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DISCOVERY OF A YOUNG SUBSTELLAR COMPANION IN CHAMAELEON

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ABSTRACT

During an imaging survey of the Chamaeleon I star-forming region with the Advanced Camera for Surveys aboard the *Hubble Space Telescope*, we have discovered a candidate substellar companion to the young low-mass star CHXR 73 ($\tau \sim 2$ Myr, $M \sim 0.35\ M_\odot$). We measure a projected separation of $1\farcs30 \pm 0\farcs03$ for the companion, CHXR 73 B, which corresponds to 210 AU at the distance of the cluster. A near-infrared spectrum of this source obtained with the Cornell Massachusetts Slit Spectrograph at the Magellan II telescope exhibits strong steam absorption that confirms its late-type nature ($\gtrsim$M9.5). In addition, the gravity-sensitive shapes of the H- and K-band continua demonstrate that CHXR 73 B is a young, pre-main-sequence object rather than a field star. The probability that CHXR 73 A and B are unrelated members of Chamaeleon I is ~ 0.001. We estimate the masses of CHXR 73 B and other known substellar companions in young clusters with a method that is consistent with the dynamical measurements of the eclipsing binary brown dwarf 2M 0535-0546, which consists of a comparison of the bolometric luminosities of the companions to the values predicted by the evolutionary models of Chabrier & coworkers and Burrows & coworkers. We arrive at mass estimates of 0.003-0.004, 0.024 ± 0.012, $0.011^{+0.01}_{-0.003}$, and $0.012^{+0.008}_{-0.005}\ M_\odot$ for 2M 1207-3932 B, GQ Lup B, DH Tau B, and CHXR 73 B, respectively. Thus, DH Tau B and CHXR 73 B appear to be the least massive companions to stars outside the solar system that have been detected in direct images, and may have masses that are within the range observed for extrasolar planetary companions ($M \lesssim 0.015\ M_\odot$). However, because these two objects (as well as 2M 1207-3932 B) probably did not form within circumstellar disks around their primaries, we suggest that they should be viewed as brown dwarf companions rather than planets.

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

1. INTRODUCTION

Since the first discovery of substellar companions outside of the solar system little more than a decade ago (Wolszczan & Frail 1992; Mayor & Queloz 1995; Butler & Marcy 1996; Oppenheimer et al. 1995), a great deal of work has focused on understanding the origin of these bodies. The three most widely explored theories for the formation of substellar companions involve the accretion of gas by rocky cores in circumstellar disks (Pollack et al. 1996), the collapse of gravitationally unstable areas of disks (Boss 1998, 2006), and the fragmentation of molecular cloud cores (Lodato, Delgado-Donate, & Clarke 2005). Testing the validity of these models requires observations of companions across a large range of companion mass, primary mass, orbital separation, and age. Searches for substellar companions at young ages are particularly valuable because they can directly constrain the formation timescale and early dynamical evolution of these objects. In addition, substellar objects are brightest when they are young, and thus can be detected at very low masses with direct imaging. For these reasons, young stars and brown dwarfs in the solar neighborhood ($\tau \sim$ 30-400 Myr, Rebolo et al. 1998; Metchev & Hillenbrand 2004; McCarthy & Zuckerman 2004; Lowrance et al. 2005), open clusters and associations ($\tau \sim$ 10-100 Myr, Martín et al. 1998, 2000, 2003; Lowrance et al. 2000; Neuhäuser et al. 2000a; Guenther et al. 2001; Chauvin et al. 2003, 2005b), and star-forming regions and OB associations ($\tau \lesssim 5$ Myr, Duchêne et al. 1999; Brandner et al. 2000; Neuhäuser et al. 2002; Luhman et al. 2005a; Kraus, White, & Hillenbrand 2005, 2006) have been popular targets for companion searches with high-resolution imaging. The most reliable substellar companions discovered to date at ages of $\tau < 10$ Myr consist of GG Tau Bb (White et al. 1999), TWA 5 B (Lowrance et al. 1999; Neuhäuser et al. 2000b), 2M 1101-7732 B (Luhman 2004b), 2M 1207-3932 B (Chauvin et al. 2004, 2005a), DH Tau B (Itoh et al. 2005), and GQ Lup B (Neuhäuser et al. 2005).

Adding to the small but quickly growing list of known young substellar companions, we report the discovery of a companion to the low-mass star CHXR 73 (M3.5, $M \sim 0.35\ M_\odot$, Luhman 2004a) in the Chamaeleon I star-forming region ($\tau \sim 2$ Myr), which was found serendipitously during a survey for free-floating brown dwarfs with the *Hubble Space Telescope* (*HST*). In this paper, we present our optical images from *HST* and near-infrared (IR) imaging and spectroscopy from the Magellan telescopes for CHXR 73 B (§ 2) and we use these data to

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assess its youth and membership in Chamaeleon I (§ 3.1). We then examine the evidence that CHXR 73 B is a companion (§ 3.2), estimate the mass of CHXR 73 B and other young substellar companions in a uniform manner (§ 3.3), and discuss the origin of these companions and whether they should be referred to as planets or brown dwarfs (§ 4).

