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Circumstellar disks and planetary formation

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Abstract

Circumstellar disks are the the cradle of planetary systems. They are found around a large number of intermediate- and low-mass stellar objects in star forming regions and young clusters. Their study can provide important clues about the timescales and physical conditions for planet formation. In this paper, I review some properties of circumstellar disks that come from the analysis of multi-wavelength observational data, and that are important in the context of planet formation. In addition, I also present the first evidences of planetary formation within the so-called transitional disks.

1 Introduction

Circumstellar (CS) disks are the cradle of planetary systems. However, the timescales and physical properties required to form planets are still not well understood.

Planet formation theories propose different mechanisms and timescales to form planets around young stars [6, 29]. From the observational point of view, the only way to test these theories is to compare the properties of CS disks and young planetary systems with theoretical predictions.

In the next sections, I will summarize some properties of CS disks that are important in the framework of planet formation. All of them refer to disks around late-type stars. In the last section, I will review the first evidences of planet formation within the transitional disks of two young objects.

2 Disk lifetimes and evolution

The lifetime of CS disks determines the time interval in which planetary systems can form. In the past, several works used near-infrared (IR) photometry to derive the fraction of young stars with IR excesses over the expected photospheric emission. These excesses are related to

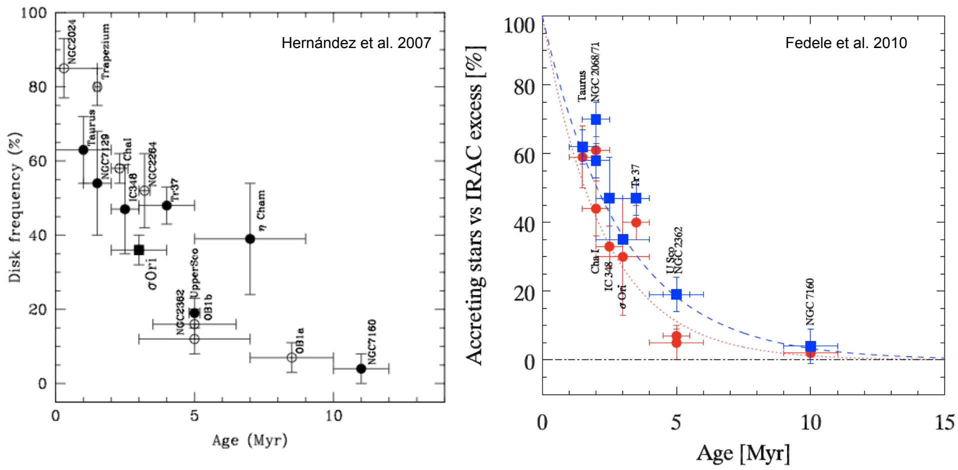

Figure 1: Estimation of disk lifetimes. *Left panel:* Fraction of late-type stars with near-IR (open circles), and mid-IR/Spitzer (filled circles) excesses in different star forming regions and clusters. There is a clear decay of IR excesses with the age, which is related with the dissipation of the dust in CS disks (adopted from [18]). *Right panel:* Fraction of late-type stars (K0-M5) with on-going accretion with respect to the total number of stars with IR excesses. The plot shows that at 5 Myr gas accretion has ceased while there is still some dust left in the inner disk (adopted from [15]).

the presence of hot dust close to the central object, so they trace the emission coming from the inner parts of the disk. The works by e.g. [3, 17] derived a disk lifetime of $\sim$ 6 Myr. Using both near-IR and mid-IR Spitzer data (the latter tracing warm dust) [18] reached a very similar result (see Fig.1, left panel). Therefore, it is commonly assumed that disk lifetimes are between 5-10 Myr. We note that this estimation refers to the dusty component of the disk.

Since gas is a key ingredient for planet formation, it is important to understand if its evolution is comparable to that of the dust. Different studies have focused on different gas tracers. As an example, [15] have derived the gas lifetime of disks around late-type stars using the Hα emission line as an accretion indicator. When they compare the fraction of stars with ongoing accretion with the total number of stars with IR excesses, they find that the gas dissipates slightly faster than the dust in the inner disk: at 5 Myr, 95 % of the stellar population has stopped accreting material at a rate of $>10^{-11}$ $M_\odot$/yr, while $\sim$20% of the stars still show near-infrared excess emission (see Fig. 1, right panel).

