ON THE TRANSITIONAL DISK CLASS: LINKING OBSERVATIONS OF T TAURI STARS AND PHYSICAL DISK MODELS

C. Espaillat\textsuperscript{1,7}, L. Ingleby\textsuperscript{2}, J. Hernández\textsuperscript{3}, E. Furlan\textsuperscript{4,8}, P. D’Alessio\textsuperscript{5}, N. Calvet\textsuperscript{2}, S. Andrews\textsuperscript{1,7}, J. Muzerolle\textsuperscript{6}, C. Qi\textsuperscript{1,7}, and D. Wilner\textsuperscript{1,7}

\textsuperscript{1} Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-78, Cambridge, MA 02138, USA; cespaillat@cfa.harvard.edu, sandrews@cfa.harvard.edu, cqi@cfa.harvard.edu, dwilner@cfa.harvard.edu
\textsuperscript{2} Department of Astronomy, University of Michigan, 830 Dennison Building, 500 Church Street, Ann Arbor, MI 48109, USA; lingleby@umich.edu, ncalvet@umich.edu
\textsuperscript{3} Centro de Investigaciones de Astronomía (CIDA), Merida 5101-A, Venezuela; jesush@cida.ve
\textsuperscript{4} National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719, USA; Elise.Furlan@jpl.nasa.gov
\textsuperscript{5} Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, 58089 Morelia, Michoacán, Mexico; p.dalessio@crya.unam.mx
\textsuperscript{6} Space Telescope Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; muzerol@stsci.edu

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ABSTRACT

Two decades ago “transitional disks” (TDs) described spectral energy distributions (SEDs) of T Tauri stars with small near-IR excesses, but significant mid- and far-IR excesses. Many inferred this indicated dust-free holes in disks possibly cleared by planets. Recently, this term has been applied disparately to objects whose Spitzer SEDs diverge from the expectations for a typical full disk (FD). Here, we use irradiated accretion disk models to fit the SEDs of 15 such disks in NGC 2068 and IC 348. One group has a “dip” in infrared emission while the other’s continuum emission decreases steadily at all wavelengths. We find that the former have an inner disk hole or gap at intermediate radii in the disk and we call these objects “transitional disks” and “pre-transitional disks” (PTDs), respectively. For the latter group, we can fit these SEDs with FD models and find that millimeter data are necessary to break the degeneracy between dust settling and disk mass. We suggest that the term “transitional” only be applied to objects that display evidence for a radical change in the disk’s radial structure. Using this definition, we find that TDs and PTDs tend to have lower mass accretion rates than FDs and that TDs have lower accretion rates than PTDs. These reduced accretion rates onto the star could be linked to forming planets. Future observations of TDs and PTDs will allow us to better quantify the signatures of planet formation in young disks.

Key words: accretion, accretion disks – circumstellar matter – protoplanetary disks – stars: formation – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

Disks around T Tauri stars (TTS) are thought to be the sites of planet formation. However, many questions exist concerning how the gas and dust in the disk evolve into a planetary system and observations of TTS may provide clues. There are some objects in particular that have gained increasing attention in this regard. Over two decades ago, Strom et al. (1989) detected “possible evidence of changes in disk structure with time” as evidenced by “small near-IR excesses, but significant mid- and far-IR excesses” indicating “inner holes” in disks. Those authors proposed that these objects were “in transition from massive, optically thick structures that extend inward to the stellar surface, to low-mass, tenuous, perhaps post-planet-building structures.”

Usage of the term “transitional disk” (TD) gained substantial momentum in the literature after it was used by Calvet et al. (2005b) to describe disks with inner holes using data from the Spitzer Space Telescope’s (Werner et al. 2004) Infrared Spectrograph (IRS; Houck et al. 2004). Before Spitzer, the spectral energy distributions (SEDs) used to identify disks with inner holes were based solely on near-infrared (NIR) ground-based photometry and IRAS mid-IR (MIR) photometry (Strom et al. 1989; Skrutskie et al. 1990). Spitzer allowed the opportunity to study these objects in greater detail. The unprecedented resolution and simultaneous wavelength coverage (∼5 and 38 \(\mu\)m) of Spitzer IRAS uncovered new details regarding these disks (D’Alessio et al. 2005; Calvet et al. 2005b; Furlan et al. 2006). Some SEDs had nearly photospheric NIR (1–5 \(\mu\)m) and MIR (5–20 \(\mu\)m) emission, coupled with substantial emission above the stellar photosphere at wavelengths beyond ∼20 \(\mu\)m. Others had significant NIR excesses relative to their stellar photospheres, but still exhibited MIR dips and substantial excesses beyond ∼20 \(\mu\)m.

Detailed modeling of many of the above-mentioned SEDs has been performed. SEDs of disks with little or no NIR and MIR emission have been fit with models of inwardly truncated optically thick disks (Calvet et al. 2002, 2005b; Espaillat et al. 2007b, 2008b). The inner edge or “wall” of the outer disk is frontally illuminated by the star, dominating most of the emission seen in the IRS spectrum. In this paper, we refer to these objects with holes in their dust distribution as TDs. Some of the holes in TDs are relatively dust free (e.g., DM Tau; Calvet et al. 2005b; Espaillat et al. 2010) while SED model fitting indicates that others with strong 10 \(\mu\)m silicate emission have a small amount of optically thin dust in their disk holes to explain this feature (e.g., GM Aur; Calvet et al. 2005b; Espaillat et al. 2010). For SEDs with substantial NIR emission accompanied by a MIR dip, we can fit the observed SED with an optically thin inner disk separated by an optically thin gap from...
an optically thick outer disk (Espaillat et al. 2007a). Here we call these pre-transitional disks (PTDs). Like the TDs, we see evidence for relatively dust-free gaps (e.g., UX Tau A; Espaillat et al. 2007a, 2010) as well as gaps with some small, optically thin dust to explain strong 10 \mu m silicate emission features (e.g., LKca 15; Espaillat et al. 2007a, 2010). For many TDs and PTDs, the truncation of the outer disk has been confirmed with submillimeter and millimeter interferometric imaging (e.g., DM Tau, GM Aur, UX Tau A, LKca 15; Hughes et al. 2007, 2009; Andrews et al. 2009, 2010, 2011) as well as NIR imaging (i.e., LKca 15; Thalmann et al. 2011). In a few cases, the optically thick inner disk of PTDs has been confirmed using the “veiling” of near-infrared spectra (Espaillat et al. 2008a, 2010) and near-infrared interferometry has confirmed that the inner disk is small (Pott et al. 2010; Olofsson et al. 2011).

The distinct SEDs of TDs and PTDs most likely signify that these objects are being caught in an important phase in disk evolution. Many researchers have posited that these disks are forming planets on the basis that cleared dust regions are predicted by planet formation models (e.g., Paardekooper & Mellema 2004; Zhu et al. 2011; Dodson-Robinson & Salyk 2011). Recently, a potential protoplanet has been reported in the PTD around LKca 15 (Kraus & Ireland 2012) as well as around T Cha (Huelamo et al. 2011). Stellar companions can also clear the inner disk (Artymowicz & Lubow 1994) but many stars harboring TDs are single stars (Kraus et al. 2011). Even in cases where stellar-mass companions have not been ruled out, the large holes and gaps observed are most likely evidence of dynamical clearing. Photoevaporation cannot explain disks with large cavities and high mass accretion rates (Owen et al. 2011) and dust evolution alone cannot explain the sharp decreases in surface density seen in the SED and interferometric visibilities.

Given the potential link between disks with gaps and holes and planet formation, interest in TDs has grown. Some studies have focused on further understanding the behavior of the currently known members in this class of objects and have discovered IR variability (Muzerolle et al. 2010; Espaillat et al. 2011, E11). Other studies have taken a broader approach, working toward expanding the known number of disks undergoing clearing (e.g., Lada et al. 2006; Hernández et al. 2007; Cieza et al. 2010; Muzerolle et al. 2010; Luhman et al. 2010; Merín et al. 2010; Currie & Sicilia-Aguilar 2011). As the literature on Spitzer observations of TTS expands, so does the terminology applied to disks around TTS. These disks are referred to as primordial, full, transitional, pre-transitional, kink, cold, anemic, homologously depleted, classical transitional, weak excess, warm excess, and evolved. However, these terms are not applied consistently. The issue is highlighted with the discrepancies in the reported fractions of TDs and disk clearing timescales (Merín et al. 2010; Luhman et al. 2010; Muzerolle et al. 2010; Currie & Sicilia-Aguilar 2011; Hernández et al. 2010). In many cases, the data are the same; the differences arise from nomenclature.

If the goal is to better understand disk evolution, it is important to look past the nomenclature and decipher the underlying disk structure we can infer from the observations, while paying special attention to the limitations of both the observations and the tools we use to interpret them, namely, disk models. To

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9 “Veiling” occurs when an excess continuum (Hartigan et al. 1989) “fills in” absorption lines, causing them to appear significantly weaker than the spectrum of a standard star of the same spectral type (Hartigan et al. 1989).

