Star-Disk Interaction in Young Stars
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Inner disk regions revealed by infrared interferometry

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Abstract. I review the results obtained by long-baseline interferometry at infrared wavelengths on the innermost regions around young stars. These observations directly probe the location of the dust and gas in the disks. The characteristic sizes of these regions are found larger than previously thought. These results have motivated in part a new class of models of the inner disk structure. However the precise understanding of the origin of these low visibilities is still in debate. Mid-infrared observations have probed disk emission over a larger range of scales revealing mineralogy gradients in the disk. Recent spectrally resolved observations allow the dust and gas to be studied separately. The few results show that the Brackett gamma emission can find its origin either in a wind or in a magnetosphere but there are no definitive answers yet. In a number of cases, the very high spatial resolution seems to reveal very close companions. In any case, these results provide crucial information on the structure and physical properties of disks surrounding young stars especially as initial conditions for planet formation.

Keywords. Accretion disks, stars: pre–main-sequence, stars: emission-line, stars: mass loss, stars: winds, outflows, planetary systems: protoplanetary disks, infrared: stars, techniques: interferometric, techniques: spectroscopic.

1. Introduction

Many physical phenomena occur in the inner regions of the disk which surrounds young stars. The matter which falls onto the stellar surface spirals in a more or less accreting circumstellar disk subject to turbulence, convection, external and internal irradiation. The disks which are rotating in a quasi Keplerian motion are probably the birth location of future planetary systems. Strong outflows, winds and even jets often find their origin in the innermost regions of many young stellar systems. The mechanisms of these ejection processes are not well understood but they are probably connected to accretion. Most of young stellar systems are born in multiple systems which can be very tight and therefore have a strong impact on the physics of the disk inner regions.

The details of all these physical processes are not yet well understood because of lack of data to constrain them. The range of physical parameters which best define the inner regions of disk in young stellar objects are:

- radius ranging from 0.1 AU to 10 AU
- temperature ranging from 150 K to 4000 K
- velocities ranging from 10 km/s to a few 100 km/s

The instrumental requirements to investigate the physical conditions in such regions are therefore driven by the spectral coverage which must encompass the near and mid infrared from 1 to 20 μm. Depending on the distance of the object (typically between 75 pc and 450 pc) the spatial resolution required to probe the inner parts of disks ranges between fractions and a few tens of milli-arcseconds. Since the angular resolution of astronomical instruments depends linearly on the wavelength and inversely on the telescope diameter, observing in the near and mid infrared wavelength domain points toward telescopes of sizes ranging from ten to several hundred meters. The only technique that allows such a spatial resolution is therefore infrared interferometry.

Millan-Gabet *et al.* (2007) review the main results obtained in infrared interferometry in the domain of young stars between 1998 and 2005. The purpose of the present review is to concentrate on the inner disk regions and to give the latest results in this field. § 2 briefly explains the principles of infrared interferometry and lists the literature on the observations carried out with this technique. § 3 focuses on the main results obtained on disk physics (sizes, structures, dust and gas components,...) and § 4 presents results on other phenomena constrained by interferometry (winds, magnetosphere, multiple systems,...). In § 5 I describe the type of results that can be expected in the future.

2. Infrared interferometry

2.1. *Principle and observations*

Long baseline optical interferometry consists in mixing the light received from an astronomical source and collected by several independent telescopes separated from each other by tens or even hundreds of meters. The light beams are then overlapped and form an interference pattern if the optical path difference between the different arms of the interferometer—taking into account paths from the source up to the detector—is smaller than the coherence length of the incident wave (typically of the order of several microns). This interference figure is composed of fringes, i.e., a succession of stripes of faint (destructive interferences) and bright (constructive interferences) intensity. By measuring the contrast of these fringes, i.e. the normalized flux difference between the darkest and brightest regions, information about the morphology of the observed astronomical source can be recovered. Figure 1 illustrates this principle.

