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TRANSITIONAL DISKS AROUND YOUNG LOW MASS STARS

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RESUMEN

Se ha encontrado una población de discos circunestelares jóvenes que presenta Distribuciones Espectrales de Energía (SEDs, en inglés) diferentes a los discos típicos, mostrando un defecto de emisión en el infrarrojo cercano, y un exceso a longitudes de onda del infrarrojo medio. Estas SEDs han sido interpretadas como producidas por discos con agujeros centrales, los cuales se han clasificado como "Discos en Transición". Estos discos se consideran la conexión evolutiva entre los discos completos encontrados frecuentemente en torno a estrellas jóvenes T Tauri y Ae de Herbig, y los discos de escombros que rodean a algunas estrellas de la secuencia principal. En esta contribución resumimos las características observadas/inferidas en estos discos en transicion, así como algunos de los modelos propuestos para explicar su peculiar geometría.

ABSTRACT

A population of young circumstellar disks have different Spectral Energy Distributions (SEDs) with respect to typical disks, showing a deficit of emission in the near-IR and an excess at mid-IR wavelengths. These SEDs have been interpreted as produced by disks with inner holes, which have been classified as "Transitional Disks". These disks are considered the evolutionary link between the full disks typically found around the young T Tauri and Herbig Ae stars, and the debris disks, found around some main sequence stars. In this contribution we summarize the observed/inferred characteristics of these transitional disks and also some of the models proposed to explain their peculiar geometry.

Key Words: accretion, accretion disks — infrared: stars — planetary systems: formation — planetary systems: protoplanetary disks — stars: pre-main sequence

1. GENERAL

Stars form in dense molecular cores which suffer gravitational collapse. A by-product of this process is the formation of a circumstellar disk by the core material with higher angular momentum. In these disks, the angular momentum is transported outwards by viscosity, probably turbulent, allowing matter to be accreted by the central star. This is why they are generally called "accretion disks". In early evolutionary states, these disks are optically thick in the Rosseland mean optical depth, from the magnetospheric radius (2–5 R_*, Muzerolle et al. 2001) to a few AU. However, their outer radii extends to hundreds of AU, as measured in disk images at different wavelengths (eg., Rodríguez et al. 1994; O'dell 1998). Their SEDs are characterized by excess of emission with respect to the stellar photosphere, from UV to millimeter wavelengths. These disks transfer mass to their central stars with accretion rates typically between 10^{-9} and $10^{-7} M_{\odot}\,\mathrm{yr}^{-1}$, as measured from the UV-optical emission excess observed in their spectra (Calvet & Gullbring 1998; Gullbring et al. 2000; Hartmann et al. 1998). The process of angular momentum and mass transportation in a disk leads to a decrease of its mass accretion rate with time (e.g.,Hartmann et al. 1998). This effect should be combined with other mechanisms, as dust growth and disk clearing, in order to explain the observed evolution of the fraction of stars surrounded by disks (Calvet et al. 2005a; Sicilia-Aguilar 2006; 2007). These *young disks* (less than few Myrs old), hereafter "full disks", are though to be a natural place to eventually form a planetary system.

The discovery of a cold dusty disk around the main sequence star Vega using IRAS (Aumann et al. 1984) started the study of the "debris disks". These are *old disks*, believed to be continuously replenished of dust by collisions between the building blocks of planets, i.e., the planetesimals (e.g., Lagrange et al. 2000; Zuckerman 2001). They show substructure, as holes and rings, (e.g. Schneider et al. 1999; Weinberger et al. 1999; Golimowski et al. 2006) probably reflecting the gravitational interaction between the dust and bigger bodies.

It seems just natural to think that full and debris disks are causally connected. The present contribution attempts to summarize in part the quest of finding this connection.

