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INTERFEROMETRIC OBSERVATIONS OF PROTOPLANETARY DISKS

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Abstract. The observation of protoplanetary disks at the astronomical unit scale is one of the most exciting key programs for long baseline interferometers. Existing observations have questioned the models of circumstellar environments of young stars; but this is just the beginning. Here, to provide the reader with a sense of what can be done today in this field, actual observations of the pre-main sequence star FU Orionis with near-infrared interferometers IOTA and PTI are presented. Every step, from raw data reduction to final interpretation, is described. The limits of current observations and the promise of future contributions from the VLTI are discussed.

1 Introduction

Optical long baseline interferometry is a key observational technique for the study of protoplanetary disks. It allows astronomical unit level resolutions at the distance of main star-forming regions and vega-like stars.

The astronomers using VLTI and equivalent interferometers such as Keck and CHARA will be able to probe near- and mid-infrared emission arising from the disks' putative planet formation region. A lot of important issues requiring direct observations of these central AU's will benefit from this new potential:

- what are the physical processes behind the accretion in a young disk (magnetic/hydrodynamic turbulence ...)?
- what is the link between accretion and ejection processes (such as collimated jets and winds) ?
- how, where, and when do planets form inside a disk and what is the influence of the disk on their evolution ?

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- what are the mechanisms of formation for more massive companions such as brown dwarfs ?

Until recently the main tool to model circumstellar disks around T Tauri and Herbig HAeBe stars was to study the Spectral Energy Distribution (SED). The standard accretion disk model (Shakura & Sunyaev 1973, Lynden-Bell & Pringle 1974), which describes the disk as geometrically thin but optically thick, steadily accreting and in Keplerian rotation, predicts a radial temperature power law $T \approx r^{-q}$ with $q = 3/4$. This model was successful in accounting for some TTauri's SED but not for most Young Stellar Objects (YSO). Following these works, several authors have extensively studied radiative transfer inside the disks to model their vertical structure, taking into account several heating sources (Malbet *et al.* 2001, D'Alessio *et al.* 1999, Bell *et al.* 1997 ...). These works allowed to account for a larger number of SED shapes. However, SED modeling suffers from the fact that the solution is highly non-unique which prevents from disentangling different models' hypotheses.

Optical Long Baseline Interferometry (OLBI) observations have proven to be an essential complement to SED modeling and their contribution will increase in the forthcoming years when bigger interferometers will be available. About 20 young stars have been observed so far with AU resolution and most of the time their near-infrared structure has been resolved (Malbet *et al.* 1998, Akeson *et al.* 2000, Millan *et al.* 2001, Akeson *et al.* 2002, Danchi *et al.* 2001, Tuthill *et al.* 2001, the last two observations were done using the aperture masking technique).

In particular, in a recent work Millan *et al.* 2001 have successfully resolved the near-infrared emission of most of the stars in a sample of 15 HAeBe with the IOTA interferometer. The bottom line of their important discovery is that the standard accretion disk model very often fails to reproduce visibility observations and that the near-infrared emission could be localized in a ring-like structure. One of the most credible interpretation of this is that the emission arise from an inner rim of a cavity carved by the stellar radiation in the circumstellar disk (see Natta *et al.* 2001 and Dullemond *et al.* 2001).

This paper is aimed at giving the reader an actual sense of what can be done *today* with a near-infrared LBI. The case of FU Orionis, a peculiar low-mass pre-main sequence star is discussed. FU Orionis properties and the interferometers used for the observations are presented in section 2, visibility raw data reduction and calibration are presented in section 3, interpretation in section 4, finally in section 5 we conclude on the VLTI-AMBER and MIDI potential for pre-main-sequence stars studies. The appendix discusses further observations of FU Orionis that could be carried out with VLTI AMBER instruments

2 FU Orionis observations

2.1 Fu Orionis stars

FU Orionis is a star that has undergone an important luminosity outburst (~ 6 magnitudes) in a time scale of ≈ 1 year, followed by a decrease in luminosity with

