The Formation of Brown Dwarfs: Observations

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We review the current state of observational work on the formation of brown dwarfs, focusing on their initial mass function, velocity and spatial distributions at birth, multiplicity, accretion, and circumstellar disks. The available measurements of these various properties are consistent with a common formation mechanism for brown dwarfs and stars. In particular, the existence of widely separated binary brown dwarfs and a probable isolated proto-brown dwarf indicate that some substellar objects are able to form in the same manner as stars through unperturbed cloud fragmentation. Additional mechanisms such as ejection and photoevaporation may play a role in the birth of some brown dwarfs, but there is no observational evidence to date to suggest that they are the key elements that make it possible for substellar bodies to form.

1. INTRODUCTION

Although many of the details are not perfectly understood, stars and giant planets are generally believed to form through the collapse of molecular cloud cores and the accretion of gas by rocky cores in circumstellar disks, respectively. In comparison, the formation of objects intermediate between stars and planets – free-floating and companion brown dwarfs – has no widely accepted explanation. A priori, one might expect that brown dwarfs form in the same manner as stars, just on a much smaller scale. However, although self-gravitating objects can form with initial masses of only $\sim 1\ M_{\rm Jup}$ in simulations of the fragmentation of molecular cloud cores, these fragments continue to accrete matter from their surrounding cores, usually to the point of eventually reaching stellar masses (*Boss*, 2001; *Bate et al.*, 2003). Thus, standard cloud fragmentation in these models seems to have difficulty in making brown dwarfs. One possible explanation is that the simulations lack an important piece of physics (e.g., turbulence), and brown dwarfs are able to form through cloud fragmentation despite their predictions (e.g., *Padoan and Nordlund*, 2004). Another possibility is that a brown dwarf is born when cloud fragmentation is modified by an additional process that prematurely halts accretion during the protostellar stage, such as dynamical ejection (*Reipurth and Clarke*, 2001; *Boss*, 2001; *Bate et al.*, 2002) or photoevaporation by ionizing radiation from massive stars (*Kroupa and Bouvier*, 2003; *Whitworth and Zinnecker*, 2004). This uncertainty surrounding the formation of brown dwarfs has motivated a great deal of theoretical and observational work over the last decade.

In this paper, we review the current observational constraints on the formation process of brown dwarfs (BDs), which complements the theoretical review of this topic provided in the chapter by *Whitworth et al.* By the nature of the topic of this review, we focus on observations of BDs at young ages ($\tau < 10$ Myr), although we also consider properties of evolved BDs that provide insight into BD formation (e.g., multiplicity). A convenient characteristic of young BDs is their relatively bright luminosities and warm temperatures compared to their older counterparts in the solar neighborhood, making them easier to observe. However, because the luminosities and temperatures of young BDs are continuous extensions of those of stars, positively identifying a young object as either a low-mass star or a BD is often not possible. The mass estimates for a given object vary greatly with the adopted evolutionary models and the manner in which observations are compared to the model predictions. Using the models of *Baraffe et al.* (1998) and *Chabrier et al.* (2000) and the temperature scale of *Luhman et al.* (2003b), the hydrogen burning mass limit at ages of 0.5-3 Myr corresponds to a spectral type of ∼M6.25, which

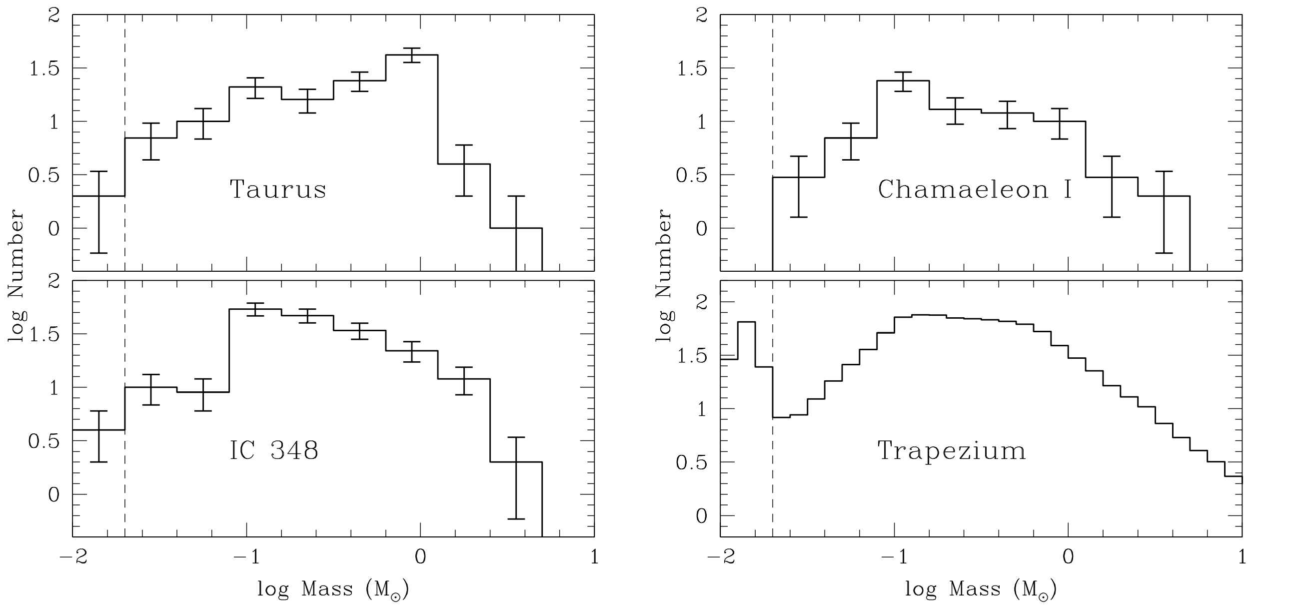

Fig. 1.— IMFs for Taurus (*Luhman*, 2004c), IC 348 (*Luhman et al.*, 2003b), Chamaeleon I (*Luhman*, in preparation), and the Trapezium Cluster (*Muench et al.*, 2002). The completeness limits for these measurements are near 0.02 $M_\odot$ (*dashed lines*). In the units of this diagram, the Salpeter slope is 1.35.

is consistent with the dynamical mass and spectral type of the first known eclipsing binary BD (*Stassun et al.*, 2006) and other observational tests (*Luhman and Potter*, 2006). Therefore, we will treat young objects later than M6 as BDs for the purposes of this review.

2. INITIAL MASS FUNCTION

One of the most fundamental properties of BDs is their initial mass function (IMF). Because BDs are brightest when they are young, star-forming regions and young clusters are the best sites for finding them in large numbers and at low masses, which is necessary for measuring statistically significant IMFs. Spectroscopic surveys for BDs have been performed toward many young populations ($\tau <$ 10 Myr) during the last decade, including IC 348 (*Luhman et al.*, 1998, 2003b, 2005a; *Luhman*, 1999), Taurus (*Briceño et al.*, 1998, 2002; *Martín et al.*, 2001b; *Luhman*, 2000, 2004c, 2006; *Luhman et al.*, 2003a; *Guieu et al.*, 2006), Chamaeleon I (*Comerón et al.*, 1999, 2000, 2004; *Neuhäuser and Comerón*, 1999; *Luhman*, 2004a,b; *Luhman et al.*, 2004), Ophiuchus (*Luhman et al.*, 1997; *Wilking et al.*, 1999; *Cushing et al.*, 2000), Upper Scorpius (*Ardila et al.*, 2000; *Martín et al.*, 2004), Orion (*Hillenbrand*, 1997; *Lucas et al.*, 2001; *Slesnick et al.*, 2004), NGC 2024 (*Levine et al.*, 2006), NGC 1333 (*Wilking et al.*, 2004), TW Hya (*Gizis*, 2002; *Scholz et al.*, 2005), λ Ori (*Barrado y Navascués et al.*, 2004b), and σ Ori (*Barrado y Navascués et al.*, 2001, 2002; *Béjar et al.*, 1999, 2001; *Martín et al.*, 2001a; *Zapatero Osorio et al.*, 1999, 2000, 2002a,b,c; *Martín and Zapatero Osorio*, 2003).

