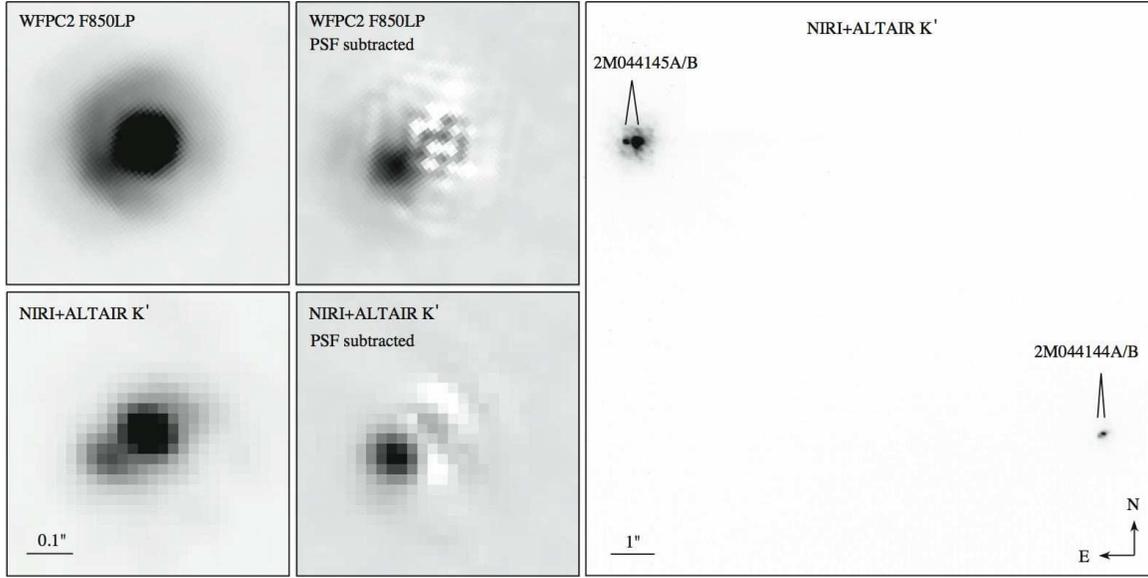| 2MASS	m_{791}	m_{850}	H	K_s
J04414489+2301513 A	18.93 ± 0.05	17.85 ± 0.05	13.94 ± 0.03	13.40 ± 0.03
J04414489+2301513 B	21.16 ± 0.10	19.91 ± 0.10	15.62 ± 0.10	14.94 ± 0.10
J04414565+2301580 A	$\cdots$	$\cdots$	10.17 ± 0.02	9.94 ± 0.02
J04414565+2301580 B	$\cdots$	$\cdots$	13.03 ± 0.06	12.59 ± 0.06

FIG. 1.— Left and middle: WFPC2 and NIRI+ALTAIR images of the young brown dwarf 2M J044144 before and after PSF subtraction ($0''\!.6 \times 0''\!.6$). The candidate companion has the same position relative to the brown dwarf in each of these epochs, indicating that they have similar proper motions (Table 1). The separation of the companion is $0''\!.105$, which corresponds to 15 AU at the distance of Taurus. Right: An expanded version of the NIRI+ALTAIR image ($13'' \times 13''$) showing both 2M J044144 and the young low-mass star 2M J044145. A candidate substellar companion to the latter is detected in these data ($\rho = 0''\!.23$). The components of 2M J044144 and 2M J044145 may comprise a young, low-mass quadruple system.
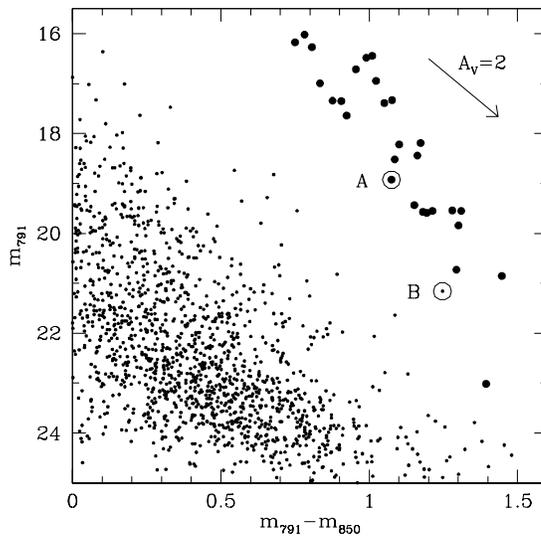
Fig. 2.— Color-magnitude diagram constructed from WFPC2 images of 32 young brown dwarfs in the Taurus star-forming region. We show the targeted brown dwarfs that have unsaturated photometry (large points) and all other point sources in these images (small points). The components of 2M J044144 are indicated (open circles, Figure 1). The secondary appears near the bottom of the sequence of known substellar members of Taurus, which is consistent with a young low-mass companion.
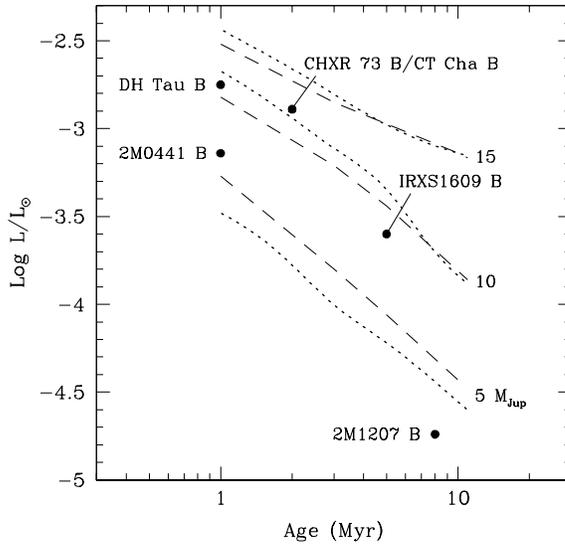
Fig. 3.— Luminosity estimates of 2M J044144 B and other young low-mass companions ($M \lesssim 15\ M_{\rm Jup}$) compared to the luminosities as a function of age predicted by the theoretical evolutionary models of Chabrier et al. (2000, dashed lines) and Burrows et al. (1997, dotted lines). CHXR 73 B and CT Cha B have nearly identical positions in this diagram. These models indicate a mass of 5–10 $M_{\rm Jup}$ for 2M J044144 B. The luminosities of all of these companions have uncertainties near ± 0.12 dex.