NEW BROWN DWARF DISKS IN THE TW HYDRAE ASSOCIATION

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ABSTRACT

In our analysis of Spitzer IRS archival data on the stellar and substellar members of the TW Hydrae association (TWA), we have discovered two new brown dwarf disks: a flat, optically thick disk around SSSPM J1102−3431 (SSSPM 1102) and a transition disk around 2MASS J11395111−315921 (2M1139). The disk structure for SSSPM 1102 is found to be very similar to the known brown dwarf disk 2MASSW J1207334−393254 (2M1207), with excess emission observed at wavelengths as short as 5 μm. No excess emission shortward of ~20 μm is seen from 2M1139, but it flares up at longer wavelengths and is the first transition disk detected among the substellar members of the TWA. We also report on Spitzer 70 μm observations and the presence of a 10 μm silicate absorption feature for 2M1207. The absorption can be attributed to a nearly edge-on disk, at 75° inclination. The 10 μm spectrum for 2M1207 shows crystalline forsterite features, with a peak in absorption near 11.3 μm. No silicate absorption or emission is observed toward SSSPM 1102. While only six of 25 stellar members show excess emission at these mid-infrared wavelengths, all of the TWA brown dwarfs that have been observed so far with Spitzer show signs of disks around them, resulting in a disk fraction of at least 60%. This is a considerable fraction at the relatively old age of ~10 Myr. A comparison with younger clusters indicates that by the age of the TWA (~10 Myr), the disk fraction for brown dwarfs has not decreased, whereas it drops by a factor of ~2 for the higher mass stars. This suggests longer disk decay timescales for brown dwarfs as compared with higher mass stars.

Subject headings: accretion, accretion disks — circumstellar matter — stars: individual (2MASSW J1207334−393254, 2MASS J11395111−315921, SSSPM J1102−3431) — stars: low-mass, brown dwarfs

Online material: color figures

1. INTRODUCTION

A large number of substellar-mass objects have been discovered over the last decade, with masses ranging from the hydrogen burning limit (<0.075 M_⊙) down to the mass of giant planets and below the deuterium burning limit (<0.013 M_⊙). Recent surveys in the near- and mid-infrared have confirmed the presence of disks around brown dwarfs (e.g., Muench et al. 2001; Liu et al. 2003; Apai et al. 2004; Luhman et al. 2005) and indicate a range in disk properties, similar to T Tauri disks. A detailed study of brown dwarf disks is important to understanding the conditions under which planets can form in these disks. Processes that may lead to planet formation such as grain growth, crystallization, and dust settling have been reported for some brown dwarfs (e.g., Apai et al. 2005), suggesting that even substellar disks of a few Jupiter masses can harbor planets. It is important to determine the disk dissipation timescales for brown dwarfs, which in turn would place constraints on the timescale for the formation of planetary systems around these substellar objects. Recent surveys of young (<5 Myr), nearby star-forming regions have indicated brown dwarf disk fractions that are comparable to, or exceed, the disk fraction for higher mass stars in the same regions (e.g., Liu et al. 2003; Luhman et al. 2005; Guieu et al. 2007; Bouy et al. 2007). At greater ages, a disk has been detected for a ~10 Myr old brown dwarf, 2MASSW J1207334−393254 (2M1207), in the TW Hydrae association (TWA) (Sterzik et al. 2004; Riaz et al. 2006). In the same association, Low et al. (2005) have determined a disk fraction of 24% for the stellar members. The TWA is currently known to have five substellar members: 2M1207, 2MASS J11395111−315921 (2M1139), SSSPM J1102−3431 (SSSPM 1102), DENIS J124514.1−442907 (DENIS 1245), and TWA 5B. The first two, 2M1207 and 2M1139, were confirmed to be TWA members by Scholz et al. (2005b) based on accurate proper motions. TWA 5B is a companion to TWA 5A and lies at a projected separation of ~100 AU (Lowrance et al. 1999). The accurate proper motion, photometry, and spectroscopy make SSSPM 1102 very likely to be a TWA member, and it may even be a common proper motion companion to the star TW Hydrae (Scholz et al. 2005b). The recently identified brown dwarf DENIS 1245 has a near-infrared spectrum that is remarkably similar to that of 2M1139, with low surface gravity features. Its position in the sky is coincident with the TWA, which makes it very likely to be a member of this association (Looper et al. 2007). The age of the TWA makes it highly favorable for the study of relatively old brown dwarf disks. In this paper, we present Spitzer Infrared Spectrograph (IRS) archival observations for three TWA brown dwarfs, along with some K and M dwarf members for which the observations have not been published elsewhere. We compare the disk fractions for brown dwarfs and stars at ~10 Myr and examine the resulting implications for the timescale of formation for planetary systems around brown dwarfs.