2.2. *Instruments available for inner regions studies*

Interferometric observations of young stellar objects were and are still performed at six facilities on seven different instruments (see Table 1). We can classify these observations into three different categories:

- **Small-aperture interferometers**: PTI, IOTA and ISI were the first facilities to be operational for YSO observations in the late 1990's (see Fig. 2 & 3). They have provided mainly the capability of measuring visibility amplitudes and lately closure phases. The latest one, CHARA, has an aperture diameter of 1 m. The instruments are mainly accessible through team collaboration.
- **Large-aperture interferometers**: KI, VLTI and soon LBT are facilities with apertures larger than 8 m. The instruments are widely open to the astronomical community through general calls for proposals. Lately, these facilities have significantly increased the number of young objects observed.
- **Instruments with spectral resolution:** CHARA, MIDI and AMBER provide a spectral resolution from a few hundred up to 10,000 whereas other instruments mainly provided broadband observations. The spectral resolution allows the various phenomena occurring in the environment of young stars to be separated.

2.3. *Elements of bibliography*

Figure 2 displays the number of published results, and show that it is increasing with time and improved facilities. At the date of the conference there were 31 refereed articles published in the field of young stars corresponding to 66 young stellar objects observed (see by chronological order: Malbet *et al.* 1998; Millan-Gabet *et al.* 1999; Akeson *et al.*

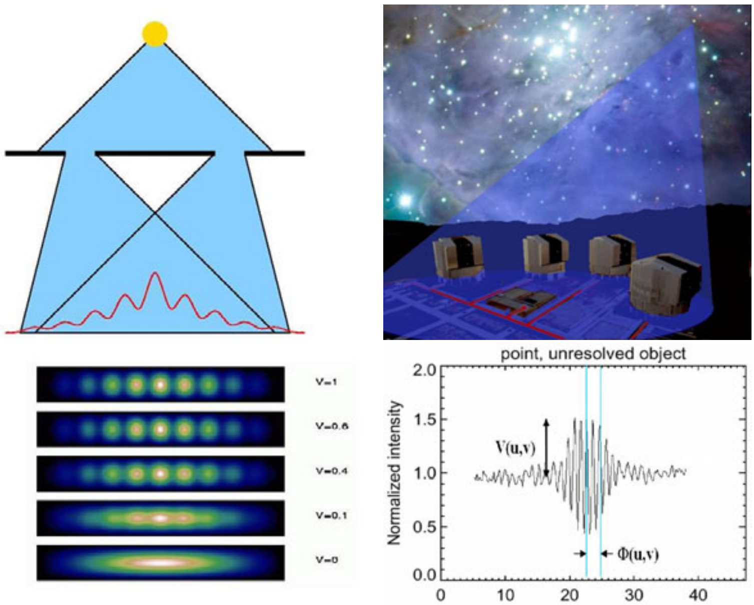

Figure 1. Principle of interferometry. Upper panels: the Young's slit experiment (left) compared to optical interferometry (right): in both cases the light travels from a source to a plane where the incoming wavefront is split. The telescope apertures play the same role as the Young's slits. The difference lies in the propagation of light after the plane. In the case of optical interferometry, the instrument controls the propagation of light down to the detectors. At the detector plane, the light beams coming from the two apertures are overlapped. Lower panels: interference fringes whose contrast changes with the morphology of the source. Left panel shows fringes whose contrast varies from 0 to 1. Right panel displays actual stellar fringes but scanned along the optical path. The measure of the complex visibilities corresponds to the amplitude of the fringes for the visibility amplitude and the position of the fringes in wavelength units for the visibility phase.