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2. TRANSITIONAL DISKS

"Transitional disks" is the name given to disks in the intermediate evolutionary state between full and debris disks, and their study is expected to provide clues for understanding how dust evolve in a disk to form planetesimals and planets, and how most of the disk gas eventually disappears. In particular, the statistical study of transitional disks around stars of different ages should help to quantify the timescales of the different processes. But before going any farther, an important step is to learn how to recognize a transitional disk and how to extract useful information from the observations to help to constrain theories.

The most obvious symptom that a disk is no longer a full disk, is the presence of a "hole". Strom et al. (1989) proposed that the disks in transition were those with small near-IR excess and large far-IR excess, reflecting the absence of disk material with the hottest possible temperatures (see § 2.1). Also, Marsh & Mahoney (1992; 1993) interpreted the SEDs with "dips" they modeled to fit some observed SEDs, as evidence of the presence of gaps in the disks, which they speculated were produced by low mass companions[2].

In the last decade, astronomers seem to better understand how full disks look like, what are their heating mechanisms and what are the effects of different disk dust models, incorporating grain growth and settling (e.g., D'Alessio et al. 2001, 2006; Dullemond & Dominik 2004, 2005). Disk models have become more complete including much more information than the vertically isothermal optically thick accretion disk models, the flat irradiated optically thick disk models or the power law models used in older works (see Dullemond et al. 2007). Armed also with more sensitive detectors and instruments with higher spatial and spectral resolution than those used in previous attempts, a new era of searching for transitional disks has started.

2.1. *TW Hya and the "hole" signatures*

Probably the first clear example of a transitional disk is the one that surrounds the Classical T Tauri star TW Hya. This 10 Myrs old star is located in the TW Hya association, 51 ± 4 pc away from the Sun. Calvet et al. (2002) illustrated the peculiarities in TW Hya SED by comparing it with the median SED of Classical T Tauri stars in the Taurus Association (i.e., ∼ 1–2 Myrs). The median can be well fitted by a typical model of a full disk (e.g, D'Alessio et al. 1999; 2006), but TW Hya has an emission deficit in the near-IR and an excess in the mid and far-IR spectral regions. Calvet et al. (2002) modeled the SED of TW Hya as produced by an optically thick accretion disk truncated at ∼ 4 AU, with a small amount (less than 0.01 lunar masses) of optically thin dust in the inner hole. TW Hya also shows accretion signatures (Muzerolle et al. 2000; Alencar & Batalha 2002), suggesting that the inner disk must contain some gas, and more recently, warm gas spectral signatures were detected in this source (e.g., Herczeg et al. 2007; Salyk et al. 2007). The same model also explained successfully the spectrum taken by the infrared spectrograph (IRS) on the Spitzer Space Telescope (SST), with higher sensitivity and resolution than the previous spectra (Uchida et al. 2004).

The size of the inner hole of a transitional disk is a physical property that can be directly inferred from the comparison between the modeled and the observed SED, as long as the disk heating mechanism is known. In general, models are based on the assumption that disks are flared and their atmospheres are heated mainly by the intercepted radiation from their central stars, as proposed by Kenyon & Hartmann (1987) in their seminal paper about disk flaring. Thus, knowing the stellar luminosity and effective temperature and estimating the disk dust atmospheric properties which can be constrained by the SED, the modeling gives the disk photospheric temperature as a function of radius. The absence of dust in a given temperature/radii interval, produces a deficit in emission in the SED in a particular wavelength range. On the other hand, the remaining disk has an inner boundary, usually modeled as a vertical cylindrical wall. This optically thick wall, being irradiated by the star frontally instead of with a less favorable incident angle, produces an excess of emission compared to what is expected for a full disk. From this combined deficit/excess of emission, a radius for the disk wall can be quantified from the SED (see Figure 1). Also, the mass in dust in the inner hole is another physical quantity inferred from the SED, using in particular the 10 μm silicate band. A fraction of the flux in the band is produced by the wall's atmosphere and another fraction is produced by the dust in the hole. The mass of this dust depends on the assumed opacity, which in turn

[2] Disks around binary stars, i.e., circumbinary disks, also have inner holes. However, the origin of these holes is not necessary related to the evolution of dust, the formation of planets and the dissipation of gas in the disk. In spite of the fact that most stars are binaries, the best candidates for transitional disks are disks around single stars or stars in a wide binary system, such that each one has its own disk. Narrowing the definition of transitional disk is a way to isolate phenomena, making them easier to study.

