Pre-Transitional Disks: The Missing Link for Planet Formation in Disks

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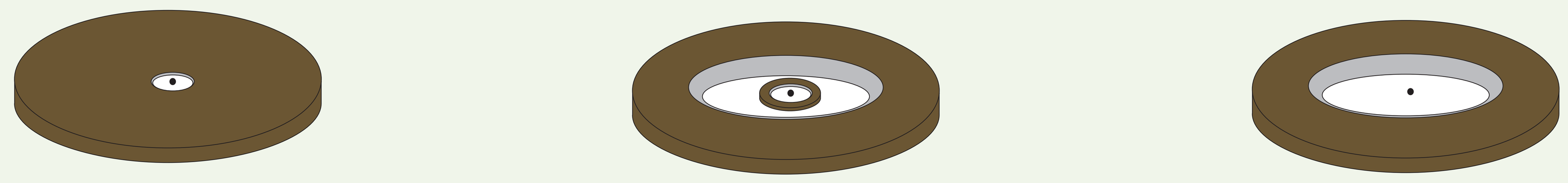
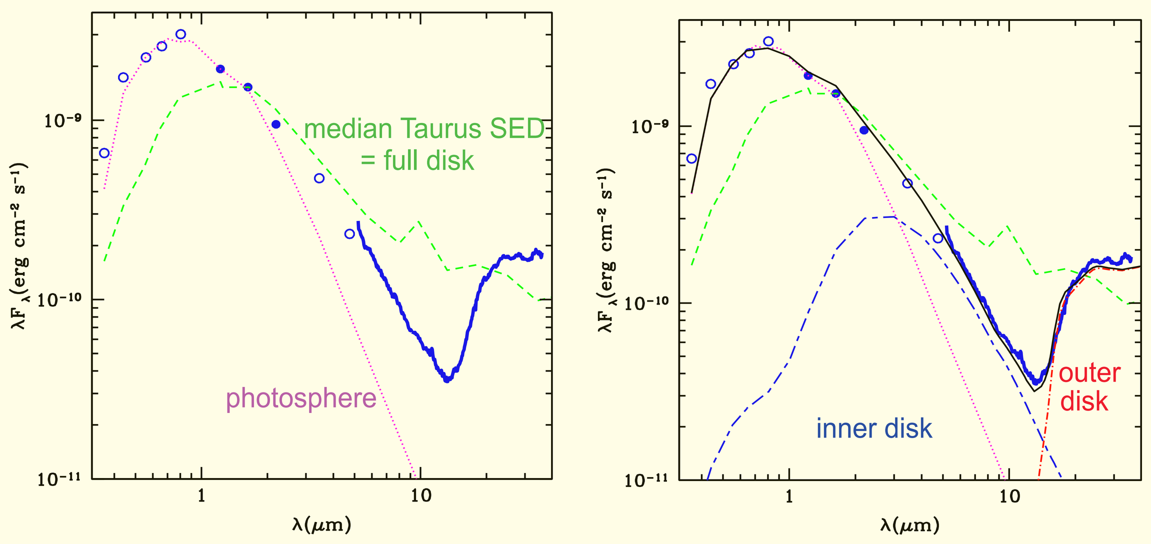
THE PRE-TRANSITIONAL DISK CLASS

In their initial stages of formation planets should interact with the accretion disk surrounding the newborn star, clearing the material around themselves and leaving behind an observational signature in the form of gaps in the primordial disk. Stars with inwardly truncated disks have been detected with Spitzer IRS spectra (Calvet et al. 2005) and have been labeled as "transitional disks" (Strom et al. 1989). While planet formation can create the inner hole in these disks (Rice et al. 2006, Varniere et al. 2006), other formation mechanisms such as photoevaporation (Clarke et al. 2001), grain growth (Dullemond & Dominik 2005), or the magneto-rotational instability (Chiang & Murray-Clay 2007) can account for this type of clearing as well. Our analysis of IRAC broad-band photometry and IRS spectra has now isolated the earliest stages of planet formation in the disk (Espaillat et al. 2007). This new class of "pre-transitional disks" has an inner optically thick disk separated from an outer optically thick disk by an optically thin gap. Physical mechanisms that have been presented to explain disk clearing in transitional disks can now be tested with this new class of disk; forming planets emerge as the most likely explanation.