2. OBSERVATIONS

We searched the Spitzer archives for IRS observations of TWA members and were able to obtain publicly released data for 13 stars and three brown dwarfs. A log of the observations is given in Table 1. The IRS is composed of four modules, with two modules providing low spectral resolution (Short-Low [SL] and Long-Low [LL], 1/6λ~90) and the other two providing high resolution (Short-High [SH] and Long-High [LH], 1/6λ~600). The SL module covers 5.2−14.5 μm in two orders, and the LL module covers 14−38 μm, also in two orders. The observations in these modules are obtained at two positions along each slit. Each high-resolution (echelle) module has a single slit, with SH covering 9.9−19.6 μm and LH covering 18.7−37.2 μm. The Basic
Calibrated Data were produced by the S15 pipeline at the Spitzer Science Center (SSC), which includes ramp fitting, dark sky subtraction, droop correction, linearity correction, flat-fielding, and wavelength calibration. For the low-resolution spectra, the sky background was removed from each spectrum by subtracting observations taken in the same module, but with the target in the other order. We could not perform sky subtraction for the high-resolution spectra. The spectra were extracted and calibrated using the Spitzer IRS Custom Extraction (SPICE) software provided by the SSC. The low-resolution spectra were extracted using a variable-width column extraction that scales with the width of the wavelength-dependent point-spread function. The SH and LH spectra were extracted with a full-slit extraction. The low-resolution spectra were calibrated with HR 7341 (K1 III), and the high-resolution ones with HR 6688 (K2 III). The spectra for each module were then averaged to obtain a single spectrum for each order. We could not perform sky subtraction for the high-resolution spectra. The spectra from some of the other K- and M-type TWA members are shown in the remaining panels of Figure 1. These are arranged in order of increasing spectral type. The main feature in the spectra for these low-mass stars at wavelengths of 5–40 μm is the H2O absorption band near 6.3 μm (Cushing et al. 2006). The strength in this band is found to increase with increasing spectral type until it saturates at the T spectral class. We have measured the depth of H2O absorption for TWA K and M dwarfs using the IRS-H2O index, defined by Cushing et al. (2006) as

\[
\text{IRS-H}_2\text{O} = f_{6.25}/(0.562f_{8.0} + 0.474f_{6.75}).
\]

where \(f_\lambda\) is the mean flux density in a 0.15 μm window centered around \(\lambda\). The errors in the indexes were computed from the

### 3. THE IRS SPECTRA

Figure 1 (top left) shows the spectra for the four strong disks, TW Hya, Hen 3-600, HD 98800B, and HR 4796A, all of which were first detected by IRAS and are known to exhibit strong excess emission at mid- and far-infrared wavelengths. We have included in Figure 1 the ground-based 10 μm photometry measured by Jayawardhana et al. (1999), the Spitzer 24 μm photometry measured by Low et al. (2005), and the IRAS 12 and 25 μm photometry. The photometric measurements by Jayawardhana et al. and Low et al. are found to be in good agreement with the IRS spectra, although the IRAS 12 μm flux densities are stronger than the values derived from the IRS spectra for TW Hya and HR 4796A. Since the narrowest IRS slit is 3.6″ wide, the IRS observations include emission from all components for the Hen 3-600, HD 98800, and HR 4796 systems. The spectra for all four of these indicate the presence of strong disks, with little or no excess emission detected shortward of ~8 μm. The spectral energy distributions (SEDs) of the T Tauri stars TW Hya and Hen 3-600 show no hint of turning over, even out to 160 μm (Low et al. 2005). For the HD 98800 system, Low et al. (2005) have shown that the B component generates the huge infrared excess, which is well fitted by a single blackbody with \(T = 160–170\) K, whereas component A lacks any measurable excess. Likewise, the infrared-excess emission for the A0 V star HR 4796A can be fitted by a single blackbody at the cooler temperature of 108 K (Low et al. 2005). The stars TW Hya, Hen 3-600, and HD 98800B also exhibit broad 10 μm silicate emission features (discussed further in § 4).