2. OBSERVATIONS

2.1. *Photometry*

As a part of a survey for young free-floating brown dwarfs, Luhman et al. (2005c) used the Advanced Camera for Surveys (ACS) aboard *HST* to image a $13\farcm3 \times 16\farcm7$ area centered on the southern cluster in the Chamaeleon I star-forming region through the F775W and F850LP filters (0.775 and 0.85 μm). In Figure 1, we plot the color-magnitude diagram produced by those data. Most members of the cluster are saturated in the ACS images and thus do not appear in Figure 1, including most of the known young brown dwarfs within the survey field. The faintest known member in the diagram is Cha 110913-773444, which was discovered with these data by Luhman et al. (2005c). As done in a similar color-magnitude diagram constructed from *HST* data for the young cluster IC 348 (Luhman et al. 2005a), we define a boundary below the lower envelope of the sequence of known members of Chamaeleon I to separate candidate cluster members and probable field stars. The reddest brown dwarf candidate in Figure 1 has a separation of only $1\farcs3$ from a known cluster member, CHXR 73, making it a promising substellar companion. We refer to this object as CHXR 73 B hereafter in this paper. The ACS images containing CHXR 73 B were obtained on 2005 February 10. A $4'' \times 4''$ area of the F775W image encompassing CHXR 73 A and B is shown in Figure 2. The ACS photometric measurements for this object are $m_{775} = 24.57 \pm 0.03$ and $m_{850} = 22.58 \pm 0.03$. CHXR 73 B has a separation of $1\farcs30 \pm 0\farcs03$ and a position angle of $234.9 \pm 1^\circ$ from the primary. The errors in these astrometric measurements are dominated by the error in the position of CHXR 73 A, which is saturated. Using a distance modulus of 6.05 for Chamaeleon I (Whittet et al. 1997; Wichmann et al. 1998; Bertout et al. 1999), this projected separation corresponds to 210 AU.

After discovering CHXR 73 B in the ACS images, we obtained photometry for it at near-IR wavelengths with Persson's Auxiliary Nasmyth Infrared Camera (PANIC) on the Magellan I telescope on the night of 2005 April 30. The instrument contained one 1024×1024 HgCdTe Hawaii array with a plate scale of $0\farcs126$ pixel^{-1}. We obtained 10, 10, and 20 dithered images in the filters J, H, and K_s, respectively, with exposure times of 3 sec. After the data at each filter were dark subtracted, flat fielded, and combined, the final images exhibited FWHM= $0\farcs5$ for point sources. The combined image of CHXR 73 A and B in K_s is shown in Figure 2. We flux calibrated the images with photometry from Luhman et al. (2005c) for unsaturated stars in these images and measured photometry of $J = 17.9 \pm 0.3$, $H = 16.5 \pm 0.3$, and $K_s = 15.5 \pm 0.25$ for CHXR 73 B, corresponding to $\Delta J = 5.2$, $\Delta H = 5.2$, and $\Delta K_s = 4.7$ relative to the primary.

2.2. *Spectroscopy*

We obtained near-IR spectra of CHXR 73 B with the Cornell Massachusetts Slit Spectrograph (CorMASS, Wilson et al. 2001) on the Magellan II telescope during the nights of 2005 April 30 and May 1. This instrument provides simultaneous wavelength coverage from 0.8-2.5 μm and a resolution of $R \sim 300$. While mounted on the Magellan II telescope, the slit of CorMASS subtended an area of $0\farcs4 \times 3''$ on the sky. To observe CHXR 73 B, we adjusted the position angle of the slit to align it with the axis connecting CHXR 73 A and B. Figure 2 shows an image of the pair taken in the slit-viewing mode of CorMASS with a K_s filter and an exposure time of 5 sec prior to starting spectroscopic observations. We then selected an exposure time of 3 min and obtained two exposures with CHXR 73 B centered on the slit, one exposure at a position several arcseconds from CHXR 73 B, and repeated this cycle two more times, resulting in total exposure times of 18 and 6 min on CHXR 73 B and the sky, respectively. This sequence was performed on both nights. A nearby A0 V star (HD 98671) was also observed for the correction of telluric absorption. The spectra were reduced with a modified version of the Spextool package (Cushing et al. 2004) and were corrected for telluric absorption (Vacca et al. 2003). The spectra from the two nights agreed well and thus were combined. For comparison, we also obtained spectra of the field dwarfs Gl 406, LHS 2065, and Kelu 1.

3. ANALYSIS

3.1. *Evidence of Membership in Chamaeleon I*

We now use the spectroscopy from the previous section to determine if CHXR 73 B is a member of the Chamaeleon I star-forming region rather than a field star or a galaxy. To classify the spectrum, we compared it to data for field dwarfs and giants and known members of star-forming regions. For the field dwarfs, we used the CorMASS spectra of Gl 406, LHS 2065, and Kelu 1. We employed as additional standards our previous spectra of late-type dwarfs, giants, and pre-main-sequence objects obtained with SpeX at the NASA Infrared Telescope Facility (Luhman et al. 2005a, 2004; Luhman 2006). For the two standards that appear in both the CorMASS and SpeX samples, Gl 406 and LHS 2065, the spectra from the two instruments agree well, which suggests that SpeX data are suitable for classifying the CorMASS spectrum of CHXR 73 B. In Figure 3, we compare the spectrum of CHXR 73 B to a standard in each of the three luminosity classes, namely the field dwarf Kelu 1 (L2V, Kirkpatrick et al. 1999), the field giant VY Peg (M7III, Kirkpatrick, Henry, & Irwin 1997), and the young object KPNO 4 (M9.5, Briceño et al. 2002). To facilitate the comparison of the spectra, the spectral slopes of the former three objects have been aligned with that of KPNO 4 ($A_J \sim 0$, Briceño et al. 2002) by reddening or dereddening the spectra according to the extinction law of Rieke & Lebofsky (1985). To match KPNO 4, the spectrum of CHXR 73 B must be dereddened by $A_J \sim 2.1$.