We now examine the IMF measurements for IC 348, Chamaeleon I, Taurus, and the Trapezium, which exhibit the best combination of number statistics, completeness, and dynamic range in mass among the young populations studied to date. These IMFs are shown in Fig. 1. Because the same techniques and models were employed in converting from data to masses for each population, one can be confident in the validity of any differences in these IMFs. For the Trapezium, we use the IMF derived through infrared (IR) luminosity function modeling by *Muench et al.* (2002) (see also *Luhman et al.*, 2000; *Hillenbrand and Carpenter*, 2000; *Lucas et al.*, 2005). The spectroscopically determined IMF for IC 348 agrees well with the IMF derived by *Muench et al.* (2003) through the same kind of luminosity function analysis, which suggests that the Trapezium IMF from *Muench et al.* (2002) can be reliably compared to the spectroscopic IMFs for IC 348, Chamaeleon I, and Taurus. We quantify the relative numbers of BDs and stars with the ratio:

$$\mathcal{R} = N(0.02 \leq M/M_\odot \leq 0.08)/N(0.08 < M/M_\odot \leq 10)$$

The IMFs for Taurus, IC 348, and Orion exhibit $\mathcal{R}$ = 0.18 ± 0.04, 0.12 ± 0.03, and 0.26 ± 0.04, respectively. Because the IMF measurement for Chamaeleon I is preliminary, a reliable BD fraction is not yet available. These BD fractions for Taurus and IC 348 are a factor of two lower than the value for Orion. However, upon spectroscopy of a large sample of BD candidates in the Trapezium, *Slesnick et al.* (2004) found a population of faint objects with stellar masses, possibly seen in scattered light, which had contaminated previous photometric IMF samples and resulted in overestimates of the BD fraction in this cluster. After

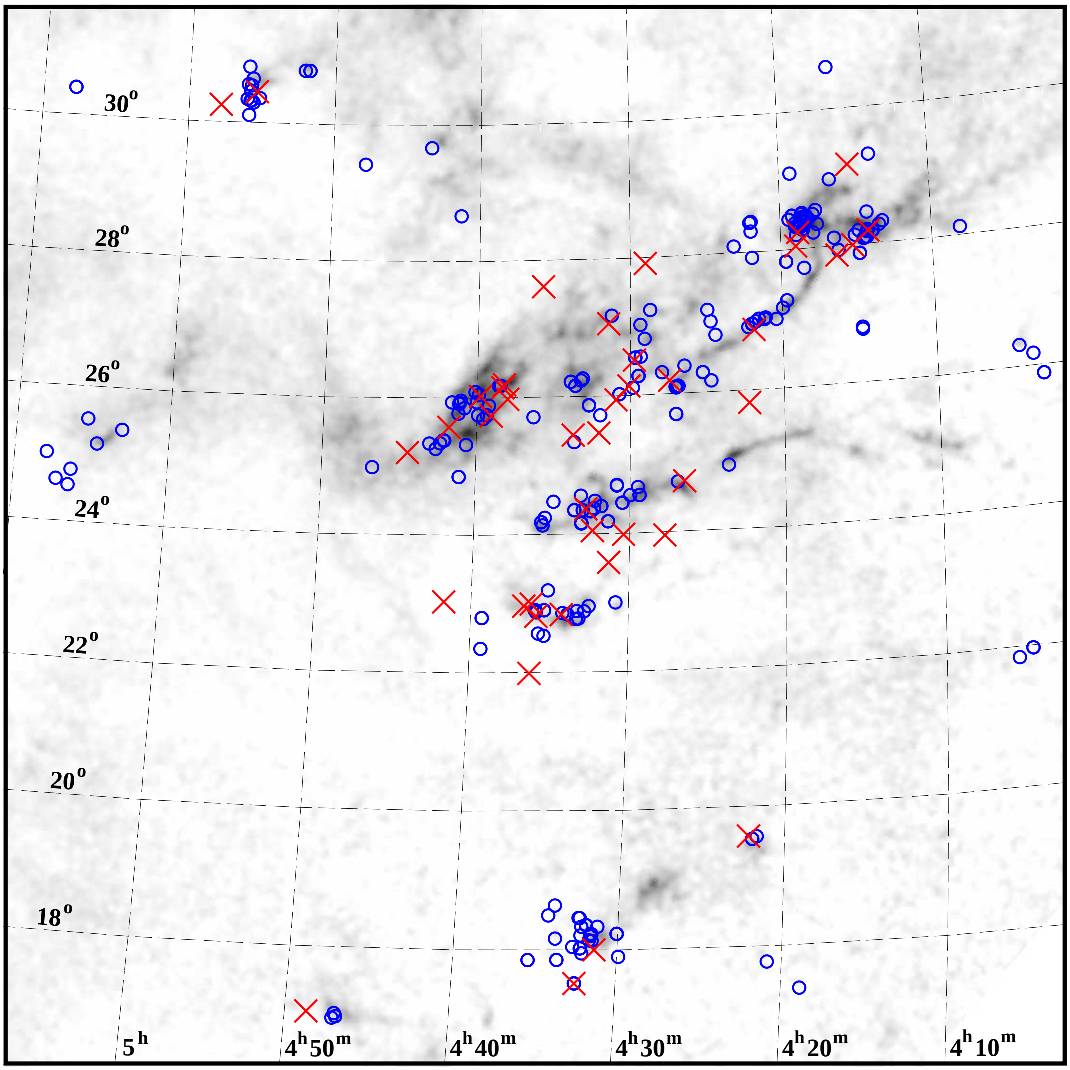

Fig. 2.— Spatial distributions of stars (≤M6, *circles*) and BDs (>M6, *crosses*) in the Taurus star-forming region shown with a map of extinction (*grayscale*, *Dobashi et al.*, 2005).

they corrected for this contamination, the BD fraction in the Trapezium was a factor of only ~ 1.4 higher than the value in Taurus from *Luhman* (2004c). Through a survey of additional areas of Taurus, *Guieu et al.* (2006) have recently discovered 17 new low-mass stars and BDs. By combining these data with the previous surveys, they measured a BD fraction that is still higher, and thus closer to the value for Orion. However, *Luhman* (2006) finds that their higher BD fraction is due to a systematic offset between the spectral types of *Guieu et al.* (2006) and the classification system used for the previously known late-type members of Taurus (*Luhman*, 1999; *Briceño et al.*, 2002). In summary, according to the best available data, the BD fractions in Taurus and IC 348 are lower than in the Trapezium, but by a factor that is smaller than that reported in earlier studies.

Because the mass-luminosity relation is a function of age for BDs at any age, and the ages of individual field BDs are unknown, a unique, well-sampled IMF of field BDs cannot be constructed. When substellar mass functions are instead compared in terms of power-law slopes (Salpeter is 1.35), the latest constraints in the field from *Chabrier* (2002) ($\alpha \lesssim 0$) and *Allen et al.* (2005) ($-1.5 \lesssim \alpha \lesssim 0$) are consistent with the mildly negative slopes exhibited by the data for star-forming regions in Fig. 1. Thus, data for both star-forming regions and the solar neighborhood are consistent with stars outnumbering BDs by a factor of $\sim$ 5-8. If BDs form through ejection and have higher velocity dispersions than stars as predicted by *Kroupa and Bouvier* (2003) (but not *Bate et al.*, 2003), then the BD fraction would be higher in the field than in star-forming regions since BD members would be quickly ejected from the latter. However, current data show no evidence of such a difference.

In addition to the abundance of BDs relative to stars, the minimum mass at which BDs can form also represents a fundamental constraint for theories of BD formation. For several of the star-forming regions cited in this section, BDs with conclusive evidence of membership and accurate spectral classifications have been discovered down to optical spectral types of M9.5, corresponding to masses of $\sim$ 10-20 $M_{\rm Jup}$. Additional BDs have been reported at cooler and fainter levels, most notably in σ Ori. However, some of these objects lack clear evidence of membership and instead could be field dwarfs (*Burgasser et al.*, 2004, references therein). Finally, *Kirkpatrick et al.* (2006) recently discovered a young L dwarf in the field that is probably comparable in mass (6-25 $M_{\rm Jup}$) to the least massive BDs found in young clusters.

3. KINEMATICS AND POSITIONS AT BIRTH

Some models for the formation of BDs via embryo ejection predict that BDs are born with higher velocity dispersions than stars and thus are more widely distributed in star-forming regions than their stellar counterparts (*Reipurth and Clarke*, 2001; *Kroupa and Bouvier*, 2003). Meanwhile, other models of ejection (*Bate et al.*, 2003) and models in which BDs form in a star-like manner predict that stars and BDs should have similar spatial and velocity distributions. Because normal dynamical evolution of a cluster can produce mass-dependent distributions like those of the first set of ejection models (*Bonnell and Davies*, 1998), clusters that are old or dense are not suitable for testing their predictions (*Moraux and Clarke*, 2005). Therefore, based on their youth and low stellar densities, the Taurus and Chamaeleon star-forming region are ideal sites for comparing the positions and kinematics of stars and BDs.