The spectra for some of the other K- and M-type TWA members are shown in the remaining panels of Figure 1. These are arranged in order of increasing spectral type. The main feature in the spectra for these low-mass stars at wavelengths of 5–40 μm is the H2O absorption band near 6.3 μm (Cushing et al. 2006). The strength in this band is found to increase with increasing spectral type until it saturates at the T spectral class. We have measured the depth of H2O absorption for TWA K and M dwarfs using the IRS-H2O index, defined by Cushing et al. (2006) as

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\]
uncertainties in the mean flux densities and were found to lie between 0.001 and 0.002. Larger values of this index indicate stronger H$_2$O absorption. The bottom panel of Figure 1 shows a plot of the IRS-H$_2$O index versus spectral type for the TWA K and M dwarfs. We note that we have only 11 data points and did not include 2M1207 and SSSPM 1102, as the observed flux densities for these around 6 $\mu$m are dominated by the disk emission.

As can be seen, the strength of the H$_2$O absorption decreases from spectral type K5 to M0 and then increases again toward later types. Two exceptions are TWA 8A (M2) and 8B (M5), which show stronger H$_2$O absorption than the brown dwarf 2M1139 (M8).

Aside from the strong disks (top right), the spectra shown in Figure 1 are all found to be photospheric, other than that of TWA 7, which is known to harbor a cold debris disk (Low et al. 2005). The spectrum for this M1 dwarf is photospheric for $\lambda \leq 24 \mu$m, but the flux densities begin to rise at longer wavelengths and are found to be in excess of the estimated photospheric emission. The spectrum for TWA 8B (M5; middle right) shows slight emission in the 10 $\mu$m silicate feature. The flux density derived from the spectrum is 14 $\pm$ 0.4 mJy, compared with the 10 $\pm$ 2 mJy reported by Jayawardhana et al. (1999). This small excess could be due to the presence of an optically thin disk; however, Low et al. (2005) did not report excess emission in the MIPS bands for this mid-M dwarf. The separation of $\sim 1^\prime$ between TWA 8A and 8B is large enough to be resolved by the IRS slits, and thus there should not be any contribution from the A component to the slight excess emission observed for the B component. A similar modest excess was measured by Jayawardhana et al. (1999) for TWA 5A. However, the spectrum for this M3 dwarf has a slope similar to that of the M2.5 star TWA 10 (Fig. 1, middle right), and there is no excess emission seen near 10 $\mu$m.

As noted by Jayawardhana et al. (1999), if a more conservative limit of $K-N \sim 0.3$ mag is used to define an excess, then the observed emission at 10 $\mu$m for TWA 5A would be photospheric. To summarize, among the stellar members of the TWA we do not find evidence of significant excess emission at wavelengths of 5–40 $\mu$m for any of the stars other than the six already known disk-bearing members mentioned above.

We now look at the IRS spectra for the TWA brown dwarfs 2M1207, SSSPM 1102, and 2M1139 (Fig. 2, top). Also included in
Fig. 2.—Top: IRS spectra for TWA brown dwarfs. Included for comparison are spectra for the field dwarfs LHS 3003 (M7), vB 10 (M8), and BRI 0021–0214 (M9). Middle and bottom: SEDs for SSSPM 1102 and 2M1139, respectively. The light gray line in these SEDs denotes the NextGen model for a $T_{\text{eff}}$ of 2600 K and $g = 3.5$ to fit the atmospheric spectrum of the central substellar source. The spectrum for 2M1139 is found to be photospheric for wavelengths shorter than $\sim 20 \mu m$, but a rise in the flux densities is observed at longer wavelengths. Riaz et al. (2006) reported an excess emission in the MIPS 24 $\mu m$ band for 2M1139 that is $\sim 3$ times brighter than the predicted photospheric emission. They discussed the possibility of this brown dwarf disk’s flaring up at $70 \mu m$ in a fashion similar to the more massive M1 V star TWA 7, for which the observed flux level at this wavelength is $\sim 40$ times brighter than the estimated photospheric emission (Low et al. 2005). Although the LL-mode observation for 2M1139 has a low S/N ($\sim 9$), the excess emission at 24 $\mu m$ and a rise in the observed flux densities at longer wavelengths strongly indicate the presence of a transition disk around it (Fig. 2, bottom); this is the first such detection among the substellar members of the TWA. We will be obtaining MIPS 70 $\mu m$ observations (PID 40922) for 2M1139, which will allow us to further confirm the presence of the disk. To summarize, all of the TWA brown dwarfs that have been observed so far with Spitzer have been found to have disks around them, compared with just six of the 25 stellar members.