Like the late-type standards in Figure 3, CHXR 73 B exhibits strong H_2O absorption bands, demonstrating that it is a cool object rather than an early-type field star or an extragalactic source. To determine the luminosity class of CHXR 73 B, we can examine the shapes of the H- and K-band continua, which are sensitive to surface gravity (Lucas et al. 2001; Luhman et al. 2004;

Kirkpatrick et al. 2006). The continua of CHXR 73 B have the same triangular shape as the young brown dwarf KPNO 4 rather than the broad plateaus that characterize the dwarf and the giant. Based on this comparison, we conclude that CHXR 73 B is a young member of Chamaeleon I rather than a field star. The presence of significant extinction toward CHXR 73 B is independent evidence that it is not a foreground object. In addition, with an extinction-corrected magnitude of $K = 14.7$, CHXR 73 B is too bright to be a background field dwarf given that field dwarfs later than M9V have $M_K > 10$ (Dahn et al. 2002; Golimowski et al. 2004) and Chamaeleon I has a distance modulus of 6.05.

The strengths of the H_2O absorption bands in the spectrum of CHXR 73 B are equal to or slightly greater than those of KPNO 4, which has an optical spectral type of M9.5. Because the variation of H_2O absorption with optical spectral type is unknown for young objects later than M9, we can place only a limit of ≥M9.5 on the spectral type. If CHXR 73 B is later than KPNO 4, then it probably has a redder intrinsic spectrum than KPNO 4, in which case CHXR 73 B would have an extinction lower than the value of $A_J = 2.1$ implied by the comparison to KPNO 4. For instance, the difference in spectral slopes between LHS 2065 (M9V) and Kelu 1 (L2V) is equivalent to $A_J \sim 0.15$. Therefore, we adopt an extinction of $A_J = 2 \pm 0.3$ for CHXR 73 B.

3.2. *Evidence of Binarity*

In the previous section, we demonstrated that CHXR 73 B is a member of Chamaeleon I. We now examine the evidence that it is a companion to CHXR 73 A. The $13.'3 \times 16.'7$ area imaged in our ACS survey encompasses 39 previously known cluster members and six new low-mass members ($m_{775} > 22$, $M \lesssim 0.015\ M_\odot$). The latter sources consist of Cha 110913-773444, CHXR 73 B, and four unpublished objects. The probability of any of these six sources having a projected separation less than $1.''3$ from any of the 39 higher mass members in the ACS survey area is ~ 0.001. Because of the low value of this probability, we conclude that CHXR 73 B is a companion to CHXR 73 A rather than an unrelated cluster member. The available evidence of binarity for each of the other young substellar companions discussed in this work is also based on statistical analysis of this kind because the published proper motion measurements for those objects are not precise enough to distinguish between true binaries and comoving unbound cluster members seen in projection near each other. For instance, consider a pair of unrelated cluster members with two-dimensional velocities differing by 0.5 km s^{-1}, which is comparable to velocity dispersions in star-forming regions. During the five years between the two epochs of images of GQ Lup B from Neuhäuser et al. (2005), the separation of this pair would change by $0.''003$, which is below the precision of the astrometry from Neuhäuser et al. (2005). Finally, we note that the extinction of CHXR 73 B ($A_J = 2$) is similar to that of CHXR 73 A ($A_J = 1.8$, Luhman 2004a), which further supports the binarity of the pair.

3.3. *Mass*

To estimate the mass of CHXR 73 B, we compare its bolometric luminosity to the values predicted for young brown dwarfs by the theoretical evolutionary models of Chabrier et al. (2000) and Burrows et al. (1997). We test the validity of this mass estimate by performing the same analysis with the eclipsing binary brown dwarfs 2M 0535-0546 A and B, whose masses have been measured dynamically (Stassun et al. 2006). To place CHXR 73 B in the context of other young low-mass companions, we also include in this exercise 2M 1207-3932 B, DH Tau B, and GQ Lup B.