2000; Millan-Gabet *et al.* 2001; Tuthill *et al.* 2002; Eisner *et al.* 2003; Colavita *et al.* 2003; Wilkin & Akeson 2003; Leinert *et al.* 2004; Eisner *et al.* 2004; van Boekel *et al.* 2004; Malbet *et al.* 2005; Akeson *et al.* 2005b; Eisner *et al.* 2005; Monnier *et al.* 2005; Boden *et al.* 2005; Akeson *et al.* 2005a; Eisner *et al.* 2006; Millan-Gabet *et al.* 2006a; Preibisch *et al.* 2006; Ábrahám *et al.* 2006; Millan-Gabet *et al.* 2006b; Monnier *et al.* 2006; Quanz *et al.* 2006; Eisner *et al.* 2007; Malbet *et al.* 2007; Tatulli *et al.* 2007; Kraus *et al.* 2007; Lachaume *et al.* 2007; Eisner 2007; Ratzka *et al.* 2007).

Graphs in Fig. 3 show that the distribution of observed objects is rather well distributed among the various facilities. Several categories of young stellar systems have been observed at milli-arcsecond scales mainly in the near-infrared wavelength domain, but also in the mid-infrared one. They include the brightest Herbig Ae/Be stars, the fainter T Tauri stars and the few FU Orionis. Finally most observations were carried out in broad band but the advent of large aperture interferometers like the VLTI and KI allow higher spectral resolution to be obtained.

3. Inner disk physics

Most of the studies carried out on YSOs are focused on the physics of inner regions of disks. They started with the determination of rough sizes of emission then led to more constraints on the disk structure. Mid infrared spectrally resolved observations were able

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Table 1. Interferometers involved in YSO science

Facility	Instrument	Wavelength (microns)	Numbers of apertures	Aperture diameter (m)	Baseline (m)
PTI	V^2	H, K	3	0.4	$80-110$
IOTA	V^2, CP	H, K	3	0.4	$5-38$
ISI	heterodyne	11	2 (3)	1.65	$4-70$
KI	V^2, nulling	K	2	10	80
VLTI/AMBER	V^2, CP (imaging)	$1-2.5$ /spectral	3 (8)	8.2/1.8	$40-130$ /$8-200$
VLTI/MIDI	V^2 (/CP)	$8-13$ /spectral	2 (4)	8.2/1.8	$40-130$ /$8-200$
CHARA	V^2, CP (imaging)	$1-2.5$ /spectral	2/4 (6)	1	$50-350$
LBT	imaging, nulling	$1-10$	2	8.4	$6-23$

V^2: visibility measurement; CP: closure phase.

Acronyms. PTI: *Palomar Testbed Interferometer*; IOTA: *Infrared and Optical Telescope Array* (closed since 2006); ISI: *Infrared Spatial Interferometer*; KI: *Keck Interferometer*; VLTI: *Very Large Telescope Interferometer*; CHARA: *Center for High Angular Resolution Array*; LBT: *Large Binocular Telescope* (not yet operational).

to identify different types of dust grains. Near infrared spectrally resolved observations are coming out and permits to spatially discriminate between gas and dust.

3.1. *Sizes of circumstellar structures*

About 10 years ago, the paradigm was that disks were present around a majority of young stars. These disks were believed to behave "normally" with a radial temperature distribution following a power-law $T \propto r^{-q}$ with q ranging between 0.5 and 0.75. The value of q depends on the relative effect of irradiation from the central star in comparison to heat dissipation due to accretion. This model was successful in reproducing ultraviolet and infrared excesses in spectral energy distributions (SEDs). Malbet & Bertout (1995) investigated the potential of optical long baseline interferometry to study the disks of T Tauri stars and FU Orionis stars. They found that the structure would be marginally resolved but observations would be possible with baselines of the order of 100 m with a visibility amplitude remaining high.

First observations of brighter Herbig Ae/Be stars showed that the observed visibilities were much smaller than the expected ones especially in these objects were the accretion plays a minor role. Monnier & Millan-Gabet (2002) pointed out that the interferometric sizes of these objects were much larger than expected from the standard disk model. They plotted the sizes obtained as a function of the stellar luminosity and found a strong correlation following a $L^{0.5}$ law over two decades. This behavior is consistent with the variation of radius of dust sublimation with respect to the central star luminosity: the