In Table 2, we compile the accretion, activity, and mid-infrared measurements for the nine disk-bearing objects in the TWA. The 10% width is the full width of the Hα line at 10% of the peak and is a strong accretion indicator. Objects with 10% widths over 200 km s$^{-1}$ are considered to be accretors (Jayawardhana et al. 2003). The three disk candidates in the TWA that are also accretors (TW Hya, Hen 3–600, and 2M1207) have $v \sin i \leq 13$ km s$^{-1}$ (Table 2), while the nonaccreting objects with disks, as well as the diskless stars, show a range in $v \sin i$ with values from under 5 km s$^{-1}$ up to 25 km s$^{-1}$ (Jayawardhana et al. 2006). This is consistent with the disk-locking scenario, in which stars with disks rotate slowly as a result of rotational braking (see, e.g., Jayawardhana et al. 2006). Figure 3 (top) indicates a strong correlation between disks and accretion. The fractional disk luminosities $L_d/L_*$ increase with increasing accretion rate. This is expected, as the stronger accretors would have more circumstellar material and thus could reprocess a larger fraction of the stellar luminosity into the infrared. The two brown dwarf disks have $L_d/L_*$ intermediate between the two cold debris disks (TWA 7 and 13) and the strong disks. Low et al. (2005) reported a bimodal distribution of warm dust in the TWA, based on the observed excess emission at 24 $\mu m$. Including the substellar disks makes the bimodal nature of the 24 $\mu m$ excess less pronounced. No connection between accretion and X-ray activity is evident among the TWA stars (Fig. 3, bottom). The two nonaccreting disks (TWA 7 and 13), as well as the diskless objects, show similar X-ray emission to that of the accreting disks. Given that TW Hya and Hen 3–600 are the only two accretors, it is difficult to determine any dependence of accretion on activity for these stars. Among the TWA brown dwarfs, both 2M1207 and SSSPM 1102 have been found to be subluminous in X-rays (Gizis & Bharat 2004; Stelzer et al. 2007). In comparison, TWA 5B is a nonaccreting (10% width = 162 km s$^{-1}$; Mohanty et al. 2003); no IR excess has yet been reported for this object, but it shows strong X-ray emission ($L_X = 4 \times 10^{27}$ erg s$^{-1}$; Tsuboi et al. 2003).
There may thus be some relation between accretion and activity among the substellar objects.

4. THE 10 µm SILICATE FEATURE

The IRS spectra cover the 10 µm region of the silicate emission/absorption feature and can be used to determine the degree of growth and crystallinity of the silicate grains present in the disk. Figure 4 shows the 8–13 µm continuum-subtracted spectra for the five disks in the TWA that display excess emission at these wavelengths. The continuum was obtained by connecting the two endpoints of the 10 µm spectrum. TW Hya, HD 98800B, and Hen 3-600 are known to exhibit broad emission features. Recent detailed modeling by Sargent et al. (2006) indicates very little crystalline material (only ~1% by mass) for TW Hya but a substantial content (~24% by mass) of large amorphous grains. In comparison, Hen 3-600 shows a mixture of crystalline and large silicates (~36% and ~32% by mass, respectively; Sargent et al. 2006). Detailed decomposition of the broad silicate feature for HD 98800B by Schütz et al. (2005) indicates the presence of highly processed dust, dominated by both large amorphous olivine and crystalline forsterite.

