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High angular resolution observations of circumstellar disks

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Abstract. High angular resolution interferometric observations are a powerful tool to investigate the composition and the structure of the circumstellar around pre-main sequence stars. AMBER, the recently developed near-infrared spectro-interferometric instrument at the focus of the VLTI, allows to spatially and spectrally resolve the gas emission on milli arcsec angular scales. On the other hand, millimeter interferometers, providing angular scales smaller than 1 arcsec, can be used to infer the kinematic and structure of the outer regions of the disks. Here I briefly summarize some recent observational results obtained in this field.

1. Introduction

High spatial angular resolution interferometric observations are providing an increasingly detailed description of the disks around pre-main sequence stars of solar (T Tauri stars) and intermediate mass (Herbig Ae/Be; hereafter HAe/Be). Both dust continuum emission and emission in molecular lines are observed and spatially resolved in a number of disks, yielding information on the disk structure (i.e, density and temperature of the circumstellar material), the dust properties, and the gas chemistry and dynamics. NIR interferometric observations albeit still challenging, probe the gas and dust distribution at fractions of AU from the central star and allow the investigation of important physical processes responsible for the disk evolution and the planet formation, namely the grain growth, the gas accretion on the central star and the launching mechanism of the observed outflows (Millan-Gabet et al. 2001, 2006; Monnier et al. 2002, 2005, 2006; Eisner et al. 2004, 2005; Isella et al. 2006; Malbet et al. 2007; Tatulli et al. 2007). On the other hand, long baseline millimeter interferometry remains a fundamental technique to study the gas kinematic, the dust properties and the disk structure details on scales to tens of AU. Recent detections of spiral structures and large gaps in the gas+dust distribution are in fact evidence of dynamical perturbations, possibly due to planet formation (Piétu et al. 2005, 2006; Corder et al. 2005; Dutrey et al. 2006; Isella et al. 2007).

In the following sections I will briefly summarize some recent results obtained using both NIR and millimetric interferometric observations of nearby HAe stars.

2. Inner disk observations through NIR interferometry

Since the first interferometric observations of pre-main sequence stars it has been clear that the structure of the innermost region of circumstellar disks strongly differs from the flaring geometry predicted by stellar irradiated active

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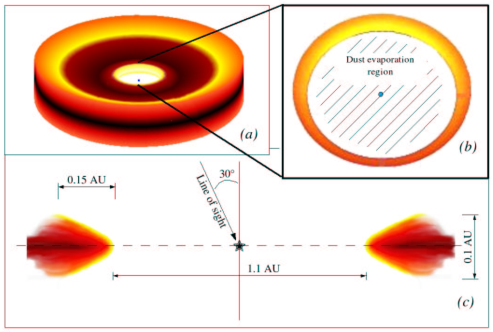

Fig. 1. From Isella et al. 2006. Sketch of the structure of the inner part of a proto-planetary disk. Panel (a) shows a disk with a "puffed-up inner rim" that casts a shadow over the outer part of the disk. Beyond 5-10 AU from the central star, the flaring disk emerges for the rim shadow. Panel (b) presents the image of the inner rim, computed using the model of Isella and Natta (2005) for a star with T_{eff}=10000 K and disk inclination of 30°. Panel (c) shows a vertical section on the inner rim (see Isella and Natta, 2005 for more details).