THE PRE-TRANSITIONAL DISK OF UX TAU A

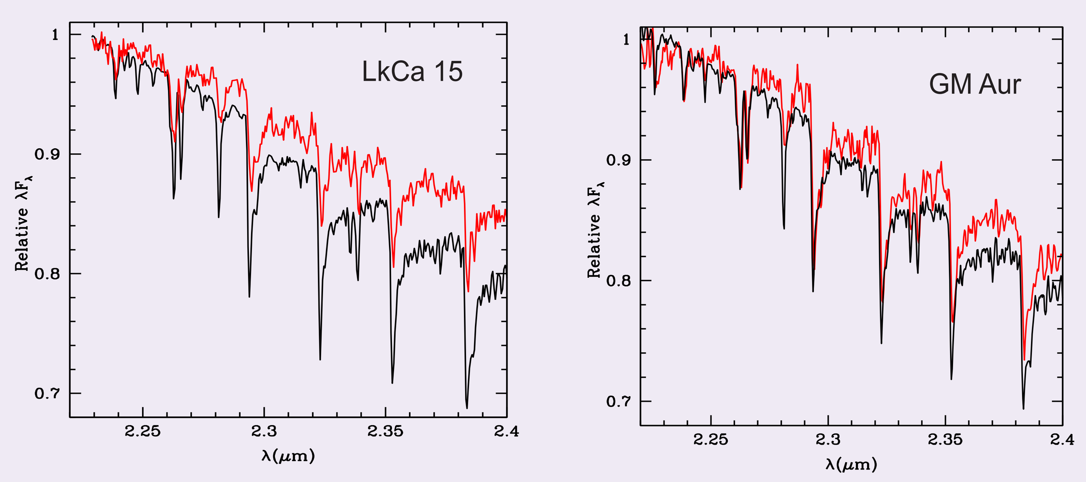


UX Tau A has a significant deficit of flux between ~6 - 20 μm relative to the median SED of T Tauri stars in Taurus. This median SED has been shown to be representative of a full disk (D'Alessio et al. 1999). UX Tau A also has a substantial near-infrared excess above the stellar photosphere between ~2 - 5 μm, comparable to what is seen in full disks. The combination of these characteristics points to a gapped disk around UX Tau A. We have modeled UX Tau A with an optically thick inner disk extending from 0.16 to 0.18 AU and an optically thick outer disk from 56 AU to 300 AU. The gap is relatively empty of small grains. This figure was adapted from Espaillat et al. 2007.

THE PRE-TRANSITIONAL DISK OF LKCA 15 VS. THE TRANSITIONAL DISK OF GM AUR

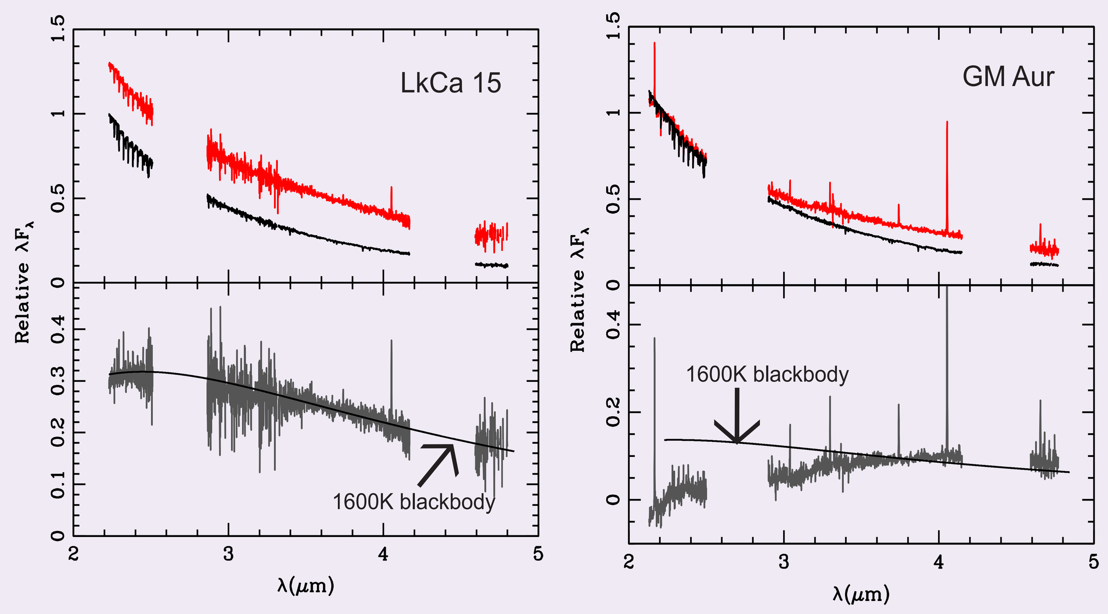
In previous studies of LkCa 15, detailed modeling of the spectral energy distribution (SED) demonstrated that although the near-infrared fluxes could be understood in terms of optically thick material at the dust sublimation radius, an alternative model of emission from optically thin dust over a wide range of radii could explain the observations as well (Espaillat et al. 2007). To unveil the true nature of LkCa 15's inner disk we obtained a near-infrared spectrum using SpeX at the IRTF. We report that the excess near-infrared emission above LkCa 15's photosphere is a blackbody continuum at the dust destruction temperature, similar to the excess found in full disks (Muzerolle et al. 2003). This excess can only be due to an optically thick disk around the star and this is the first confirmation of an inner primordial disk in an object with a separated outer disk (Espaillat et al. 2008). We also present the first comparison between the near-infrared excess of a pre-transitional disk (LkCa 15) and a transitional disk (GM Aur) using medium resolution near-infrared SpeX spectra.