Precise radial velocities of low-mass stars and BDs in Chamaeleon I measured from high-resolution spectra are slightly less dispersed (0.9±0.3 km/s) but still consistent with those of stars (1.3±0.3 km/s) (*Joergens and Guenther*, 2001; *Joergens*, 2006b). The BDs do not show a high velocity tail as predicted by some models of the ejection scenario (*Sterzik and Durisen*, 2003; *Umbreit et al.*, 2005). Similar results have been found for Taurus (*White and Basri*, 2003; *Joergens*, 2006b). While the absence of a significant mass dependence of the velocities is consistent with some models of the ejection scenario (*Bate et al.*, 2003; *Delgado-Donate et al.*, 2004), the observed global radial velocity dispersion (BDs and stars) for Chamaeleon I members is smaller than predicted by any model of the ejection scenario.

Over time, the surveys for BDs in Taurus have encompassed steadily larger areas surrounding the stellar aggregates (see references in previous section). These data have exhibited no statistically significant differences in the spatial distribution of the high- and low-mass members of Taurus (*Briceño et al.*, 2002; *Luhman*, 2004c; *Guieu et al.*, 2006). This result has been established definitively by the completion of a BD survey of 225 deg^2 encompassing all of Taurus (*Luhman*, 2006). As shown in Fig. 2, the BDs follow the spatial distribution of the stellar members, and there is no evidence of a large, distributed population of BDs. As with the kinematic properties, these spatial data are consistent with a common formation mechanism for stars and BDs and some models for ejection (*Bate et al.*, 2003), but not others (*Kroupa and Bouvier*, 2003).

4. MULTIPLICITY

As with stars, the multiplicity properties of BDs (frequency, separation, and mass ratio distributions) are intimately tied to their formation. As discussed in the chapter by *Whitworth et al.*, embryo-ejection scenarios predict few binaries and only close orbits, while isolated fragmentation models allow for higher binary frequencies and larger maximum separations. Therefore, accurately characterizing the multiplicity of BDs can help distinguish between these scenarios (and others). Moreover, the identification of very low-mass companions to BDs will delimit better the types of environments in which planets can form. The chapter by *Burgasser et al.* provides a comprehensive review of the observational and theoretical work on the binary properties of BDs. In this section, we discuss highlights of the latest observational work and their implications for the origin of BDs.

4.1. Brown Dwarf Companions to Stars: The Brown Dwarf Desert

Among companions at separations less than a few AU from solar-type stars, radial velocity surveys have revealed a paucity of BDs (20-80 $M_{\rm Jup}$) relative to giant planets and stellar companions (*Marcy and Butler*, 2000). Deficiencies in substellar companions have been observed at wider separations as well, as illustrated in Fig. 8 from *McCarthy and Zuckerman* (2004), which compared published frequencies of stellar and substellar companions as a function of separation. At separations less than 3 AU, the frequency of BD companions is $\sim$ 0.1% ($<$ 0.5%) (*Marcy and Butler*, 2000) and the frequency of stellar companions is $13 \pm 3\%$ (*Duquennoy and Mayor*, 1991; *Mazeh et al.*, 1992), indicating that BDs are outnumbered by stars among close companions by a factor of $\sim$ 100 ($>$ 20). In comparison, the ratio of the frequencies of stellar and substellar companions is between $\sim$ 3 and 10 at wider separations (*McCarthy and Zuckerman*, 2004), which is comparable to the ratio of the numbers of stars and BDs in isolation ($\sim$ 5-8, Section 2). Thus, for solar-type primaries, only the close companions exhibit a true desert of BDs. The similarity in the abundances of BDs among wider companions and free-floating objects suggests that they arise from a common formation mechanism (e.g., core fragmentation.)

4.2. Binary Brown Dwarfs

Binary surveys of members of the solar neighborhood have found progressively smaller binary fractions, smaller average and maximum separations, and larger mass ratios ($q \equiv M_2/M_1$) with decreasing primary mass from stars to BDs (*Duquennoy and Mayor*, 1991; *Fischer and Marcy*, 1992; *Reid et al.*, 2001; *Bouy et al.*, 2003; *Burgasser et al.*, 2003; *Close et al.*, 2003; *Gizis et al.*, 2003; *Siegler et al.*, 2005). To help identify the sources of these trends (e.g., formation mechanism, environment), it is useful to compare the field data to measurements in young clusters and star-forming regions. Because young clusters have greater distances than the nearest stars and BDs in the field, the range of separations probed in binary surveys of young clusters is usually smaller than that for field objects. As a result, accurate measurements of the multiplicity as a function of mass are difficult for young populations. However, for one of the best studied star-forming regions, Taurus-Auriga, *White et al.* (in preparation) and *Kraus et al.* (2006) have measured the binary fraction (for a = 9-460 AU, $q \geq 0.09$, defined for completeness) as a function of mass from 1.5 to 0.015 $M_{\odot}$. As shown in Fig. 3, the binary fraction in Taurus declines steadily with primary mass, which resembles the trend observed for the solar neighborhood. This behavior can be explained by simple random pairing from the same mass function without the presence of different formation mechanisms at high and low masses. Out of the 17 Taurus members with spectral types cooler than M6 ($\lesssim 0.1\ M_{\odot}$), none have spatially resolved companions, which again is consistent with the small separations of $a < 20$ AU that have been observed for most of the binary low-mass stars and BDs in the field. A similar paucity of wide low-mass pairs has been found in other young regions, including IC 348 (*Duchêne et al.*, 1999; *Luhman et al.*, 2005c), Chamaeleon I (*Neuhäuser et al.*, 2002), Corona Australis (*Bouy et al.*, 2004), Upper Scorpius (*Kraus et al.*, 2005), and the Trapezium Cluster in Orion (*Lucas et al.*, 2005). However, in both the field and in young clusters, a few wide binary low-mass stars and BDs have been found at projected separations that range from 33-41 AU (*Harrington et al.*, 1974; *Martín et al.*, 2000; *Chauvin et al.*, 2004, 2005; *Phan-Bao et al.*, 2005) to beyond 100 AU (*White et al.*, 1999; *Gizis et al.*, 2001; *Luhman*, 2004b, 2005; *Billères et al.*, 2005; *Bouy et al.*, 2006). Because these wide binaries are weakly bound and extremely fragile, it would seem unlikely that they have been subjected to violent dynamical interactions, suggesting that some low-mass stars and BDs are able to form without the involvement of ejection, apparently through standard, unperturbed cloud fragmentation. Indeed, in embryo-ejection simulations, *Bate et al.* (2002) found that "because close dynamical interactions are involved in their formation...binary brown dwarf systems that do exist must be close, $\lesssim 10$ AU". However, in more recent calculations by *Bate and Bonnell* (2005), a wide binary BD was able to form when two BDs were simultaneously ejected in similar directions.

Because the surveys for binary BDs cited above employed direct imaging, they were not sensitive to very close binaries ($a \lesssim 1$ and $a \lesssim 10$ AU for the field and clusters, respectively), making the resulting binary fractions only lower limits. Spectroscopic monitoring for radial velocity variations provides a means of identifying the closest companions, which is essential for assessing whether the formation mechanism of companions in substellar multiple systems changes with separation. The first free-floating BD to be discovered, PPL 15 (*Stauffer et al.*, 1994), turned out to be a spectroscopic binary with companions of nearly equal mass in a 6 day orbit (*Basri and Martín*, 1999). More recently, *Guenther and Wuchterl* (2003) started a systematic survey for close companions to 25 low-mass stars and BDs in the field, finding two candidate double-lined spectroscopic binaries. An additional object in their sample was found to be a binary by *Reid et al.* (2002). *Joergens and Guenther* (2001) started a similar survey for close low-mass binaries in the Chamaeleon I star-forming region. Among a subsample of ten low-mass objects ($M \lesssim 0.12\ M_{\odot}$, M5–M8), none show signs of companions down to the masses of giant planets for orbital periods $P < 40$ d, corresponding to separations of $a < 0.1$ AU (*Joergens*, 2006a). For Cha Hα 8 (M6.5), data recorded across a longer period of time does indicate the existence of a spectroscopic companion of planetary or BD mass with an orbital period of several months to a few years, as shown in Fig. 4. In a combination of the above old and young samples, 3 ($\sim 9\%$) and 4 ($\sim 11\%$) objects have possible companions at $P < 100$ d and $P < 1000$ d, respectively. For comparison, the frequencies of binaries among solar-type field stars are 7% and 13% in these same period ranges (*Duquennoy and Mayor*, 1991).

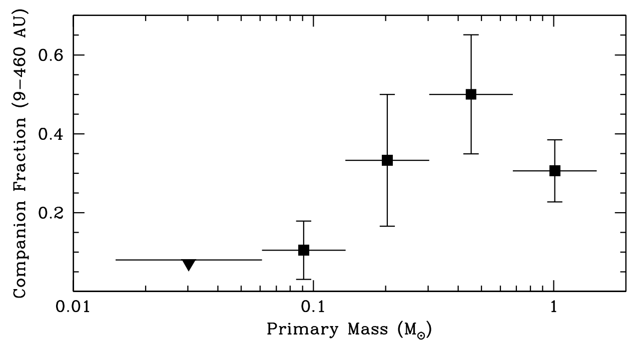

Fig. 3.— Binary fraction over the separation range 9-460 AU versus primary mass for young stars and BDs in the Taurus star-forming region (*White et al.*, in preparation; *Kraus et al.*, 2006).