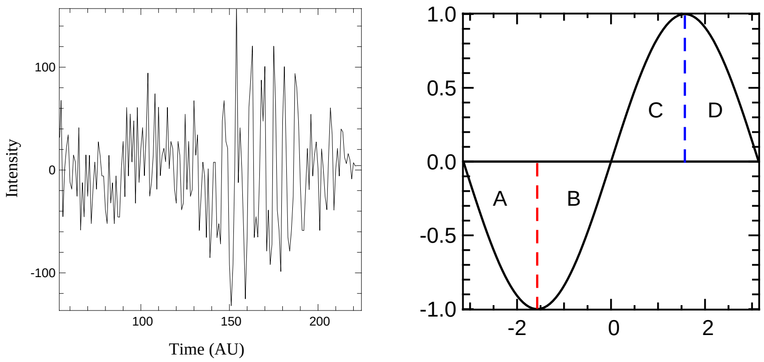

Fig. 1. Left: Example of FU Orionis interferogram obtained on Iota. The whole temporal coherence envelope is visible. Right: Sampling of the central fringe at PTI. The raw output of the instrument is a set of four numbers A,B,C and D that correspond to the sample of the flux through four positions in the fringe.

a timescale of ≈ 100 years. This star is associated with a star forming region. Its spectral type varies with wavelength (F-G supergiant in the visible, K-M in the near-infrared). Its Spectral Energy Distribution (SED) shows an important infrared excess. Evidence for differential rotation is seen by the presence of double-peaked photospheric-like lines. The presence of strong winds by important line broadening. Several other stars have been classified as FU Orionis stars due to similar properties (see Harmann & Kenyon 1996 for a review).

These properties have been interpreted as the signature of a Keplerian accretion disk in which thermal instabilities have provoked its luminosity to outshine that of the star by a factor of several hundreds. This kind of source is therefore an excellent target to test accretion disks models.

2.2 The interferometers

At the time when these observations were done only two interferometers provided enough sensitivity in the near-infrared to observe the brightest pre-main sequence stars, among which FU Orionis. The observation campaign reported here spans 4 years of observations at IOTA and PTI.

The Palomar Testbed Interferometer operated by JPL for NASA provided three 45 cm siderostats with an 80 m and 110 m baseline. The Infrared Optical Telescope Array operated by Harvard-Smithsonian Center for Astrophysics provided two 45 cm siderostats in an L shaped configuration of maximum baseline 38 m. Both of them allowed visibility observations in the K band and H band.

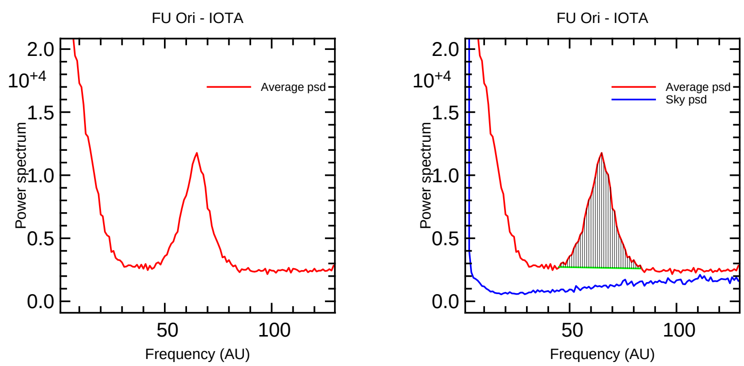

Fig. 2. Left: Average power spectral density for 100 FU Orionis interferograms. Right: The average psd of an average dark field is added to the previous power spectral density. The dashed domain corresponds to the coherent photon energy that has to be estimated to compute visibility.

3 Interferometric observations

3.1 Raw data processing

IOTA and PTI provided two different kinds of raw data, very comparable for the first to the data given by the VLTI Vinci instrument and, for the second to the data that will be provided by the AMBER instrument. Processing interferometric data requires us to define a visibility estimator. The IOTA fringe detector scheme temporally encodes the fringe pattern an records the whole fringe envelope. The PTI one is able to equalize the optical path differences to a fraction of a wavelength and therefore allows sampling of the central fringe alone.

