Disks around Brown Dwarfs and Cool Stars

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Abstract. We review the current picture of disks around cool stars and brown dwarfs, including disk fractions, mass estimates, disk structure and dispersal, accretion, dust composition, the debris disk phase. We discuss these in the framework of recent planet formation models.

The study of disks around brown dwarfs and cool stars allows testing disk physics and planet formation processes in a parameter range vastly different from those characteristic to the vicinity of Sun–like stars. This chapter provides a concise summary of seven reviews presented in the splinter session ”Disks around Cool Stars and Brown Dwarfs” that placed the most recent results into an evolutionary picture.

1. Disk Fractions and Disk Lifetimes

Disk fractions for young stars are measured through IR photometry of young clusters, and these data are used to identify the stars that have long wavelength excess emission that is indicative of disks. Combining disk fractions for populations across a range of ages then provides an estimate of the average disk lifetime. Because the Spitzer Space Telescope is highly sensitive and can quickly image young clusters, it can reliably and efficiently detect disks for brown dwarfs at very low masses and for large numbers of brown dwarfs. For instance, Luhman et al. (2005) 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 < 0.08 M⊙). They found that 42±13% and 50±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 ± 4% and 45 ± 7% (M0-M6, 0.7 M⊙ > M > 0.1 M⊙). The similarity of the disk fractions of stars and brown dwarfs indicates that the raw materials for planet formation are available around brown dwarfs as often
as around stars and supports the notion that stars and brown dwarfs share a common formation history. However, as with the continuity of accretion rates from stars to brown dwarfs, these results do not completely exclude some scenarios in which brown dwarfs 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 (Hillenbrand et al. 1998; Haisch et al. 2001). The most accurate measurements of disk fractions for brown dwarfs are for IC 348 and Chamaeleon I, both of which have ages near 2 Myr, and so a comparable estimate of the disk lifetime for brown dwarfs is not currently possible. However, the presence of a disk around a brown dwarf 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 brown dwarf disks might be at least as long as that of stars. In fact, a preliminary measurement of the disk fraction of low-mass members of Upper Scorpius (5 Myr) is similar to that found in IC 348 and Chamaeleon I (Bouy et al. 2007), whereas the disk fraction of stars is significantly lower in Upper Scorpius than in IC 348 (Lada et al. 2006; Carpenter et al. 2006). Thus, disk lifetimes may be longer around brown dwarfs than stars. Photometry and spectroscopy of a much larger number of low-mass members of Upper Scorpius is currently ongoing with the Spitzer Space Telescope, which should more definitively address this issue.

2. Accretion in Substellar Disks

The first detection of accretion in an object near the hydrogen burning limit was presented by Muzerolle et al. (2000) for V410 Anon 13 in Taurus (Briceno et al. 2002). The Hα profile for this object exhibited an infall asymmetry indicating ballistic infall at velocities consistent with the object’s mass and radius. Modeling of the profile yielded \( \dot{M} \sim 5 \times 10^{-12} \, \text{M}_\odot \, \text{yr}^{-1} \), much smaller than the average rate of \( \sim 10^{-8} \, \text{M}_\odot \, \text{yr}^{-1} \) for solar-mass T Tauri stars (Gullbring et al. 1998). Since the work on V410 Anon 13, dozens of substellar accretors have been identified down to masses approaching the deuterium burning limit and with ages from 1 to 10 Myr (e.g., Jayawardhana et al. 2003; Mohanty et al. 2005; Muzerolle et al. 2003, 2005), allowing systematic studies of the accretion properties from stellar to substellar masses. Estimates of \( \dot{M} \) based on line profile modeling decrease with mass down to \( \dot{M} \sim 0.02 \, \text{M}_\odot \) with a functional form of \( \dot{M} \propto M^2 \) (Muzerolle et al. 2003, 2005, Fig. 1). The continuity of this correlation across the substellar limit supports the idea that brown dwarfs form via fragmentation and collapse of cloud cores in the same manner as stars.