5. ACCRETION

The past 10-15 years has seen the establishment of a disk accretion paradigm in low-mass T Tauri stars that explains many of their observed characteristics. The picture centers on the concept of magnetospheric accretion, whereby the stellar magnetic field truncates the circumstellar disk and channels accreting material out of the disk plane and onto the star (see the chapter by *Bouvier et al.* and references therein). Models of magnetospheric accretion successfully describe many features of classical T Tauri stars (CTTSs) including the broad, asymmetric permitted line emission (e.g., *Muzerolle et al.*, 2001) and blue/UV continuum excess (e.g., *Calvet and Gullbring*, 1998). The investigation of accretion and disk signatures in lower-mass objects extending below the substellar limit is a natural extension of the CTTS studies, helping to address the origin of BDs.

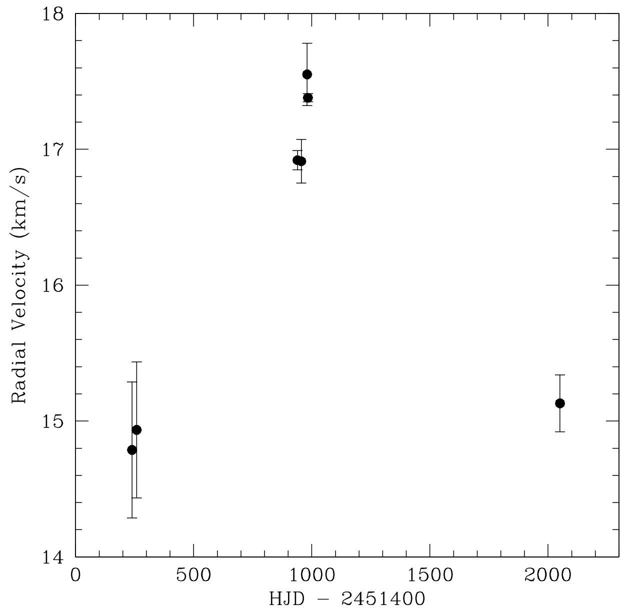

Fig. 4.— Radial velocity data for the young low-mass object Cha Hα 8 (M6.5) recorded with UVES/VLT: significant variability occurring on time scales of months to years hint at a companion at a >0.2 AU and M $\sin i \gtrsim 6\ M_{\rm Jup}$ (*Joergens*, 2006a).

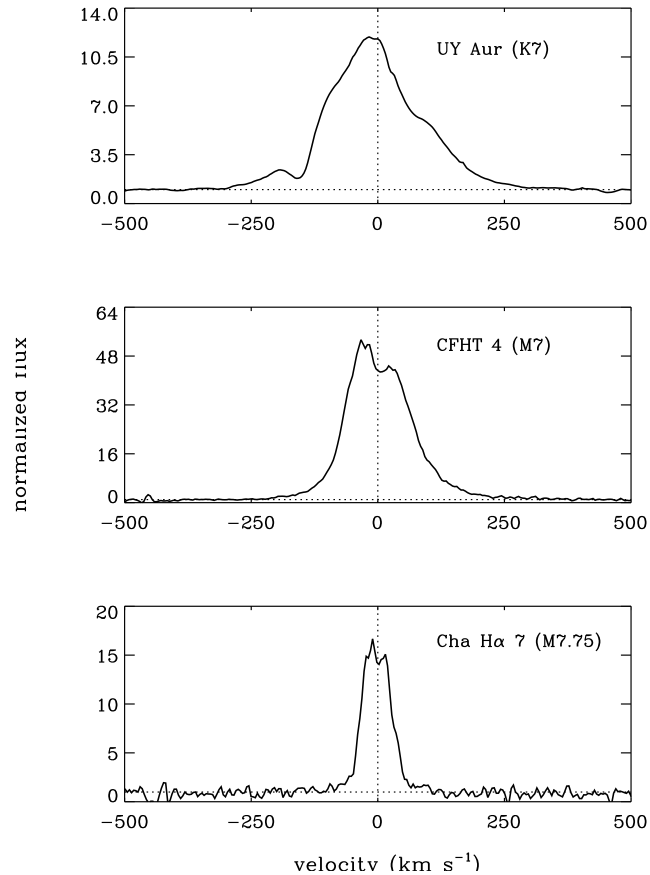

Fig. 5.— Comparison of Hα profiles of (from top to bottom) a typical CTTS (*Muzerolle et al.*, 1998), a typical substellar accretor (note the smaller line width indicative of the much smaller gravitational potential), and a substellar non-accretor exhibiting the narrow and symmetric profile produced by chromospheric emission (*Muzerolle et al.*, 2005).

Accretion in young BDs is fundamental to our understanding of formation mechanisms, and hence has undergone considerable scrutiny following the discovery of the first substellar objects in nearby star-forming regions. Spectroscopy of the first known young BDs (e.g., *Luhman et al.*, 1997; *Briceño et al.*, 1998; *Comerón et al.*, 1999) revealed that many were superficially similar to CTTSs in terms of emission line activity. In particular, equivalent widths of Hα emission in many cases exceeded levels typical of chromospheric activity in low-mass CTTSs and main sequence dMe stars, suggesting the presence of accretion. With the advent of 8-10 m class telescopes, high-resolution optical spectroscopy of young BDs became possible. As a result, research by many groups over the last 5 years has provided conclusive evidence of ongoing accretion in many young substellar systems. This evidence includes the presence of broad, asymmetric Balmer line profiles, continuum veiling of photospheric absorption features, and in a few cases forbidden line emission, all similar to features seen in CTTSs.

5.1. Diagnostics

The first demonstration of accretion infall in a very low-mass object was presented by *Muzerolle et al.* (2000) for the Taurus member V410 Anon 13 ($\sim 0.1\ M_\odot$, *Briceño et al.*, 2002). The Hα profile for this object shows a clear infall asymmetry similar to that commonly seen in CTTSs, albeit with a narrower line width and a lack of opacity-broadened wings. Such features indicated ballistic infall at velocities consistent with the object's mass and radius, and a much lower mass accretion rate ($\dot{M}$) than typical of higher-mass CTTSs with similar ages. Modeling of the profile in fact yielded an extremely small value of $\dot{M} \sim 5 \times 10^{-12}\ M_\odot\,{\rm yr}^{-1}$, a mere trickle in comparison with the average rate of $\sim 10^{-8}\ M_\odot\,{\rm yr}^{-1}$ for solar-mass CTTSs (*Gullbring et al.*, 1998).

Evidence for accretion in many other very low-mass stars and BDs has since accumulated by various techniques. *White and Basri* (2003) were the first to publish measurements of continuum veiling from accretion shock emission from objects near and below the substellar limit, providing more direct measures of mass accretion rates that were again lower than the typical of CTTSs. However, measurable veiling has turned out to be very rare in substellar accretors because of their small accretion rates. Models of substellar accretion shock emission (*Muzerolle et al.*, 2000) show that measurable veiling is produced only when $\dot{M} > 10^{-10}\ M_\odot\,{\rm yr}^{-1}$. Since H$\alpha$ emission from the accretion flow is detectable at much lower $\dot{M}$, Hα emission line profiles remain the most sensitive accretion diagnostics available for young BDs. Chromospheric emission associated with magnetic activity appears to be a common feature of both young and older field dwarfs (e.g., *Mohanty and Basri*, 2003), producing generally larger Hα equivalent widths at later spectral types as a result of decreasing contrast with the photosphere; Hα equivalent widths of 20 Å are not uncommon in young objects with spectral types M5 or later. Spectral type-dependent equivalent width criteria have been proposed by several authors (*Barrado y Navascués and Martín*, 2003; *White and Basri*, 2003). However, line profiles offer the most unambiguous discriminant, as chromospheric emission produces much narrower and symmetric profiles compared to the broader and often asymmetric accretion profiles, as illustrated in Fig. 5.