The brown dwarf 2M1207 shows a weak silicate absorption feature. Kessler-Silacci et al. (2005, hereafter K05) have discussed that the strength in the silicate absorption is a function of the optical depth of the absorbing dust and produce the same effect as a more inclined star. A mixture of crystalline forsterite and large amorphous pyroxene can account for the observed feature in 2M1207. It shows a broad, flat profile that is indicative of the presence of large (>2 µm) grains. The observed peaks near ~11.3 and ~10.2 µm can be attributed to crystalline forsterite. The smaller peak observed at ~9.5 µm is indicative of amorphous pyroxene. There is also a small peak at ~10.7 µm that can be attributed to crystalline orthoenstatite (Honda et al. 2003). No silicate absorption or emission is observed toward SSSPM 1102. A possible explanation for the lack of a 10 µm feature could be grain growth to sizes larger than the wavelength at which they radiate (>10 µm).

Such large grains would then only produce a blackbody continuum (Bouwman et al. 2001). Flat spectra such as these could also indicate a dearth of small (<2 µm) grains in the upper disk layers probed by the 10 µm feature. We do not find any evidence for a 20 µm silicate feature in 2M1207 or SSSPM 1102. The low S/N (~9) in the LL module for these very faint sources makes it difficult...
to identify any significant absorption or emission due to silicate at 20 \( \mu \)m. The two brown dwarfs show weaker, flatter features than the TWA stars, which can be explained by the differences in the location of the silicate formation zone. This is defined to be the radial zone where the cumulative flux reaches 20%--80% of the total 10 \( \mu \)m emission and varies as \( R_{10} = 0.35(L_c/L_\odot)^{0.56} \) AU (Kessler-Silacci et al. 2007, hereafter K07). The silicate formation thus occurs at smaller radii \( (R_{10} < 0.001\text{--}0.1 \text{ AU}) \) in disks around brown dwarfs than in disks around T Tauri stars \( (R_{10} > 0.1\text{--}3 \text{ AU}) \) and would therefore be more affected by inner disk evolution due to processes such as grain growth and dust crystallization (K07). Furthermore, the size of the region producing the optically thin silicate feature is smaller for late-type stars, resulting in weaker features (Sicilia-Aguilar et al. 2007).

Figure 5 shows a plot of the “shape” versus the “strength” of the 10 \( \mu \)m silicate feature for the TWA stars and brown dwarfs. The shape is indicated by the 11.3 \( \mu \)m to 9.8 \( \mu \)m flux ratio, while the feature strength can be estimated from the peak flux above or below the continuum (see, e.g., K05). Table 3 lists the values for these parameters. The vertical dashed line in Figure 5 at \( F_{\text{peak}} = 1 \) represents the continuum; objects to the left of this line show emission in the silicate feature, while those to the left show absorption. TW Hya, Hen 3-600, and HD 98800B follow the trend shown by the solid line, which indicates a change in the feature shape from peaked to flat caused by an increase in the size of amorphous grains (K07). Hen 3-600 and HD 98800B, with broad features due to the presence of a mixture of amorphous and crystalline silicates, lie above and to the left of TW Hya, which shows a comparatively narrower profile with a peak that indicates amorphous olivine. The brown dwarf SSSPM 1102, which lacks a silicate feature, lies at the upper left near \( F_{\text{peak}} \sim 1 \). Among the absorption features, a smaller value of \( F_{11.3}/F_{9.8} \) indicates more

Fig. 5.—Shape vs. strength of the silicate feature. 2M1207 and SSSPM 1102 are represented by the medium-gray square and diamond, respectively. The three TWA stars TW Hya, Hen 3-600, and HD 98800B are denoted by black squares. The vertical dashed line represents the continuum: objects to the left show absorption in the feature, while those to the right of this line show emission. The solid line denotes the fit obtained by K07 to the points with \( y < 1.1 \), \( y = -0.18 \pm 0.02 \) \( \times (1.23 \pm 0.03) \). Also included for comparison are young (1--3 Myr) brown dwarfs in the Chamaeleon I star-forming region (Apai et al. 2005; dark gray diamonds), T Tauri stars from Przygodda et al. (2003) and K07 (asterisks), and young low-mass embedded sources from K05 (circles). [See the electronic edition of the Journal for a color version of this figure.]