From all these studies, we could conclude that planets should be formed within the first $\sim 5-10$ Myr of the stellar life. However, different works have shown that the disk evolution is not only age-dependent but it can also vary with other parameters like e.g. the stellar mass, the binarity, etc (see [23, 10, 18, 14]). In fact, most of these works show that late-type stars harbor longer-lasting disks than early-type stars. Moreover, in a given stellar cluster or star forming region (SFR), where stars are born under the same physical conditions, it is possible to find disks at different evolutionary stages for a given stellar mass, i.e. optically thick (primordial), transitional (see Section 4), and more evolved disks.

An interesting work that illustrates the disk evolution within a given SFR is that from [16]. The authors analyzed Spitzer/IRS mid-IR spectroscopy of 85 objects in Taurus, concluding that there is not a clear trend among the sample, i.e. while some sources show properties consistent with primordial disks, some other sources show evidences of dust processing and grain growth.

To summarize, it is clear that CS evolve within the first ~ 10 Myr. However, age is not the only factor determining disk evolution. Other parameters like e.g. the initial conditions of the star-forming core, the angular momentum, the stellar mass, and the binarity (among others) can have an impact on the dust and gas content of CS disks.

3 Circumstellar disks as seen by the Herschel Space Observatory

The launch of the Herschel Space Observatory (HSO) has opened a new window to study the gas and dust content of circumstellar disks. Currently, there are several on-going Key Projects focused on the study of disks at different evolutionary stages (e.g. GASPS, DIGIT, WISH, DUNES, DEBRIS). The final conclusions of these works will be drawn once the projects are completed. As an example, it will be possible to estimate the disk fractions from 70–500 μm data, and compare them with the results obtained at shorter wavelengths.

However, the HSO has already provided very interesting results in the field of CS disks. One of them is the estimation of the gas-to-dust mass ratios in three sources [32, 26, 34]. These works show that (i) the ratio can vary significantly from one disk to another, and (ii) it can be very different from the interstellar medium (ISM) canonical value of 100. This result has important implications in the estimation of disks masses, which are normally derived using a ratio of 100. This fact, together with the uncertainties associated to the dust opacities, limits our ability to derive reliable disk masses.

4 Planetary formation: Transitional disks

The analysis of the spectral energy distributions (SEDs) of young objects has revealed a large number of disks characterized by a lack of significant IR excesses at wavelengths shorter than ~ 8 μm, and a rise in emission at longer wavelengths e.g. ≥ 15 μm (see [9, 7, 27, 13]). These are the so-called transitional disks, and they are thought to be in an intermediate evolutionary state between primordial Class II protoplanetary disks and Class III debris disks.

The lack of mid-IR excesses in transitional objects has been interpreted as a sign of dust clearing within the disk, resulting in the presence of gaps or holes: a gap is defined as a drop in surface density, leaving an inner disk close to the star and an outer disk further away from the central object, as opposed to a disk hole where there is not inner disk left. Sub-millimeter (mm) observations have allowed to spatially resolve a significant number of transitional disks, confirming the presence of gaps or holes within them [8, 4].