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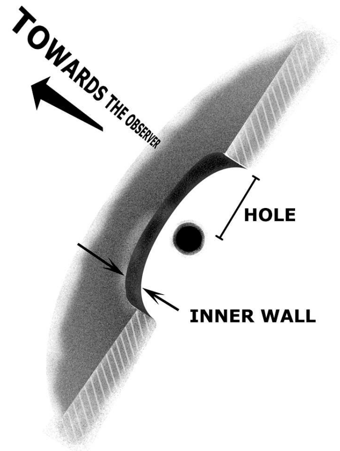

Fig. 1. Ilustration of the model of an inner disk hole and the inner wall of the outer disk, irradiated by the star with a normal incident angle (Ilustration by Rolando Prado).

depends on the dust chemical composition, optical properties, geometry, size distribution, and density radial distribution.

SEDs are a powerful tool for studying transitional disks, however, they give integrated information and, regarding geometry and sizes, the properties inferred from high spatial resolution images or visibilities are more generally accepted. For instance, Eisner et al. (2006) spatially resolved the disk of TW Hya at 2 μm using the Keck Interferometer, and their visibilities are consistent with an inner optically thin region, that can be the hole proposed by Calvet et al. (2002). Hughes et al. (2007) resolved the disk of TW Hya at 7 mm using the Very Large Array (VLA) confirming the existence of a $\sim$ 4 AU hole. However, Ratzka et al. (2007) found that their mid-IR visibility observations seems to be consistent with a transition in disk properties between 0.5 and 0.8 AU, and not at 4 AU. Their result might also reflect substructure in the optically thin dust that seems to be responsible for the 10 μm emission (Calvet, priv. comm.). In any case, these observations reflect that the inner disk of TW Hya is a fascinating and complex place, worth to be studied in every detail.

2.2. *Transitional disks in $\sim$ 1–2 Myr old associations*

The infrared spectrograph on Spitzer produces highly sensitive spectra between 5 to 40 μm, allowing to search disks with hole radii between 0.6 and 80 AU (corresponding to outer-disk-wall temperatures between 75 and 600 K). Using this tool, the "IRS Disk Team" has found 3 clear examples of disks with empty or optically thin inner holes in the 1–2 Myrs old Taurus Association, $\sim$ 140 pc away. These are: CoKu Tau 4 (Forrest et al. 2004; D'Alessio et al. 2005), DM Tau and GM Aur (Calvet et al. 2005b). Each of these objects has its own peculiarities.

The spectrum of CoKu Tau 4 shows a defect in near-IR emission, a very weak 10 μm silicate band and a strong rise in flux around 20 μm. The SED of this object was modeled as produced mainly in the atmosphere of the inner wall of the outer disk. The inferred size of the inner disk hole was $\sim$ 10 AU. In contrast to TW Hya, the inner disk of CoKu Tau 4 is very clean, with less than 0.0007 lunar masses of silicates. It has no accretion signatures, suggesting also the absence of gas in its inner hole. DM Tau is a transitional disk with a $\sim$ 3 AU hole, an almost empty inner disk and accretion signatures that imply a mass accretion rate to the star of $\dot{M} \sim 10^{-9}\ M_\odot\,\mathrm{yr}^{-1}$ (Calvet et al. 2005b). GM Aur has a higher mass accretion rate $\dot{M} \sim 10^{-8}\ M_\odot\,\mathrm{yr}^{-1}$. Also, rovibrational CO emission has been detected in the inner 1 AU region, confirming that there is gas in GM Aur's inner disk (Salyk et al. 2007). Its pre-Spitzer IR SED was modeled by Rice et al. (2003) who proposed that the disk of GM Aur had a 6 AU hole. Using IRS, Calvet et al. (2005b) found that the SED of GM Aur is consistent with being produced by a disk with a $\sim$ 24 AU hole, with $\sim$ 0.0035 lunar masses of silicate grains between the dust sublimation radius and 5 AU, and a dust-free gap between 5 and 24 AU. Recent images obtained using the Sub Millimeter Array (SMA) show a $\sim$ 20 AU inner hole, consistent with Calvet's model (Wilner et al., in prep.).