TABLE 3
Spectral Parameters for the Silicate Feature

| Name            | \( \lambda_{\text{peak}} \) (\( \mu \)m) | \( F_{\text{peak}} \) | \( F_{11.3}/F_{9.8} \) | \( L_s \) (\( L_\odot \)) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| TW Hya          | 9.87            | 2.12            | 0.78            | 0.24            |
| HD 98800B       | 10.35           | 1.28            | 0.97            | 0.53            |
| Hen 3-600       | 11.08           | 1.55            | 0.98            | 0.35            |
| 2M1207          | 11.50           | 0.69            | 0.91            | 0.0031          |
| SSSPM 1102      | 9.26            | 1.11            | 1.0             | 0.0031          |

Fig. 4.—Normalized 10 \( \mu \)m spectra in units of \((F_\nu - F_\nu)/F_\nu + 1\) for TWA stars and brown dwarfs. The dashed line represents the continuum level. Top to bottom, TW Hya, HD 98800B, Hen 3-600, 2M1207, and SSSPM 1102.
absorption near 11.3 \( \mu m \), while the feature strength decreases with increasing \( F_{\text{peak}} \). The absorption feature thus becomes flatter in moving from upper left to lower right, which could be explained by an increase in the size of amorphous grains. For features that show stronger absorption near 11.3 \( \mu m \) (\( F_{11.3}/F_{9.8} < 1 \)), crystallization may become more dominant and grain growth alone may not be able to explain the flattening. In their study of silicate emission features in young brown dwarf disks, Apai et al. (2005) showed that for highly processed grains, the feature strength may increase with increasing crystallinity and will reverse the observed correlation. A similar reversal may also occur in the case of the absorption features. The location of 2M1207 below and to the right of the protostars is indicative of highly processed grains, due to grain growth, dust crystallization, or both.

5. DISK MODELING

The top panel of Figure 6 shows the extent of excess emission at 24 \( \mu m \) for the TWA stars and brown dwarfs. The dot-dashed line represents the limit of \( F_{24}/F_K \) under the assumption that both bands lie on the Rayleigh-Jeans tail of the stellar spectrum. The four strong disks are about a factor of 100 brighter at 24 \( \mu m \) relative to the \( K \) band than other stars in the TWA (Low et al. 2005). The brown dwarf disks lie intermediate between the two debris disks TWA 7 and 13 and the four strong disks. The \( F_{24} \)-to-\( F_K \) ratio for 2M1207 is higher than that for TWA 7 or 13, indicating a warmer debris disk around this brown dwarf compared with the cold 80 \( K \) disk around TWA 7 or the 65 \( K \) disk around TWA 13AB. The dashed line represents a geometrically thin, optically thick flat disk with a spectral slope \( \lambda F_\lambda \propto \lambda^{-4/3} \). The three transition disks with no observed excess emission shortward of \( \sim 20 \mu m \) lie below this line. SSSPM 1102 and 2M1207 lie just at the dashed line, indicating optically thick, flat disks around these two brown dwarfs.

We have used the two-dimensional radiative transfer code of Whitney et al. (2003) to model the disks around 2M1207 and SSSPM 1102. The circumstellar geometry consists of a rotationally flattened envelope, bipolar cavities, and a flared accretion disk in hydrostatic equilibrium. The disk density is proportional to \( \omega^{-\alpha} \), where \( \omega \) is the radial coordinate in the disk midplane and \( \alpha \) is the radial density exponent. The disk scale height increases with radius: \( h = h_0(\omega/R_*)^{\beta} \), where \( h_0 \) is the scale height at \( R_* \) and \( \beta \) is the flaring power. Since we are fitting a disk source, the envelope was turned off by setting its mass infall rate to zero. For the stellar parameters, we used \( T_{\text{eff}} = 2550 \text{ K} \) and \( M_*=0.024 M_\odot \) (Gizis 2002). Using this \( T_{\text{eff}} \) and \( M_* \), the evolutionary tracks of Burrows et al. (1997) imply \( R_* \sim 0.26 R_\odot \). The NextGen (Hauschildt et al. 1999) atmosphere file for \( T_{\text{eff}} = 2600 \text{ K} \) and \( g = 3.5 \) was used to fit the atmospheric spectrum of the central substellar source. A distance of \( 54 \pm 3 \text{ pc} \) (Gizis et al. 2007) was used to scale the output fluxes from the models to the luminosity and distance of the two brown dwarfs.