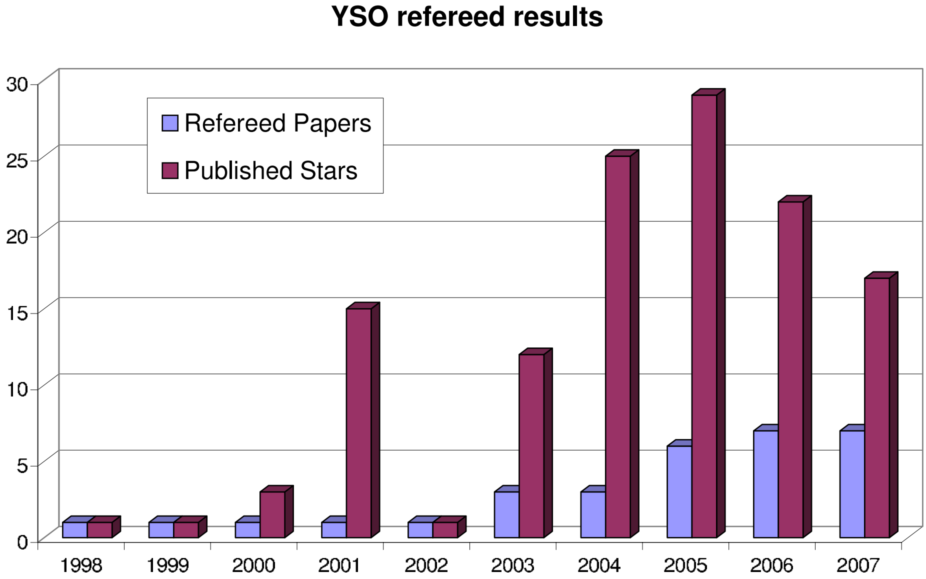

Figure 2. Young stellar objects observed by interferometry and number of refereed papers published in the period 1998-2007. The statistics of the year 2007 is not complete.

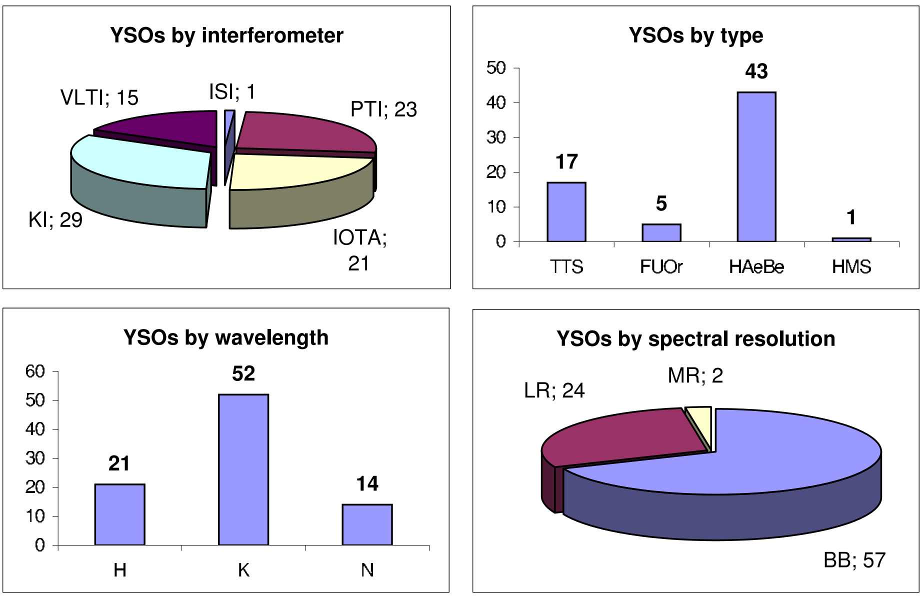

Figure 3. Young stellar objects observed by interferometry in the period 1998-2007. Upper left: distribution by interferometer. Upper right: distribution by YSO type. Lower left: distribution by wavelength of observation. Lower right: distribution by spectral resolution. The statistics is the same as the one of Fig. 2.

more luminous the object the further the dust can survive in solid form at a temperature lower than the sublimation limit ($\sim 1000 - 1500\,\mathrm{K}$). Only the most massive Herbig Be stars seem to be compliant with the standard accretion disk model.

