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The VLTi/PIONIER survey of southern TTauri disks†

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Abstract. Studying the inner regions of protoplanetary disks (1-10 AU) is of importance to understand the formation of planets and the accretion process feeding the forming central star. Herbig AeBe stars are bright enough to be routinely observed by Near IR interferometers. The data for the fainter T Tauri stars is much more sparse. In this contribution we present the results of our ongoing survey at the VLTI. We used the PIONIER combiner that allows the simultaneous use of 4 telescopes, yielding 6 baselines and 3 independent closure phases at once. PIONIER's integrated optics technology makes it a sensitive instrument. We have observed 22 T Tauri stars so far, the largest survey for T Tauri stars to this date.

Our results demonstrate the very significant contribution of an extended component to the interferometric signal. The extended component is different from source to source and the data, with several baselines, offer a way to improve our knowledge of the disk geometry and/or composition. These results validate an earlier study by Pinte *et al.* 2008 and show that the dust inner radii of T Tauri disks now appear to be in better agreement with the expected position of the dust sublimation radius, contrary to previous claims.

Keywords. techniques: interferometric, stars: pre–main-sequence, interferometric survey

1. Introduction

The inner parts of the disks are intensively studied for the formation of terrestrial planets, the accretion process and more generally the evolution of the disk shape and composition. While near-infrared (NIR) interferometry is able to resolve these regions, the first data sets published were limited to a few baselines (generally 1 or 2) at low sensitivity. Simple geometrical models were used to interpret the data, e.g., the (gaussian) ring model. That model is based on the assumption that all of the NIR emission comes from the heated disk's inner rim thus creating a luminous ring around the star. Inner radii inferred by such model are coherent with the sublimation radius for the more luminous Herbig stars but suggest significant deviations for the less luminous T Tauri stars. Various physical mechanisms have been proposed to explain this unexpected discrepancy (Eisner *et al.* 2007). However, Pinte *et al.* (2008) resolved this discrepancy

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by taking into account scattered light in details in the models allowed to resolve the apparent discrepancy between the inferred inner radius and the sublimation radius for low luminosity stars. Scattered light has a further interesting observable consequence: it is expected to produce a rapid decrease of the visibilities at short baselines, which is due to the fact that the scattered "halo" is very extended. Detecting such "drop-off" requires a good u-v coverage of faint targets. We present the results of our survey below.

2. PIONIER observations

The interferometric data were obtained with the four relocatable Auxiliary Telescopes (AT) of the Very Large Telescope Interferometer (Haguenauer *et al.* 2010) and the 4-telescope combiner PIONIER (Lebouquin *et al.* 2011). We observed 22 southern T Tauri stars brighther than 8.5 in H band during 25 nights distributed over 5 semesters. The weather condition were average for the majority of the nights with a total of 13/25 nights lost due to bad weather. The stars were selected based on available evidence for the presence of a circumstellar disk, usually NIR excess in the SED or evidence from radio interferometry.

The use of 4 telescopes simultaneously allows for measurements of 6 different baselines, resulting also in 3 independent closure phase measurements. PIONIER is also more sensitive than its predecessors, allowing a significant sample of the relatively fainter T Tauri stars to be observed. During the first 4 runs, the ATs were stationed in an extended array configuration, providing separations on the ground between telescopes ranging from 47 to 129 meters The last run has been carried out in compact configuration (separations between 11 and 36 meters).

The observation strategy was designed to intertwine the science target between different calibrators. A typical observation sequence was then CAL1 - SCI - CAL2 - SCI - CAL1 and repeat as needed, with each observation block (either science or calibrator) typically composed of 5 exposures each of which composed of 100 scans. Data reduction and calibration was performed by running the dedicated PNDRS package† (Lebouquin *et al.* 2011).

3. Description of the data sets

For the data collected in the extended array configuration, only the intermediate baselines of the visibility curve is sampled, i.e., neither the drop-off at short baselines nor the "fully resolved range" at very long baselines where the visibilities plateau are measured. In that middle range, the visibilities vary roughly as a straight line for simple star+disk sources. If an extended structure is present, causing a quick drop-off at short baselines, then extrapolation of the observed mid-range visibility curve to zero spacings should yield values below unity. We performed a linear fit on our sample (Figure 1). A large fraction of the visibility curves has an intercept at 0m baseline below V^2=1, as expected from the presence on an extended source of incoherent light, e.g., extended scattered light over the disk surface.