We compute the bolometric luminosities of 2M 0535-0546 A and B by combining their temperature ratio and radii (Stassun et al. 2006) with an optical spectral type of M6.75 for A+B (K. Luhman, in preparation) and a temperature scale for young objects (Luhman et al. 2003). For each of the remaining companions, we estimate the luminosity from a combination of the observed K magnitude, extinction, distance, K-band bolometric correction (Golimowski et al. 2004), and an absolute bolometric magnitude for the Sun of $M_{\rm bol\odot} = 4.75$. For CHXR 73 B, we adopt $K = 15.5 \pm 0.25$ (§ 2.1), $A_J = 2 \pm 0.3$ (§ 3.1), a distance modulus of 6.05 ± 0.13, and $BC_K = 3.2 \pm 0.18$ for an assumed spectral type of M9-L1. For 2M 1207-3932 B, we adopt $M_K = 13.30 \pm 0.29$ from Mamajek (2005), which is based on his distance estimate and the photometry reported by Chauvin et al. (2004). At a given optical spectral type, near-IR steam absorption bands are stronger in young objects than in field dwarfs (Lucas et al. 2001; Luhman et al. 2004), as illustrated in Figure 3. As a result, because Chauvin et al. (2004) classified 2M 1207-3932 B by comparing the strength of its steam absorption to that of field dwarfs, their spectral classification of L5-L9.5 is probably systematically too late. Therefore, we assume an earlier range of possible types, L0-L7, and adopt the corresponding bolometric correction of $BC_K = 3.23 \pm 0.16$. For GQ Lup B, we adopt the distance of 150 ± 20 pc measured for Lupus I (Hughes et al. 1993; Crawford 2000; Franco 2002), $K_s = 13.1 \pm 0.1$ (Neuhäuser et al. 2005), and the extinction of $A_V = 0.4 \pm 0.2$ measured for the primary (Batalha et al. 2001). As with 2M 1207-3932 B, the IR classification of GQ Lup B from Neuhäuser et al. (2005) was performed through a comparison of its steam absorption to that of dwarf standards, making the resulting spectral type too late. Because GQ Lup B is similar to known late-type Taurus members in terms of M_K, it probably has a similar spectral type. Therefore, we adopt the bolometric correction that applies to M8-L0, $BC_K = 3.15 \pm 0.18$. For DH Tau B, we adopt $K_s = 14.19 \pm 0.02$ and $A_J = 0.3 \pm 0.3$ (Itoh et al. 2005) and a distance modulus of 5.76 ± 0.2 (Wichmann et al. 1998). Because M_K for DH Tau B is similar to that of CHXR 73 B, the value of BC_K for CHXR 73 B is also applied to DH Tau B. Through the above calculations, we arrive at $\log L_{\rm bol} = -2.85 \pm 0.14$, -1.58 ± 0.07, -1.73 ± 0.07, -4.71 ± 0.13, -2.71 ± 0.12, and -2.23 ± 0.14 for CHXR 73 B, 2M 0535-0546 A and B, 2M 1207-3932 B, DH Tau B, and GQ Lup B, respectively.

We must adopt an age for each companion to convert its luminosity to a mass with the evolutionary models. On the Hertzsprung-Russell, the median age of the known members of Chamaeleon I is 2 Myr (Luhman 2004a) and the position of CHXR 73 A also implies an age of 2 Myr. Therefore, we adopt this value for CHXR 73 B. The star-forming regions containing

DH Tau B, GQ Lup B, and 2M 0535-0546 A and B appear to be slightly younger with ages closer to ~ 1 Myr (Hillenbrand 1997; Luhman et al. 2003). For reasons described by Luhman et al. (2005c), we adopt conservative lower and upper age limits of 0.5 to 10 Myr for the above companions in star-forming clusters. Meanwhile, for 2M 1207-3932 B we assume an age of 8^{+4}_{-3} Myr as done by Chauvin et al. (2004).

In Figure 4, we plot the positions of CHXR 73 B, 2M 0535-0546 A and B, 2M 1207-3932 B, DH Tau B, and GQ Lup B with the luminosities predicted as a function of age for masses from 0.005-0.06 $M_\odot$ by Burrows et al. (1997) and Chabrier et al. (2000). For an age of 1 Myr, these models imply masses of 0.055-0.065 and 0.05-0.06 $M_\odot$ for 2M 0535-0546 A, which agrees with the dynamical measurement of 0.05-0.059 $M_\odot$ (Stassun et al. 2006). Meanwhile, the model estimates of 0.045-0.055 and 0.04-0.05 $M_\odot$ for 2M 0535-0546 B are higher than the dynamical mass of 0.031-0.037 $M_\odot$. The models of Burrows et al. (1997) are consistent with the dynamical masses of both components if they are younger than 1 Myr. These data for 2M 0535-0546 indicate that the evolutionary models produce reasonably accurate mass estimates for young brown dwarfs when they are derived from bolometric luminosities, confirming the results of other recent observational tests (Luhman et al. 2005b; Luhman & Potter 2006)[5]. Thus, our mass estimates for the other young low-mass companions in Figure 4 should not be wildly in error, although the models are untested at the lowest masses and could have larger errors in that regime.