An example of an IOTA raw interferogram is shown in the left side of Figure 1. The signal's periodic oscillations due to the presence of the fringe are clearly visible while lower spatial frequency random oscillations attributed to the atmosphere variation are also present. There is no example for PTI raw data since PTI outputs a series of 4 numbers for each visibility measurement. These measurements correspond to the measurements of the flux at 4 different positions ($\pi/2$ shifted) in the central fringe (see right side of Figure 1).

Extracting visibilities from these raw data requires hunting for all sorts of possible errors and biases. This is particularly important in the case of pre-main sequence stars, where the surrounding environment might be only barely resolved (high visibilities). It is therefore important to come up with visibilities that can be trusted. Among the source of possible biases one can find:

- photon noise;

- readout noise;

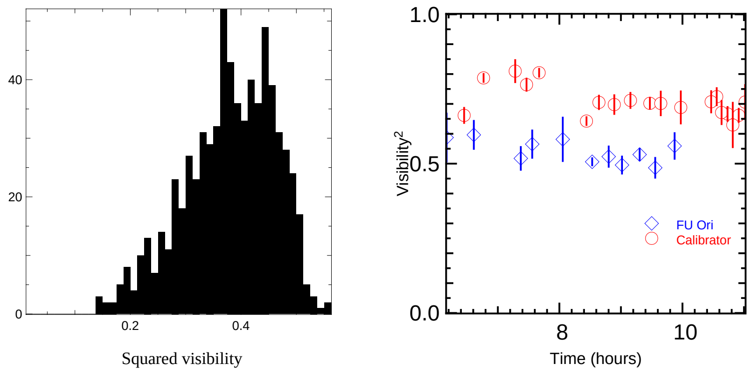

Fig. 3. Left: Example of a histogram of squared visibilities obtained on a batch of 100 IOTA interferograms. Right: One night of data spanning 5 hours, raw visibilities for FU Orionis (blue diamonds) and its calibrators (red circles). A structure is clearly resolved around FU Ori.

- photometric noise;
- piston noise.

It is often the case that some sort of interferogram selection rules have to be applied to eliminate bad data, a potential source of bias also !

Figure 2 illustrates the different processes of visibility estimation at the IOTA interferometer. The fringe visibility is estimated from the fringe energy in the power spectral density (psd). The left side of this figure shows the average psd of 100 interferograms similar to the one displayed in the left side of figure 1. The right part of this figure shows the contribution of the readout noise to this psd superimposed on the interferogram psd. The dashed part of the psd is the energy corresponding to the coherent photons. Estimating carefully this energy with limited biases is the hard part of the process. Once it is done it allows us estimating the squared visibility.

Once the visibility has been estimated one has to proceed with the error estimation. Figure 3 shows a typical distribution of squared visibilities in a set of 100 consecutive FU Orionis interferograms recorded at IOTA. At this stage one has to consider all the tests that would reveal any bias in the data. External constraints such as information from the fringe tracker, tip/tilt system (etc ...) can be used to track down the biases. Extracting the true visibility estimation and its corresponding error might require the use of numerical methods. Among those the bootstrap technique is probably the most robust (see Effron & Tibshirami 1998).

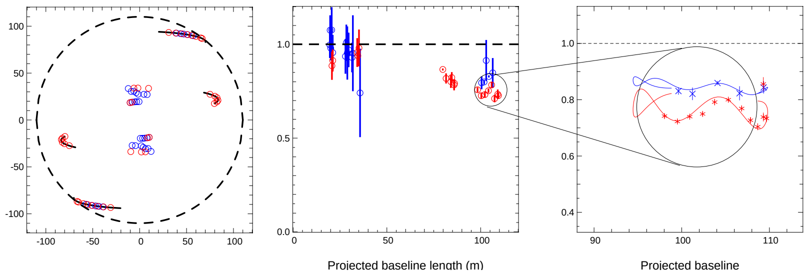

Fig. 4. Left: Actual (u, v) coverage obtained on FU Orionis with the IOTA and PTI interferometers. Center: squared visibilities as a function of projected baselines. Red color corresponds to K, blue to H band. Right: zoom on 110 m points showing evidence for oscillations in the squared visibility curve. Solid lines show best fit for the model consisting of a gaussian disk + unresolved point.