3. Disk Structure and Mineralogy

Flared disks (opening angle increasing with the disk radius) have been successful in explaining the infrared spectral energy distributions (SEDs) of disks around
intermediate–mass stars and many sun–like stars (e.g. Kenyon & Hartmann 1987). Mid–infrared studies of disks around brown dwarfs, however, may suggest a somewhat different picture. Disk models constrained by accurate ground–based mid–infrared and sub–millimeter observations (e.g. Natta et al. 2002, Apai et al. 2002, Pascucci et al. 2003, Apai et al. 2004, Mohanty et al. 2004, Sterzik et al. 2004, Apai et al. 2005, Scholz et al. 2006) found that flat or mildly flared disks often provide better fits to the data than flared disks. This reduced flaring may be the result of the larger dust grains settling toward the disk mid–plane, a possible first step toward planet formation (e.g. Apai et al. 2005, Scholz et al. 2006).

The 10 μm–window also offers a potential to probe the dust properties: The strength and shape of the silicate emission bands is characteristic to the size, chemical composition and lattice structure of the material. Broad–band photometry of the 10 μm silicate feature showed weak or absent silicate emission feature around six brown dwarfs, including 1–4 Myr–old Cha I members, ρ Oph and Taurus members (Apai et al. 2002, 2004; Mohanty et al. 2004) and the 8 Myr–old TW Hy group member 2M1207 (Sterzik et al. 2004). These observations showed that the optically thin upper layers of these disks are often lacking sub–micron sized amorphous silicate grains, a major component of the interstellar medium. The absence of these grains suggested dust processing through collisional evolution.

Recently, Spitzer spectroscopy has been providing a new, detailed picture on the silicate emission feature for an increasing number of disks around cool stars. Crystalline emission features has been identified by several groups (e.g. Forrest et al. 2004; Furlan et al. 2005; Apai et al. 2005; Kessler-Silacci et al. 2006). In a large sample of disks Kessler-Silacci et al. (2006) found an

Figure 1. 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 & 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.
anti–correlation between the feature strength and the spectral type of the stars, suggesting larger silicate grains around lower–mass stars. In a comparative, quantitative dust composition study of Herbig Ae/Be, T Tauri and brown dwarf disks Apai et al. (2005) found that the crystalline mass fraction of the micron–sized dust particles is higher around cooler central stars. Both these studies suggest that the observed dust is more processed around lower–mass stars than around higher–mass stars. However, as pointed out in Apai et al. (2005) and Kessler-Silacci et al. (2006) the mid–infrared observations probe different radii around stars with different luminosity. Nevertheless, larger disk samples and an extended wavelength range will allow in the near–future quantitative comparisons of the dust processing and help identify the role of radial mixing, stellar luminosity, and disk structure in dust evolution.

4. Disk Masses

The mass of circumstellar disks is one of the key parameters determining their potential to form planetary systems. Disk mass measurements require detecting the dust emission at optically thin wavelengths, a major observational challenge for the tenuous disks around cool stars and brown dwarfs. A second obstacle is the set of untested assumptions necessary to convert the dust emission to total disk mass. Nevertheless, the first surveys of disks around brown dwarfs demonstrated the observational feasibility of these studies providing the first insights on how disk mass scales with stellar mass.

Using a combined sub–millimeter and millimeter survey Klein et al. (2003) carried out the first systematic search for optically thin dust emission from brown dwarf disks. The age of the targets spread from 1–4 Myr–old disks in the Taurus star–forming region through the Pleiades (~100 Myr) to older brown dwarfs in the Solar neighborhood that may harbor debris disks. This survey has identified sub–millimeter emission from two young disks, allowing disk mass estimates and powerful constraints for the disk models.

Recently, Scholz et al. (2006) carried out a sub–millimeter survey in the Taurus star–forming region. This large and sensitive study covered 20 young brown dwarfs and identified five new possible detections of millimeter emission from circumstellar dust. Using standard assumptions, Scholz et al. (2006) derived probable disk masses ranging from 0.3 to 6.8 $M_{\text{Jup}}$. The authors argue that these disk masses are difficult to explain with truncated disks, predicted to surround brown dwarfs ejected early from their accreting envelope.

