The Morphologies and Lifetimes of Transitional Protoplanetary Disks

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Abstract. I describe new constraints on the lifetimes and morphologies of transitional protoplanetary disks from observations of 1–10 Myr old stars with the Spitzer Space Telescope. New Spitzer results clearly show evidence for two kinds of transitional disks and thus two main disk evolutionary pathways: disks which form an inner hole/gap and clear from the inside out and disks that deplete more homologously. Analyzing the disk populations of 1–10 Myr old clusters such as Taurus, IC 348, NGC 2362, and η Cha show that the mean transitional disk lifetime must be an appreciable fraction of the mean protoplanetary disk lifetime: ≈ 1 Myr out of 3–5 Myr. The varieties of transitional disk SEDs and correlations with other disk diagnostics are consistent with multiple mechanisms responsible for clearing disks.

1 Background

Transitional protoplanetary disks bridge the evolutionary gap between luminous optically-thick primordial disks of gas and small dust, which presumably have yet to make planet-mass bodies and gas-poor/free optically-thin debris disks, which have ended any gas giant planet formation (Strom et al. 1989; Currie et al. 2009). Stars surrounded by transitional disks have near-to-mid IR dust emission intermediate between primordial disk-bearing stars and diskless photospheres, implying that much of their solid mass is in the process of being lost from the system and/or incorporated into large planetesimals/protoplanets. Ground-based studies of transitional disks from IR to submm photometry find evidence for structural features in these disks, large inner holes/gaps in the disks’ dust distribution, indicative of active disk dispersal (e.g. Calvet et al. 2002). Thus, transitional disks may provide valuable insights into how and when planet formation ends.

The unprecedented mid-IR sensitivity of the Spitzer Space Telescope made spectroscopic observations of nearby transitional disks and photometry for many transitional disks beyond ~ 200–400 pc accessible for the first time. In this contribution, I summarize new Spitzer results that clarify our understanding of morphologies and lifetimes of transitional disks.
These results reveal two types of transitional disks, which may be evidence for a range of mechanisms responsible for dispersing disks and show that the transitional disk phase typically comprises an appreciable fraction of the total protoplanetary disk lifetime. Furthermore, analyzing the accretion frequency/rate and submillimeter fluxes of transitional disks provides some insight into the processes that are plausibly responsible for transitional disk morphologies and thus potentially crucial for dispersing disks and shutting off planet formation.

2 Spitzer Results on the Morphologies of Transitional Disks

Like primordial disks, transitional disks are considered to be a particular kind of “first-generation”, protoplanetary disk. Unlike primordial disks, they show strong evidence of dust removal. While some early papers discussing transitional disks differed about how this dust removal proceeds (e.g. Strom et al. 1989; Skrutskie et al. 1990), pre-Spitzer studies typically associated the term “transitional disk” with “disks with inner holes”. Such disks show the most dramatic evidence for dust clearing, clearing in such disks could be confirmed by spatially-resolved imaging, and physical processes responsible for disk dispersal often lead to an inside-out clearing (e.g. Clarke et al. 2001; Quillen et al. 2004). New Spitzer results better characterize the properties of transitional disks with inner holes and also find that transitional disks may also have a second morphology, exhibiting a more global or ‘homologous’ depletion of dust. Below, we describe properties of both transitional disk morphologies in more detail.

- Transitional disks with inner holes/gaps have photospheric or weak, optically-thin 5–10 $\mu m$ emission unlike primordial disks but have more optically-thick emission at longer wavelengths (e.g. 10–20 $\mu m$) like primordial disks. Because longer wavelength emission preferentially originates from colder, more distant regions of a disk, their SEDs provide evidence for a substantial depletion of warm dust with respect to their cold dust population. The strong radially-dependent clearing of dust in these disks implies an inside-out dispersal of dust.

The presence of an inner hole is consistent with sophisticated SED modeling of photometric and spectroscopic data (e.g. Calvet et al. 2005) and confirmed by spatially-resolved submillimeter observations (e.g. Hughes et al. 2009). A slight variant on this morphology is a disk whose weak mid-IR emission provides evidence for large disk regions with optically-thin warm dust and an optically-thick outer disk made of cold dust but whose near-IR emission reveals optically-thick hot dust close to the star. The SEDs of these disks are then more consistent with a large gap instead of an inner hole extending to the stellar magnetosphere (Espaillat 2009). Figure 1 shows the
SEDs for a M2 star in NGC 2362 that has a transitional disk with a > 4 AU inner hole (Currie et al. 2009).