LINE "VEILING"



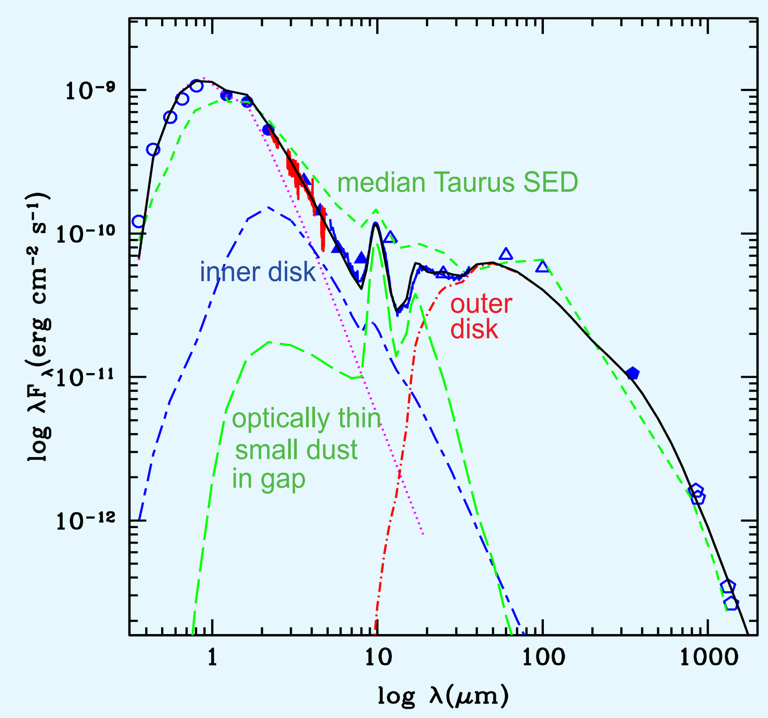
The spectrum of LkCa 15 (left, red) has absorption lines that are significantly less deep relative to the spectrum of a standard star of the same spectral type (black). This phenomena, called ``veiling," is akin to that observed in similar spectra of full disks and is explained by emission from dust located at the dust sublimation radius (Muzerolle et al. 2003). In contrast, the absorption lines in GM Aur's spectrum are not substantially veiled. For LkCa 15, we measure a veiling factor ($r=F_{excess}/F_{star}$; Hartigan et al. 1990) of 0.3 at ~2.3 μm which is fully consistent with the excess above the photosphere measured from simple broad-band photometry. GM Aur has r=0 at ~2.3 μm. Note that fluxes are relative to the template's flux at ~2.2 μm.