In the meantime, in order to account for the near-infrared characteristics of SEDs and in particular a flux excess around $\lambda = 3\mu$m, Natta *et al.* (2001) proposed that disks

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around Herbig Ae/Be stars have optically thin inner cavity and create a puffed-up inner wall of optically thick dust at the dust sublimation radius. More realistic models were developed afterward which take more physical properties into account (Dullemond *et al.* 2001; Muzerolle *et al.* 2004; Isella & Natta 2005). However as pointed out by Vinković *et al.* (2003) the models are not unique and they proposed another model with a disk halo.

Observations at KI (Colavita *et al.* 2003; Eisner *et al.* 2005; Akeson *et al.* 2005b) found also large NIR sizes for lower-luminosity T Tauri stars, in many cases even larger than would be expected from extrapolation of the HAe relation. It is interpreted by the fact that the accretion disk contributes significantly to the luminosity emitted by the central region and therefore this additional luminosity must be taken into account in the relationship. However in these systems the error bars are still large and very few measurements have been obtained per object. In order to interpret all the T Tauri measurements, Akeson *et al.* (2005b) need to introduce new physical phenomena like optical thick gas emission in the inner hole and extended structure around the objects.

Characteristic dimensions of the emitting regions at $10\,\mu$m were found by Leinert *et al.* (2004) to be ranging from 1 AU to 10 AU. The sizes in their sample stars correlated with the slope of the $10 - 25\,\mu$m infrared spectrum: the reddest objects are the largest ones. Such a correlation is consistent with a different geometry in terms of flaring or flat (self-shadowed) disks for sources with strong or moderate mid-infrared excess, respectively, demonstrating the power of interferometry not only to probe characteristic disk sizes but also to derive information on their vertical structure.

3.2. *Constraints on disk structure*

Theoreticians start discussing slightly different scenarios of the inner regions around young stars. For example, the shape of the inner puffed-up wall is modeled with a curved shape by Isella & Natta (2005) due to the very large vertical density gradient and the dependence of grain evaporation temperature on gas density as expected when a constant evaporation temperature is assumed. Recently, Tannirkulam *et al.* (2007) proposed that the geometry of the rim depends on the composition and spatial distribution of dust due to grain growth and settling.

Vinković & Jurkić (2007) presented a model-independent method of comparison of NIR visibility data of YSOs. The method based on scaling the measured baseline with the YSO distance and luminosity removes the dependence of visibility on these two variables. They found that low luminosity Herbig Ae stars are best explained by the uniform brightness ring and the halo model, T Tauri stars with the halo model, and high luminosity Herbig Be stars with the accretion disk model, but they admit that the validity of each model is not well established.

At the moment, only one object has been thoroughly studied: FU Orionis (Malbet *et al.* 1998, 2005; Quanz *et al.* 2006). This young stellar object has been observed on 42 nights over a period of 6 years from 1998 to 2003 with 287 independent measurements of the fringe visibility at 6 different baselines ranging from 20 to 110 m in length, in the H and K bands. The data not only resolves FU Ori at the AU scale, but also allows the accretion disk scenario to be tested. The most probable interpretation is that FU Ori hosts an active accretion disk whose temperature law is consistent with the standard model. In the mid infrared, Quanz *et al.* (2006) resolved structures that are also best explained with an optically thick accretion disk. A simple accretion disk model fits the observed SED and visibilities reasonably well and does not require the presence of any additional structure such as a dusty envelope. This is why one should remain careful with results coming from surveys having only few measurements per object.