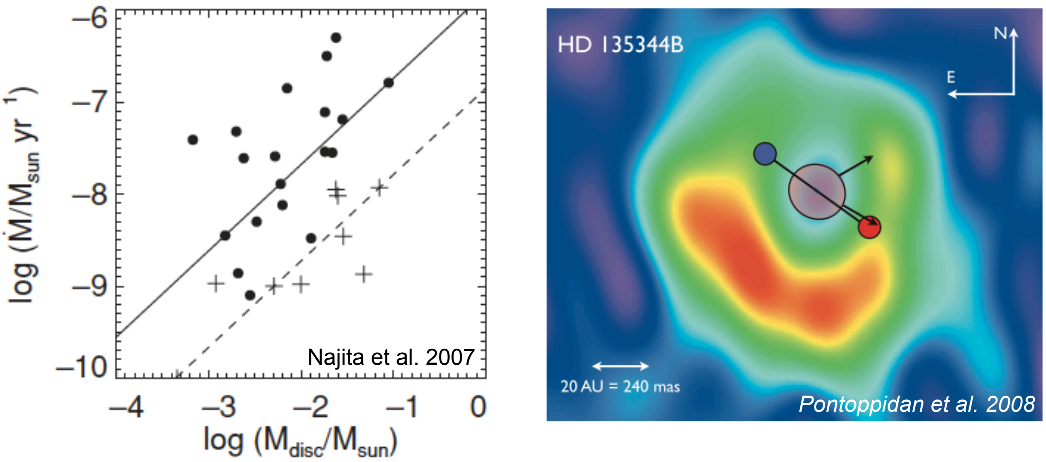

Figure 2: Characterization of transitional disks. *Left panel:* Study of the disk population in the Taurus star forming region. The plot represents the estimated accretion rates versus the disk masses. The filled circles represent primordial disks, while the 'plus' symbols are associated with transitional disks. For a given disk mass, transitional disks show accretion rates 10 times smaller than non-transitional objects. *Right panel:* Spectro-astrometry observations of the transitional disk HD 135344 B (from [30]). The plot shows the sub-mm image of the resolved disk, together the detection of the CO molecular line within the gap. The gas is detected from 10–15 AU to 0.5 AU from the central star (filled region).

Radial dust clearing (gaps and holes) can be the consequence of several mechanisms. For example, the presence of a stellar companion can result in the truncation of the disk through gravitational interactions with the binary system [21] (Fig. 2). This is the case of CoKu Tau 4, which shows a SED consistent with a transitional disk and its was resolved into a very close binary system [20]. Another mechanism that can generate holes is the clearing of the inner disk by photo-evaporation (e.g. [1]). In this context, the most exciting mechanism that can be responsible of dust clearing is the formation of a young planet (e.g. [25]).

A way to distinguish between the different mechanisms is to study the gas and dust content (and their spatial distribution) within the gaps and holes: as an example, both photo-evaporation and a stellar companion would clear out the inner disk completely producing a hole (e.g. [2]), while a planetary-mass companion, with a mass below a given threshold ($\sim$ 10 M_J), can allow some gas and small dust grains to accrete through its orbit [25], resulting in a non-empty gap.

Several works have studied in detail different samples of transitional disks to better understand the origin of their gaps and holes. As an example, [28] analyzed the properties of a sample of transitional disks in the Taurus star forming region. They showed that transitional disks display accretion rates one order of magnitude smaller than those found in non-transitional objects for the same disk mass, while the median disk masses were approximately four times larger. Interestingly, some of these properties were already predicted by planet formation theories, and suggest that the formation of giant planets could explain the origin of the gaps in some of the studied objects.

Using a different approach, [30] observed a sample of four transitional disks using spectro-astrometric (SA) techniques. SA provides superb angular resolution and allows to study the gas content and its spatial distribution well within the disk gaps. As a result, they reported the detection of molecular CO inside the dust gaps of three disks, supporting partial clearing by a planetary body, or removal of the dust by extensive grain coagulation and planetesimal formation.

As it follows, transitional disk with gaps sculpted by planetary systems are prime targets to image young planets in formation. In the next section we discuss the first evidences of planetary formation within two transitional objects.

5 Evidences of planetary formation in transitional disks: T Chamaeleontis and LkCa 15

In the last ten years, a big effort has been made to obtain direct images of giant planets around young stars. Most of these works have used Adaptive Optics (AO) systems and different observational techniques (e.g. differential imaging, coronography, LOCI). However, the limitations of current adaptive optics (AO) systems have restricted the search for giant planets to separations of ≥ 0.1", with maximum sensitivity at ≥ 1", corresponding to several tens or hundreds of AU in most nearby star forming regions (e.g. [24, 12]).

Lately, AO systems have been used in combination with a well-known interferometric technique: sparse aperture masking (SAM). AO+SAM allows the direct imaging of massive Jupiter analogues around young stars as close as $\sim$50 mas, or just $5 - 10$ AU at a distance of 100 pc [33]. As shown by [33], this technique has been well-established as a means of achieving the full diffraction limit offered by a telescope.