The veiling observed in pre-transitional disks is similar to that observed in full disks where the veiling has been explained by emission from the inner disk edge or “wall” of an optically thick disk (Muzerolle et al. 2003).
Figure 1. High-resolution Hα line profiles obtained using the MIKE spectrograph for three of our IC 348 targets and all five of our NGC 2068 targets. Wide and asymmetric profiles (i.e., FM 515, FM 581, FM 618, LRLL 21) indicate substantial accretion onto the star and gas in the inner disk while narrow profiles indicate low accretion rates onto the star (e.g., White & Basri 2003). We note that the spectrum of LRLL 72 has been binned up by a factor of \( \sim 5 \) here for clarity.

| Target     | \( V \)    | \( U - V \) | \( V - R \) | \( V - I \) |
|------------|------------|-------------|-------------|------------|
| LRLL 2     | sat.       | sat.        | sat.        | sat.       |
| LRLL 6     | sat.       | sat.        | sat.        | sat.       |
| LRLL 21    | 15.68 ± 0.03 | 3.51 ± 0.06 | 1.35 ± 0.08 | sat.       |
| LRLL 31    | 19.30 ± 0.08 | <0.8        | 2.00 ± 0.09 | 3.89 ± 0.09 |
| LRLL 37    | 15.85 ± 0.04 | 2.68 ± 0.25 | 1.24 ± 0.05 | 1.19 ± 0.06 |
| LRLL 55    | 21.68 ± 0.33 | <−1.58      | 2.03 ± 0.22 | 4.19 ± 0.38 |
| LRLL 67    | 16.23 ± 0.02 | 2.04 ± 0.11 | 1.16 ± 0.04 | 2.50 ± 0.04 |
| LRLL 68    | 17.49 ± 0.03 | 2.53 ± 0.31 | 1.64 ± 0.03 | 3.46 ± 0.03 |
| LRLL 72    | 17.55 ± 0.03 | 2.38 ± 0.20 | 1.62 ± 0.03 | 3.32 ± 0.03 |
| LRLL 133   | 20.00 ± 0.30 | <0.1        | 1.50 ± 0.50 | 3.70 ± 0.30 |

Notes. We use “sat.” to refer to observations that were saturated and note upper limits for bands in which sources were not detected.

In order to obtain mass accretion rate estimates (Section 3.1.1 and Figure 1), we collected MIKE double-echelle spectrograph (Bernstein et al. 2003) data on the 6.5 m Magellan Clay telescope for all of our targets in NGC 2068 (FM 177, FM 281, FM 515, FM 581, and FM 618) and some of our objects in IC 348 (LRLL 21, LRLL 67, and LRLL 72). The observations for the NGC 2068 and IC 348 objects were taken on 2007 February 10–11 and 2009 January 19, respectively. We used a slit size of \( 0.7 \times 5.0 \) and \( 2 \times 2 \) pixel on-chip binning with exposure times of 800–1200 s. Data were reduced using the MIKE data reduction pipeline.

2.3. Infrared Spectroscopy

Here, we present Spitzer IRS spectra for each of our targets. Spectra for NGC 2068 and IC 348 were obtained in Program 58 (PI: Rieke) and Program 2 (PI: Houck), respectively. All of the observations were performed in staring mode using the IRS low-resolution modules, short–low (SL) and long–low (LL), which span wavelengths from 5 to 14 \( \mu m \) and 14 to 38 \( \mu m \), respectively, with a resolution \( \lambda/\delta \lambda \sim 90 \).

Details on the observational techniques and general data reduction steps can be found in Furlan et al. (2006) and Watson et al. (2009). We provide a brief summary. Each object was observed twice along the slit, at a third of the slit length from the top and bottom edges of the slit. Basic calibrated data (BCD)

\[ \text{http://web.mit.edu/~burles/www/MIKE/} \]
Figure 2. SEDs of transitional disks in our sample. We show both the observed fluxes (red) and dereddened fluxes (blue; see Table 3 for $A_V$). In the NIR the emission is similar to that of the stellar photosphere (broken magenta line; Kenyon & Hartmann 1995), but rises in the MIR and at longer wavelengths. This indicates that the dust in the inner disk has been removed and that there is a hole in the disk. Open circles correspond to ground-based $U$, $B$, $V$, $R$, $I$, and $L$-band photometry; closed circles are 2MASS $J$, $H$, and $K$-band photometry; triangles are Spitzer IRAC and MIPS photometry. See Section 3.1 for data references. Solid lines are Spitzer IRS spectra from this work.

(A color version of this figure is available in the online journal.)

with pipeline version S18.7 were obtained from the Spitzer Science Center. With the BCDs, we extracted and calibrated the spectra using the SMART package (Higdon et al. 2004). Bad and rogue pixels were corrected by interpolating from neighboring pixels.

Most of the data were sky subtracted using optimal extraction (Lebouteiller et al. 2010). The exceptions were LRLL 37, LRLL 55, and LRLL 68. In LRLL 37, there was an artificial structure in the 5–8 μm region which was removed by performing off-nod sky subtraction. A similar structure was seen in LRLL 55 and LRLL 68, but due to the high background in the area, optimal extraction was necessary for the LL order. Therefore, the final spectra for LRLL 55 and LRLL 68 are a combination of the off-nod sky-subtracted SL spectra and the optimally extracted LL spectra.

To flux calibrate the observations we used a spectrum of α Lac (A1 V). We performed a nod-by-nod division of the target spectra and the α Lac spectrum and then multiplied the result by a template spectrum (Cohen et al. 2003). The final spectrum was produced by averaging the calibrated spectra from the two nods. Our spectrophotometric accuracy is 2%–5% estimated from half the difference between the nodded observations, which is confirmed by comparison with IRAC and MIPS photometry. We note that there are artifacts in the spectra of LRLL 68 and LRLL 133 beyond ∼30 μm. For clarity, we manually trim the spectra to exclude these regions. The final spectra used in this study are shown in Figures 2–4.

2.4. Millimeter Flux Densities

We observed LRLL 21, LRLL 31, LRLL 67, LRLL 68, and LRLL 72 in IC 348 with the Submillimeter Array (SMA) on 2008 November 12. We used the Compact Configuration with six of the 6 m diameter antennas at 345 GHz (860 μm) with a full correlator bandwidth of 2 GHz. Calibration of the visibility phases and amplitudes was achieved with observations of the quasars 3C 111 and 3C 84, typically at intervals of 20 minutes. Observations of Uranus provided the absolute scale for the flux density calibration. The data were calibrated using the MIR software package.13 We detected LRLL 31 and LRLL 67 with flux densities of 0.062 ± 0.006 Jy and 0.025 ± 0.011 Jy, respectively. We did not detect LRLL 21, LRLL 68, or LRLL 72 and measure a 3σ upper limit of 0.015 Jy for these objects.

3. ANALYSIS

Here, we model the SEDs of the targets in our sample. First we collect the stellar properties of our objects, either by adopting literature values or deriving our own in Section 3.1. These stellar properties are important input parameters for our physically motivated models which we discuss in Section 3.2. In Section 3.3, we discuss the results of our SED model fitting, as well as the degeneracies that exist given that we lack millimeter observations for many of our targets.

13 http://www.cfa.harvard.edu/~cqi/mircook.html
3.1. Stellar Properties

Stellar parameters are listed in Table 3. \( M_\ast \) was derived from the H-R diagram and the Siess et al. (2000) evolutionary tracks using \( T_\ast \) and \( L_\ast \). Stellar temperatures are from Kenyon & Hartmann (1995), based upon the spectral types adopted for the targets in NGC 2068 and IC 348 (Flaherty & Muzerolle 2008; Luhman et al. 2003, respectively). Luminosities are calculated with dereddened \( J \)-band photometry following Kenyon & Hartmann (1995) assuming a distance of 400 pc for NGC 2068 (Flaherty & Muzerolle 2008) and 315 pc for IC 348 (Luhman et al. 2003). \( R_\ast \) is calculated using the derived luminosity and adopted temperature. The derivation of the mass accretion rates and accretion luminosities are discussed in Section 3.1.1.

All photometry for our NGC 2068 objects is taken from Flaherty & Muzerolle (2008). This includes \( BVRI \), Two Micron All Sky Survey (2MASS) \( JHK \), IRAC, and MIPS data. We note that Flaherty & Muzerolle (2008) present photometry from the Sloan Digital Sky Survey (SDSS), which we convert to Johnson-Cousins \( BVRI \) following Jordi et al. (2006). IRAC and MIPS photometry for IC 348 comes from Lada et al. (2006) and 2MASS \( JHK \) data are from Skrutskie et al. (2006). \( UBVRI \) photometry for our IC 348 targets comes mainly from this work but is supplemented by values in the literature. All \( UBVRI \) photometry for LRLL 31, LRLL 55, LRLL 67, LRLL 68, LRLL 72, and LRLL 133 are solely from this work. \( UVR \) data for LRLL 21 and LRLL 37 are from this work, but we use \( I \)-band magnitudes from Luhman et al. (2003) for both and a \( B \)-band magnitude for LRLL 21 from Herbig (1998). We use \( R \) and \( I \) data from Herbig (1998) for LRLL 2. \( BVRI \) data for LRLL 6 are also from Herbig (1998). All \( L \)-band magnitudes are from Haisch et al. (2001).