Other disks in Taurus have been proposed as transitional disks e.g., DN Tau, FQ Tau, CX Tau, FO Tau and others (Najita et al. 2007). However, since their SEDs show flux deficits in both, the near and mid-IR wavelength ranges, these could be just the low density/low mass accretion rate tail of the distribution of disks, and not necessarily disks in transition. They might also be suffering dust growth and settling, but homologously at every radius, making their SEDs look more similar to flat disk SEDs (Dullemond & Dominik 2004; D'Alessio et al. 2006). In some cases it is also possible that the outer disk is in the shadow of the inner disk (Dullemond et al. 2007, and references therein), decreasing its overall emission. In other words, the interpretation of these SEDs is not very clear, and including these as transitional disks might be misleading. Najita et al. (2007) have also included UX Tau A and LkCa 15 in their list of transitional disks. The detailed modeling

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of these two objects (§ 2.4) has motivated the creation of a new intermediate class. It is important to say that demographic studies, as the one described by Najita et al. (2007), are very necessary, but they need a better defined sample.

Chameleon is another star forming region ~ 2 Myrs old, at 160 pc. Espaillat et al. (2007a) have found a transitional disk around CS Cha, with a huge inner hole of ~ 40 AU, with 5×10^{-5} lunar masses of silicates between 0.1 and 1 AU. It has a mass accretion rate $\dot{M} \sim 10^{-8}\ M_{\odot}\,\mathrm{yr}^{-1}$ suggesting that there should be some gas in the optically thin hole. Indeed, Espaillat et al. (2007a) analyze [NeII] 12.81 μm fine-structure emission which could be excited by EUV or by X-Rays. In Ophiuchus, ~ 1 Myrs, at 120 pc, Geers et al. (2007) study in detail the mid-IR SED and images of the transitional disk around IRS 48. They find an optically thin hole, a sharp edge at ~ 30 AU, and evidences of dust size segregation between the outer disk and the optically thin hole.

2.3. *Transitional disks around Brown Dwarfs*

Brown Dwarfs (BD) are substellar objects, with $0.012 < M_{\rm BD} < 0.07\ M_{\odot}$), and several young BD show the emission excess characteristic of a circumstellar disk. Some of these even have SEDs which suggest inner disk clearings. Examples of transitional disks around BD are L316 and 30003 in IC 348, with inner holes of $\sim 0.5-0.9$ AU (Muzerolle et al. 2006) and 2MASS J04381486+261399, with an inner hole of ~ 0.3 AU (Luhman et al. 2007). The fact that BDs have such small masses and are so cold, can help to place constraints on the physical mechanism responsible for the holes in their transitional disks (§ 3).

2.4. *The Pre-transitional disks or disks with gaps*

All the transitional disks described so far have inner optically thin holes, with more or less dust, with or without accretion signatures, with hole sizes spanning few AU to few tens of AU. However, using IRS spectra, Espaillat et al. (2007b) have re-observed and re-interpreted the SEDs of two known T Tauri disks, coining for them a new class of objects: "pre-transitional disks". A disk of this class seems to have a gap instead of a hole, i.e., it has an inner optically thick disk, an optically thin intermediate region, and an optically thick outer disk. The two examples of this new class in Taurus are UX Tau A and LkCa 15 (Espaillat et al. 2007b). In both cases, the SED shows excess in the near-IR which is well described as emission from the inner wall of the optically thick disk, at the silicates sublimation radius ($T_{\rm sub} \sim 1400$ K). In the case of LkCa 15, the inner radius of the outer disk is at 46 AU, consistent with a millimeter interferometric image (Pietu et al. 2006). To explain the 10 μm silicate band, this gap should have 0.001 lunar masses of silicates between 0.15 and 5 AU. Optically thin dust at $R > 5$ AU would have an important contribution to the mid-IR SED which is not observed.