A popular high-resolution accretion criterion has been the Hα 10% line velocity width. Accretion profile widths are related to the maximum ballistic infall velocity $V_{inf} \sim \sqrt{\frac{2GM_*}{R_*}(1-\frac{1}{R_m})} \sim 160$ km s^{-1} for $M_* = 0.05\ M_\odot$, $R_* = 0.5\ R_\odot$, and a magnetospheric truncation radius $R_m = 3\ R_*$ (see *Muzerolle et al.*, 2003). Most chromospheric profiles generally exhibit velocity half-widths $\lesssim 70$ km s^{-1}, much lower than the characteristic infall velocity. Broadening from rapid rotation can create larger line widths, as has been observed, but this is rare (typical rotation velocities are $v \sin i \lesssim 20$ km s^{-1}: *Muzerolle et al.*, 2003, 2005) and in any case can be checked with v sin i measurements. Also, objects with large Hα velocity widths consistent with infall tend to have larger Hα *equivalent* widths than those with chromospheric profiles and also tend to correlate with the presence of other accretion signatures such as other permitted and forbidden emission lines. Adopting a 10% line width threshold of $V_{10} \gtrsim 180-200$ km s^{-1} gives reasonably accurate accretor identifications in BDs (*Jayawardhana et al.*, 2003b; *Muzerolle et al.*, 2005), although occasional misidentifications can occur for rapidly rotating nonaccretors or pole-on accretors.

Dozens of substellar accretors have now been identified down to masses approaching the deuterium burning limit and with ages from 1 to 10 Myr (e.g., *Jayawardhana et al.*, 2003b; *Mohanty et al.*, 2005; *Muzerolle et al.*, 2003, 2005). Such a statistically robust sample has allowed systematic studies of accretion properties across nearly the entire range of substellar masses yet identified. For instance, magnetospheric accretion requires disk material to be present at or within the corotation radius, which should be detectable at near- or mid-IR wavelengths. Comparing known substellar accretors in Chamaeleon I and Ophiuchus with IR excesses detected by ISO at 6.7 and 14.3 μm (*Natta et al.*, 2004) and Spitzer at 3.6-8 μm (*Luhman et al.*, 2005d), 3/10 and 7/10 in each region, respectively, exhibit both accretion and disks, while 3/10 in each region show disks but no accretion. There are no cases of accretion without disk signatures. The objects with disks and lacking accretion signatures may simply be accreting at rates below the observable threshold. The larger fraction of these in Chamaeleon I compared to Ophiuchus may be a reflection of the slightly older age of the former, so that the disks have evolved to lower accretion rates on average (see below). Indeed, many studies have now found strong indications of a decreasing fraction of accreting objects with age, both above and below the substellar limit. Typical values range from 30-60% in 1-3 Myr-old regions such as Taurus and Chamaeleon I, but drop significantly to 0-5% in 3-5 Myr-old regions such as σ Ori and Upper Scorpius (*Muzerolle et al.*, 2005; *Mohanty et al.*, 2005). These numbers are consistent with similar declines observed in the accretor fraction at stellar masses, indicating similar evolutionary timescales for accretion between stars and BDs. The same result is found for the disk fractions of stars and BDs, as we discuss in Section 6.2.

5.2. Substellar Accretion Rates

The results summarized above show that the overall accretion characteristics are essentially continuous across the substellar boundary, which is consistent with stars and BDs forming via the same accretion processes. A more quantitative assessment can be made from measurements of mass accretion rates. Most of the estimates of $\dot{M}$ based on line profile modeling (*Muzerolle et al.*, 2003, 2005) and secondary IR calibrators such as Paschen β and Brackett γ (*Natta et al.*, 2004) and the Ca II triplet (*Mohanty et al.*, 2005) have shown that very small accretion rates are in fact typical of very low-mass young objects. The average value for substellar accretors is roughly 2-3 orders of magnitude lower than that of 1 Myr-old CTTSs. A clear trend of decreasing accretion rate with decreasing mass was found by *Muzerolle et al.* (2003) and subsequently extended down to $M \sim 0.02\ M_\odot$ by *Mohanty et al.* (2005) and *Muzerolle et al.* (2005), with a functional form of $\dot{M} \propto M^2$ (Fig. 6). The surprising correlation between mass and accretion rate has profound implications for BD origins. The lack of any obvious shift in the correlation about the substellar limit implies a continuity in the formation processes of stars and BDs. This lends support to BD formation via fragmentation and collapse of low-mass cloud cores. However, the physical origins of accretion in young stellar objects need to be better understood before definitive conclusions can be made.

What is the source of the mass-accretion correlation? The general theory of viscously accreting disks does not predict a strong relation between these two quantities. The answer may lie in the essentially unknown source of viscosity needed to drive accretion. A commonly invoked mechanism is the Balbus-Hawley instability, which requires sufficient ionization of disk gas to effectively couple with magnetic fields. X-ray activity from the stellar magnetic field is a potential ionization source (*Glassgold et al.*, 2004); *Muzerolle et al.* (2003) suggested that the observed correlation $L_X \propto M_*^2$ (e.g., *Feigelson et al.*, 2003) may then be related to the similar dependence of accretion rate on mass. However, a comparison between L_X and $\dot{M}$ for the small number of objects for which both quantities have been measured reveals no statistically significant correlation, although the

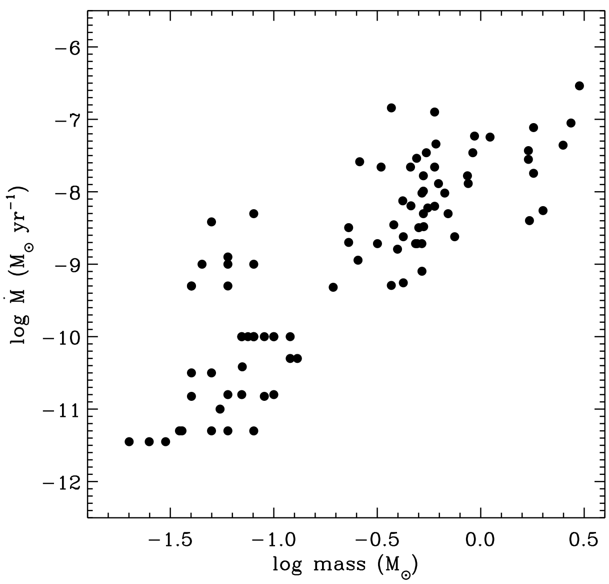

Fig. 6.— Mass accretion rate as a function of substellar and stellar mass for objects in Taurus (1 Myr), Cha I (2 Myr), IC 348 (2 Myr), and Ophiuchus (0.5 Myr) (*Gullbring et al.*, 1998; *White and Ghez*, 2001; *Muzerolle et al.*, 2000, 2003, 2005; *Natta et al.*, 2004; *Mohanty et al.*, 2005). These regions exhibit similar accretion rates at a given mass, except for slightly higher rates in Ophiuchus.

mass range covered is not very large. More observations of both quantities are needed; a particularly interesting analysis would be to compare accretion variability at the onset of and subsequent to an X-ray flare event.

More recently, *Padoan et al.* (2005) have proposed a modified Bondi-Hoyle accretion model in which young stars and BDs accrete primarily from the large-scale medium in which they are moving rather than from their disks alone. In this case, the accretion rate can be determined by the density and sound speed of the surrounding gas and the relative velocity between the object and that material. The resultant relation produces the correct mass dependence. However, it is not clear how a Bondi-Hoyle flow would interact with the disk. For instance, it may be incorporated into the disk prior to reaching the star; note that the observed accretion diagnostics are inconsistent with spherical infall onto the stellar surface. If so, the Bondi-Hoyle relation may in fact determine the rate of residual infall onto the disk, but not necessarily the rate of accretion onto the star, which is what is measured. In addition, the model cannot explain accretors located in low-density regions far from molecular clouds, such as the well-known CTTS TW Hydrae. Comparisons of mass accretion rates versus surrounding cloud temperatures and densities need to be made to further assess the applicability of this model.

5.3. Jets and Outflows

Many other similarities in accretion activity between stars and BDs have been found, including photometric and line profile variability (*Caballero et al.*, 2004; *Scholz and Eisloffel*, 2004, 2005; *Scholz et al.*, 2005), detections of H_2 emission in the UV (*Gizis et al.*, 2005), possible detections of UV continuum excesses (*McGehee et al.*, 2005), and evidence of accretion-generated outflows such as blueshifted absorption and forbidden emission (*Fernández and Comerón*, 2001; *Muzerolle et al.*, 2003; *Barrado y Navascués et al.*, 2004a; *Luhman*, 2004c; *Mohanty et al.*, 2005). Among the four accretors at M6 or later from *Muzerolle et al.* (2003), one shows forbidden line emission, while the two Class I objects at M6 from *White and Hillenbrand* (2004) show forbidden line emission. Based on small number statistics, jet signatures appear to be less often associated with accretion signatures for low-mass stars and BDs than for stars. However, this may stem from lower mass loss rates in substellar jets producing emission that is more difficult to detect (*Masciadri and Raga*, 2004). *White and Hillenbrand* (2004) found that the ratio of mass loss to mass accretion rate is the same for objects with both high and low mass accretion rates, though with considerable dispersion. Thus, the low accretion rates inferred for BDs likely correspond to diminished mass loss rates and less luminous forbidden line emission, possibly below typical detection levels. Overall, the sparse data on jets from young accreting BDs are similar to those of higher mass CTTSs, but on a smaller and less energetic scale.

