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# WARPS AND INTRA-CAVITY KINEMATICS IN TRANSITION DISKS

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RESUMEN

La inferencia de brechas radiales la etapa de evolución de discos protoplanetarios llamada de "transición", motiva preguntas sobre sus orígenes, y posibles conexiones con formación planetaria. Esta charla presentó observaciones recientes de cavidades en discos protoplanetarios. Aquí reportamos sobre los aspectos relaciones con las observaciones de "torcimientos" de la estructura plana, y sobre la estructura y cinemática del gas residual adentro de las cavidades.

ABSTRACT

The inferrence of radial gaps in the "transition disk" stage of protoplanetary disk evolution motivates questions on their origin, and possible link to planet formation. This talk presented recent observations of cavities in transition disks. Here we report on the aspects related to the observations of warps, and on the structure and kinematics of the residual gas inside TD cavities.

*Key Words:* stars: pre-main sequence — protoplanetary disks

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## 1. INTRODUCTION

In the Class II stage of young circumstellar disks evolution (e.g. Shu et al. 1987; Zuckerman 2001; Williams & Cieza 2011), the gaseous accretion disk is exposed. Central cavities have been inferred through the spectral energy distribution models in so-called "transition disks" (and pre-transitional disks, Espaillat et al. 2007, TDs hereafter). This proceeding from the LARIM symposium 2016 presents a selection of structures seen in TDs. Resolved observations inform on possible astrophysical phenomena at work in disks, although they are biased to the larger and brighter disks (i.e. mostly HAeBe stars). Section 2 summarises evidence for disk inclination changes based on scattered light imaging data in the optical and infrared (OIR). Sec. 3 explains how line emission from the residual gas inside TD cavities, along with knowledge of disk orientation from the OIR, allows to interpret the intra-cavity dynamics, through a potentially warped structure. Due to space limitations, we have omitted to include observation of dust trapping and possible grain growth, and also of spiral structure. Casassus (2016) provides a more complete account of these topics.

## 2. TILTED INNER DISKS

The possibility of disk inclination changes, or warps, was first clearly observed in debris disks (following the dissipation of primordial gas), such as in $\beta$ Pic (e.g. Golimowski et al. 2006) or AU Mic (e.g. Boccaletti et al. 2015). In debris disks the warp structure is difficult to ascertain since it has so far only been constrained in dust continuum emission, in an edge-on orientation.

In gas-rich disks, warps have been proposed to account for the light-curve variability of the so-called 'dipper stars', or AA Tau-like classical T-Tauris. The introduction of a magnetically induced warp on scales of a few stellar radii or $\lesssim$0.1 AU (Esau et al. 2014), could result in periodic dimming events. Part of the occulting structure may extend beyond 1 AU (Schneider et al. 2015). Some of these dipper stars, thought to have edge-on circumstellar disks near the star, have face-on disks when imaged with ALMA, such as the case of J1604-2120 (Ansdell et al. 2016, also a TD).

In TDs, warps have been proposed to account for disk orientation changes in observations with different angular resolutions. For example in GM Aur Hughes et al. (2009) propose a central warp to explain the change in disk position angle from the mm-continuum on 0.3 arcsec scales to that of CO(3-2) on 2 arcsec scales. Similarly in AB Aur (Piétu et al. 2005; Tang et al. 2012), in MWC 758 (Isella et al. 2010) and in HD 135344B (e.g. Fedele et al. 2008; Dent et al. 2005).