In 2011, [19] presented SAM observations of the transitional object T Chamaeleontis, a high probable member of the ϵ-Cha association with an age of 7 Myr [31]. They analyzed K_s & L' observations obtained with NACO, the AO system at the VLT. As a result, they detected a companion candidate at a separation of $\sim 62 \pm 7$ mas and position angle of 78° (see Fig. 3, left). Assuming a distance to the source of 108$\pm$9 pc, the companion lies at a projected separation of 6.7 AU, that is, well within the disk gap according to [7].

Taking into account the photometric data of the primary and the derived contrast, $\Delta L'$=5.1$\pm$0.2, the estimated brightness of T Cha b is L'=10.9$\pm$0.2 mag, and $K_s > 12.15$ mag. The comparison of the photometry of T Cha b with DUSTY evolutionary models by [11] shows that the companion is in the brown dwarf regime, although its observed properties are not consistent with any unextincted object at the distance and age of the source. Its extremely red $K_s - L'$ color can only be explained if the target is surrounded by a significant amount of dust. On the other hand, such unusual properties might be related with a young planet forming within the disk, when its brightness only depends on the accretion history and accretion rate. In this case, planet formation models should be used to derive the properties

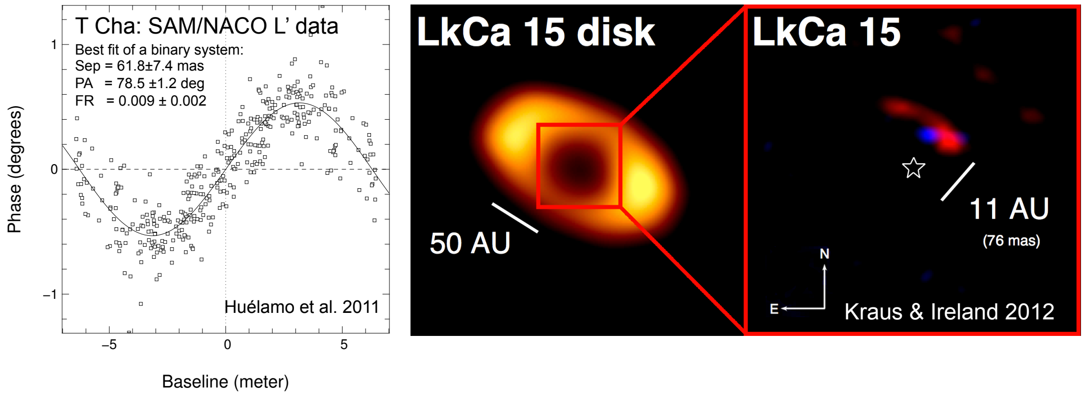

Figure 3: *Left panel:* SAM/NACO data of the transitional object T Cha. The interferometric observations (closure phases) are represented by small open squares, and have been fitted with a model of a binary system (solid line). The best fit is obtained for a companion at a separation of $\sim$ 63 mas, position angle of 78°, and a contrast ratio of $\Delta L' = 5.1$ mag (adopted from [19]). *Center panel*: LkCa 15 transitional disk spatially resolved by [5], and showing a gap of 50 AU. *Right panel:* Keck/SAM L' (red) and K_s (blue) data of the source. These observations have revealed the presence of a planetary-mass companion candidate at a separation of 11 AU, that is, well within the disk gap. Interestingly, the detected emission is extended, suggesting the presence of significant amount of dust around the companion.

of the companion candidate.

Very recently, [22] have presented evidences of planetary formation in the transitional disk of LkCa 15, a young star (3 Myr) in the Taurus star forming region. The source is surrounded by a disk that has been spatially resolved at sub-mm wavelengths [5], and shows a gap that extends up to 50 AU of radius (Fig. 3, middle). SAM observations obtained at Keck Observatory have revealed the presence of a planetary-mass companion candidate at a projected separation of ~76 mas (or 11 AU at 140 pc), that is, well within the disk gap. Interestingly, the reconstructed L' and K_s-band images show extended emission coming from this source which suggests that the object might be surrounded a significant amount of dust (Fig. 3, middle and right panels).