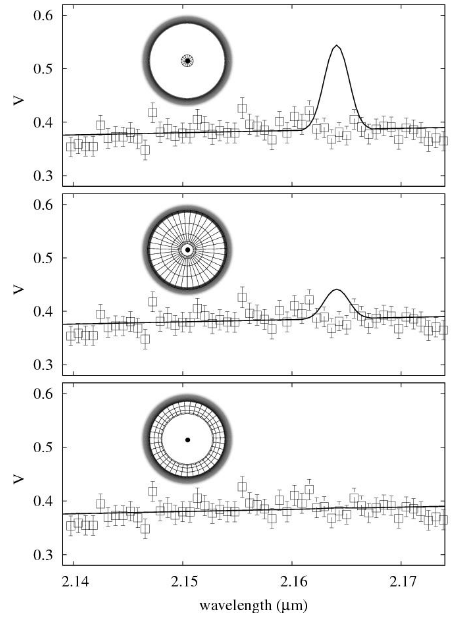

Fig. 2. From Tatulli et al. 2007. Comparison between the observed visibilities (empty square with error bars) and the predictions (solid curves) of the simple geometrical models for the HD 104237 Brγ emission (sketched in the same panels). The observed visibilities are scaled to match the continuum value predicted by the "puffed-up" inner rim model (see Fig. 1). The continuum emission arises both from the stellar photosphere (≈20%) and from the dusty disk inner rim, located at the dust evaporation distance R_{rim} = 0.45 AU and which appears as the bright ring. The Brγ emission regions are shown as grid surfaces. The upper panel represents the *magnetospheric accretion* model in which the Brγ emission originates very close to the star, inside the corotational radius R_{corot} =0.07 AU; in the middle panel the Brγ emission originates between R_{corot} and the rim radius R_{rim} =0.45 AU, representing the *gas within the disk* model; the bottom panel shows the *outflowing wind* model, in which the emission is confined close to the inner rim, between ~ 0.2 AU and ~ 0.5 AU.

disk models (i.e., Chiang and Goldreich 1997). Both the interpretation of the observed NIR excess (Natta et al. 2001) and the measurements of the inner radius of a number of circumstellar disks (Millan-Gabet et al. 2001) suggested that the dust evaporation process, which occurs close to the central star, introduces a strong discontinuity in the gas+dust opacity which may result in the formation of a "puffed-up" inner rim of the dusty disks (Dullemond et al. 2001). More detailed models of the dust evaporation (Isella and Natta, 2005) showed that the "puffed-up" inner rim is located at a distance from the central star that depends on the dust properties and it has a shape characterized by the dependence of the dust evaporation temperature on the gas density (see Fig. 1). Using such models, Isella et al. (2006) showed that micron size dust grains are present inside 1 AU from a number of HAe stars confirming the results obtained using mid-infrared and millimeter interferometry (van Boekel et al. 2005; Natta et al. 2007).

In addition to the analysis of the broad band NIR emission, recent spectro-interferometric observations of circumstellar disk are providing new interesting information on the accreating gas distribution. Using spectrally resolved VLTI/AMBER observations of the HBe star MWC 297 across the Brγ line emission (2.17 μm), Malbet et al. (2007) proved the

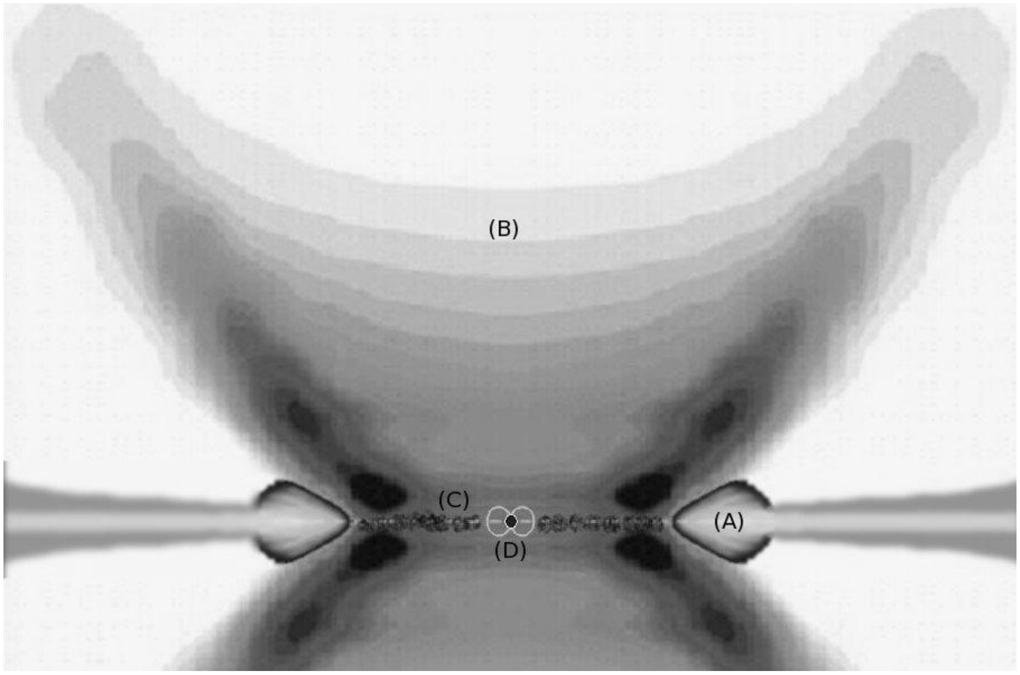

Fig. 3. Pictorial conception of the inner part (R¡2 AU) of the HD 104237 circumstellar disk. The dusty disk inner rim (A) is located at 0.45 AU (as predicted by Isella and Natta 2005) and it emits more than 80% of the observed NIR flux. The Brγ line is emitted by a diffuse wind (B) propagating by the disk region inside the inner rim (modified from Thiébaut et al., 2003). The gaseous disk inside the dust evaporation radius (C) is truncated at about 0.1 AU by the stellar magnetic field; inside this radius the gas accreates on the central star along the magnetic field line forming ionized columns (D).