There is an observational degeneracy in the line-of-sight kinematics due to a warp, and infalling gas, as identified in TW Hya and HD 142527 by Rosenfeld et al. (2012, 2014). In HD 142527, the infalling gas reported by Casassus et al. (2013c,b) could also be

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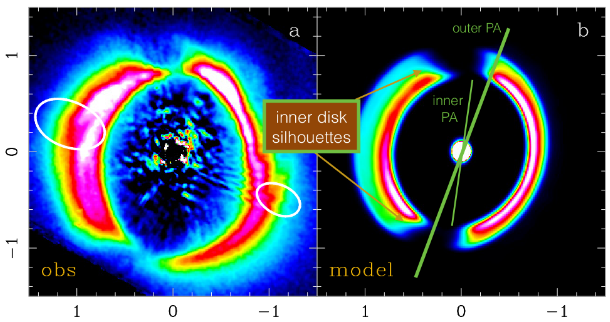


Fig. 1. Comparison between the observed H-band polarised intensity image of HD 142527 (**a-** from Avenhaus et al. 2014) and 3D radiative transfer predictions (**b-** from Marino et al. 2015). The kinematics of $C^{18}O$(2-1) emission (Perez et al. 2015) give the orientation of the outer disk; the white contours in **a-** correspond to systemic velocities, so that the PA of the outer disk lies at $\sim 160$ deg East of North, as indicated on **b-**. The inner disk shadows cast on the outer disk are best reproduced with a PA of 172 deg, the curvature of their outline (or silhouette) is reminiscent of the observations for the Eastern side. The similarities with the observations are particularly good given the idealisations of the model, which assumes a circular cavity.

due to a warp. However, for the case of HD 142527 it turned to be possible to unambiguously determine the disk orientation and the existence of variable inclinations thanks to a comparison of direct imaging observations with radiative transfer predictions Marino et al. (2015). In this case the relative inclination change between the outer and inner disks reaches $\sim 70 \pm 5$ deg (see Fig. 1).

Despite these hints for the frequent occurrence of variable inclinations in TDs, so far only in a couple of cases has it been possible to constrain the warp orientation based on high-contrast imaging observations. There is the case of HD142527, where the outline of the shadows can be related to the flaring of the inner and outer disks. But also in in HD 100453, dips seen in OIR data (Wagner et al. 2015) have been interpreted as shadows cast by a tilted inner disk (Benisty et al. 2017).

## 3. GAS IN CAVITIES

Cavities cleared by the dynamical interaction between the disk and embedded protoplanets, or by binaries with a low mass ratio, should be very deeply depleted in mm-sized grains, but should also contain residual gas in detectable amounts (e.g. Paardekooper & Mellema 2006; Fouchet et al. 2010). With currently observable gas tracers, i.e. mostly CO emission observed with ALMA, it has been possible to detect such gas, and place some constraints on its kinematics on scales of tens of AUs.

Before routine observations with ALMA, long-slit spectroscopy provided evidence for gas inside cavities assuming Keplerian rotation in a fixed and unique disk orientation (Carr et al. 2001; Najita et al. 2003; Acke & van den Ancker 2006; van der Plas et al. 2008; Salyk et al. 2009). Spectro-astrometry allowed to infer the residual gas mass from ro-vibrational CO emission (Pontoppidan et al. 2008; van der Plas et al. 2009; Pontoppidan et al. 2011; van der Plas et al. 2015; Banzatti & Pontoppidan 2015). In general, the conclusion is that dust cavities do contain gas in amounts expected in the context of dynamical clearing due to planetary-mass objects.

Surprises were brought by the first resolved images (Casassus et al. 2013c), made possible thanks to the advent of ALMA. Cycle 0 observations could already resolve the largest TD cavity, i.e. that of the HD 142527 disk. A few $M_{\rm jup}$ worth of gas were found inside this cavity from CO isotopologues (Perez et al. 2015). However, the gas kinematics did not match pure Keplerian rotation, and instead the fast and centrally peaked $HCO^+$(4-3) suggest radial infall. The slower $HCO^+$ signal appear to be non-axially symmetric, and perhaps even filamentary, but new observations are required to constrain its structure.