Brown et al.(2007) have found four pre-transitional disks with large gaps around F-G stars, using IRS spectra and MIPS fluxes, from the Cores to Disks Legacy Project (c2d) of the SST.

3. DUST EVOLUTION, PLANETS, GAS DISSIPATION AND/OR GAS ACCRETION?

How can a disk develop a gap or a hole? There are several proposed explanations for these phenomena. For instance, an opacity hole might form because dust grains grow much faster in the inner disk than in the outer disk (Weidenschilling 1997). If grains grow, the number of small grains and consequently, the opacity at short wavelengths ($\lambda \lesssim 2\pi a$, where a is the grain radius) decreases. It has been suggested that the radius of the hole is the limit between an inner zone, where dust has grown to sizes that makes the disk optically thin, and an outer zone, where the disk has a much larger optical depth. Since dynamical stable disks have a mass surface density that decreases with distance to the star, the grains growth rate has to compensate for this in order to have an optical depth that increases with distance. This mechanism probably produces a transition region between the inner and outer disks, but not a sharp edge (e.g. Geers et al. 2007).

Other possible explanation is that a planet has formed in the disk (see Armitage 2007, and references therein). When the planet's mass is larger than a critical value that depends on the disk viscosity, it produces a torque in the disk that results in the formation of a gap. The inner disk should disappear forming a hole in a viscous time scale, however, there are numerical simulations showing mass transfer between the outer and inner disk, and this can maintain an inner low density disk.

Another possibility is the UV-switch model, proposed by Clarke et al. (2001). In this model, the UV radiation produced by the star or by the accretion shocks at the stellar surface, photoevaporates the disk gas, beyond a critical radius, with a typical mass loss rate $\sim 4 \times 10^{-10}\ M_{\odot}\,\mathrm{yr}^{-1}$. In the normal viscous evolution of a disk, as described for instance by Hartmann et al. (1998), the disk mass accretion decreases with time (§ 1). When this mass accretion rate reaches a value similar to the mass loss rate of the photoevaporative wind, matter from the outer disk cannot reach the regions inside the critical radius. Since the matter in the inner disk, which is being accreted by the central star, cannot be replenished by the outer disk, a *clean* hole is formed. When the inner disk has disappeared in $\sim 10^5$ years, the ionizing radiation can penetrate the outer disk, and few 10^5 years later, the gas in the whole disk is lost by photoevaporation (Alexander et al. 2006).

Other model, recently proposed by Chiang & Murray-Clay (2007), explains the inside-out evacuation in transitional disks by the magneto-rotational instability (MRI). In this model, the disk has a pre-existing hole with a radius bigger than 1 AU and only the inner rim of the disk, with a gas column that can be penetrated by stellar X-rays, has enough ionization fraction to activate the MRI and be accreted by the star. They propose that the accretion rate is steady inside the rim and that dust is blown outwards by the stellar radiation pressure, making the inner hole almost dust free and optically thin.