existence of a large wind that extend beyond the region responsible for the dust continuum emission. Similar observations of the HAe star HD 104237 suggest that, in this case, the Brγ line emission arises from a distance between 0.2 and 0.5 AU from the central star, inside the dust evaporation radius (Tatulli et al. 2007, see Fig. 2). In both cases, spectro-interferometry provides a new powerful tool to investigate the gas distribution in the inner disk regions, testing theoretical models of gas accretion and disk evolution (see Fig. 3).

3. Millimeter imaging of HD 163296

Using different millimeter interferometers, we have recently performed observation of the circumstellar disk around the HAe star HD 163296 in the dust continuum from 0.87 to 7 mm, ^{12}CO (J=2-1 and J=3-2) and ^{13}CO (J=1-0) lines (Isella et al. 2007). Comparing the observations with self-consistent disk models, we find that the disk has an outer radius of 540 AU and it shows a Keplerian rotation pattern consistent with a central stellar mass of 2.6 $M_\odot$. Within the observational errors, there is no evidence of non-keplerian motions and/or significant turbulent broadening (see Fig. 4). The analysis of the dust emission at different wavelengths leads to a dust opacity $k \propto \lambda^{-\beta}$ with $\beta = 1.0 \pm 0.1$, indicating that the solid material in the disk has coagulated into very large bodies, of millimeter and centimeter size (Natta et al. 2007). The continuum observations constrain the circumstellar material surface density profile ($\Sigma \propto r^{0.8}$) for r$\lesssim$200 AU. At larger radii, the continuum emission drops with respect to the model predictions by a factor 30 at least. We argue that this may due to the clearing of a vary large gap by dynamical pertur-

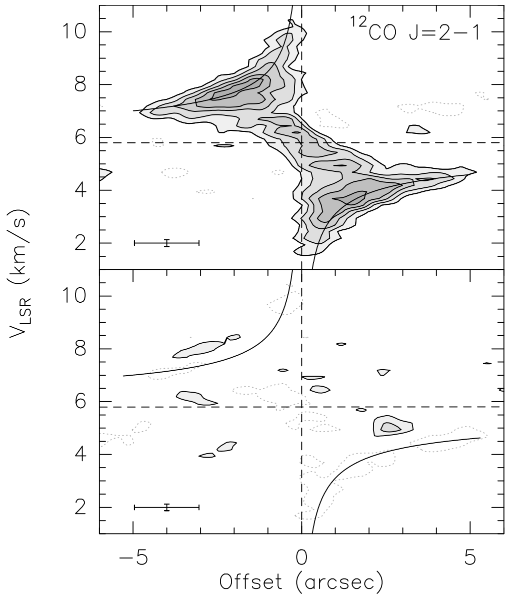

Fig. 4. From Isella et al. (2007). Comparison between the observed and the model predicted ^{12}CO J=2-1 emission at ∼1.3 mm observed around the HAe star HD 163296 using the IRAM Plateau de Bure Interferometer. The upper panel shows the position-velocity diagram measured along the major axis of the disk. The angular offset is measured with respect to the position of the central star. The contour levels are spaced by 2σ corresponding to 0.14 Jy/beam. The cross in the lower left gives the angular and the spectral resolution. The horizontal and vertical straight lines mark the systemic velocity (5.8 Km/sec) and the position of the continuum peak emission. The lower panel shows the residual relative to a Keplerian disk model with $M_\star$=2.6 $M_\odot$, distance = 122 pc, disk inclination = 45°, outer radius = 550 AU, disk mass ∼ 0.2 $M_\odot$.

bations from a low mass companion or to the inward migration of the large bodies that may form in the outer disk. The temperatures derived for CO lines of different optical depth are similar and equal to the dust temperature in the disk interior. This requires that the dust opacity in the UV (which controls the CO dissociation) and in the wavelength range where the stellar radiation peaks are similar, as expected if grains have grown to micron size.

We argue that all these results can be interpreted as the clues of the evolution occurring in the HD 163296 system. In particular, we suggest that the circumstellar disk is probably harboring the formation of large bodies, being in between a Class II pre-main sequence disk and an older debris disk.

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