3.2 Data calibration

Every observation of the science target should be accompanied by the observation of one or several calibrators as close in time as possible. The calibrator star is supposedly unresolved or at least its photospheric diameter should be known well enough. That way a calibrator's raw visibility will lead to a proper estimation of the atmosphere+instrument response. The uncertainty linked to the calibrator diameter estimation can be the limiting factor in the final error estimation. Using several calibrators with spectral types as close as possible to that of the target star is the most efficient way to reduce this incertitude. Care should be taken to interleave the target observation with calibrator observations on a very regular basis. The right side of Figure 3 shows 5 hours of consecutive observations of FU Orionis and its calibrators at PTI. One can see that raw visibilities are smaller than those of the calibrators. The final true visibility will be estimated by

- interpolating the instrumental visibility at the position of each FU Orionis measurement;
- dividing each FU Orionis visibility by the estimated instrumental visibility.

The error estimation should take into account the measurement error on each data point plus the estimated error on the calibrator diameter.

4 Interpretation

4.1 Results

After processing raw data and calibrating all visibilities, the final result is a *uv* table which contains for each (u,v) point the measured squared visibility and its corresponding error. The left panel of Figure 4 displays the (u, v) coverage obtained with the association of IOTA and PTI. This coverage allows sampling of several scales of the structure around FU Orionis. The center panel of Figure 4 displays the squared visibilities as a function of projected baseline. Obviously a structure is resolved around FU Orionis. This figure contains only part of the information but is sufficient to notice two main trends:

- a small scale structure around FU Orionis revealed by long baseline observations (PTI);
- oscillations in the visibility curves (mostly in the K band observations at 110m) are detected. Their spatial frequency is smaller than the first structure.

4.2 Accretion disk scenario

The limited number of visibility points forbids trying an exhaustive list of models. We limit ourselves here to testing the standard model of standard accretion disk. This model has proven to be successful to reproduce several FU Orionis indirect observational features (see Harmann & Kenyon 1996). Constraining such a model requires reproducing visibilities and the spectral energy distribution at the same time.

The standard accretion disk model is described with several parameters: the temperature distribution law as a function of radius, the accretion rate, the visual extinction, the central star's mass and the disk inclination. We take standard FU Orionis parameters derived from indirect observations except for the power law which will obviously be the most constrained by the visibility data.

Power Law	To be determined
Accretion Rate	$4.10^{-5} M_{\odot} yr^{-1}$
Visual extinction	1.2 mag
Star mass	$1 M_{\odot}$
Disk inclination	$i \leq 30°$

The preliminary interpretation strategy is:

- fitting average visibilities (without taking into account the oscillation) with a standard disk model;
- fitting the oscillations with a double component model consisting of gaussian disk model and an unresolved spot separated by an amount s mas.

In the first step we were not successful in fitting at the same time the spectral energy distribution and the visibility curve with the standard power law ($T \approx r^{-3/4}$). The SED requires a power law exponent of 3/4 but the visibilities a power law of 0.6. The SED fit is mostly constrained by the thermal infrared to mm emission, while the visibility fit is constrained by the near-infrared emission. The interferometric observations in two colors (H and K) provide a strong constraint by showing that sizes in H and K are marginally compatible to what is expected from the power law.