Extinctions were measured by comparing \( V - R \), \( V - I \), \( R - I \), and \( I - J \) colors to photospheric colors from Kenyon & Hartmann (1995). We used the Mathis (1990) extinction law for objects with \( A_V < 3 \). For \( A_V \geq 3 \), we use the McClure (2009) extinction law. We adopt \( R_V = 5 \) which is more appropriate for the denser regions studied here (Mathis 1990). In most cases, extinctions based on \( I - J \) colors gave the best fit. Since we have no \( I \)-band data for FM 581 we adopt an extinction based on \( V - R \); LRLL 2 and LRLL 6 have no \( VRI \) photometry in the literature and so we adopt the extinction measured by Luhman et al. (2003). All extinctions used in this work are listed in Table 3. We note that most of our extinctions are similar to those in the literature (Luhman et al. 2003; Flaherty & Muzerolle 2008). In cases where we found differences, we chose to rely on our measurements since they are based on \( I - J \) colors which have recently been shown to be the least affected by excess emission at shorter wavelengths (Fischer et al. 2011, M. K. McClure et al. 2012, in preparation). For early-type stars, the peak of the stellar emission would be at shorter wavelengths. However, the early-type star in our sample (LRLL 2) has bad photometry so we do not explore this point further.
Figure 4. SEDs of full disks in our sample. The emission decreases at all wavelengths. The color scheme, symbols, and lines are the same as those used in Figure 2.

(A color version of this figure is available in the online journal.)

Table 3

| Target | $A_V$ | Spectral Type | $T_{\ast}$ (K) | $L_\ast$ ($M_\odot$) | $M_\ast$ ($M_\odot$) | $R_\ast$ ($R_\odot$) | $M$ ($10^{-8} M_\odot$ yr$^{-1}$) | $L_{\text{acc}}$ ($L_\odot$) | $M$ Source |
|--------|-------|---------------|----------------|----------------------|----------------------|----------------------|--------------------------------|----------------------|-----------|
| FM 177 | 1.6   | K4            | 4590           | 1.0                  | 1.2                  | 1.5                  | 0.004                          | 0.0009               | $H\alpha$ |
| FM 281 | 2.0   | M1            | 3720           | 0.4                  | 0.5                  | 1.6                  | 0.002                          | 0.0002               | $H\alpha$ |
| FM 515 | 1.6   | K2            | 4900           | 2.5                  | 1.5                  | 2.2                  | 3.10                           | 0.68                 | $H\alpha$ |
| FM 581 | 4.1   | K4            | 4590           | 4.1                  | 1.6                  | 3.1                  | 2.57                           | 0.40                 | $H\alpha$ |
| FM 618 | 2.9   | K1            | 5080           | 2.2                  | 1.5                  | 1.9                  | 1.21                           | 0.29                 | $H\alpha$ |
| LRLL 2 | 3.8   | A2            | 8970           | 57.1                 | 2.8                  | 3.1                  | ...                            | ...                  | ...       |
| LRLL 6 | 3.9   | G3            | 5830           | 16.6                 | 2.4                  | 4.0                  | ...                            | ...                  | ...       |
| LRLL 21| 4.7   | K0            | 5250           | 3.8                  | 1.6                  | 2.4                  | 0.20                           | 0.04                 | $H\alpha$ |
| LRLL 31| 8.6   | G6            | 5700           | 5.0                  | 1.6                  | 2.3                  | 1.4                            | 0.3                  | F11       |
| LRLL 37| 2.8   | K6            | 4205           | 1.3                  | 0.9                  | 2.2                  | 0.13                           | 0.02                 | $U$-band |
| LRLL 55| 8.5   | M0.5          | 3850           | 1.0                  | 0.6                  | 2.2                  | ...                            | ...                  | ...       |
| LRLL 67| 2.0   | M0.75         | 3720           | 0.5                  | 0.5                  | 1.8                  | 0.01                           | 0.001                | $H\alpha$ |
| LRLL 68| 2.1   | M3.5          | 3470           | 0.5                  | 0.5                  | 2.0                  | 0.04                           | 0.002                | $U$-band |
| LRLL 72| 3.0   | M2.5          | 3580           | 0.7                  | 0.4                  | 2.1                  | <0.0003                        | <0.00001             | $H\alpha$ |
| LRLL 133| 3.6  | M5            | 3240           | 0.2                  | 0.2                  | 1.5                  | <0.8                           | <0.78                | $U$-band |

Notes. Spectral types for objects in NGC 2068 and IC 348 are adopted from Flaherty & Muzerolle (2008) and Luhman et al. (2003), respectively, except in the case of LRLL 31 where we adopt the spectral type of Flaherty et al. (2011). $T_{\ast}$ is taken from Kenyon & Hartmann (1995), based on the adopted spectral type. $L_\ast$, $M_\ast$, and $R_\ast$ are calculated in this work. $A_V$ measurements for most of the objects are from this work except for LRLL 2 and LRLL 6 where this value is adopted from Luhman et al. (2003). The last column lists the method with which our mass accretion rates were calculated; $H\alpha$ and $U$-band are from this work; F11 is from Flaherty et al. (2011). For sources where mass accretion rate estimates are not listed here, we adopt $1 \times 10^{-8} M_\odot$ yr$^{-1}$.
3.1.1. Accretion Rates

During the classical TTS phase of stellar evolution, young objects accrete material from the disk onto the star via magnetospheric accretion (Uchida & Shibata 1984). The infalling gas impacts the stellar surface at approximately the free fall velocity creating a shock which heats the gas to ~1 MK (Calvet & Gullbring 1998). The shock emission is reprocessed in the accretion column and the observed spectrum peaks in the ultraviolet (Calvet & Gullbring 1998). The best estimate of the accretion rate is found by measuring the total luminosity emitted in the accretion shock, i.e., the accretion luminosity. While ultraviolet emission is difficult to observe from ground-based observatories, there are many tracers of the accretion luminosity at longer wavelengths (see Rigliaco et al. 2011 for a comprehensive list). A few of those tracers include excess emission observed in $U$-band photometry, emission in the NIR Ca α triplet lines, and the Hα line profile.

Second to the ultraviolet excess, $U$-band excesses are the best measure of the flux produced in the shock and have been shown to correlate with the total shock excess (Calvet & Gullbring 1998). However, at low mass accretion rates, $U$-band emission may be dominated by chromospheric emission (Houdebine et al. 1996; Franchini et al. 1998); this chromospheric excess can confuse determinations of the accretion rate (Ingleby et al. 2011). While possible from the ground, $U$-band observations are still difficult to obtain, especially when extinction toward the source is relatively high as in the case of our sample, all with $A_V > 1$. Observations of the Ca α near-infrared triplet are easily obtained from the ground, even for high $A_V$ sources, and the flux in the 8542 Å line also correlates with the accretion luminosity (Muzerolle et al. 1998). Ca α is observed in emission in accreting sources but is unreliable at low accretion rates, when the chromospheric emission rivals that from accretion in strength (Yang et al. 2007; Batalha & Basri 1993; Ingleby et al. 2011). Hα is commonly used as a tracer of accretion, both by measuring the equivalent width and the velocity width of the line in the wings (White & Basri 2003; Barrado y Navascués & Martin 2003; Natta et al. 2004). Models of magnetospheric accretion have reproduced the observed velocities in Hα, tracing material traveling at several hundred km s$^{-1}$ near the accretion shock (Lima et al. 2010; Muzerolle et al. 2003).

The mass accretion rates adopted for our sample are listed in Table 3. We used $U$-band photometry from this work and the relation in Gullbring et al. (1998) to measure mass accretion rates for LRLL 37 and LRLL 68 and an upper limit for LRLL 133.$^{14}$ For FM 177, FM 281, FM 515, FM 581, FM 618, LRLL 21, LRLL 67, and LRLL 72, we used high-resolution echelle spectra obtained with MIKE to measure the width of the Hα line in the wings (at 10% of the maximum flux; Figure 1). We then compared this to the relation between line width and $M$ in Natta et al. (2004) to obtain mass accretion rate estimates for these eight sources. While our MIKE spectra covered both Hα and the Ca α triplet, Hα provided a more accurate estimate of $M$ due to confusion with chromospheric Ca α emission at the levels of accretion found in these sources. Given the chromospheric appearance of the Hα profile of LRLL 72, its mass accretion rate should be taken as an upper limit. For LRLL 31 we adopted a mass accretion rate from the literature. We do not have mass accretion rate measurements for LRLL 2 or LRLL 6.

$^{14}$ We measured an upper limit for LRLL 55 of $4 \times 10^{-6}$ $M_\odot$ yr$^{-1}$ using $U$-band photometry. However, this very high upper limit does not provide useful constraints for the purposes of this paper and so we do not comment on it further.

For NGC 2068, we compared our derived accretion rates to those in Flaherty & Muzerolle (2008) who calculated the amount of excess continuum emission necessary to produce the observed veiling of the photospheric lines. Within a factor of 2–3, the normal error in $M$ estimations, both calculations of the accretion rate agree, with a few exceptions. When comparing the Hα line widths at 10% we find that our MIKE line profile of FM 281 is ~180 km s$^{-1}$ narrower than when observed by Flaherty & Muzerolle (2008). In addition, our observation of FM 177 is consistent with an accreting source, while when observed by Flaherty & Muzerolle (2008) its Hα profile was consistent with that of chromospheric emission. Variability is known to occur in T Tauri stars so the decrease in Hα and $M$ is not unexpected (Cody & Hillenbrand 2010). For these objects we chose to adopt the accretion rate obtained from our MIKE observations. The biggest uncertainty in calculating accretion rates using veiling is the choice of bolometric correction, which can vary in value by a factor of 10 depending on which analysis is used (White & Hillenbrand 2004) and the spectrum of the excess emission which veils the photospheric lines can be complicated (Fischer et al. 2011).