According to Figure 4, 2M 1207-3932 B has a mass of 0.003-0.004 $M_\odot$. We used the same data and models for this object as Mamajek (2005) except for a slightly different bolometric correction, and thus arrived at the same mass. For GQ Lup B, the models imply a mass of 0.024 ± 0.012 $M_\odot$ if it has an age less than ~ 7 Myr, which is similar to the values estimated by Neuhäuser et al. (2005) and Janson et al. (2006) from the luminosity and the same sets of models. For DH Tau B and CHXR 73 B, we derive masses of $0.011^{+0.01}_{-0.003}$ and $0.012^{+0.008}_{-0.005}$ $M_\odot$, respectively. Finally, although we are focusing on the youngest substellar companions, it is useful to also consider AB Pic B (Chauvin et al. 2005b), which is probably the least massive companion directly imaged at ages of $\tau > 10$ Myr. The combination of its K-band magnitude (Chauvin et al. 2005b), an appropriate bolometric correction (Golimowski et al. 2004), and the distance of the primary (Perryman et al. 1997) produce $\log L_{\rm bol} = -3.7 \pm 0.1$, which corresponds to 0.013-0.014 $M_\odot$ for an age of $\tau = 30$ Myr based on the models in Figure 4. Thus, the mass of AB Pic B appears to be similar to, or perhaps slightly greater than, those of DH Tau B and CHXR 73 B.

4. DISCUSSION

We have estimated masses for CHXR 73 B and other young low-mass companions in a uniform manner, and with a method that produces masses that are consistent with dynamical measurements for the one known young eclipsing binary brown dwarf, which allows us to examine both the relative and absolute masses of these companions. Neuhäuser et al. (2005) reported that GQ Lup B could have a mass as low as 1 $M_{\rm Jup}$, possibly making it the first planetary-mass companion imaged around a star. However, GQ Lup B is only slightly less luminous than 2M 1101-7732 B (Luhman 2004b) and is significantly brighter than DH Tau B (Itoh et al. 2005). If 2M 1101-7732 B and 2M 1207-3932 A were placed on the diagram of luminosity versus age in Figure 4, they would have masses comparable to that of GQ Lup B. For added perspective, we note that GQ Lup B has a higher luminosity than many of the known late-type members of nearby star-forming regions (>M8, Briceño et al. 2002; Luhman et al. 2003). Thus, it appears that GQ Lup B was not the least massive companion imaged at the time of its discovery and our mass estimate of 0.024 ± 0.012 $M_\odot$ suggests that it is unlikely to be a planet by any definition of the term.

DH Tau B and CHXR 73 B are the faintest known companions to young stars ($\tau < 10$ Myr). If our mass estimates of $0.011^{+0.01}_{-0.003}$ and $0.012^{+0.008}_{-0.005}$ $M_\odot$ are accurate, then they (and possibly AB Pic B) are the least massive companions directly imaged near stars outside the solar system. In fact, these estimates are just below both the maximum mass observed for extrasolar planetary companions ($M \sim 0.015$ $M_\odot$, Marcy et al. 2005) and the deuterium burning limit ($M \sim 0.014$ $M_\odot$, Saumon et al. 1996; Chabrier et al. 2000). If DH Tau B and CHXR 73 B have planetary masses, then are they planets? We can pose the same question for 2M 1207-3932 B, which has an even lower mass according to the models. In other words, is a planetary-mass companion always a planet?

The definition of a planet can be based on a companion's mass or on its formation mechanism. Following Chabrier et al. (2006), we advocate the latter definition in which a planet is an object that forms in the disk around a star or a brown dwarf, while a substellar companion that forms in another manner (e.g., core fragmentation) is a brown dwarf. We apply this definition of a planet to DH Tau B, CHXR 73 B, and 2M 1207-3932 B by drawing on theoretical work on planet formation in disks. The maximum separations at which giant planet formation can occur via both core accretion ($\lesssim 10$ AU, Pollack et al. 1996; Inaba et al. 2003) and disk instability ($\lesssim$ 20-100 AU, Boss 2003, 2006) are much lower than the projected separations of 200 and 300 AU for CHXR 73 B and DH Tau B, respectively. In addition, these systems are too young ($\tau \sim 1-2$ Myr) for the production of planets through core accretion. Thus, CHXR 73 B and DH Tau B probably did not form in disks around their primaries. Formation via disk instability cannot be ruled out for 2M 1207-3932 B (Lodato, Delgado-Donate, & Clarke 2005), but it would require an unusually high ratio of disk mass to brown dwarf mass for 2M 1207-3932 A when it was younger (Klein et al. 2003; Scholz et al. 2006). Meanwhile, it has been shown that cloud fragmentation can produce isolated objects that reach into the planetary mass regime. For instance, the least massive free-floating brown dwarf in Chamaeleon I is one magnitude fainter

[5] However, the relative masses implied by the temperature ratio of 2M 0535-0546 A and B are inconsistent with the dynamical measurements, which may indicate that the components are not coeval or that they are subject to a physical process that is not adequately treated by the models (Stassun et al. 2006).

than CHXR 73 B ($M \sim 0.08\ M_\odot$, Luhman et al. 2005c), so it seems plausible that the same process produced CHXR 73 B, but in a binary system instead of in isolation. Based on these various theoretical and observational considerations, we conclude that CHXR 73 B and other known young substellar companions probably did not form in a planetary fashion in disks and instead should be referred to as brown dwarfs. However, because the products of planet formation and core fragmentation may overlap in separation as well as in mass (e.g., 5 $M_{\rm Jup}$ at 10 AU), future surveys may uncover companions that cannot be classified unambiguously as either planets or brown dwarf companions.