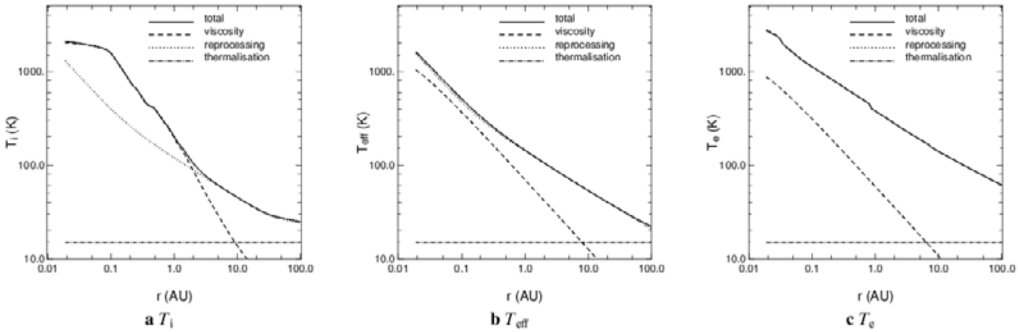

Figure 4. Radial distribution of temperature at different location in the disk computed with a two-layer model by Lachaume *et al.* (2003). Left: temperature in the equatorial plane. Center: effective temperature. Right: surface temperature. The different lines represent the various contribution to the heating: viscosity, reprocessing of the stellar light, thermalization with the ambient temperature.

Millan-Gabet *et al.* (2006a) obtained K-band observations of three other FU Orionis objects, V1057 Cyg, V151 Cyg, and Z CMa-SE and found that all three objects appear significantly more resolved than expected from simple models of accretion disks tuned to fit the SEDs. They believe that emission at the scale of tens of AU in the interferometer field of view is responsible for the low visibilities, originating in scattering by large envelopes surrounding these objects. In a not yet published study, Li Causi *et al.* have measured again interferometric visibilities of Z CMa with VLTI/AMBER and propose to interpret the data by the presence of a very close companion.

On the theoretical side, very few physical models achieved to fit interferometric data simultaneously with SEDs. Using a two-layer accretion disk model, Lachaume *et al.* (2003) found satisfactory fits for SU Aur, in solutions that are characterized by the midplane temperature being dominated by accretion, while the emerging flux is dominated by reprocessed stellar photons (see Fig. 4). Since the midplane temperature drives the vertical structure of the disk, there is a direct impact on the measured visibilities that are not necessarily taken into account by other models.

Very interesting results have been presented at this conference by Kraus *et al.* (this volume) showing that they are able to derive the temperature radial distribution of the disk around MWC 147 from interferometric measurements using the spectral variation of the visibilities at low resolution. A similar work has been attempted at PTI with larger error bars (Eisner *et al.* 2007).

3.3. *Dust mineralogy*

The mid-infrared wavelength region contains strong resonances of abundant dust species, both oxygen-rich (amorphous or crystalline silicates) and carbon-rich (polycyclic aromatic hydrocarbons, or PAHs). Therefore, spectroscopy of optically thick protoplanetary disks offers a diagnostic of the chemical composition and grain size of dust in disk atmosphere.

van Boekel *et al.* (2004) spatially resolved three protoplanetary disks surrounding Herbig Ae/Be stars across the N band. The correlated spectra measured by MIDI at VLTI correspond to disk regions ranging from 1 to 2 AU. By combining these measurements with unresolved spectra, the spectrum corresponding to outer disk regions at 220 AU can also be derived. These observations have revealed that the dust in the inner regions was highly crystallized (40 to 100%), more than any other dust observed in young

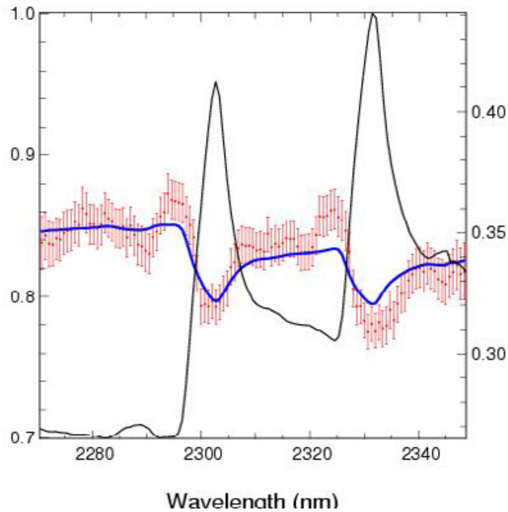

Figure 5. Spectrally dispersed visibility amplitudes of 51 OPh in the CO bandhead spectral region. Overimposed is the spectrum as measured by VLTI/AMBER (black line). The blue curve corresponds to the addition of simple uniform disk model for the excess emission in the line with a typical diameter of 0.2 AU. From Tatulli et al. (priv. comm.)