3.2. Disk Model

We try to reproduce the SEDs presented in Figures 2–4 using the irradiated accretion disk models of D’Alessio et al. (1998, 1999, 2001, 2005, 2006). We point the reader to those papers for details of the model and to Espaillat et al. (2010) for a summary of how we apply the model to the SEDs of TDs and PTDs. Here, we provide a brief review of the salient points of the above works.

When we refer to an FD model we mean a disk model composed of an irradiated accretion disk and a frontally illuminated wall at the inner edge of the disk which is located at the dust sublimation radius. The inner wall dominates the emission in the NIR, the wall and disk both contribute to the MIR emission, and the disk dominates the emission at longer wavelengths. Compared to an FD model, a PTD model has a gap within the disk. In this case, we include a frontally illuminated wall at the dust sublimation radius and another wall at the gap’s outer edge. For this outer wall we include the shadow cast by the inner wall (Espaillat et al. 2010). We do not include an inner irradiated accretion disk behind the inner wall since previous work has shown that the inner wall dominates the emission at these shorter wavelengths (Espaillat et al. 2010). Behind the outer wall we include an irradiated accretion disk in cases where we have millimeter data, which is necessary to constrain the outer disk. The inner wall dominates the NIR emission while the outer wall dominates the emission from ~20 to 30 $\mu$m. The outer disk dominates the emission beyond ~40 $\mu$m. A TD model is very similar to that of a PTD model except that we do not include an inner wall at the dust sublimation radius. In some instances, we include a small amount of optically thin dust in the inner hole or gap in TDs and PTDs to reproduce the 10 $\mu$m silicate emission feature. We calculate the emission from this optically thin dust region following Calvet et al. (2002).

3.2.1. Disk Properties

Table 4 lists the model-derived properties of our sample. The heights of the inner and outer walls ($z_{\text{wall}}$) and the maximum grain sizes ($a_{\text{max}}$) are adjusted to fit the SED. $T_{\text{wall}}$ is the temperature at the surface of the optically thin wall atmosphere. The temperature of the inner wall of FDs and PTDs ($T_{\text{wall}}^{i}$) is held fixed at 1400 K (except for FM 515, see Section 3.3) which is the
Table 4

| Target  | Disk Type | Inner Wall | Outer Wall |
|---------|-----------|------------|------------|
|         |           | $a_{\text{max}}$ ($\mu$m) | $T_{\text{wall}}$ (K) | $z_{\text{wall}}$ (AU) | $R_{\text{wall}}$ (AU) | $a_{\text{max}}$ ($\mu$m) | $T_{\text{wall}}$ (K) | $z_{\text{wall}}$ (AU) | $R_{\text{wall}}$ (AU) |
| FM 177  | TD        | ...        | ...        | ...        | 0.25 | 90   | 3.1 | 49 |
| FM 281  | TD        | ...        | ...        | ...        | 0.25 | 90   | 3.6 | 31 |
| LRLL 67 | TD        | ...        | ...        | ...        | 5.0  | 130  | 1.5 | 10 |
| LRLL 72 | TD        | ...        | ...        | ...        | 1.0  | 190  | 0.6 | 5  |
| LRLL 133TD | ...       | ...        | ...        | ...        | 0.25 | 180  | 0.6 | 4  |
| FM 515  | PTD       | 10         | 1700$^a$   | 0.0071     | 0.12 | 0.25 | 150 | 5  |
| FM 618  | PTD       | 1.0        | 1400       | 0.0055     | 0.22 | 5.0  | 180 | 0.7 | 11 |
| LRLL 21 | PTD       | 2          | 1800$^a$   | 0.0017     | 0.13 | 2.0  | 220 | 0.9 | 9  |
| LRLL 31 | PTD       | 1.0        | 1400       | 0.01      | 0.32 | 5.0  | 180 | 1.5 | 14 |
| LRLL 37 | PTD       | 0.25       | 1400       | 0.0098     | 0.17 | 0.25 | 240 | 0.6 | 5  |
| FM 581  | FD        | 0.25       | 1400       | 0.016     | 0.3  | ...  | ... | ... | ... |
| LRLL 2  | FD        | 0.25       | 1400       | 0.013     | 1.68 | ...  | ... | ... | ... |
| LRLL 6  | FD        | 1.0        | 1400       | 0.005     | 0.54 | ...  | ... | ... | ... |
| LRLL 55 | FD        | 0.25       | 1400       | 0.02      | 0.14 | ...  | ... | ... | ... |
| LRLL 68 | FD        | 10.0       | 1400       | 0.0023    | 0.07 | ...  | ... | ... | ... |

Notes. Column 1: name of target. Column 2: Assigned classification for our targets. We label objects as transitional disks (TDs), pre-transitional disks (PTDs), and full disks (FDs). Column 3: Maximum grain size of dust used for the inner wall of the disk. The superscript $i$ denotes “inner wall.” Column 4: Temperature of the inner wall. Column 5: Height of the inner wall. Column 6: Radius of the inner wall. Column 7: Maximum grain size of dust used for the outer wall of the disk. The superscript $o$ denotes “outer wall.” Column 8: Temperature of the outer wall. Column 9: Height of the outer wall. Column 10: Radius of the outer wall.

For FM 515, the inner wall model required a temperature of 1700 K in order to fit the slope of the NIR emission. In some cases, temperatures $>1400$ K for the inner wall have also been needed to fit the SED previously (e.g., T35, UX Tau A; Espaillat et al. 2010, E11).

We adopt a temperature of 1800 K for the inner wall based upon NIR SpeX spectral fitting (Flaherty et al. 2012).

dust mass transport across the outer disk (see Section 4.4). We also do not expect that the mass accretion rate is constant throughout the disk. However, for simplicity, here we assume that the mass accretion rate measured onto the star is representative of the disk’s accretion rate.

We will discuss how the lack of millimeter constraints leads to degeneracies in our outer disk model fitting in Section 3.3. There we also discuss the effect the adopted disk inclination and outer radius have on the simulated SED. We assume that the inclination of the disk is 60$^\circ$ for all of our objects and that they have an outer disk radius of 300 AU (except FM 581, see Section 3.3).

3.2.2. Dust Properties

The opacity of the disk, and hence the temperature structure and resulting emission, is controlled by dust. The dust opacity depends on the composition of the dust assumed. It also depends on changes in the dust due to grain growth and settling. Grains grow through collisional coagulation and settle to the disk midplane due to gravity. Since in this work we include models of several FDs, here we review the effect that the dust properties have on the disk structure in more detail following D’Alessio et al. (2006).

Dust settling. The settling of dust has important, and often overlooked, effects on the disk’s density–temperature distribution and emission. When there is some degree of settling, the dust-to-gas mass ratio of grains in the disk atmosphere decreases with respect to the standard value (i.e., the diffuse interstellar medium). This has several effects: (1) it decreases the opacity of the upper layers; this allows the impinging external radiation to penetrate deeper into the disk, decreasing the height of the irradiation surface and making it geometrically flatter (see Section 4.4).
Figure 3 in D'Alessio et al. (2006), which in turn decreases the fraction of the irradiation flux intercepted by this surface, de-
creasing the continuum flux emerging from the disk; (2) since most of the external radiation is deposited at the irradiation sur-
face, lowering it changes the temperature–density structure of the atmospheric layers, where the temperature inversion occurs (also called the super-heated layers), modifying their contribu-
tion to the SED; and finally (3) it changes the emissivity of the disk interior; in this region the dust-to-gas mass ratio of the grains increases given that the grains removed by depletion from the upper layers are now located deeper in the disk.

Some of the above-mentioned effects can be accounted for by arbitrarily changing the disk surface height as a function of radius (e.g., Miyake & Nakagawa 1995; Currie & Sicilia-Aguilar 2011; Sicilia-Aguilar et al. 2011), and this will probably give a reasonable estimate of the continuum SED of the disk. However, the contribution of the upper layers to the SED or the role of the deeper layers in millimeter images and emergent flux would not be consistent for this simple approach to settling. On the other hand, taking into account the detailed physics of settling (e.g., Weidenschilling et al. 1997; Dullemond & Dominik 2005; Birnstiel et al. 2011).

In our SED modeling we have adopted a different approach following D'Alessio et al. (2006) by parameterizing settling as a depletion of dust in the upper layers, with a corresponding increment of the dust-to-gas mass ratio near the midplane. The maximum grain sizes in the disk atmosphere and interior are allowed to change, reflecting the possibility of grain growth. We can also vary the height in the disk that separates the atmosphere from the interior as well as the degree of settling. The amount of settling is parameterized by $\epsilon = \varepsilon_{\text{atm}}/\varepsilon_{\text{sd}}$, (i.e., the dust-to-gas mass ratio of the disk atmosphere divided by the standard value). The main point of this approach is that the same grains that determine the height and shape of the irradiation surface and the amount of intercepted external flux are the ones that are emitting in the MIR silicate bands, and their emissivity and temperature distribution are consistent with their properties. Also, the grains near the midplane which are responsible for the mm emergent intensity have a dust-to-gas mass ratio related to the properties of the atmospheric grains. The advantage of such an approach is that, in principle, observations can be used to constrain the grains’ composition, size, and spatial distribution, and this can be related to models of the detailed dust evolution in disks. However, to really fulfill this goal, we need observations that cover a wide range of wavelengths with high resolution. Given our present observations, we have chosen to adopt a radially constant $\epsilon$ and to assume that the interior grains are concentrated very close to the midplane (at $z \lesssim 0.1$ H). These assumptions will not affect the MIR SED (D'Alessio et al. 2006; Qi et al. 2011) and we avoid introducing new sets of free parameters to the problem, retaining the important physical properties of settling.