From observations of transitional disks or from physical information inferred by interpreting observations using models, several authors have tried to decide which of these explanations, if any, is true in each case. Calvet et al. (2002) proposed that a planet could be responsible for clearing up the hole in the disk of TW Hya and Setiawan et al. (2008) have reported the detection of a 10 Jupiter's mass planet with in this system, using the radial velocity technique. However, this planet has an orbit radius of 0.04 AU, which is much smaller than the holes in TW Hya disk detected so far by different techniques (§ 2.1). There seems to be no connection between this planet and the 4 AU hole, but this does not rule out the possibility that other planets can exist in this disk, escaping from detection because they are farther away and/or less massive. On the other hand, Eisner et al.(2006) argue that a planet would migrate with the outer disk, and a clearing could not be maintained over the 10 Myrs lifetime of this system. They propose instead that the hole in TW Hya disk is produced by dust growth. Since the estimated removal time of small grains by stellar radiation pressure is $\lesssim 1$ year in the inner disk, they suggested that these grains should be continuously replenished through collisions between planetesimals. Also, the existence of planetesimals in the outer disk of TW Hya, has been proposed by Wilner et al. (2005) to explain the non variable fluxes and visibilities measured at 3.5 cm. Speculating, it is possible that TW Hya has planetesimals and planets, and its 4 AU hole (detected in the mid-IR SED and in the 7 mm image) could be produced by one of the planets, recently formed. In a system with several planets, the migration is not necessarily inwards (e.g., Veras & Armitage 2004; Martin et al. 2007). The inner disk substructure might be reflecting the gravitational interaction between planets, planetesimals and dust, but affected also by the gas.

The clean hole of CoKu Tau 4 has been modeled by Quillen et al. (2004) as produced by a planet with a mass $\gtrsim 0.1$ Jupiter masses. However, it also has been cited as an example of the hole produced by the UV-swith model (see Alexander & Armitage 2007), since the absence of accretion signatures in this case is consistent with a mass accretion rate as low as the $\sim 4 \times 10^{-10}\ M_\odot\,\mathrm{yr}^{-1}$ required by this model. The other transitional disks, GM Aur, DM Tau and CS Cha, have higher mass accretion rates that are incompatible with the UV-switch model, and according to Alexander & Armitage analysis, are more consistent with having formed a planet. For TW Hya, Muzerolle et al. (2000) estimate a mass accretion rate $\dot{M} \sim 5 \times 10^{-10}\ M_\odot\,\mathrm{yr}^{-1}$, but Alencar et al. (2002) find $\dot{M} \sim 2 \times 10^{-9}\ M_\odot\,\mathrm{yr}^{-1}$. The difference might be reflecting intrinsic variability and/or different methods of analysis. In any case, the evidence of warm gas in the inner disk (§ 2.1) seems difficult to reconcile with the UV switch model.

On the other hand, the model of inside-out evacuation by MRI (Chiang & Murray-Clay, 2007) applies to transitional disks with accretion signatures. In this model, the inner disk mass accretion rate increases as the square of the hole radius. DM Tau, GM Aur and TW Hya show no clear correlation between $\dot{M}$ and hole radius. However, there are several free parameters that can be adjusted in each case.

With respect to the transitional disks around BD, Muzerolle et al. (2006) argue that these objects are not expected to have a large chromospheric UV flux and, in particular, L316 has a mass accretion rate smaller than $10^{-12}\ M_\odot\,\mathrm{yr}^{-1}$, implying very low UV emission in accretion shocks. Thus, in this case the UV switch model seems not very likely, in spite of the low mass accretion rate of this object. Muzerolle et al. favor the idea that a a planet is responsible for the hole. However, they recognize that the chromospheric UV flux has not been measured yet in BD. The pre-transitional disks (Espaillat et al. 2007b), interpreted as disks with gaps, seems to favor also the planet model, since it is difficult to justify the formation of a gap in the context of the other proposed models.

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In summary, studying these disks with high spatial and spectral resolution is very important to determine geometry, mass accretion rates, outer disk masses, hole sizes, dust and gas masses in the holes, dust properties, etc. These inferred properties, combined with detailed predictions of the different models, will help to understand how disks evolve. Also, it is important to study larger samples of transitional disks, with different ages and environments to quantify the time scales of relevant processes and the dependence on environment and on stellar properties.

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