stars until now. The spectral shape of the inner-disk spectra shows surprising similarity with Solar System comets. Their observations imply that silicates crystallize before terrestrial planets are formed, consistent with the composition of meteorites in the Solar System. Similar measurements were also carried out by Ratzka *et al.* (2007) on the T Tauri system, TW Hya. According to the correlated flux measured with MIDI, most of the crystalline material is located in the inner, unresolved part of the disk, about 1 AU in radius.

3.4. *Gas/dust connection*

Gil *et al.* (2005) observed the young stellar system 51 Oph confirming the interpretation of Thi *et al.* (2005) and more recently Berthoud *et al.* (2007) of a disk seen edge-on: the radial distribution of excitation temperatures for the vibrational levels of CO overtone ($\Delta v = 2$) emission from hot gas is consistent with the gas being in radiative thermal equilibrium except at the inner edge, where low vibrational bands have higher excitation temperatures. In yet unpublished results, Tatulli *et al.* (priv. comm.) confirm the high inclination of the disk but also detect the CO bandheads allowing the dust responsible for the continuum to be separated from the gas emitting these CO bands. As a matter of fact, the visibilities in the CO bands is lower than the ones measured in the continuum implying that the region responsible for this gas emission is larger than the region responsible for the dust emission. Figure 5 illustrates this result.

This result shows that the combination of very high spatial information with spectral resolution opens brand new perspectives in the studies of the inner disk properties by discriminating between species.

4. Other AU-scale phenomena

Several other physical phenomena have been investigated in the innermost region of disks: wind, magnetosphere and close companions.

4.1. *Outflows and winds*

The power of spectrally resolved interferometric measurements provides detailed wavelength dependence of inner disk continuum emission (see end of § 3.2). These new capabilities enable also detailed studies of hot winds and outflows, and therefore the physical conditions and kinematics of the gaseous components in which emission and absorption lines arise like Brγ and H_2 lines. With VLTI/AMBER, Malbet *et al.* (2007) spatially resolved the luminous Herbig Be object MWC 297, measuring visibility amplitudes as a function of wavelength at intermediate spectral resolution (R = 1500) across the $2.0-2.2\,\mu$m band, and in particular the Brγ emission line. The interferometer visibilities in the Brγ line are about 30% lower than those of the nearby continuum, showing that the Brγ emitting region is significantly larger than the NIR continuum region. Known to be an outflow source, a preliminary model has been constructed in which a gas envelope, responsible for the Brγ emission, surrounds an optically thick circumstellar disk. The characteristic size of the line-emitting region is 40% larger than that of the NIR disk. This model is successful at reproducing the VLTI/AMBER measurements as well as previous continuum interferometric measurements at shorter and longer baselines (Millan-Gabet *et al.* 2001; Eisner *et al.* 2004), the SED, and the shapes of the Hα, Hβ, and Brγ emission lines. The precise nature of the MWC 297 wind, however, remains unclear; the limited amount of data obtained in these first observations cannot, for example, discriminate between a stellar or disk origin for the wind, or between competing models of disk winds (see e.g. Ferreira's and Shu's contributions in this volume).