In addition to the above indirect evidence for outflows provided by forbidden line emission, *Whelan et al.* (2005) and *Bourke et al.* (2005) have spatially resolved outflows toward ISO 102 in Ophiuchus (also known as GY 202) and L1014-IRS through optical forbidden lines and millimeter CO emission, respectively. Although *Whelan et al.* (2005) referred to ISO 102 as a BD, the combination of its M6 spectral type from *Natta et al.* (2002), the evolutionary models of *Chabrier et al.* (2000), and the temperature scale of *Luhman et al.* (2003b) suggest that it could have a stellar mass of $\sim 0.1\ M_{\odot}$. It appears likely that L1014-IRS has a substellar mass (*Young et al.*, 2004; *Huard et al.*, 2006), but this is difficult to confirm because of its highly embedded nature. The molecular outflow detected toward this object by *Bourke et al.* (2005) is one of the smallest known outflows in terms of its size, mass, and energetics.

6. CIRCUMSTELLAR DISKS

The collapse of a cloud core naturally produces a circumstellar disk via angular momentum conservation. Thus, understanding the formation of BDs requires close scrutiny of their circumstellar disks. In addition, as with stars, studying disks around BDs should provide insight into if and how planet formation occurs around these small bodies. In this section, we summarize our knowledge of disks around BDs and discuss the resulting implications for the origin of BDs, the evolution of their disks, and the formation of planets.

6.1. Detections of Disks

Although resolved images of disks around BDs are not yet available, there is mounting evidence for their existence through detections of IR emission above that expected from stellar photospheres alone. Modeling of the IR spectral energy distributions (SEDs) of young BDs showing excess emission strongly suggests that the emitting dust resides in disk configurations. For instance, *Pascucci et al.* (2003) considered different shell and disk geometries for a BD system in Taurus and demonstrated that spherically distributed dust with a mass estimated from the millimeter measurements (*Klein et al.*, 2003) would produce much more extinction than observed toward the BD. In comparison, when the same material is modeled as a disk, the SED can be well reproduced without conflicting with the observed low extinction.

Excess emission in the K and L bands has been observed for several young objects at M6-M8 and for a few as late as M8.5 (*Luhman*, 1999, 2004c; *Lada et al.*, 2000, 2004; *Muench et al.*, 2001; *Liu et al.*, 2003; *Jayawardhana et al.*, 2003a). Excesses at longer, mid-IR wavelengths have been detected for CFHT 4 (M7, *Pascucci et al.*, 2003; *Apai et al.*, 2004), Cha Hα 1 (M7.75, *Persi et al.*, 2000; *Comerón et al.*, 2000; *Natta and Testi*, 2001; *Sterzik et al.*, 2004), 2MASS 1207-3932 (M8, *Sterzik et al.*, 2004), GY141 (M8.5, *Comerón et al.*, 1998), and several late-type objects in Ophiuchus (*Testi et al.*, 2002; *Natta et al.*, 2002; *Mohanty et al.*, 2004). *Klein et al.* (2003) has extended these detections of circumstellar material to millimeter wavelengths for CFHT 4 and IC 348-613 (M8.25).

Because the Spitzer Space Telescope (*Werner et al.*, 2004) is far more sensitive beyond 3 μm than any other existing facility, it is capable of detecting disks for BDs at very low masses. To search for circumstellar disks around BDs at the lowest possible masses, *Luhman et al.* (2005b) obtained mid-IR images (3.6-8 μm) of the Chamaeleon I star-forming region with the Infrared Array Camera (IRAC, *Fazio et al.*, 2004) on Spitzer. In these data, they detected mid-IR excess emission from the coolest and least massive known BD in the cluster, OTS 44 (*Oasa et al.*, 1999), which has a spectral type of $\gtrsim$M9.5 and a mass of $M \sim 15\ M_{\rm Jup}$ (*Luhman et al.*, 2004). By obtaining even deeper IRAC images of Chamaeleon I and combining them with optical and near-IR images from the Hubble Space Telescope and the CTIO 4 m, *Luhman et al.* (2005e) discovered a BD that is twice as faint as OTS 44 and exhibits mid-IR excess emission. By comparing the bolometric luminosity of this object, Cha 1109-7734, to the luminosities predicted by the evolutionary models of *Chabrier et al.* (2000) and *Burrows et al.* (1997), *Luhman et al.* (2005e) estimated a mass of $8^{+7}_{-3}\ M_{\rm Jup}$, placing it within the mass range observed for extrasolar planetary companions ($M \lesssim 15\ M_{\rm Jup}$, *Marcy et al.*, 2005). *Luhman et al.* (2005e) successfully modeled the mid-IR excess emission for Cha 1109-7734 in terms of an irradiated viscous accretion disk with $\dot{M} \lesssim 10^{-12}$ M$_\odot$ yr^{-1}, as shown in Fig. 7, making it the least massive BD observed to have a circumstellar disk and demonstrating that the basic ingredients for making planets are present around free-floating planetary-mass bodies.

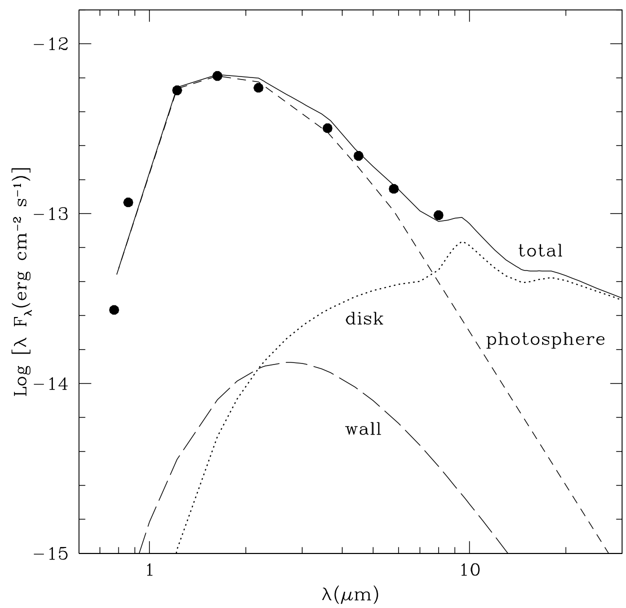

Fig. 7.— SED of the least massive BD known to harbor a disk, Cha 1109-7734 (*points*, *Luhman et al.*, 2005e). Relative to the distribution expected for its photosphere (~M9.5, *short dashed line*), this BD exhibits significant excess emission at wavelengths longer than 5 μm. The excess flux is modeled in terms of emission from a circumstellar accretion disk (*dotted line*) and a vertical wall at the inner disk edge (*long dashed line*). The sum of this disk model and the photosphere (*solid line*) is a reasonable match to the data for Cha 1109-7734.

6.2. Disk Fractions and Lifetimes

Extensive work has been done in measuring disk fractions for stars (e.g., *Kenyon and Hartmann*, 1995; *Hillenbrand et al.*, 1998; *Haisch et al.*, 2001), which typically consists of IR photometry of a significant fraction of a young stellar population and identification of the objects with excess emission. Attempts have been made to extend measurements of this kind to low-mass stars and BDs. Using $JHKL'$ photometry, *Jayawardhana et al.* (2003a) searched for excess emission among 53 objects in IC 348, Taurus, σ Ori, Chamaeleon I, the TW Hya association, Upper Scorpius, and Ophiuchus, 27 of which are later than M6 and thus likely to be substellar. For the individual populations, the disk fractions for the stars and BDs exhibited large statistical errors of $\sim$ 25%. For a sample combining Chamaeleon I, IC 348, Taurus, and U Sco, the number statistics were better, and *Jayawardhana et al.* (2003a) found a disk fraction of 40-60%. Their disk/no disk classifications agreed well with those based on the Spitzer data from *Luhman et al.* (2005d) for types of $\leq$M6. However, the two objects later than M6 in IC 348 and Chamaeleon I that were reported to have disks by *Jayawardhana et al.* (2003a) show no excess emission in the Spitzer colors. *Liu et al.* (2003) also performed an L'-band survey of low-mass objects. They considered a sample of 7 and 32 late-type members of Taurus and IC 348, respectively, 12 of which have optical spectral types later than M6. For their entire sample of low-mass stars and BDs, *Liu et al.* (2003) found a disk fraction of $77 \pm 15\%$, which is a factor of two larger than measurements for IC 348 from Spitzer (*Luhman et al.*, 2005d). 9/10 objects with $E(K - L') > 0.2$ in the data from *Liu et al.* (2003) did exhibit significant excesses in the Spitzer colors, but the putative detections of disks with smaller L' excesses were not confirmed by Spitzer. Any bona fide detection of a disk at L' would be easily verified with Spitzer given that the contrast of a disk relative to the central object increases with longer wavelengths.