Dust grain growth. In this work we also change the maximum grain size in the disk. The models assume spherical grains with a distribution of $a^{-p}$ where $a$ is the grain radius between $a_{\text{min}}$ and $a_{\text{max}}$ and $p$ is 3.5 (Mathis et al. 1977). A mixture with a smaller $a_{\text{max}}$ has a larger opacity at shorter wavelengths than a mixture with a larger $a_{\text{max}}$. Since the height of the disk surface, $z_s$, is defined by the region where $\tau_s \sim 1$ small grains will reach this limit higher in the disk relative to big grains. Therefore, disks with a small $a_{\text{max}}$ are more flared than disks with a large $a_{\text{max}}$ for the same dust-to-gas mass ratio. One difference between increasing the settling and increasing the grain size is that with settling, small grains remain in the upper disk layers and so we still see silicate emission while with grain growth in the disk atmosphere, the silicate emission disappears since larger grains do not have this feature in their opacity. In the walls and the outer disk, $a_{\text{min}}$ is held fixed at 0.005 $\mu$m while $a_{\text{max}}$ is varied between 0.25 $\mu$m and 10 $\mu$m to achieve the best fit to the silicate emission features. In the outer disk, there are two dust grain size distributions as mentioned above. In the disk interior the maximum grain size is 1 mm (D'Alessio et al. 2006). The maximum grain size of the disk atmosphere is adjusted as noted earlier.

Dust composition. The composition of dust used in the disk model impacts the resulting SED and derived disk properties (see Espaillat et al. 2010 for a discussion). We follow E11 and perform a detailed dust composition fit for the silicates seen in the IRS spectra including olivines, pyroxenes, forsterite, enstatite, and silica. We list the derived silicate mass fractions in Tables 6 and 7 below. In addition to silicates, we also included organics, troilite, and water ice following Espaillat et al. (2010) and E11. We note that only silicates exist at the high temperatures at which the inner wall is located. In transitional and pre-transitional objects where we include optically thin dust within the hole, the silicate dust composition and abundances are listed in Tables 8 and 9 below, respectively.

3.3. SED Modeling

In this work, we present the first detailed modeling of disks with IRS spectra in NGC 2068 and IC 348. We find that all the objects are reasonably reproduced with TD, PTD, or FD models. It is not the goal of this paper to find a unique fit to the SED. To arrive at a unique fit, one would ideally have a finely sampled, multi-wavelength SED as well as spatially resolved data at multiple wavelengths. Finely sampled data on the time domain would also be necessary since the emission of TTS is known to be variable (e.g., Espaillat et al. 2011). Given that this situation is not currently achievable, here we focus on finding a fit that is consistent with the observations presented in this work. Our assumptions of the disk structure are an oversimplification. Recent hydrodynamical simulations show that the inner regions of TDs and PTDs should be complex (Zhu et al. 2011; Dodson-Robinson & Salyk 2011). However, in the absence of data capable of confirming these simulations, we proceed with our simple model. We discuss additional assumptions and how they play into the degeneracies of our modeling in Section 4.2. We present details of the derived dust composition in Appendix A.

3.3.1. Results

We find a large range of hole and gap sizes for our TDs and PTDs. Our TDs have holes spanning 4 to 49 AU (Figure 5, Table 4). Our PTD targets have gaps ranging from 5 to 45 AU.
Figure 5. IR SEDs and disk models (solid, black lines) of transitional and pre-transitional disks in our sample. Here, we show only the dereddened data from Figures 2 and 3. Refer to Section 3.3 and Table 4 for model details. Separate model components are the stellar photosphere (magenta dotted line), the inner wall (gray short-long-dashed line), the outer wall (red dot-short-dashed line), and the optically thin small dust located within the inner disk (green long-dashed line).

(17) The three objects easily identified by dips in the SED (FM 515, FM 618, LRLL 31) have gap sizes of 11–45 AU. We note that here we classify LRLL 21 as a PTD even though its NIR emission is weaker than the other PTDs in our sample and it resembles the emission expected from a TD. Flaherty et al. (2012) find that LRLL 21 has significant NIR emission in more recent IRS observations, pointing to strong intrinsic variability in the inner disk linked to changes in the inner wall (Espaillat et al. 2011). Therefore, here we classify LRLL 21 as a PTD. Another PTD in our sample that is not obvious based on its SED alone is LRLL 37 which has the smallest gap size in our sample (5 AU; Figure 6). It is not possible to fit the IRS data of LRLL 37 with an FD model, even within the uncertainties of the observations. In particular, we could not fit the strong 10 μm silicate emission with our FD model. This could be a sign that LRLL 37 is a PTD with a small gap that contains some small optically thin dust, reminiscent of RY Tau (E11) and we will return to this point in Section 4.1.

(17) As mentioned in Section 3.2, we do not include an inner disk behind the inner wall. Espaillat et al. (2010) find that the inner wall dominates the NIR emission of PTDs. Pott et al. (2010) confirm that the inner disks in PTDs are small. High resolution imaging is needed to further constrain the gap sizes of the objects presented in this work.

Most of the TDs and PTDs have small optically thin dust within the inner 1 AU of the hole or gap. The exceptions are the transitional disk LRLL 72, where we find that the 10 μm silicate emission can be produced by the optically thin atmosphere of the outer wall, and the pre-transitional disk LRLL 31, where the 10 μm silicate emission comes from the inner wall’s atmosphere and optically thin dust within the gap is not necessary to fit the observations. The mass of dust and sizes of the grains in this region are given in Appendix A.
Figure 6. Left: IR SED and full disk model fit of LRLL 37. We cannot successfully reproduce the 10 μm and 20 μm emission. This disk model has $\epsilon = 0.001$, $\alpha = 0.0008$, and $a_{\text{max}} = 0.25$ μm. Right: IR SED and pre-transitional disk model of LRLL 37. We can fit the strong silicate emission with a model that has a gap in the disk with most of the silicate emission arising from small, optically thin dust within the gap. The color scheme, symbols, and lines are the same as in Figure 2. (A color version of this figure is available in the online journal.)

Figure 7. Left: IR SEDs and disk models of the pre-transitional disk LRLL 31 and the transitional disk LRLL 67. Right: broadband SEDs and disk models of LRLL 31 and LRLL 67 which include SMA millimeter data (from this work). With millimeter data we can constrain the outer disk and so we include both the outer wall and the disk behind it in the model presented here (red dot-short-dash). We also show the contribution to the SED from the inner wall of LRLL 31 (gray short-long-dash) and the optically thin small dust located within the inner hole of LRLL 67 (green long-dash). Other symbols and lines are the same as used in Figure 2. (A color version of this figure is available in the online journal.)

detections for FM 581, LRLL 2, LRLL 6, LRLL 55, and LRLL 68 and so we cannot constrain the mass of the disk. Therefore, the models presented here are more uncertain, but we show them to illustrate that a disk model with dust settling and no holes or gaps in the disk can reproduce the observed SEDs. We do have an upper limit for the millimeter flux of LRLL 68 and we use this object as an example to discuss the degeneracies inherent in the modeling presented, mainly due to lack of millimeter detections, in Section 3.3.2. To briefly summarize, disk models with the same $\epsilon$-to-$\alpha$ ratio will produce very similar emission in the IR but substantially different emission in the millimeter. Therefore, millimeter data are crucial to disentangle this degeneracy and the disk parameters in this work should only be taken as indicative of a model that can reproduce the observed SEDs.

With the above degeneracies in mind, we limited our parameter search and set $\epsilon = 0.001$, changing only $\alpha$ until we achieved a good fit to the SED. We could have also set $\alpha$ to a certain value and fit for $\epsilon$ instead, however, as mentioned above and as discussed in Section 3.3.2, $\epsilon/\alpha$ is the most relevant result. For LRLL 2, LRLL 55, and LRLL 68 we find $\alpha = 0.06, 0.004, 0.006$, respectively. For LRLL 6 using an $\epsilon$ of 0.001 required $\alpha > 0.1$ which would lead to a viscous timescale shorter than the lifetime of the disk (Hartmann et al. 1998), so instead we set $\epsilon = 0.0001$; the best-fitting $\alpha$ in this case was 0.1. To fit the very steep downward slope of FM 581, we needed to significantly
Figure 8. IR SEDs and disk models of full disks in our sample. We can explain all of these disks with irradiated accretion disk models which incorporate dust settling. In the case of FM 581, we need to truncate the outer disk radius to < 1 AU in order to reproduce its very steep slope. Refer to Section 3.3 and Table 4 for model details. Here, we show the contribution to the SED from the stellar photosphere (magenta dotted line), the inner wall (gray short-long-dash), and the outer disk (red dot-short-dash).