Typical inner hole sizes inferred from SED modeling of Spitzer IRS spectra range from ∼ 4 AU to ∼ 60 AU (e.g. Calvet et al. 2005; Kim et al. 2009). Broadband IR photometry alone may identify transitional disks with large inner holes/gaps around solar-mass stars, where the star-to-disk contrast is good (Ercolano et al. 2009). However, the IR fluxes for other transitional disks with inner holes/gaps can be very similar to those for primordial disks (e.g. SZ Cha, Kim et al. 2009). Moreover, even Spitzer IRS spectroscopy may fail to distinguish between primordial disks and transitional disks with smaller, ∼ AU-scale cleared regions, especially if they also have...
optically-thick near-IR emission (C. Espaillat, pvt. comm.). Thus, many transitional disks with smaller holes/gaps probably have yet to be discovered. Analysis of these systems would probe the earliest stages in inside-out disk clearing.

- **Homologously depleted transitional disks** lack evidence for a strong radially-dependent depletion of dust and, therefore, an inner hole. However, their mid-IR fluxes are substantially weaker than typical primordial disk fluxes, lying below the lower-quartile Taurus SED (Currie et al. 2009). Their emission is also weaker than that for geometrically flat, reprocessing blackbody disks viewed face on (e.g. Kenyon and Hartmann 1987, see Figure 1). Because face-on flat disks exhibit the weakest IR emission that can come from an optically-thick disk, homologously depleted disks have a substantially reduced IR optical depth and thus a depleted mass of IR-emitting dust. If this IR emitting dust traces the bulk disk mass, then these disks are losing disk mass simultaneously over a wide range of radii.

Disk masses for homologously depleted disks, as inferred from submm fluxes and from modeling IR-to-submm SEDs, are systematically lower than those for primordial disks ($M_d < 10^{-3} M_\odot$, Currie et al. 2009; Cieza et al. 2010). Additionally, these disks have a lower frequency of accretion and lower typical accretion rates (Muzerolle et al. 2010; Cieza et al. 2010); disks lacking evidence for accretion have the lowest masses. In light of these properties, homologously depleted disks are much more likely undergoing an overall depletion of disk mass, not simply dust settling. Thus, homologously depleted disks likely represent a distinct evolutionary outcome (Muzerolle et al. 2010; Cieza et al. 2010; Currie et al. 2009).

### 3 Spitzer Results on the Lifetimes of Transitional Disks

Comparing the frequencies of transitional disks to primordial disks derived from SED modeling for 1–10 Myr-old clusters constrains the mean transitional disk lifetime. Traditionally, the transitional disk lifetime was thought to be short, $\sim 0.01$–0.1 Myr, based on the paucity of transitional disks in Myr-old star-forming regions like Taurus. However, if disks spend $\approx 0.01$–0.1 Myr of their 3–5 Myr lifetime as transitional disks, then transitional disks should also be far rarer than primordial disks in older (3–10 Myr) clusters.

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1 Disks that are viewed close to edge on and disks with flaring have stronger emission relative to the stellar photosphere (e.g. Chiang and Goldreich 1999; Kenyon and Hartmann 1987; Wood et al. 2002).
Spitzer observations show that < 20% of disks surrounding 1–2 Myr-old 0.5–1.4 M$_\odot$ stars are in transition, but at least 50% and as many as 80% of disks are transitional disks by $\sim$ 5–6 Myr (Currie et al. 2009; Sicilia-Aguilar et al. 2009). Based on these results, Currie et al. (2009) show that the transition timescale is $\approx$ 1 Myr. To investigate this issue further, I have applied the disk classification scheme from Currie et al. (2009) to other 1–10 Myr-old clusters, modified to include the flat reprocessing disk SED as an additional check on whether a disk is primordial or whether it is a homologously depleted transitional disk.

As shown by Figure 2, the transitional disk frequency increases with time, climbing above $\sim$ 40–50% for all clusters older than 4 Myr. For reference, I overplot the approximate locus of transitional disk frequencies assuming a clearing timescale of $\sim$ 0.5 Myr (Alexander and Armitage 2009). Transitional disk frequencies for all clusters, most obviously those older than 3 Myr, lie above the 0.5 Myr locus indicating that the typical transitional disk lifetime must be longer. Muzerolle et al. (2010) also find that the transitional disk frequency increases with time. Their frequencies for 3–10 Myr-old clusters agree with those here if both disks with inner holes and homologously depleted ("warm"/"weak" excess sources in their terminology) are counted as transitional disks.

Luhman et al. (2010) dispute these claims, arguing that many of the transitional disks identified by Currie et al. (2009) and Sicilia-Aguilar et al. (2009), especially the homologously depleted disks, are simply primordial disks with dust settling. To make this argument, they determine
the IRAC and MIPS colors for a two grain population disk model from D’Alessio et al. (2006) with an extremely low accretion rate ($\dot{M} = 10^{-10} \, M_\odot \, yr^{-1}$) and a ”depletion factor”, $\epsilon = 0.001$, which removes 99.9% of the small dust grains and compare these colors to those for several 1–10 Myr-old clusters.