Our current understanding of disk masses is severely limited by four factors: 1) the very small number of firm millimeter disk detections; 2) the uncertain dust opacities; 3) the grain size distribution that may vary from disk to disk; and, 4) the gas–to–dust mass ratio, canonically assumed to be 100. In addition, the interpretation of the data is further complicated from the strong bias introduced by the flux limits imposed by the sensitivity of the current detector technology. In spite of these uncertainties, the current data set — assuming that the typical dust properties are independent of the stellar mass — is consistent with a disk mass/star mass ratio that is similar (few percent) over a large range of stellar masses, from intermediate–mass stars through young Sun–like stars to the substellar regime. The new generation of sub–millimeter receiver arrays will
bring a marked improvement in the sample size and the sensitivity of the observations. However, the other three factors represent a serious limitation to our understanding of disk masses and may account for non-systematic uncertainties of two orders of magnitude.

5. Transition Disks around Cool Stars

Disk dispersal sets the time available for planet formation and thus understanding this process is essential for understanding disk evolution and planet formation. Disks around very low-mass stars offer a very different parameter set to study these processes. While the disk fraction studies discussed previously measure the median disk lifetime and its dispersion, the study of a few individual objects in the phase of dispersing their disks — transition disks — provide import insights on the mechanisms in work. Transition disks have been identified around a dozen young Sun–like stars and low–mass stars (e.g. Calvet et al. 2002). These disks display a partly or fully evacuated inner cavity, outside of which they harbor an optically thick dust disk. Several mechanisms have been invoked to account for the observed inner disk clearing, including UV–photoevaporation, dynamical clearing via gravitational interactions with a forming giant planet, or grain growth beyond tens of micron size in the inner disk.

The recent discovery of a transition disk around a brown dwarf in the star–forming region IC 348 (Muzerolle et al. 2006) demonstrated that inner disk clearing is a common phenomenon around a very broad range of stars. Using SED models Muzerolle et al. (2006) estimated the inner disk hole size to be 0.5–1 AU, much larger than what could be explained by magnetospheric truncation or dust sublimation alone. The photoevaporation models critically depend on the UV flux, which may originate from the chromosphere or the accretion shocks. As Muzerolle et al. points out the UV flux expected around brown dwarfs is most likely too low to account for the dispersal of the inner disk within the observed few Myr. Most recently, Spitzer IRS spectrum of this brown dwarf disk showed some silicate emission feature, which would argue against dust evolution as the cause of the disk dispersal. Another, possibly viable option is the gravitational influence of a forming super–Earth or giant planet; such a planet would have needed to form on time scales less than a few Myr, the age of the IC 348 cluster.

Sensitive Spitzer Space Telescope surveys are further increasing the number of known transition disks around brown dwarfs. By pinpointing the mechanisms responsible for clearing out individual disks for a large sample and comparing them to transition disks around more massive stars Spitzer is expected to provide a deeper understanding of the disk dispersal process.

6. Planet Formation around Cool Stars

The recent exoplanet discoveries suggest that although exoplanetary systems are frequent around M–dwarfs, their architecture differs from those around F, G, and K–type stars. Overall, preliminary statistics suggests that gas giant planets in the inner planetary systems are ~ 3× less common than around Sun–like stars (e.g., Butler et al. 2006). The discovery of two Neptune–mass exoplanets (GJ
three Jupiter–mass planets (GJ 849; two in the GJ 876 system, e.g. Butler et al. 2006) and recently two probable "super–Earths" (e.g., Beaulieu et al. 2006) poses several theoretical challenges.

Laughlin et al. (2004) pointed out that the lower disk mass and longer orbital periods around low–mass stars prolong the core accretion time beyond the typical disk lifetimes. This effect suppresses the efficiency of gas giant formation around M–dwarfs, also confirmed by the more realistic simulations by Ida & Lin (2005), which also include the decreased accretion of gap opening–planets and subsequent orbital migration. They find that while Jupiter–mass planets will be less frequent around M–dwarfs, a second peak corresponding to isolated, close–in Neptune–mass planets will be more pronounced than around Sun–like stars. Kennedy, Kenyon & Bromley (2006) points out that the snowline – that separates rocky and icy planetesimals – moves inward throughout the pre–main sequence evolution of the low–mass star, which effect will even further enhance the frequency of close–in super–Earths.