One of the simplest ways to reconcile both SED and visibility observations in the framework of the standard accretion disk model is to consider that near-infrared emission arises from a region of the disk that has a different power law. This kind of behaviour could be a consequence of the presence of strong winds (300km/s) which alter the accretion rate and therefore a heating source. It is too early and the available data is not sufficient to come to a conclusion. With this simple model we note that a power of 0.6 between 0 to 2.5 AU and a power of 0.75 between 2.5 to the external parts of the disk allows us to fit both visibility and SED data (see left and center part of Figure 5).

The visibility oscillation detected at 100 m in K is at the limit of the instrument accuracy but we consider it a significant trend. We interpret that with the simplest model made of a gaussian disk (that accounts for the drop in visibility at large baselines) and an unresolved point (see right side of Figure 5). The equation of such a double component object can be easily used in a fit (see Berger, same volume, for an introduction to visibility modeling). A visibility fit allows us to determine basic parameters for this point:

Separation	$33mas$
Position angle	$160°\text{mod}180°$
ΔH	≈ 5
ΔK	≈ 4

The origin of such a point is puzzling. The two simplest explanations are:

- there is a stellar companion to the disk;
- a hot spot is present on the disk.

These observations call for others with a better (u,v) coverage but also with a greater visibility accuracy. Better models are also required. Lachaume *et al.* (2002) have tried to reproduce our observations with a more complete accretion disk model that takes into account most of the heating sources and also the vertical structure of the disk.

5 Conclusion: VLTI and YSO disks.

VLTI will soon bring a unique opportunity to probe the inner AU of young stars' circumstellar environment in a more systematic and accurate way. During the first years visibility and closure phases will be the main observables (and not images) and the astronomer should be prepared to deal with those quantities. The four years spent on the FU Orionis case should take much less time and allow systematic surveys.

Both AMBER and MIDI will allow probing of the near- and mid-infrared emission of T Tauri and HAeBe stars. This emission originates in the 0 to 20AU region

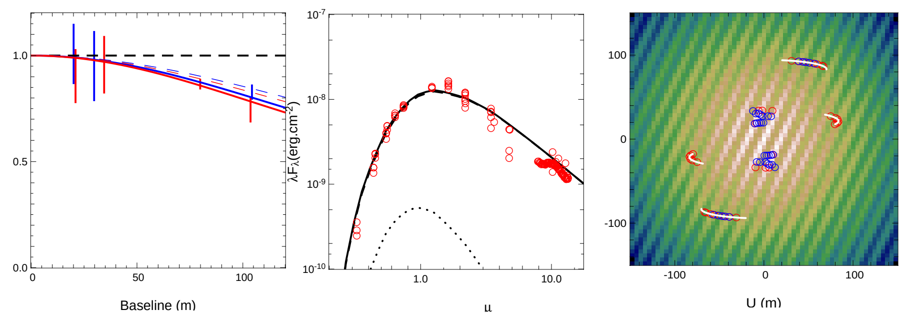

Fig. 5. Left: Average visibilities for each baseline. Solid lines represent the best fit obtained with a standard accretion disk model in the H and K band. Center: FU Orionis spectral energy distribution with our best accretion disk model fit. Right: a (u,v) plane image of the gaussian + point model showing the gaussian envelope perturbated by the oscillation due to the double structure. The (u,v) tracks overplotted allow to understand the data showed in Figure 4

where planets supposedly form. Both instruments are very complementary and common studies of the same objects are highly desirable to probe different regions of the internal part of the disk. The quantities of interest here are:

- the physical sizes of the infrared emission in the J,H,K and N band.
- the degree of asymmetry of the detected structures.
- spectral-depending structures in lines such as CO overtone absorption, Brackett γ, silicate emission ...

These measurements will probably require different instruments and interferometer setups for optimum performance (signal to noise, visibility accuracy, (u,v) coverage etc...). Successful observations should allow to answer important actual questions (not exhaustive list):

- what is the geometry and vertical structure of the disk ?
- do we find a link between detected structures and age, spectral type (...) ?
- do we confirm the presence of the internal rim in HAeBe's ? is the same for T Tauri stars ?
- do we confirm the presence of circumstellar disks around components of multiple systems;
- do we find evidence of dust processing ?
- do we find evidence of mass loss (winds, jets) ? what is the localisation, size and symmetry of the line emission or absorption ?