(A color version of this figure is available in the online journal.)

Truncate the outer disk radius down to 0.6 AU. We fit FM 581 with $\epsilon = 0.001$ and $\alpha = 0.00006$.

3.3.2. Model Degeneracies and Millimeter Constraints

Here, we explore the degeneracies introduced into the modeling presented in this paper due to the lack of millimeter data. Rather than do this for each object, we selected LRLL 68 for this test since it has an upper limit to its millimeter flux at 860 $\mu$m from the SMA observations reported in this paper.

First, disk models (around the same star) with the same $\epsilon$-to-$\alpha$ ratio will have SEDs with similar emission in the IR. This is because disks with equal $\epsilon/\alpha$ have similar disk surfaces. The disk surface is defined as the point in the upper disk layers where the radial optical depth (which depends on the product of the opacity and column density) to the stellar radiation reaches one. $\epsilon$ determines the abundance of small dust (i.e., the opacity of the upper disk layers) while $\alpha$ affects the surface density. Therefore, in disks with equal $\epsilon/\alpha$ the same fraction of stellar flux will be intercepted by the disk. Since the IR is dominated by the upper layers of the inner disk, their emergent intensity in the IR will be similar.

While the IR emission is similar, the emission seen in the millimeter will be different. A disk with an $\alpha$-viscosity has a mass surface density given by $\Sigma \approx M \Omega_k / \alpha \langle c_s \rangle$, where $\Omega_k$ is the Keplerian angular velocity and $\langle c_s \rangle$ is the sound speed. This implies that the disk mass, for a given disk radius and similar outer disk temperature distribution, would be proportional to $\alpha^{-1}$. Therefore, a disk with a smaller $\alpha$ will have a larger disk mass. In the millimeter, we are more sensitive to the big grains in the midplane of the disk, where most of the disk’s mass is stored, and so disks with small $\alpha$ and a higher column density will have more millimeter emission. This means that models with similar $\epsilon \cos(i) \dot{M}/\alpha$ would have similar IR SEDs, but different millimeter SEDs. Millimeter data are necessary to disentangle this degeneracy.

Because of the above, we can find a best-fit $\epsilon/\alpha$ to the IR emission if we hold $i$ and $\dot{M}$ constant. However, each model will have different emission in the millimeter and since we have no millimeter data, we cannot claim that a particular combination of $\epsilon$ and $\alpha$ is better than another. For the models shown in Figure 9 (Models 1, 2, and 3 in Table 5) we hold the mass accretion rate, stellar parameters, inclination ($i$), and outer disk radius $R_d$ fixed and change only $\epsilon$ and $\alpha$. We set $\epsilon$ to 0.0001, 0.001, 0.01, and 0.1, the values given in D’Alessio et al. (2006) and fit the SED by changing $\alpha$. We do not discuss cases where $\alpha \geq 0.1$ since these disks would have short viscous timescales (Hartmann et al. 1998). For LRLL 68, we find that the best-fitting $\epsilon/\alpha$ is 0.2.
Figure 9. Disk model fits to the SED of LRLL 68 with $\epsilon/\alpha = 6$. Models with the same $\epsilon$-to-$\alpha$ ratio will have similar emission in the IR but substantially different emission in the millimeter. Here, we show the following models from Table 5: Model 1 ($\epsilon = 0.0001$; short-dashed line), Model 2 ($\epsilon = 0.001$; dotted line), and Model 3 ($\epsilon = 0.01$; long-dashed line). Note that each model falls below the millimeter upper limit presented in this work (open triangle). This reflects the need for millimeter detections to constrain disk models. (A color version of this figure is available in the online journal.)

Table 5

| Model | $i$ (°) | $R_d$ (AU) | $\epsilon$ | $\alpha$ | $M_{\text{disk}}$ ($M_\odot$) |
|-------|--------|-----------|-----------|---------|-----------------|
| 1     | 60     | 100       | 0.0001    | 0.0006  | 0.005           |
| 2     | 60     | 100       | 0.001     | 0.006   | 0.0005          |
| 3     | 60     | 100       | 0.01      | 0.06    | 0.000004        |
| 4     | 60     | 300       | 0.001     | 0.006   | 0.001           |
| 5     | 60     | 20        | 0.001     | 0.006   | 0.00001         |
| 6     | 20     | 100       | 0.001     | 0.006   | 0.001           |
| 7     | 40     | 100       | 0.001     | 0.006   | 0.001           |
| 8     | 80     | 100       | 0.001     | 0.006   | 0.001           |

We also look at how varying the outer disk radius and inclination affect the simulated SED. Changing the radius changes the mass of the disk but the millimeter emission does not change significantly (Figure 10). This is because the mass depends on the disk radius ($M_d = \int_{R_i}^{R_d} \Sigma 2\pi R dR$). However, the column density of the annuli contributing to the mm flux remains the same. This highlights that disk sizes cannot be firmly constrained without resolved imaging. We find that changing the inclination angle while holding other parameters fixed changes the IR emission, but does not significantly alter the millimeter emission. In order of increasing inclination (i.e., from nearly face-on to nearly edge-on) we show the following models from Table 5: Model 6 ($i = 20^\circ$; short-long-dashed line), Model 7 ($i = 40^\circ$; dot-long-dashed line), Model 4 ($i = 60^\circ$; dotted line), and Model 8 ($i = 80^\circ$; dot-short-dashed line). (A color version of this figure is available in the online journal.)

(Dullemond et al. 2001). If the wall is curved, we would expect to see more emission at lower inclinations (Isella & Natta 2005).
4. DISCUSSION

4.1. Limitations of Observations

As discussed by Espaillat et al. (2010), the sizes of gaps and holes we can detect in the disk are limited by broadband SEDs. Given that the majority of the emission at \( \sim 10 \mu m \) in a typical disk traces the dust within the inner 1 AU of the disk (D'Alessio et al. 2006; Espaillat 2009), the Spitzer IRS instrument will be most sensitive to clearings in which much of the dust located at radii \(< 1 \) AU has been removed. Because of this, IRS is more effective in picking out disk holes where dust at small radii has been removed. However, IRS cannot easily detect gaps whose inner boundary is outside of \( \sim 1 \) AU. For example, a disk with a gap ranging from 5 to 10 AU will be difficult to distinguish from an FD (Espaillat et al. 2010). The gaps currently inferred solely from SEDs, which have been modeled and imaged in the millimeter, are typically quite large. This reflects an observational bias toward picking out PTDs with large gaps since their mid-infrared deficits will be more obvious in Spitzer spectra. Smaller gaps will not have as obvious of a deficit and will be difficult to detect. Broadband colors from IRAC and MIPS have their limitations as well. They are useful for picking out TDs, but it is difficult to distinguish the NIR colors of a PTD from an FD.

LRLL 37 may be a case of a disk with a small 5 AU gap. The dip in the SED is not obvious, but the strong silicate emission seen in this object is reminiscent of RY Tau. RY Tau has a large cavity in its disk based on millimeter imaging (Isella et al. 2010) and its SED was modeled with a gap of \( \sim 20 \) AU (E11). There are many other disks that exhibit strong 10 \( \mu m \) silicate emission (Furlan et al. 2009) and perhaps this is a hint pointing to small gaps in disks. That said, we cannot exclude the presence of small gaps in what we have labeled FDs in this paper or for that matter any FDs in general. High-resolution imaging is crucial to investigate this further and current TD fractions should be taken as lower limits.

4.2. Limitations of Models

The underlying physical structure inferred from the SED is dependent on the model one uses. For example, there are five disks in Taurus with decreasing emission at IR wavelengths, much like the disks studied in this work, that have seemingly contrasting interpretations presented by Luhanan et al. (2010) and Currie & Sicilia-Aguilar (2011). The main difference between the two papers is in the models adopted. Currie & Sicilia-Aguilar (2011) use the model grid presented in Robitaille et al. (2007). The authors account for the observed SEDs by decreasing the mass of models with well-mixed gas and dust in the disk (i.e., a disk with no settling) to the point where it becomes entirely optically thin. The Luhman et al. (2010) results are based on synthetic colors from the model grid of Espaillat (2009). Those models are the same in this work, where dust settling is incorporated. Luhman et al. (2010) can reproduce the observed colors with disks that have dust settling. To illustrate that a settled disk can reproduce the broadband SED as well, in Appendix B we model ZZ Tau, one of the five disks in question. Therefore, it becomes clear that the different interpretation between the two groups is biased by the models adopted. The most one can say is that both a well-mixed low-mass disk and a settled disk can reproduce the observations. In the former case the disk is optically thin to its own radiation at all radii; for the latter case the innermost disk is still optically thick to its own radiation.