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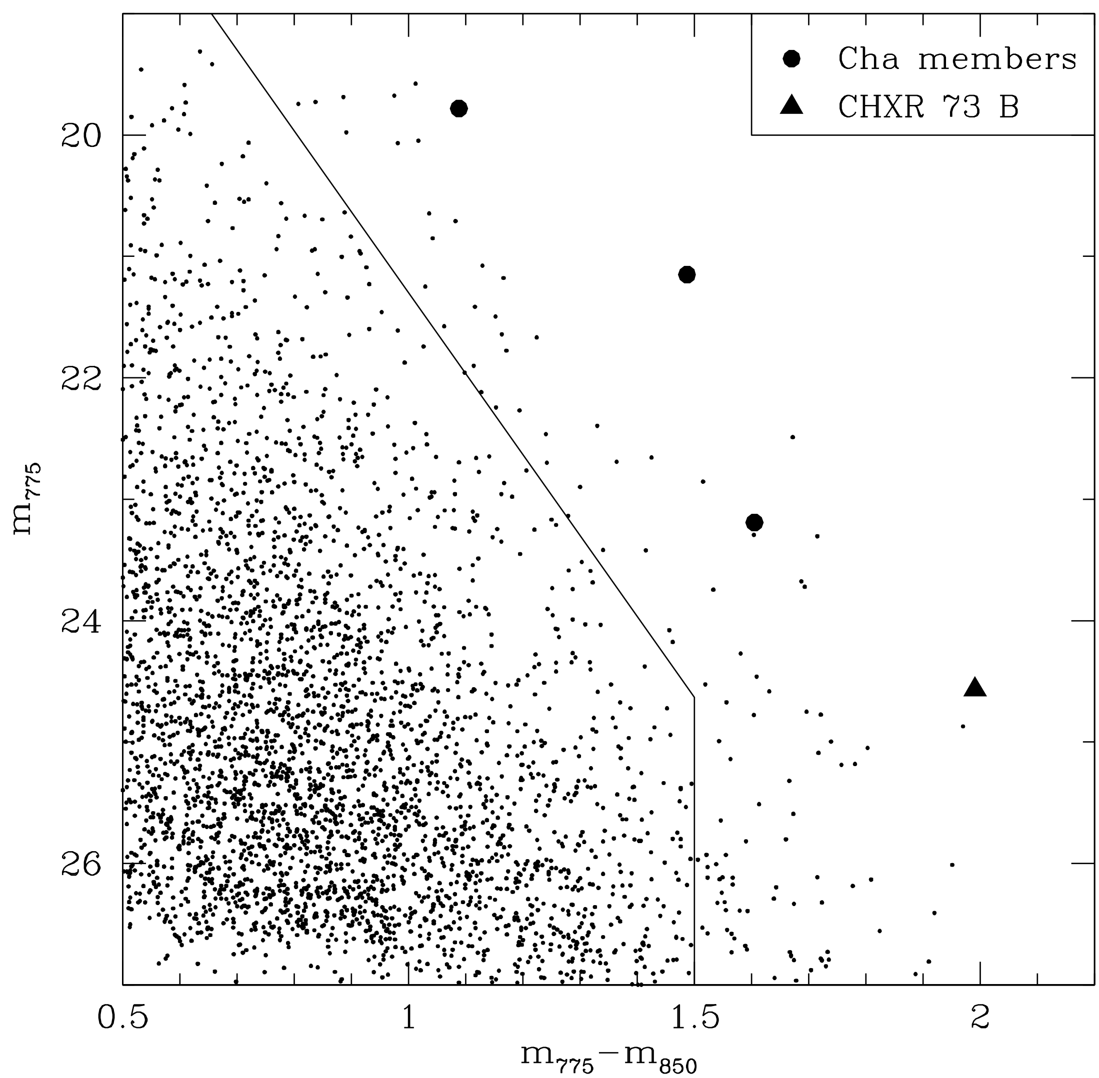

FIG. 1.— Color-magnitude diagram for unsaturated stars in ACS images of a 13$'$.3 × 16$'$.7 area in the southern cluster of the Chamaeleon I star-forming region. We indicate the unsaturated previously known cluster members in these data (*large points*) and the candidate companion to CHXR 73 shown in Figure 2 (*triangle*). The solid boundary was designed to follow the lower envelope of the sequence of known members.