An alternative, competing mechanism to explain planet formation is gravitational instability in a marginally unstable disk. Boss (2006a) showed that such disks – even when orbiting M–dwarf stars – undergo rapid spiral arm formation, followed by the formation of massive clumps. Although the current simulations are unable to trace the clumps for time scales comparable to the lifetime of the disk, several arguments suggest that the clumps became self–gravitating and will undergo collapse. These simulations demonstrate that gravitationally unstable disks may be able to form gas giant planets with 4–7 AU semi–major axes, in contrast to the core accretion scenario. Boss (2006b) suggests that such unstable disks, when formed in high–mass, dense stellar clusters, are likely to be exposed to EUV/FUV irradiation that may quickly erode the contracting protoplanetary atmospheres. This mechanism may explain the existence of Uranus– and Neptune–like exoplanets at larger radii.

The predictions of the core accretion and gravitational instability models differ for low–mass stars and likely even more for brown dwarfs. The expanding period coverage of the ongoing RV–searches and the increasing number of planets detected via microlensing and transit surveys will directly test the predictions of the different planet formation models in the very near future.

7. Debris Disks around Cool Stars

After dissipation of their primordial planet-forming disks of gas and dust, many stars possess debris disks (Backman & Paresce 1993). The dust in debris disks is continually generated from collisions of larger bodies (comets and asteroids) that are otherwise undetectable. Debris disks represent the extrasolar analogs of the asteroid belt and Kuiper Belt in our own solar system.

Ground- and space-based photometric studies have identified over a hundred debris disks around AFGK-type dwarfs from their thermal dust emission (e.g., Zuckerman 2001), Greaves & Wyatt 2003, Beichman et al. 2005, Rhee et al. 2006). However, little is known about debris disks around M dwarfs, as only a handful of examples have been found from integrated-light searches (e.g., Song et al. 2002, Liu et al. 2004, Low et al. 2005, Lestrade et al. 2006). Past debris-disk searches have mostly neglected and/or overlooked low-mass stars, largely due to
sensitivity limitations. M dwarfs have $>10–1000\times$ lower luminosities compared to other (AFGK-type) debris disk host stars, and thus the thermal continuum emission from circumstellar dust is expected to be significantly fainter. (In a similar fashion, one would expect that the thermal emission of debris disks around brown dwarfs will be even more difficult to detect, if such objects exist.) For instance, IRAS could only detect the photospheres of a handful of nearby M dwarfs at 60 $\mu$m. In addition, stellar winds from M dwarfs might rapidly remove circumstellar dust, leading to much smaller IR excesses compared to higher mass stars (Plavchan et al. 2005).

The potential value of these systems is demonstrated by the young ($\approx 12$ Myr) star AU Mic, the first robustly identified M dwarf debris disk system (Song et al. 2002, Liu et al. 2004). At a distance of only 10 pc, its disk is seen in scattered light as far as 20$''$ in radius (Kalas, Liu & Matthews 2004). Adaptive optics and HST imaging of the AU Mic disk achieves a spatial resolution as good as 0.4 AU (Liu 2004, Krist et al. 2005, Metchev et al. 2005, Graham et al. 2007). A rich variety of substructure is observed, including multiple clumps and a large-scale warp, and is suggestive of planetary companions. The overall disk surface brightness profile follows a broken power-law, with a relatively shallow slope inside of $\approx 40$ AU and a much steeper slope at larger distances; this can be attributed to the combined dynamical effects of drag forces (from the Poynting-Robertson effect and stellar winds) and radiation pressure blowout of small grains (Augereau & Beust 2006, Strubbe & Chiang 2006).

Thanks to its proximity to Earth and its status as the first large scattered-light disk (in angular extent) found since the discovery of the $\beta$ Pic disk more than 20 years ago, the AU Mic disk has been the subject of intense recent study, with more than a dozen refereed papers since its discovery. Indeed, the AU Mic disk bears a striking degree of similarity to the $\beta$ Pic disk in its properties and features; given that these two systems are both members of the $\beta$ Pic moving group, the common age and birth environment of the two stars provides a means to study the degree of synchronicity (or divergence) in disk evolution (e.g. Liu 2004). However, thus far AU Mic is the singular example of a resolved debris disk around a low-mass star. Ongoing searches with space-based and ground-based facilities (e.g., Spitzer, AKARI, JCMT/SCUBA-2, and Herschel) offer the opportunity to find more such systems amenable to scrutiny.

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