Sicilia-Aguilar et al. (2011) also independently find that they need to incorporate settling to reproduce the SED of objects with decreasing IR emission. We note that the implementation of settling in that work and ours is very different. Sicilia-Aguilar et al. (2011) simulate settling in their modeling by lowering the disk surface, but its shape remains the same. In addition, the dust-to-gas mass ratio is held fixed throughout the disk (i.e., there is no dust depletion in the upper disk layers). Since the surface is still flared and the opacity remains the same, the disk is hotter than it would be if the disk was geometrically flatter and the opacity was lower. Therefore, such a disk will produce more emission and there will be an inherent bias toward decreasing the disk mass in order to reproduce lower observed fluxes. In the models used in this work we deplete the small grains in the upper atmosphere of the disk and self-consistently calculate the disk height and shape. This is an iterative process given that the height of the disk irradiation surface dictates how much energy is captured by the disk and this depends on the opacity set by the dust properties and the density of the disk, which in turn depends on the temperature through the scale height. We note that it is still possible to have a disk which is both settled and low mass. Our point is that in order to constrain the disk mass and avoid the degeneracies discussed in Section 3.3.2, millimeter data are necessary and the full effects of dust settling need to be taken into account.

This leads to another issue that is quite model dependent: the disk mass. Not only does the disk mass depend on the opacity one assumes, it also depends on the surface density and temperature radial profiles. For example, our mass determinations (i.e., E11) are consistently higher than Andrews & Williams (2005) since our opacities are \( \sim 3 \) times lower, we assume the outer disk radius is larger, and we use a self-consistent surface density and temperature instead of power-law approximations. Therefore, masses obtained by different models cannot be meaningfully compared.

4.3. Disk Structure and Semantics

There are many terms in the literature aiming to categorize SEDs of TTS surrounded by disks. At times this leads to confusion. For example, what some researchers call a TD others would call an anemic disk or an evolved disk or a homologously depleted disk. The effect of not consistently applying the term “transitional” in the literature is seen when looking at TD fractions in the literature. Some call “transitional” any objects whose SED does not resemble the median SED of Taurus. Others use the more restrictive definition of disks that have holes. If we only consider objects with IR dips in their SEDs as transitional, the TD fraction is lower; including objects with decreasing emission at all wavelengths increases the reported TD fraction from 20% to 70% at \( \sim 10 \) Myr (Muzerolle et al. 2010). This difference is not trivial and presents an unclear picture when attempting to compare theoretical simulations of planet formation that predict disk holes with a TD fraction that encompasses objects which do not have apparent evidence for cleared regions in their disks, as also discussed by Alexander (2008).

Another related issue is encountered when trying to discern the disk clearing timescale. These timescales usually include TDs and PTDs and evolved disks (which are optically thin), and are measured with respect to FDs. Defining the boundaries between transitional, pre-transitional, evolved, and full disks is crucial in order to obtain an accurate estimate of the disk clearing timescale. TDs are relatively easier to identify, whether looking
Currie & Sicilia-Aguilar (2011) use a disk mass of 0.001 $M_\odot$ for homologously depleted disks, which is highly dependent on the cutoff. Reported fraction of optically thin disks (i.e., evolved disks or transitional disks) based on colors alone. Evolved disks are also difficult to identify a gap in the IR color–color diagrams which leads to fewer objects in this phase. Here, we suggest that the term “transitional” be used for disks with weak MIR emission could instead be the result of another mechanism that may have a different rate of evolution (e.g., photoevaporation). Alternatively, FDs with SEDs such as those in this paper could simply be the tail end of continuous distribution of FDs. This could be related to a large spread in disk properties ($M$, $M_\text{dust}$, composition) in a given population as well as a distribution in the initial conditions. Another possibility, that we cannot fully test in this paper due to a lack of millimeter detections, is that the FDs in our sample have experienced a greater degree of dust settling than other FDs. In this case, we would see more of these disks in older regions since settling is expected to increase with age.

4.4. Mass Accretion Rates of Transitional and Pre-transitional Disks

Najita et al. (2007) showed that the mass accretion rates of TDs in Taurus tend to be lower than those of FDs in the same region. If planets are the clearing agent in TDs, then lower mass accretion rates are expected onto the star since a giant planet that opens a gap in the disk will intercept and accrete material from the outer disk (Lubow & D’Angelo 2006). To explore this further we compared the distribution of mass accretion rates of FDs and TDs and PTDs in Taurus, Chamaeleon, and NGC 2068 (Figure 12; see Appendix C for details). We note that Najita et al. (2007) used a broader definition of TD which included all objects with less emission than the median SED of Taurus. As discussed in Section 4.3, the link between these disks and planet formation is less clear. Therefore, here we use our more restrictive definition of TD and PTD which includes only objects with holes and gaps. We find that the mass accretion rates of TDs and PTDs tend to be ~5 times lower than the FDs in these three regions. The median mass accretion rate for the FDs is $1.3 \times 10^{-8} M_\odot$ yr$^{-1}$ and for the TDs and PTDs it is $3.1 \times 10^{-9} M_\odot$ yr$^{-1}$. A Kolmogorov–Smirnov (K-S) test indicates that the FD and TD and PTD mass accretion rate samples are not drawn from the same distribution (the K-S probability is 0.02).

While the mass accretion rates of TDs and PTDs are overall lower than those of FDs, they are still too high to be compatible with current models of disk clearing by planets. This is especially seen in the cases of TDs and PTDs with higher mass accretion rates and large gaps and holes. Zhu et al. (2011) find that multiple planets are needed to open these large clearings in the dust distribution. However, more planets in the disk should lead to lower mass accretion rates onto the star than those observed. Our results suggest that multiple planets in TDs and PTDs could be lowering the mass accretion rate onto the disk.

![Figure 12](image_url) Distribution of mass accretion rates for Taurus, Chamaeleon, and NGC 2068. We separate full disks (white area) and transitional and pre-transitional disks (shaded area); overall, transitional and pre-transitional disks have lower mass accretion rates than full disks.

(A color version of this figure is available in the online journal.)
star somewhat, but that there is another mechanism taking effect that we have not accounted for, possibly dust evolution as proposed by Zhu et al. (2011). More simulations of disk clearing by planets are needed to reconcile the large gap sizes and mass accretion rates currently observed.

We also see that the TDs tend to have lower mass accretion rates than the PTDs in our sample, by a factor of $\sim 10$. The median mass accretion rate for our five TDs is $9.7 \times 10^{-10} \, M_\odot \, \text{yr}^{-1}$ while the median for the 10 PTDs in the sample is $8.8 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$. (More observations of PTDs and TDs are needed to expand the sample size and confirm this result given that the K-S probability that the samples are drawn from the same distribution is 0.27.) Given that the evolution and relationship between TDs and PTDs is not currently completely understood, the underlying reason for this apparent discrepancy in mass accretion rates is not obvious. One can speculate that the difference is due to the same mechanism clearing the holes and gaps in these disks. In the case of planet formation, Zhu et al. (2011) find that the mass accretion rate onto the star will decrease with time as planets grow in the disk. The difference in mass accretion rate between PTDs and TDs could then possibly indicate that PTDs are in the early stages of planet formation while TDs are in the later stages. However, refinement of planet forming simulations is needed to study this further given the complex structure expected in the inner disk region.

5. SUMMARY

Here, we modeled the broadband SEDs of 15 disks in NGC 2068 and IC 348. We presented IRS spectra for all our targets as well as mass accretion rates estimated with $U$-band photometry obtained at the MDM Observatory and H$_2$ profiles from the MIKE spectrograph on the Magellan telescope. We also presented SMA millimeter data for some of our sources in IC 348.

The observed SEDs of the objects in our sample are diverse, yet can be separated into three groups. Some of our targets have dips in both their NIR and MIR emission, some have dips only in their MIR emission, and some have decreasing emission at all IRS wavelengths. We modeled the first group as TDs (i.e., objects with holes in their disk’s dust distribution), the second group as PTDs (i.e., objects with gaps in their disk’s dust distribution), and the last group as FDs (i.e., objects with no cleared regions in their disks). We found that millimeter data are crucial in breaking model degeneracies between the amount of dust settling in the disk and the disk’s mass.

### Table 6

| Target | Amorphous Olivine | Amorphous Pyroxene | Crystalline Forsterite | Crystalline Enstatite | Crystalline Silica |
|--------|-------------------|-------------------|-----------------------|----------------------|------------------|
| FM 177 | 80                | ...               | 10                    | ...                  | 10               |
| FM 281 | 90                | ...               | ...                   | ...                  | 10               |
| FM 515 | 100               | ...               | ...                   | ...                  | 10               |
| FM 618 | 100               | ...               | ...                   | ...                  | ...              |
| LRLL 21| 80                | ...               | 20                    | ...                  | ...              |
| LRLL 31| 80                | ...               | ...                   | 20                   | ...              |
| LRLL 37| 70                | ...               | 20                    | 10                   | ...              |
| LRLL 67| 100               | ...               | ...                   | ...                  | ...              |
| LRLL 72| 60                | 30                | 5                     | 5                    | ...              |
| LRLL 133| 90              | ...               | 10                    | ...                  | ...              |

### Table 7

| Target | Amorphous Olivine | Amorphous Pyroxene | Crystalline Forsterite | Crystalline Enstatite | Crystalline Silica |
|--------|-------------------|-------------------|-----------------------|----------------------|------------------|
| FM 581 | 60                | ...               | 20                    | 10                   | 10               |
| LRLL 2 | 60                | ...               | 20                    | 10                   | 10               |
| LRLL 6 | 50                | ...               | 20                    | 10                   | 20               |
| LRLL 55| 80                | ...               | ...                   | 5                    | 5                |
| LRLL 68| 85                | ...               | 5                     | 5                    | 5                |

We discussed the limitations of the observations, namely, that we currently do not have high enough resolution to discern very small gaps in disks, and the limitations of disk models, especially with respect to simulating the effects of dust settling and determining masses. We pointed out that much of the disagreement in the literature over reported TD frequencies and disk clearing timescales is mainly due to inconsistent application of the term “transitional” in the literature. We suggested that only objects showing evidence of an abrupt change in their radial disk structure be referred to as “transitional.” Specifically, here we use TD when referring to disks with holes and PTD for disks with gaps. Finally, we compared the mass accretion rates of TDs and PTDs to FDs in Taurus, Chamaeleon, and NGC 2068 and find that PTDs and TDs have lower accretion rates overall. We also find that the TDs have lower mass accretion rates than PTDs, but due to our small sample more objects are needed to confirm this.