Future observations will help to properly characterize the companion candidates detected in these two systems, the first substellar candidates within the gap of transitional disks.

6 Future perspectives

New instrumentation will help to better understand the conditions for planet formation within the disks of young stars. As an example, new and more powerful AO systems (e.g. SPHERE, Gemini Planet Imager) will allow to detect very faint giant planets close to the central stars. On the other hand, ALMA will be crucial in our understanding of the gas and dust properties of CS disks.

Acknowledgments

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References

[1] Alexander, R.D., Clarke, C.J., & Pringle, J.E. 2006, MNRAS, 369, 216
[2] Alexander, R.D. & Armitage, P.J. 2007, MNRAS, 375, 500
[3] Alves, J., Lada, C., & Lada, E., 2000, Ap&SS, 272, 213
[4] Andrews, S.M., Wilner, D.J., Espaillat, C., et al. 2011, ApJ, 732, 42
[5] Andrews, S.M., Rosenfeld, K., Wilner, D.J., et al. 2011, ApJ, 742, L5
[6] Boss, A.P. 1997, Science, 276, 1836
[7] Brown, J.M., Blake, G.A., Dullemond, C.P., et al. 2007, ApJ, 664, 107
[8] Brown, J. M., Blake, G. A., Qi, C., Dullemond, C.P., et al. 2009, ApJ, 704, 496
[9] Calvet, N., D'Alessio, P., Hartmann, L., et al. 2002, ApJ, 568, 1008
[10] Carpenter, J.M., Mamajek, E.E., Hillenbrand, L.A., et al. 2006, ApJ, 651, L49
[11] Chabrier, G., Baraffe, I., Allard, F., et al. 2000, ApJ, 542, 464
[12] Chauvin, G., Lagrange, A.M., Bonavita, M., et al. 2010 A&A ,509, 52
[13] Cieza, L. A., Schreiber, M. R., Romero, G. A., et al. 2012, ApJ, 750, 157
[14] Currie, T. & Sicilia-Aguilar, A. 2011, ApJ, 732, 24
[15] Fedele, D., van den Ancker, M., Henning, T., et al. 2010, A&A, 510, 72
[16] Furlan, E., Hartmann, L., Calvet, N., et al. 2006, ApJS, 165, 568
[17] Haisch, K.E., Jr., Lada, E.A., Lada, C.J., 2001, ApJ, 553, 153
[18] Hernández, J., Hartmann, L., Megeath, T., et al. 2007, ApJ, 662, 1067
[19] Huélamo, N., Lacour, S., Tuthill, P., et al. 2011, A&A, 528, L7
[20] Ireland, M. & Kraus, A. 2008, ApJ, 678, L59
[21] Jensen & Mathieu 1997, AJ, 114, 301
[22] Kraus A. & Ireland, M., 2012, ApJ, 745, 5
[23] Lada, C.J., Muench, A., Luhman, K.L., et al. 2006, AJ, 131, 1574
[24] Lafreniere, D., Doyon, R., Marois, C., et al. 2007, ApJ, 670, 1367
[25] Lubow, S.H., Seibert, M., & Artymowicz, P. 1999, ApJ, 526, 1001
[26] Meeus, G., Pinte, C., Woitke, P., et al. 2010, A&A, 518, 124
[27] Merin, B., Brown, J.M., Oliveira, I., et al. 2010, A&A, 718, 1200
[28] Najita, J.R., Strom, S.E., & Muzerolle, J. 2007, MNRAS, 378, 369
[29] Pollack, J.B., et al. 1996, Icarus, 124, 62
[30] Pontoppidan, K.M., Blake, G. A., van Dishoeck, E., et al. 2008, ApJ, 684, 1323
[31] Schisano, E., Covino, E., Alcal, J.M., et al. 2009, A&A, 501, 1013
[32] Thi, W.F., Mathews, G., Ménard, F., et al. 2010, A&A 518, 125
[33] Tuthill, P., Lacour, S., Amico, P., et al. 2010, SPIE, 7735, 56
[34] Woitke, P., Riaz, B., Duchene, G., et al. 2011, A&A, 234, 44