Besides not knowing whether their adopted disk model is physically realistic\(^2\), their analysis contains questionable features which undermine their conclusions. For example, the Luhman et al. conclusions are extremely sensitive to assumed values for their free parameters ($\epsilon$ and $\dot{M}$). Assuming either that disks only remove 99% of their small dust instead of 99.9% or have a still-tiny accretion rate of $\dot{M} = 10^{-9} \, M_\odot \, yr^{-1}$ revises their fiducial IRAC and MIPS primordial disk colors redwards by $\sim 0.5$ mags, which then yields the results from Currie et al. (2009). More generally, of the 16 combinations of $\epsilon$ and $\dot{M}$ shown in Figure 13 of D’Alessio et al., the only combination yielding the Luhman et al. results is the one Luhman et al adopts. Thus, models yielding the conclusions of Luhman et al (2010) occupy a very narrow range of parameter space. Many 1–10 Myr-old sources identified as transitional by Currie et al. and others are accreting at rates that must be much greater than $10^{-10} \, M_\odot \, yr^{-1}$ (e.g. ID-36 in NGC 2362), so the appropriate D’Alessio et al model in many cases clearly cannot be the one they adopt.

Furthermore, SED modeling of sources show that some claimed to be primordial by Luhman et al such as ID-3 in NGC 2362 have large inner holes. The Luhman et al classification scheme would also identify UX Tau and LkCa 15 as primordial disks. However, as the same authors showed in previous work (e.g. Espaillat et al. 2008), these disks have large, $\sim 50$ AU-scale holes consistent with substantial disk clearing and inconsistent with a primordial disk morphology. Using the colors of UX Tau, LkCa 15, DM Tau and others as an empirical division between primordial and transitional disks also recovers the results from Currie et al. (2009)\(^3\).

\(^2\) Numerical simulations indicate that micron-sized grains must produce small fragments when they grow, otherwise mid-IR emission from disks would disappear $\sim 100$-1000 times faster than observed (Dullemond and Dominik 2003). Since fragmentation in a collisionally dominated disk produces copious amounts of small dust, it is unclear whether disks can lose 99.9% of their small dust while retaining their 10 $\mu$m to 1 mm-sized dust, especially in the presence of turbulence.

\(^3\) Additionally, Luhman et al. (2010) mischaracterize the Currie et al. (2009) criteria as identifying transitional disks with emission weaker than the median Taurus SED. Rather, the Currie et al. (2009) selection criteria is a dual one, relying on comparing observed SEDs to the lower quartile Taurus SED and the grid of disk models from Robitaille et al. (2006). This criteria was clarified in Currie and Kenyon (2009). Several NGC 2362 source are discarded by Luhman et al. (2010) who claim, based on inspection of the post-BCD mosaic they lack have SNR < 2–3. However, PRF-fitting photometry and supplemental analysis of the processed mosaic show that most have SNR > 5 and thus should not be excluded.
Figure 3. A schematic illustrating disk evolution from the primordial disk phase to the debris disk phase, including the morphologies and lifetimes of transitional disks (Currie et al. 2009).

Figure 3 summarizes the general picture of disk evolution outlined by Currie et al. (2009). Most optically-thick primordial disks last between 2 Myr and 5 Myr, depending on stellar mass. After this time, they begin to show evidence of dust clearing either at a wide range of disk locations simultaneously (a “homologously depleted” disk) or open a gap/inner hole and deplete from the inside out. After 5 (3, 10) Myr, most solar-mass stars (2.0 M⊙ stars, subsolar-mass stars) either lack disks or have debris disks (e.g. Carpenter et al. 2009, Hernandez et al. 2009, Currie et al. 2008).

4 Mechanisms Responsible for Transitional Disks

Comparing transitional disk properties to other disk diagnostics and stellar properties constrains plausible mechanisms responsible for forming such disks. For transitional disks with inner holes, the hole size is correlated with stellar mass/T star and x-ray luminosity but is only weakly correlated/not correlated with accretion rate (Kim et al. 2009). Najita et al. (2007) identify a correlation between accretion rate and disk mass in Taurus: transitional disks systematically have larger disk masses (as inferred from submm data) than primordial disks with the same accretion rates. Based on a sample of stars with transitional disks at a wider range of ages, Cieza et al. (2008,
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find instead that disk mass and accretion rate are anticorrelated. Since clearing induced by a gas giant planet probably occurs in more massive disks and photoevaporate clearing occurs after disks have lost significant mass (Clarke et al. 2001), the conflicting results over $\dot{M}$ vs. $M_{\text{disk}}$ may point to multiple processes responsible for forming inner holes (Cieza et al. 2010; Alexander and Armitage 2009). Since homologously depleted transitional disks lack evidence for inner holes/gaps, their morphologies are not naturally explainable by gap-opening planets. Based on results from Cieza et al. (2010) and Muzerolle et al. (2010), their accretion properties and disk masses may be consistent with a simple viscous draining of disk material with time, perhaps accelerated by weak photoevaporation.