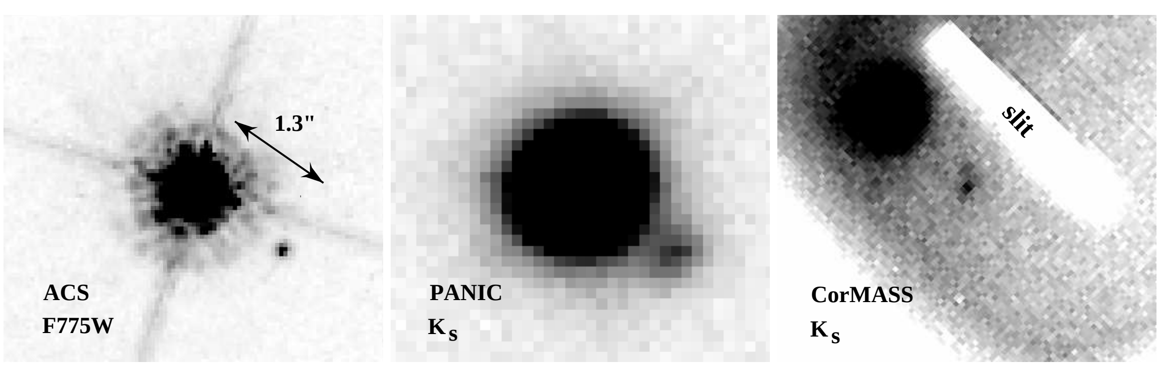

FIG. 2.— Images of CHXR 73 A and B obtained with ACS on *HST* (F775W), PANIC on Magellan I (K_s), and CorMASS on Magellan II (K_s). After the CorMASS exposure, the spectrograph's slit was centered on CHXR 73 B for spectroscopic observations (Figure 3). These images exhibit FWHM= 0$''$.1, 0$''$.5, and 0$''$.2, respectively, and have dimensions of 4$''$ × 4$''$. North is up and east is left in these images.

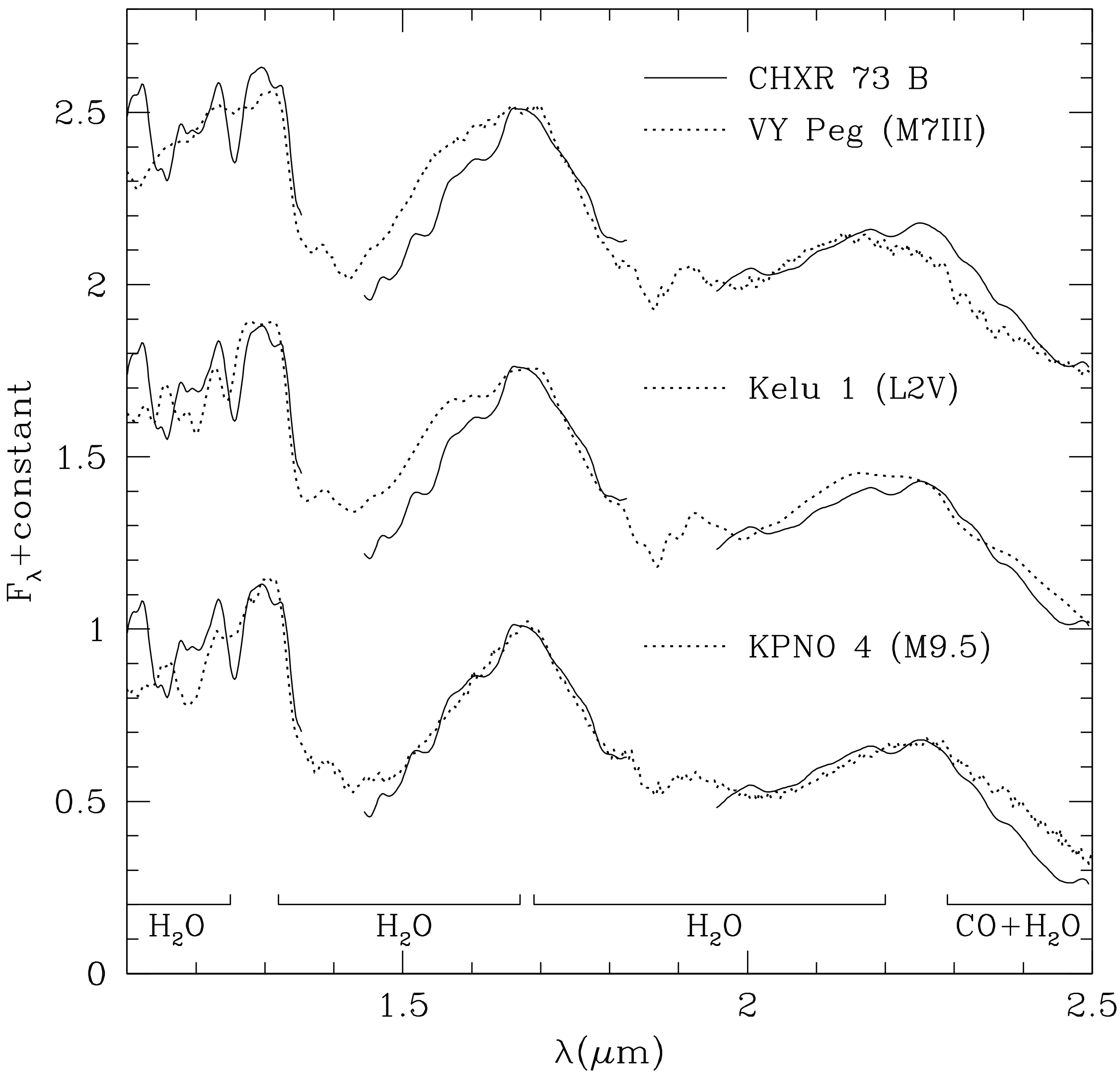

Fig. 3.— CorMASS infrared spectrum of the candidate substellar companion CHXR 73 B compared to spectra of the field M giant VY Peg, the field L dwarf Kelu 1, and the young Taurus member KPNO 4 ($\tau \sim 1$ Myr). CHXR 73 B exhibits the triangular H- and K-band continua that are indicative of young late-type objects rather than the broad plateaus found in the field objects, confirming its youth and membership in the Chamaeleon I star-forming region. The spectrum of CHXR 73 B has been dereddened by $A_J = 2.1$ to match the slope of KPNO 4, which has $A_J \sim 0$. To facilitate comparison to CHXR 73 B, the spectra of VY Peg and Kelu 1 were then reddened by $A_J = 0.4$ to match the slope of this dereddened spectrum of CHXR 73 B. Because the observed spectrum of CHXR 73 B is very red, the signal-to-noise ratio is lower at shorter wavelengths, and thus the continuum structure at <1.3 μm is noise rather than photospheric absorption features. The spectra are displayed at a resolution of $R = 100$ and are normalized at 1.68 μm.