4.2. *Magnetosphere*

The origin of the hydrogen line emission in Herbig Ae/Be stars is still unclear. The lines may originate either in the gas which accretes onto the star from the disk, as in magnetospheric accretion models (Hartmann *et al.* 1994), or in winds and jets, driven by the interaction of the accreting disk with a stellar (Shu *et al.* 1994) or disk (Casse & Ferreira 2000) magnetic field. For all models, emission in the hydrogen lines is predicted to occur over very small spatial scales, a few AUs at most. To understand the physical processes that happen at these scales, one needs to combine very high spatial resolution with enough spectral resolution to resolve the line profile.

One one hand, Tatulli *et al.* (2007) performed interferometric observations of the Herbig Ae star HD 104237, obtained with the VLTI/AMBER instrument with $R = 1500$ spectral resolution. The observed visibility was identical in the Brγ line and in the continuum, even though the line represents 35% of the continuum flux. This immediately implies that the line and continuum emission regions have the same apparent size. Using simple toy models to describe the Brγ emission, they showed that the line emission is unlikely to originate in either magnetospheric accreting columns of gas or in the gaseous disk but more likely in a compact outflowing disk wind launched in the vicinity of the rim, about 0.5 AU from the star. The main part of the Brγ emission in HD 104237 is unlikely to originate in magnetospheric accreting matter.

On the other hand, Eisner (2007) measured an increase of the Brγ visibility in MWC 480 implying that the region of emission of the hydrogen line is very compact, less than 0.1 mas in radius which could be interpreted as an emission originated in the magnetosphere of the system.

At the present time, given the limited number of samples, it is difficult to derive a general tendency but it seems that all possible scenari can be found.

4.3. *Binaries and multiple systems*

Boden *et al.* (2005) performed the first direct measurement of pre-main sequence stellar masses using interferometry, for the double-lined system HD 98800-B. These authors established a preliminary orbit that allowed determination of the (subsolar) masses of the individual components with 8% accuracy. Comparison with stellar models indicates the need for subsolar abundances for both components, although stringent tests of competing models will only become possible when more observations improve the orbital phase coverage and thus the accuracy of the stellar masses derived.

In another instance, based on a low-level oscillation in the visibility amplitude signature in the PTI data of FU Ori, Malbet *et al.* (2005) claim the detection of an off-centered spot embedded in the disk that could be physically interpreted as a young stellar or protoplanetary companion located at $\sim 10\,\mathrm{AU}$, and could possibly be at the origin of the FU Ori outburst itself. Using another technique, Millan-Gabet *et al.* (2006b) reported on the detection of localized off-center emission at 1-4 AU in the circumstellar environment of AB Aurigae. They used closure-phase measurements in the near-infrared. When probing sub-AU scales, all closure phases are close to zero degrees, as expected given the previously determined size of the AB Aurigae inner-dust disk. However, a clear closure-phase signal of $-3.5° \pm 0.5°$ is detected on one triangle containing relatively short baselines, requiring a high degree of asymmetry from emission at larger AU scales in the disk. They interpret such detected asymmetric near-infrared emission as a result of localized viscous heating due to a gravitational instability in the AB Aurigae disk, or to the presence of a close stellar companion or accreting substellar object.

5. Future prospects and conclusion

As emphasized in this review, more interferometric data is required with better accuracy and also wider coverage of the baselines in order to better constrain the models that have been proposed. Like for radio astronomy, these supplementary data will allow image reconstruction without any prior knowledge of the observed structure. Several projects are ready to obtain interferometric images although with few pixels across the field: MIRC at CHARA and AMBER at the VLTI in the near-infrared. However at the moment MIRC is limited in sensitivity and AMBER in number of telescopes (3) which makes it difficult to routinely achieve imaging. In the mid-infrared the MATISSE instrument is being proposed to ESO to provide imaging with 4 telecopes at the VLTI. VSI is also a proposed VLTI instrument of second generation which can combine from 4 to 8 beams at the same time so that imaging becomes easier. LBT will also provide imaging capability.

All these instruments provide spectral resolution that make them indeed spectro-imagers. Therefore in the future, one should be able to obtain a wealth of information from the innermost regions of disks around young stars. However in the meantime, observations are already mature enough to allow detailed modeling of the phenomena occuring in these inner regions.

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