Because disks around BDs produce little L'-band emission compared to stellar systems, the L'-band surveys were not able to reliably detect BD disks. Meanwhile, BD disk excesses are larger at longer wavelengths, but measurements of this kind are feasible for only a small number of the brighter, more massive objects with most telescopes. In comparison, because Spitzer is highly sensitive and can survey large areas of sky, it can reliably and efficiently detect disks for BDs at very low masses and for large numbers of BDs in young clusters. *Luhman et al.* (2005d) used IRAC on Spitzer to obtain mid-IR images of IC 348 and Chamaeleon I, which encompassed 25 and 18 spectroscopically confirmed low-mass members of the clusters, respectively (>M6, $M \lesssim 0.08\ M_\odot$). They found that $42 \pm 13\%$ and $50 \pm 17\%$ of the two samples exhibit excess emission indicative of circumstellar disks. In comparison, the disk fractions for stellar members of these clusters are $33 \pm 4\%$ and $45 \pm 7\%$ (M0-M6, $0.7\ M_\odot \gtrsim M \gtrsim 0.1\ M_\odot$). The similarity of the disk fractions of stars and BDs indicates that the raw materials for planet formation are available around BDs as often as around stars and supports the notion that stars and BDs share a common formation history. However, as with the continuity of accretion rates from stars to BDs from Section 5.2, these results do not completely exclude some scenarios in which BDs form through a distinct mechanism. For instance, during formation through embryo ejection, the inner regions of disks that emit at mid-IR wavelengths could survive, although one might expect these truncated disks to have shorter lifetimes than those around stars.

When disk fractions for stellar populations across a range of ages (0.5-30 Myr) are compared, they indicate that the inner disks around stars have lifetimes of $\sim$ 6 Myr (*Haisch et al.*, 2001). Accurate measurements of disk fractions for BDs are available only for IC 348 and Chamaeleon I, both of which have ages near 2 Myr, and so a comparable estimate of the disk lifetime for BDs is not currently possible. However, the presence of a disk around a BD in the TW Hya association (*Mohanty et al.*, 2003; *Sterzik et al.*, 2004), which has an age of 10 Myr, does suggest that the lifetime of BD disks might be similar to that of stars.

6.3. Disk Mass

A few estimates of dust masses of disks around BDs have been obtained through deep single-dish millimeter observations. In a survey of 9 young BDs and 10 field BDs, *Klein et al.* (2003) detected disks around two of the young objects. Because the millimeter emission is optically thin, fluxes could be converted to total disk masses assuming dust emission coefficients typical to disks for low-mass stars and the standard gas-to-dust mass ratio of 100. They derived disk masses of 0.4-6 $M_{\rm Jup}$, which are a few percent of the BD masses, thus suggesting that disk masses scale with the mass of the central object down to the substellar regime. Similar measurements for larger samples of low-mass stars and BDs are needed to confirm such a trend.

6.4. Disk Geometry

Various theoretical studies have shown that the disk geometry strongly impacts the SED and have investigated the link between disk geometry and dust evolution (e.g., *Dullemond and Dominik*, 2005). Flared disks are those with opening angles increasing with the disk radius as a consequence of vertical hydrostatic equilibrium (*Kenyon and Hartmann*, 1987). Such geometry characterizes the early phases of the disk evolution prior to dust processing (grain growth and dust settling, see also the chapter by *Natta et al.*). Flatter disk geometries supposedly represent the evolutionary stage after flared disks (see also the chapter by *Dullemond et al.*). Because flared disks intercept more stellar radiation than flat ones, especially at large distances from the star, flared disks produce larger mid- and far-IR fluxes and a more prominent silicate emission feature than flat ones (e.g., *Chiang and Goldreich*, 1997). *Walker et al.* (2004) calculated that, under the assumption of vertical hydrostatic equilibrium, BD disks should be highly flared with disk scale heights three times larger than those derived for disks around CTTSs.

The work by *Natta and Testi* (2001) represents the first attempt to investigate the geometry of disks around low-mass objects. The authors used scaled-down T Tauri disks to reproduce ISO mid-IR measurements of two low-mass stars (Cha Hα 2 and 9, M5.25 and M5.5) and one BD (Cha Hα 1, M7.75) in the Chamaeleon I star-forming region. They considered passive flared and flat disks and made a number of simplifying assumptions following the method of *Chiang and Goldreich* (1997, 1999). Passive disks are appropriate for BDs because of their very low accretion rates (Section 5.2). They concluded that models of flared disks were required to fit the SEDs of these three objects. A similar approach was used by the authors to investigate a larger sample of nine low-mass stars and BDs in the Ophiuchus star-forming region (*Testi et al.*, 2002; *Natta et al.*, 2002). A more careful inspection of the flared

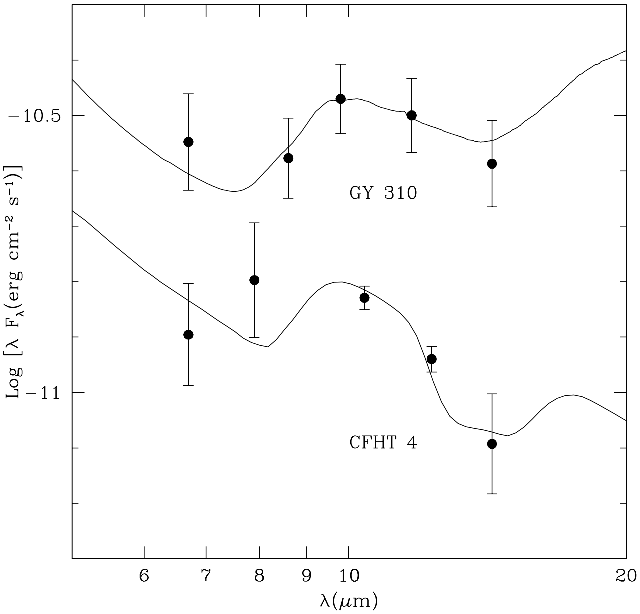

Fig. 8.— Comparison of geometries for two BD disks. The best model fit for GY 310 consists of a flared disk with dust dominated by small sub-micron grains (*Mohanty et al.*, 2004). A good match to the SED of CFHT 4 can be achieved with a disk model with a little flaring and micron-sized grains (*Apai et al.*, 2004). The SED of GY 310 has been shifted up by 0.5 dex.

and flat disk predictions revealed that two ISOCAM broadband measurements were not always sufficient to determine the disk geometry. *Apai et al.* (2002) used ground-based mid-IR narrowband photometry to probe the silicate emission feature in the disk of Cha Hα 2 and thus add an important new constraint to the disk models from *Natta and Testi* (2001). Their measurements ruled out the presence of strong silicate emission that was predicted by *Natta and Testi* (2001) and found that a flatter disk structure was required to fit the observed SED.

Recent ground- and space-based measurements have provided more comprehensive SEDs for about a dozen low-mass stars and BDs (*Pascucci et al.*, 2003; *Mohanty et al.*, 2004; *Apai et al.*, 2004; *Sterzik et al.*, 2004; *Furlan et al.*, 2005a; *Hartmann et al.*, 2005; *Muzerolle et al.*, 2006; *Pascucci et al.*, in preparation). The modeling of these disks shows that flared, flat and intermediate flaring geometries all occur in BD disks (see Fig. 8). A similar trend is found for disks around more massive stars (e.g., *Furlan et al.*, 2005b). As with studies of disks at stellar masses, samples of BD disks from a greater variety of ages and star-forming conditions are needed to distinguish between the effects of evolution and environment on disk structure.

6.5. Dust Processing

Grain growth and dust settling are thought to represent the first steps of planet formation (e.g., *Henning et al.*, 2006). Studies of disks around intermediate-mass stars also indicate a possible link between grain growth and crystallinity, with high crystallinity measured in disks having grains larger than the dominant sub-micron interstellar grains (e.g., *van Boekel et al.*, 2005). Determining whether BD disks evolve into planetary systems requires first identifying the presence of such dust processing. Because dust settling is related to the disk geometry, some evidence of dust processing can be gained by the kind of SED modeling described in the previous section. For instance, *Mohanty et al.* (2004) concluded that the SED of a young BD in Ophiuchus, GY 310, was consistent with a flared disk geometry and small interstellar grains, while *Apai et al.* (2004) found that the SED of CFHT 4 was indicative of a flat disk structure (Fig. 8). The latter authors also found that the peak position of the silicate emission feature and the line-to-continuum flux ratio demonstrated that the emission was dominated by grains about 10 times larger than the dominant 0.1 μm interstellar grains. Fitting the emission and the overall continuum required a disk with intermediate flaring. This work indicated that young BD disks process dust in a similar fashion as disks around stars (e.g., *Przygodda et al.*, 2003).