NEAR-IR EXCESS EMISSION



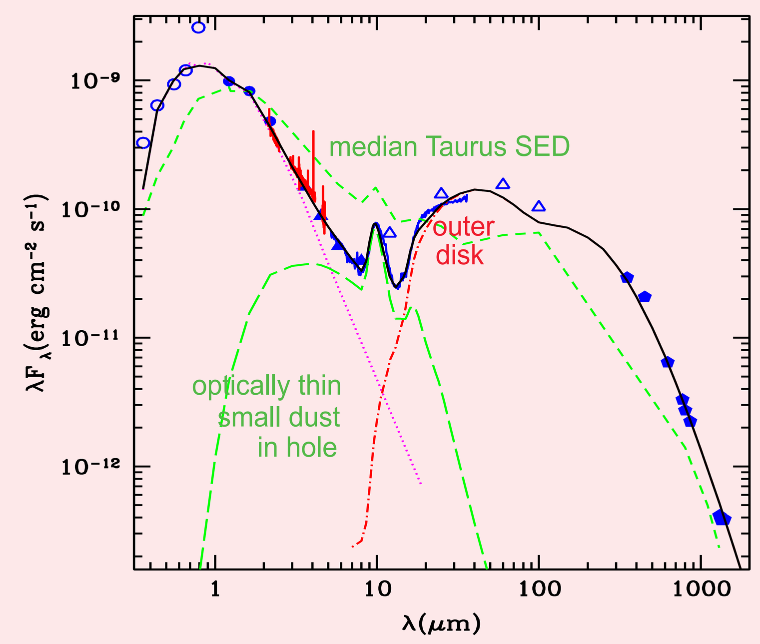
We subtracted the veiling-scaled target spectrum (top, red) by the standard star (black) to see the shape of the excess emission above the photosphere (bottom, gray). The near-IR excess of LkCa 15 can be fit by a single-temperature blackbody of 1600K (bottom, solid black line). This is within the range of dust sublimation temperatures found for a much larger sample of CTTS and Herbig Ae/Be stars by Monnier & Milan-Gabet (2002). The near-IR excess of GM Aur, which is due to optically thin dust (Calvet et al. 2005), cannot be fit with a 1600 K blackbody, highlighting the difference between the origin of the near-IR excesses in pre-transitional and transitional disks.

THE PRE-TRANSITIONAL DISK OF LKCA 15



Modeling of LkCa 15's broad-band SED finds an outer disk that is inwardly truncated at 46 AU (Espaillat et al. 2007), in agreement with millimeter imaging (Pietu et al. 2006). The optically thick inner disk around LkCa 15 extends from the dust destruction radius at 0.1 AU out to 0.15 AU. LkCa 15 has a small amount of optically thin dust located within the inner 5 AU of the gap. We note that Espaillat et al. 2007 used T=1400K for the inner wall and here we use 1600K which was derived from a blackbody fit to the near-IR excess of LkCa 15 (see left) obtained with SpeX data (red).

THE TRANSITIONAL DISK OF GM AUR



GM Aur's IRS spectrum was first modeled by Calvet et al. (2005). Here we add additional millimeter constraints from the SMA. We model GM Aur with an inner disk hole of 20 AU. This hole has been confirmed by millimeter interferometric imaging (see talk by S. Andrews for more details). There is optically thin submicron-sized dust located within GM Aur's hole and it is located between the dust destruction radius and ~1 AU. The SpeX spectrum is shown in red.

CONCLUSIONS

- We have identified a new class of "pre-transitional disks" which have a deficit of mid-infrared flux in addition to a significant near-IR excess comparable to the median SED of T Tauri disks. This indicates that pre-transitional objects have an optically thick inner disk separated from an optically thick outer disk and that we are seeing the development of gaps within protoplanetary disks.

- We have obtained the first independent confirmation of a gap in a disk by demonstrating that the near-IR excess of LkCa 15 can be fit with a 1600 K blackbody. In contrast, the near-IR excess of the transitional disk of GM Aur cannot be fitted with a blackbody at the dust destruction temperature.

- The existence of a remnant inner optically thick disk cannot be explained by inside-out clearing mechanisms. However, a planet can sweep away and accrete nearby dust and gas, creating a gap within the disk. Pre-transitional disks may be an indicator of the first stages of disk clearing by planets that will eventually lead to the the inner holes that are seen in transitional disks as the isolated inner part of the disk accretes onto the star.

REFERENCES

Calvet, N. et al. 2005, ApJL, 630, L185
Chiang, E. I. & Murray-Clay, R. A., 2007, Nature Physics, 3, 604
Clarke, C. J., Gendrin, A., & Sotomayor, M. 2001, MNRAS, 328, 485
D'Alessio, P., et al., 1999, ApJ, 527, 893
Dullemond, C.P.,& Dominik, C. 2005, A, 434, 971
Espaillat, C., et al. 2007, ApJ, 670, L135
Espaillat, C. et al. 2008, ApJ, 682, L125
Hartigan, P., et al. 1990, ApJL, 354, L25
Monnier, J.D.,\& Millan-Gabet, R. 2002, ApJ, 579, 694
Muzerolle et al., 2003, ApJL, 597,L159
Pietu, V., et al, 2006, A&A, 460, L43
Rice, W.K.M., et al. 2006, MNRAS, 373, 1619
Strom, K.M., et al. 1989, AJ, 97, 1451
Varniere et al. 2006, ApJ, 640, 1110

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