The homologously depleted disk morphology may occupy an important region of disk/star parameter space. Compared to 1–3 M$_\odot$ stars, the frequency of massive, RV-detected planets orbiting $\sim$ 0.5 M$_\odot$ stars is far lower (Johnson et al. 2007). These low-mass stars may have a higher frequency of homologously depleted transitional disks (e.g. Muzerolle et al. 2010). Disk clearing timescales from photoevaporation may also be longest for the lowest-mass stars (≥ 1 Myr Gorti et al. 2009). A homologously depleted disk morphology is then a plausible outcome of a disk that fails to form gas giant planets and is irradiated by a low stellar UV flux.

5 Uncertainties and Future Work

Many caveats qualify these conclusions about transitional disk properties. Since there may be multiple mechanisms responsible for explaining the morphologies of transitional disks a "transition timescale" derived from the number of all transitional disks regardless of morphology is only a mean value of the timescales from a number of different mechanisms. For example, it’s entirely possible that disk clearing from gap-opening planets explains a subset of transitional disks and often occurs on fast $\sim$ 0.1 Myr timescales, whereas other mechanisms operate more slowly. Differentiating between a rapidly operating disk clearing mechanism and one that operates less frequently requires sophisticated multiwavelength analyses of disks around stars with a wide range of ages (e.g. Cieza et al. 2010).

The disk clearing time for many candidate mechanisms (e.g. gas giant planet formation, UV photoevaporation) depends on properties that likely have a large intrinsic dispersion, such as disk viscosity, initial angular momentum, mass. In turn, there may be an intrinsic dispersion in transition timescales like the intrinsic dispersion in protoplanetary disk lifetimes. While the mean transition timescale (averaged over all disk clearing mechanisms) may be closer to $\sim$ 1 Myr as found by Currie et al. (2009), it is

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4 Because more massive disks produce gas giant planets (Kennedy and Kenyon 2008; Currie 2009).
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quite plausible that many disks, including those in the youngest regions like Taurus, disperse on much shorter timescales (Currie and Kenyon 2009).

Finally, inferring gas and dust masses in transitional disks from IR to submm dust emission is fraught with uncertainties. Deriving the dust mass from IR to submm SED modeling requires assuming a dust opacity, $\kappa$. Since the dust opacity is not strictly known, what is actually derived from SED modeling is the product of the dust mass and dust opacity, not simply the dust mass. The total disk mass is even more uncertain since it requires assuming a gas-to-dust ratio. The models used here, in Currie et al. (2009), and other work (e.g. Cieza et al. 2010; Andrews and Williams 2005) assume standard values for $\kappa$ and a solar gas-to-dust ratio. However, comparing derived disk masses from these methods to estimates based on accretion rates indicates that the former methods may systematically underestimate the total disk mass (Andrews and Williams 2007). SED modeling and accretion diagnostics for both types of transitional disks indicate that they are evolutionary states distinct from primordial disks. But quantitatively assessing how transitional disks probe clearing of both gas and dust requires diagnostics of circumstellar gas sensitive to the bulk gas mass in planet-forming regions.

New and upcoming facilities allow studies of transitional disks that complement and clarify results based on Spitzer work. The Atacama Large Millimeter Array (ALMA) will provide extremely sensitive, high angular-resolution data to better constrain spatial extents, inner hole sizes, surface density profiles, and masses of known transitional disks. ALMA may also identify new transitional disks with inner holes/gaps too small to be confidently inferred from SED modeling.

The most crucial, hitherto underexplored angle for investigating transitional disks is the disks’ gas content. Gas diagnostics for transitional disks are typically limited to accretion, which identifies the presence of hot circumstellar gas near the star. However, gas in cooler planet-forming regions is more relevant in the context of disks evolving from pre planet building to post-planet building stages. Herschel offers a sensitive probe of far-IR line emission to identify cool gas in disks. Herschel programs such as GASPS will survey many 1–10 Myr-old stars for evidence of circumstellar gas and thus provide strong constraints on gas dissipation as a function of time. Comparing the gas properties of transitional disks with those for primordial disks will more definitively determine how transitional disks are clearing their gas, complementing studies of dust clearing.

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