CO(6-5) observations of the intra-cavity gas in HD 142527 provided finer angular resolutions, and were also free of interstellar absorption that affected the lower J CO (Casassus et al. 2013a,b). Given the orientation of HD 142527 inferred from the OIR, with its tilted inner disk, the CO(6-5) kinematics correspond to infall at the observed stellar accretion rate, but along and through the warp (Casassus et al. 2015, see Figs. 2 and 3). The kinematics are Doppler-flipped where the disk plane crosses the sky, so that blue turns to red. Interestingly, the agreement with the observations improves if the two disk orientations are connected within $\sim$3 AU, at a radius of 20 AU, with material flowing orthogonal to the local disk plane at a velocity comparable to Keplerian. Further observations are required to unambiguously determine the structure of the gaseous flow inside this warp.

It is likely that the warped kinematics in HD 142527 result from circumbinary dynamics involving the low-mass companion, at $\sim$12 AU and with a mass ratio $\lesssim 1/10$ (Biller et al. 2012; Close et al. 2014; Rodigas et al. 2014). General considerations on this possibility can be found in (Casassus et al. 2015). A full understanding of these gas dynamics requires devoted 3D simulations, such as

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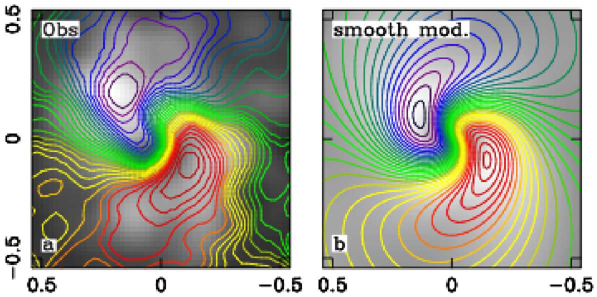


Fig. 2. Figure adapted from Casassus et al. (2015, part of their Fig. 26, ©AAS, reproduced with permission), showing the observed CO(6-5) kinematics in the central regions of HD 142527, and comparing with model predictions for the accretion through the warp represented in Fig. 3 (convolved at the resolution of the centroid map). The origin of coordinates is set to the stellar position.

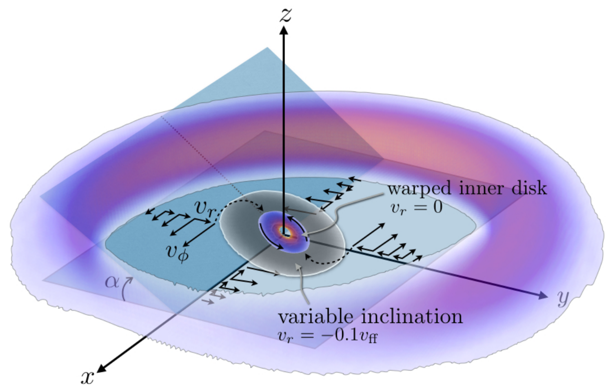


Fig. 3. Sketch of the accretion kinematics through the warp in HD 142527 (from Casassus et al. 2015). The crescent in hues of red and purple represents the distribution of mm-sized grains. Inside the warp, as it connects the two disk inclination material flows along the dashed and curved arrows.

performed by Martin & Lubow (2017).

A summary of ALMA observations of residual gas in TD cavities is given in van Dishoeck et al. (2015). The linear resolutions, relative to the cavity size, are just beginning to be comparable to the case of HD 142527, with the largest cavity known. While the kinematics are not yet sampled in enough detail, the inferred gas surface density structures (e.g. van der Marel et al. 2016) suggests that the gas cavities are $\sim 3$ times smaller than the dust rings, and that the drop in gas surface density can be up to $\sim 10^{-2}$.

Finer angular resolutions with ALMA will soon constrain the cavity edges, and so better understand the process of grain-size filtering (and the radial trapping of the mm-sized grains). Accurate measures of the gas kinematics will help understand how the mass reservoirs in the outer disks flows onto the inner disks, and hence feed stellar accretion. This is a first step towards explaining the high stellar accretion seen in the brighter TDs (e.g. Owen 2015), which also have the largest cavities.

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