The middle and bottom panels of Figure 6 show the model fits obtained for 2M1207 and SSSPM 1102. Also indicated are the separate contributions from the disk, the stellar photosphere, and the scattered flux. In the disk midplane, we have used large grains with a size distribution that decays exponentially for sizes larger than 50 \( \mu m \), up to 1 mm. In the disk atmosphere, we used grains with sizes of \( a_{\text{max}} \sim 1 \mu m \). Decreasing the grain size in the disk midplane results in more emission in the silicate feature, while the effect is reversed in the disk atmosphere. We have explored a range of inclination angles to the line of sight. The silicate feature is found to be more in absorption for highly inclined disks. Because of the binning of photons in the models, there is a total of 10 viewing angles, with “edge-on” covering 87°–90° inclinations. For 2M1207, a more edge-on viewing angle of 75° provides a good fit to the observed silicate absorption, while a 63° inclination is a good fit to the flat feature for SSSPM 1102. On the basis of the redshifted absorption component in the H\( \alpha \) profile, Scholz et al. (2005a) concluded that 2M1207 is seen at an inclination of \( i \gtrsim 60° \). Our model fits are thus consistent with the previous conclusion about the inclination angle. For SSSPM 1102, a disk mass
of $10^{-5} M_\odot$ and flaring power $\beta = 1.02$ provide a good fit to the disk emission. For 2M1207, there is a change in slope observed between 24 and 70 $\mu$m due to a slight increase in the scale height at 70 $\mu$m. Increasing the disk mass to $10^{-4} M_\odot$ and $\beta$ to 1.06 fits both the IRS spectrum and the 70 $\mu$m point. The mass accretion rate was set at $10^{-11} M_\odot$ yr$^{-1}$ for 2M1207 and $10^{-11} M_\odot$ yr$^{-1}$ for SSSPM 1102 (Scholz et al. 2005a; Stelzer et al. 2007). The disk outer radius was set to 100 AU. Since the disk mass is fixed, a smaller $R_{	ext{in}}$ results in larger optical depth. The changes, however, are more evident at far-IR/submillimeter wavelengths. We varied the inner disk radius $R_{\text{in}}$ in multiples of $R_{\text{sub}}$, which is the dust sublimation radius and varies with the stellar radius and temperature, $R_{\text{sub}} = R_{\text{in}} (T_{\text{sub}}/T)^{-2.085}$ (Whitney et al. 2003). $T_{\text{sub}}$ is the dust sublimation temperature and was set to 1600 K. For 2M1207 and SSSPM 1102, $R_{\text{sub}} \sim 3 R_*$ increasing the inner disk radius results in higher fluxes near the 10 $\mu$m silicate band and at longer wavelengths. The best-fit (based on a reduced-$\chi^2$ comparison) was obtained using $R_{\text{in}} = 1 R_{\text{sub}}$, which implies the absence of an inner hole in the disk, since it would have to be larger than the dust sublimation radius. The fractional disk luminosities for 2M1207 and SSSPM 1102 are found to be 0.06 and 0.05, respectively, and lie intermediate between the strong disks such as TW Hya, with $L_{\text{IR}}/L_*$ of 0.27, and the cool debris disks such as TW 7, with $L_{\text{IR}}/L_*$ of 0.002 (Low et al. 2005). We note here that while our Infrared Array Camera (IRAC) and MIPS photometry matches the IRS spectrum for 2M1207 (Fig. 6, middle), the flux density reported by Sterzik et al. (2004) at 10.4 $\mu$m is higher by a factor of $\sim$1.6 than that derived from the spectrum. Riaz & Gizis (2007) found a good fit to Sterzik et al.'s measurement by using submicron-sized grains in the upper disk layers, which results in a narrow and peaked 10 $\mu$m silicate emission feature. The IRS spectrum, on the other hand, shows absorption and thus rules out the measurement reported by Sterzik et al. (2004).