The recent Spitzer spectroscopy of disks around low-mass stars and BDs has confirmed the results from the SED modeling. Most of the spectra show a silicate emission feature broader than that from the interstellar medium and peaks that are indicative of crystalline grains (see Fig. 9). *Furlan et al.* (2005a) found that the disk model of V410 Anon 13 also required a reduced gas-to-dust ratio, which was suggestive of some settling. A quantitative analysis of the dust composition of disks in Chamaeleon I reveals large grains and high crystallinity mass fractions ($\sim$40%) for the majority of the sources (*Apai et al.*, 2005). In addition, most of the SEDs are consistent with flatter disk structures than those predicted by vertical hydrostatic equilibrium. These results demonstrate that dust processing is largely independent of stellar properties and mainly determined by local processes in the disk.

6.6. Planet Formation

The identification of grain growth, crystallization, and dust settling in BD disks indicate that the first steps leading to planet formation occur in disks around BDs. In fact, there now appears to be tantalizing evidence for planet formation at a more advanced stage around a low-mass object in IC 348, source 316 from *Luhman et al.* (2003b). This object has a spectral type of M6.5, indicating a mass near the hydrogen burning mass limit, and no strong signature of accretion based on its small Hα equivalent width. Spitzer photometry has revealed strong excess emission at 24 μm, indicating a substantial disk (Fig. 10). Interestingly, no excess emission is seen at wavelengths shortward of 8 μm, strongly suggesting the presence of an inner hole in the disk that is cleared of at least small dust grains. Disk models of the SED require an inner hole size of 0.5-1 AU to fit the

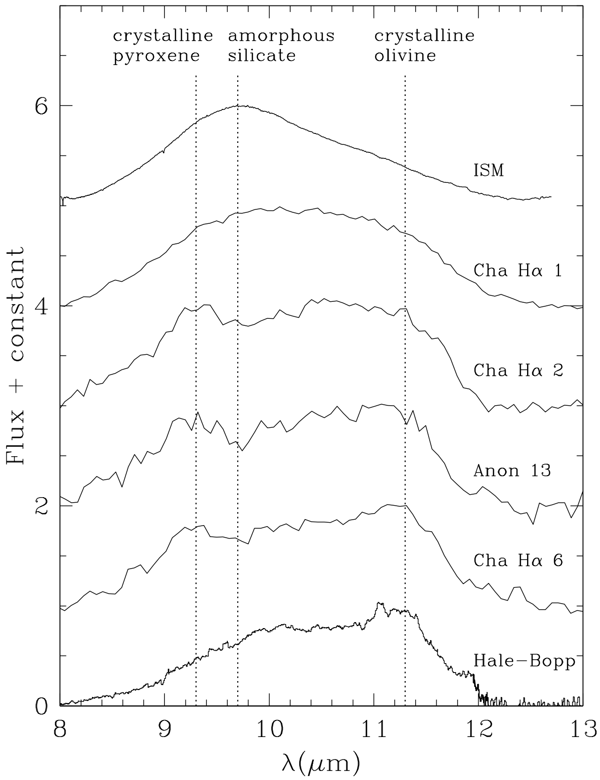

Fig. 9.— Spitzer spectra of disks around low-mass stars and BDs (*Furlan et al.*, 2005a; *Apai et al.*, 2005). The spectra have been continuum-subtracted and normalized to the peak emission in the range between 7.6 and 13.5 μm. For comparison we show the spectra of the amorphous silicate-dominated interstellar medium and the crystalline-rich comet Hale-Bopp.

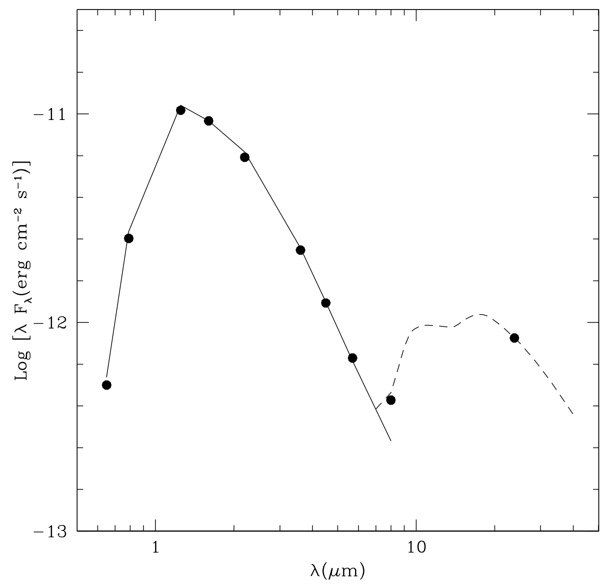

Fig. 10.— SED of an object near the hydrogen burning limit in IC 348 (*points, Muzerolle et al.*, 2005) compared to the median SED of late-type members of IC 348 that lack IR excess emission (*solid line, Lada et al.*, 2006). This object exhibits excess emission only at $\lambda \geq 8$ μm, which has been fit with a model of a disk with an inner hole (*dashed line*).

observations (*Muzerolle et al.*, 2006). IC 348-316 is thus the first low-mass object known to possess significant inner disk clearing akin to that seen in higher-mass CTTSs such as CoKu Tau/4 (*D'Alessio et al.*, 2005). The origin of this clearing is a matter of considerable debate. *Muzerolle et al.* (2006) ruled out the photoevaporation model, in which a photoevaporative wind generated by UV radiation from the central object can remove material from the inner disk (e.g., *Clarke et al.*, 2001), because the mass loss timescale is much longer than the age of IC 348-316 (1-3 Myr) given plausible UV flux from an accretion shock or chromosphere. Other possibilities include inside-out dust coagulation into meter or kilometer-sized planetesimals, or the rapid formation of a single planet which is preventing further accretion from the outer disk. For the latter scenario, *Muzerolle et al.* (2006) estimated a plausible mass range of $M_p \sim 2.5 - 25$ $M_\oplus$. This type of SED analysis is not conclusive proof of the presence of a planetary companion, but nevertheless it strongly suggest that the same steps to planet formation interpreted from observations of disks around stars are also possible in disks around BDs. Higher resolution data for IC 348-316 through Spitzer spectroscopy should better constrain the nature of its inner disk hole.

7. Summary

We summarize the current observations of BDs that are relevant to their formation as follows:

1. The least massive known free-floating BDs have masses of ~ 10 $M_{\rm Jup}$. No conclusive measurement of the minimum mass of BDs is yet available.

2. Stars outnumber BDs at 20-80 $M_{\rm Jup}$ by a factor of $\sim$ 5-8 in star-forming regions. This ratio is consistent with data for BDs in the solar neighborhood, although the larger uncertainties in the field data allow for modest differences from star-forming regions (factor of a few).

3. Stars and BDs share similar velocity and spatial distributions in the available data for star-forming regions.

4. In the original BD desert observed at separations less than 3 AU from solar-type primaries, BD companions are less common than stellar companions by a factor of $\sim$ 100. BDs are outnumbered by stars at larger separations as well, but the size of the deficiency ($\sim$ 3-10) is smaller than at close separations, and is consistent with the deficiency of BDs among isolated objects ($\sim$ 5-8). These data suggest that

wider stellar and substellar companions form in the same manner as their free-floating counterparts, and that a true BD desert for solar-type stars is restricted to small separations.

5. For both star-forming regions and the solar neighborhood, binary fractions decrease continuously with mass from stars to BDs and most binary BDs have small separations, although a few wide systems do exist.

6. Accretion rates decrease continuously with mass from stars to BDs (as $\dot{M} \propto M^2$).

7. Circumstellar disks have been found around BDs with masses as low as $\sim 10\ M_{\rm Jup}$.

8. The disk fraction of BDs is similar to that of stars at ages of a few million years. BDs also appear to have similar disk lifetimes, although a definitive statement is not possible with available data.

9. Disks around BDs exhibit a range of geometries from flat to flared, and some of these disks experience grain growth and settling and may develop inner holes, which are possible signatures of planet formation. All of these characteristics are also found among disks around stars.

All of these data are consistent with a common formation mechanism for BDs and stars. In particular, the existence of widely separated binary BDs and a likely isolated proto-BD (*Young et al.*, 2004; *Bourke et al.*, 2005; *Huard et al.*, 2006) indicate that some BDs are able to form in the same manner as stars through unperturbed cloud fragmentation. It remains possible that additional mechanisms such as ejection and photoevaporation influence the birth of some BDs, just as they likely do with stars. However, it appears that they are not essential ingredients in making it possible for these small bodies to form.

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