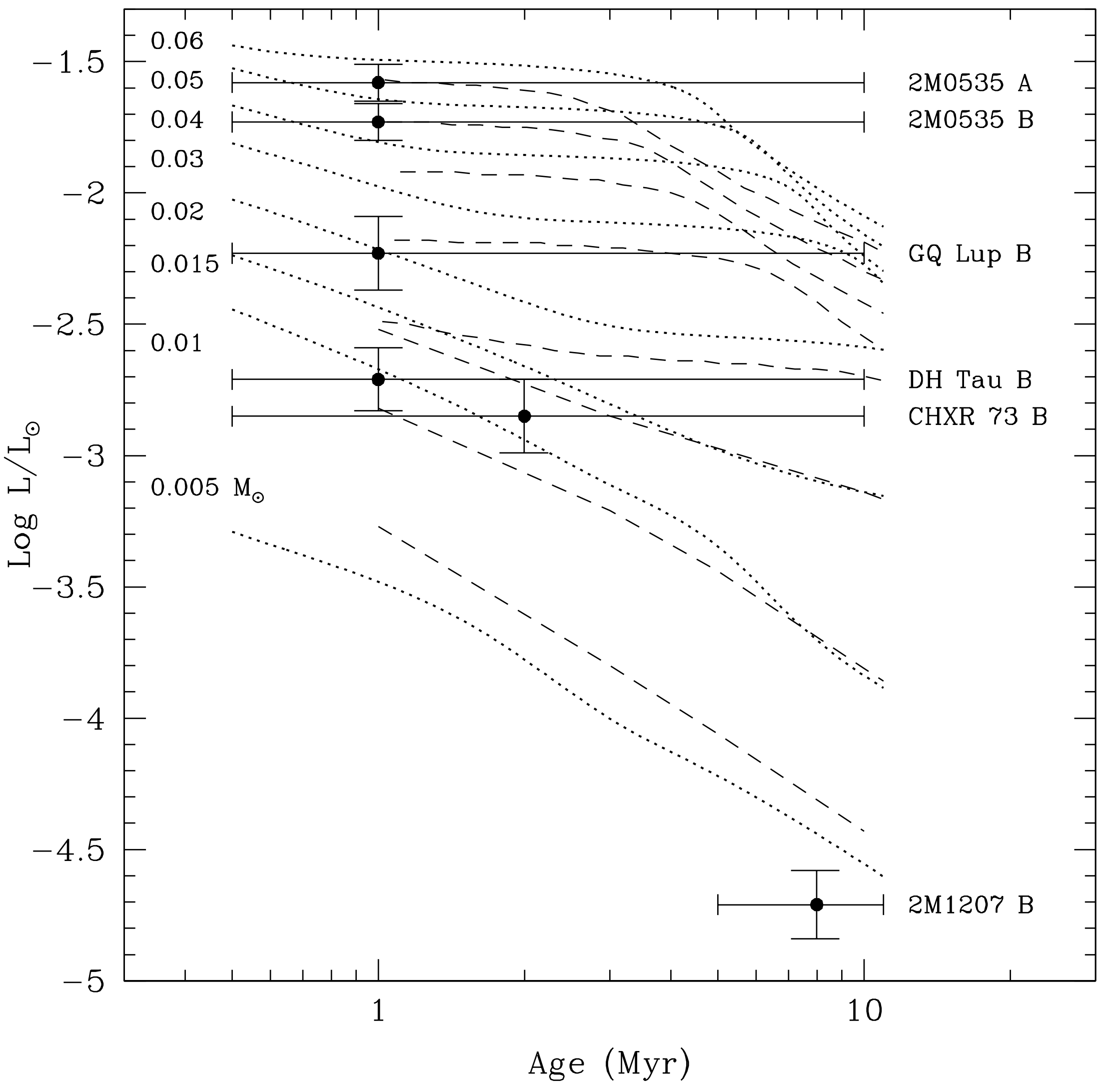

Fig. 4.— Luminosities of the young companions 2M 0535-0546 A and B, GQ Lup B, 2M 1207-3932 B, DH Tau B, and CHXR 73 B (*points*) compared to the luminosities as a function of age predicted by the theoretical evolutionary models of Chabrier et al. (2000) (*dashed lines*) and Burrows et al. (1997) (*dotted lines*) for masses of 0.005 to 0.06 $M_\odot$. CHXR 73 B has a mass of $0.012^{+0.008}_{-0.005}$ $M_\odot$ according to these models.