6. DISK LIFETIMES

It seems as though all of the brown dwarfs in the TWA have disks around them, as shown here for the three out of five substellar members observed with Spitzer. We note that we could not resolve the IRS spectrum for TWA 5AB and therefore cannot make a conclusion about the presence or absence of a disk around the brown dwarf TWA 5B. The age of the TWA (~10 Myr) makes it interesting for the study of brown dwarf disks at relatively older ages. In younger clusters, Luhan et al. (2005) have reported disk fractions of 42% ± 13% and 50% ± 17% for the substellar ($M_\ast \leq 0.08 M_\odot$) members of IC 348 (2–3 Myr) and Chamaeleon I (~1 Myr), respectively, while the fractions for stellar (M0–M6, 0.7 $M_\odot$ $\geq M_\ast \geq 0.1 M_\odot$) members are 33% ± 4% and 45% ± 7%. These fractions are based on observations made in the Spitzer IRAC bands. In their IRAC and MIPS survey of brown dwarfs in Taurus (1–2 Myr), Guieu et al. (2007) found a 48% ± 14% disk fraction, which is similar to that obtained by Hartmann et al. (2005) for T Tauri stars in Taurus. At ~5 Myr, Carpenter et al. (2006) report a 19% ± 5% fraction for KO–M5 stars in Upper Scorpius, all of which show excess emission at 8 and 16 $\mu$m, but none significant at shorter wavelengths, indicating a lack of warm dust in the inner disk (~0.1 AU) region. In comparison, Bouy et al. (2007) have reported a much higher 50% ± 16% fraction for brown dwarfs (spectral type later than M6) in Upper Sco, half of which show a clear excess at 8 $\mu$m. In the same star-forming region, Scholz et al. (2007) have conducted a Spitzer survey of 35 brown dwarfs and report a fraction of 37% ± 9%. These authors also report the presence of large inner holes (~5 AU), indicating an inner disk dissipation timescale of $\leq 10^5$ yr. At ~10 Myr, the disk fraction for the stellar members of the TWA is found to be 24% (6/25), compared with 60% (3/5) for the brown dwarfs. If we consider only the M0–M6 stars, then the fraction drops to ~16% (3/18). A comparison with younger clusters then indicates that by the age of ~10 Myr, the disk fraction for brown dwarfs has not decreased, whereas it drops by a factor of ~2 for the higher mass stars. This indicates longer disk decay timescales for brown dwarfs compared with higher mass stars, consistent with the conclusions made by Bouy et al. (2007) and Scholz et al. (2007) of a mass-dependent disk lifetime. The low accretion rates in brown dwarfs would imply that their disks should live longer (Natta et al. 2004). The viscous scaling times for brown dwarfs are expected to be on the order of $10^6$ yr, longer than the typical $10^7$–$10^8$ yr for T Tauri stars (Alexander & Armitage 2006). If disks persist for a longer time, then the planet formation timescale might also be longer around brown dwarfs.

Payne & Lodato (2007) have investigated the potential for Earth-like planet formation around substellar objects. Their simulations indicate that a rocky planet with an icy constitution and a mass as large as ~0.1 $M_\odot$ can form around a brown dwarf at a semimajor axis as small as ~0.2 AU, for an average brown dwarf disk mass of $1.5 \times 10^{-4} M_\odot$ and an outer disk radius of 100 AU. However, the growth of such planetary cores is at a much slower rate around brown dwarfs compared with solar-type stars. Both 2M1207 and SSSPM 1102 show flat features due to highly processed grains. Best-fit disk models require large-sized (>50 $\mu$m) grains in the disk midplane, indicative of grain growth and dust settling. These are the processes that may lead to planet formation. On the other hand, rapid planet formation within ~10 Myr may be responsible for the inner disk clearing observed in 2M1139. The disk fraction of 60% obtained here is considerably higher than those reported for the TWA stellar members, or for brown dwarfs in younger clusters. More substellar members of the TWA may remain to be identified, and observations of them, along with brown dwarfs at older ages, will be valuable in determining whether disks indeed persist for a longer time around substellar objects compared with higher mass stars.

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