Significant progress will be made in the near future on the issues raised in this paper. Herschel SPIRE will provide us with a large, consistent sample of submillimeter fluxes to help break model degeneracies. With the high resolution of ALMA we can soon test if the above classifications used in this paper hold and modify them if necessary.

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APPENDIX A

DUST COMPOSITION OF SAMPLE

We performed fitting of the silicate emission features visible in the IRS spectra and derived the mass fraction of amorphous and crystalline silicates in the disk (Tables 6–8). See E11 for a discussion of the degeneracies inherent in deriving the dust composition. The results here should be taken as representative of a dust composition that can reasonably explain the observed silicate features in the SED. We leave it to future work to further constrain the mass fractions of silicates in these disks.

For the inner wall of our pre-transitional objects, we adopted a silicate composition consisting solely of amorphous olivines. This is because the inner wall does not produce significant 10$\mu$m silicate emission in most of the objects in this study and so we have no way to distinguish between pyroxene and olivine silicates in the inner wall. The exception is LRLL 31 where we need 60% amorphous olivine and 40% forsterite in the inner wall in order to fit the 10$\mu$m silicate emission feature. For TDs and PTDs we changed the silicate composition in the optically thin dust region and outer wall to fit the SED (Table 7).
Table 8
Mass Fraction (in %) of Silicates in Optically Thin Dust Region in Transitional and Pre-transitional Objects

| Target | Amorphous | Amorphous | Crystalline | Crystalline | Crystalline | Crystalline |
|--------|-----------|-----------|-------------|-------------|-------------|-------------|
|        | Olivine   | Pyroxene  | Forsterite  | Enstatite   | Silica      |             |
| FM 177 | 20        | ...       | 40          | 40          | ...         |             |
| FM 281 | 80        | ...       | 20          | ...         |             |             |
| FM 515 | 100       | ...       | ...         | ...         | ...         |             |
| FM 618 | 100       | ...       | ...         | ...         | ...         |             |
| LR LL 21 | 50       | ...       | 20          | ...         |             |             |
| LR LL 31 | ...     | ...       | ...         | ...         | ...         |             |
| LR LL 37 | 40       | ...       | 20          | 20          | ...         |             |
| LR LL 67 | 95       | 5         |             |             |             |             |
| LR LL 72 | ...     | ...       | ...         | ...         | ...         |             |
| LR LL 133 | 90      | ...       | 10          | ...         | ...         |             |

Notes. For LR LL 31, we did not need an optically thin region to account for the 10 μm silicate emission. This feature comes from the inner wall which has 60% amorphous olivine and 40% crystalline forsterite.

Table 9
Properties of Optically Thin Dust Region in Transitional and Pre-transitional Objects

| Target | Organics (%) | Troilite (%) | Silicates (%) | $M_{\text{dust}}$ (10^{-12} $M_\odot$) | $a_{\text{max}}$ (μm) |
|--------|--------------|--------------|---------------|--------------------------------------|----------------------|
| FM 177 | 42           | 11           | 47            | 2                                    | 5                    |
| FM 281 | 19           | 15           | 66            | 0.9                                  | 0.25                 |
| FM 515 | 19           | 15           | 66            | 0.8                                  | 0.25                 |
| FM 618 | 12           | 9            | 79            | 2                                    | 3                    |
| LR LL 21 | 19       | 15           | 66            | 0.6                                  | 2                    |
| LR LL 37 | ...     | ...          | ...           | ...                                  | ...                  |
| LR LL 67 | 26       | 14           | 60            | 7                                    | 5                    |
| LR LL 72 | ...     | ...          | ...           | ...                                  | ...                  |
| LR LL 133 | 42      | 11           | 47            | 6                                    | 0.25                 |

Note. We use a minimum grain size of 0.005 μm in the optically thin dust region.

For the FDs, we changed the silicate composition in the inner wall and disk (Tables 6 and 8). The silicate composition was not allowed to vary between the inner wall and disk in the FD models.

APPENDIX B
COMMENTS ON FITTING ZZ TAU WITH A SETTLED, IRRADIATED ACCRETION DISK MODEL

Here, we present modeling of the SED of ZZ Tau using the disk model of D’Alessio et al. (2006) discussed in Section 3.2. Stellar parameters used in the disk model ($L_*= 3470$ K; $L_*= 0.75 L_\odot$; $M_* = 0.35 M_\odot$; $R_* = 2.4 R_\odot$) were derived in the same manner as other objects in this work (see Section 3.1) using a spectral type of M3 adopted from Kenyon & Hartmann (1995) and a visual extinction ($A_V$) of 0.98 using $R_V = 3.1$ from Furlan et al. (2011). We adopt a mass accretion rate of $1.3 \times 10^{-9} M_\odot$ yr⁻¹ from White & Ghez (2001). We note that this is slightly higher than the mass accretion rate measured from $U$-band photometry ($9 \times 10^{-10} M_\odot$ yr⁻¹).

In Figure 13, we present two models with different outer radii. In one model we use an outer disk radius of 100 AU for comparison with previous modeling performed by Currie & Sicilia-Aguilar (2011). The best-fit parameters are $\epsilon = 0.001$ and $\alpha = 0.02$ and this disk has a mass of $5 \times 10^{-4} M_\odot$. We also explored disks with other $\epsilon$ values. A disk with a higher $\epsilon$ of 0.01 needs an $\alpha$ of 0.2 to fit the SED, but this $\alpha$ results in a viscous timescale shorter than the lifetime of the disk (Hartmann et al. 1998). A disk with $\epsilon = 0.0001$ and $\alpha = 0.002$ with a higher mass of 0.005 $M_\odot$ is excluded by the millimeter upper limits. Here, we use amorphous silicates to fit the disk with $a_{\text{max}} = 10 \mu$m. Crystalline silicate features are evident in the IRS spectrum (Sargent et al. 2009), but we leave a detailed fit to M. K. McClure et al. (2012, in preparation). In Figure 14, we show that ZZ Tau is optically thick to its own radiation ($\tau_{\text{Ross}} > 1$) out to about ~1 AU in the disk. Over 80% of the emission seen at 40 μm is from within these radii (see Figure 2.16 in Espaillat 2009). Therefore, the optically thick part of the disk of ZZ Tau dominates the emission seen in the IRS spectrum.

We also present a model with an outer radius of 3 AU in Figure 13. This is because ZZ Tau is a close binary with a separation of 0.06 (Schafer et al. 2006), which corresponds to 8 AU at the distance of Taurus (140 pc). Therefore, the IRS spectrum presented here includes both objects. (ZZ Tau IRS, which is 36° away, did not enter the IRS slit and could be a wide companion Furlan et al. 2011.) If a circumbinary disk is present, its inner edge would be located at ~16 AU according to expectations of dynamical clearing by companions (Artymowicz & Lubow 1994). However, we detect NIR blackbody emission which indicates that instead we are seeing a circumprimary disk. In this case, the outer edge of the disk would be truncated to ~3 AU (Artymowicz & Lubow 1994) and have a mass of $2 \times 10^{-3} M_\odot$. As discussed in Section 3.3.2 and shown in Figure 14, since the IRS emission is dominated by the inner AU of the disk, changing the outer radius of the disk does not significantly alter the IR emission.
Figure 13. ZZ Tau is optically thick to its own radiation ($\tau_{\text{Ross}} > 1$) out to $\sim 1$ AU in the disk. It is these innermost disk radii that dominate the emission seen in the IRS spectrum.

APPENDIX C

COMMENTS ON THE DISTRIBUTION OF MASS ACCRETION RATES

When plotting the distribution of mass accretion rates of FDs and TDs and PTDs in Taurus, Chamaeleon, and NGC 2068 (Figure 12) we restricted ourselves to TDs and PTDs whose SEDs have been modeled. The mass accretion rates for TDs and PTDs are taken from Espaillat et al. (2011) for Taurus and Chamaeleon and from this work for NGC 2068. The mass accretion rates for FDs in Taurus were taken from Najita et al. (2005a). In total we have 45 FDs and 15 TDs and PTDs.

We note that the majority of these mass accretion rates are derived using $U$-band photometry and the relation in Gullbring et al. (1998). The exceptions are objects in NGC 2068. The mass accretion rates for TDs and PTDs in NGC 2068 are taken from this work and the mass accretion rates for the FDs are adopted from Flaherty & Muzerolle (2008). In Section 3.1.1, we discuss the derivation methods used in both works. In short, the typical error (a factor of 2–3) inherent to mass accretion rate estimation methods should not lead to systematic differences between different samples.
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