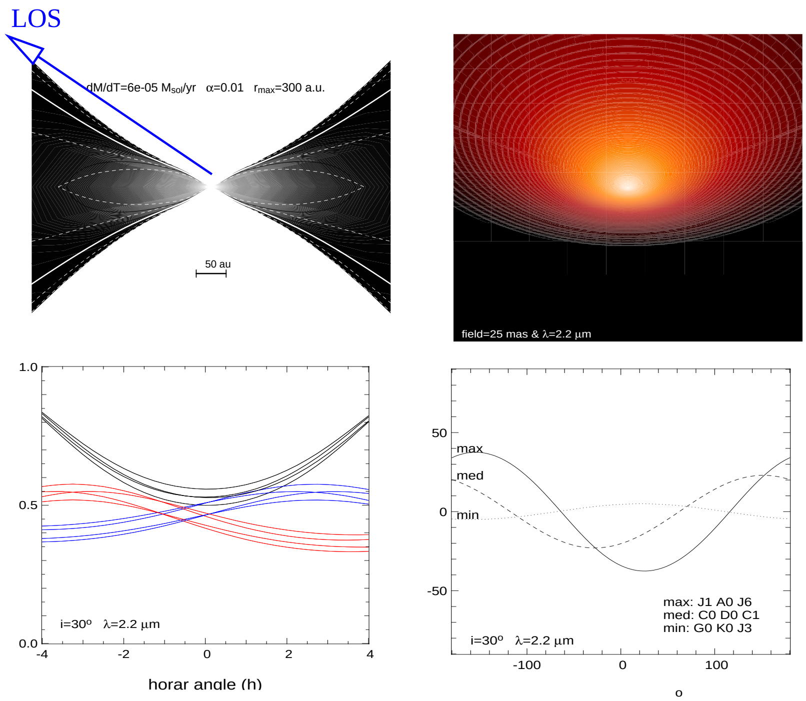

Fig. 6. Top left: Vertical structure of the FU Orionis accretion disk (Malbet *et al.* 2000). The inclination with respect to the line of sight (LOS) induces an apparent asymmetry of the disk image. Top right: corresponding synthetic image in the K band of an inclined Fu Orionis flared disk. Bottom left: expected visibilities curves for three VLTI configurations spanning different spatial scales. Bottom right: Expected closure-phase curves due to the asymmetry.

We can surely expect that such sub-AU observations will bring together an increasing astronomical community coming from different horizons. An important effort should be carried out to develop detailed models of the sub-AU YSO environment and estimate their impact on visibility measurements.

Appendix: Proposition for a VLTI observation

As an example of what could be done with the VLTI we propose here to use the AMBER capability to measure accurate visibilities and closure phases to explore the vertical structure of FU Orionis. Viscosity and stellar light reprocessing are the two main heating sources and will compete in shaping the disk vertical structure. VLTI observations (visibilities and closure phases for AMBER) will provide some hints to what the actual vertical structure is allowing to probe regions in the disk with different physical conditions (see Lachaume *et al.* 2002 for a more extended discussion accompanied with actual examples). The interest of closure phase measurement is that it is a direct indicator or asymmetry. The vertical structure of the disk (top left Figure 6 will induce that the image of the disk alone a non polar line of sight (LOS)) will show evidence for asymmetry. The simulation show that using different combinations of VLTI telescope triplets one should be able to clearly detect visibility and closure phase variations in direct relation with the vertical structure. The choice in triplets is made to allow sampling of different spatial scales.

The AMBER configuration required here is:

- broadband K filter;
- 1% visibility accuracy;
- maximum baseline triplet: J1-A0-J6;
- intermediate baseline triplet: C0-D0-C1;
- minimum baseline triplet: G0-K0-J3.

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