To explain that "drop-off", consider an object composed of a unresolved star + its disk, which visibility can be splitted (to first order) into the thermal emission coming from the inner rim and the scattered emission coming from all over the surface. With

† http://apps.jmmc.fr/~swmgr/pndrs

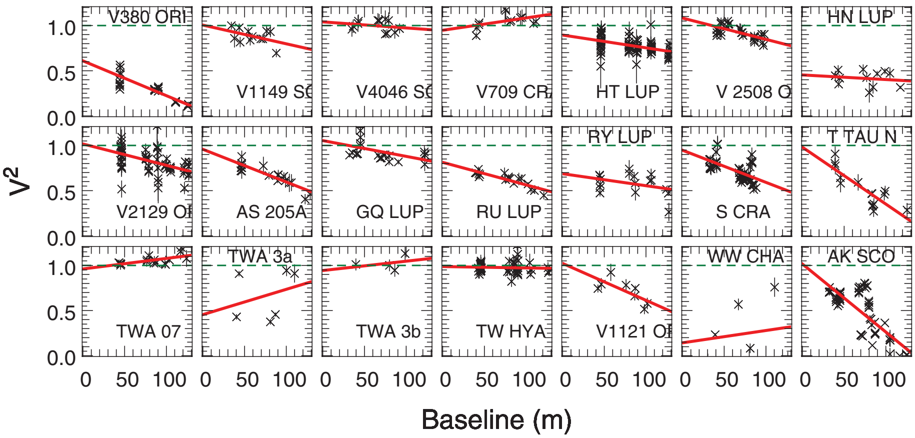

Figure 1. Visibility data (black points) of our sample and their associated linear regression (solid line).The dashed horizontal line indicate $V^2 = 1$. For the majority of the resolved non binary stars with low inclination (that is to say all the stars which visibility profile differ from one, minus TWA 3a and WW Cha), the intercept of the linear fit is below 1, indicating an extended component, varying from star to star.

these assumptions, the total visibility can be written :

$$V_{tot} = \frac{V_{star}F_{star} + V_{therm}F_{therm} + V_{ext}F_{ext}}{F_{star} + F_{therm} + F_{ext}}$$

with V the visibility and F the flux coming from the star (X_{star}), the disk's thermal emission (X_{therm}) and the disk's scattered light (X_{ext}).Because scattered light is spatially extended over a large area, its visibility curves drops rapidly with increasing baseline. The short baseline data now available provide constraints on the size of the scattering region as the drop-off is detected up to ≈10m baselines, therefore the angular scale of the scattering region must be larger than 33mas. For the 2 objects which have short baseline data (HT and RU Lupi which are at 150 parsecs), it corresponds to structures larger than 5 AU .

4. Detailed modelling

While the simple linear fitting of our data provides some information about the large scattering emission, it is a *qualitative* tool limited to simple systems with low inclinations.Moreover, that kind of analysis provides little information about the disk's structure and composition. To derive more quantitative information, we are running disk models and radiative transfer, including more data as well, for the individual sources.

As an exemple we present the model created to adjust both SED and the interferometric data of the TTauri star HT Lupi. To do so, we used the radiative transfert code *MCFOST* (Pinte *et al.* 2006), including full scattered light treatment. The modelled disk is composed of an inner dusty disk, a gap (to fit the 70μm MIPS photometric point and to take into account the clearing that might be operated by the close companion discovered by Ghez *et al.* 1997) and a massive outer disk. This model also matches the Spitzer IRS spectra when the inner disk is filled with small astrosilicate grains (as defined by Draine & Lee 1984). To constrain the inclination and the position angle, we calculated the values of the visibility and closure phase of our model (at the same baselines and for the same closed triangles) by rotating our image model in order to find the best position angle value, and doing this for each inclination. As we can see in the Figure 2 our model

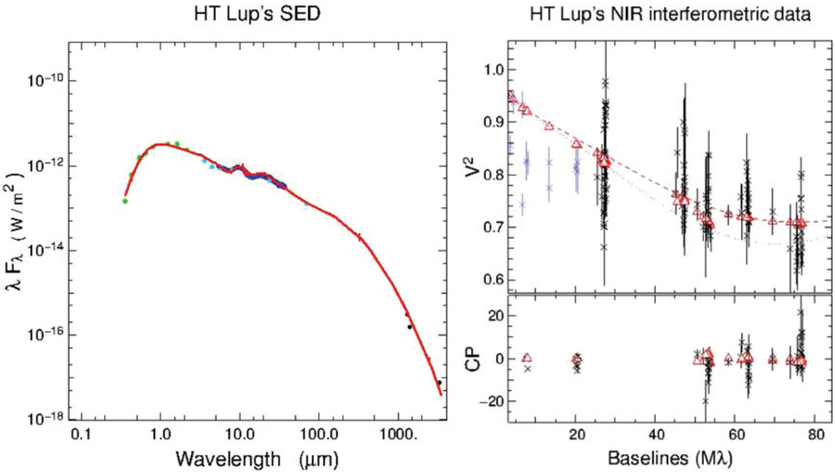

Figure 2. *Left*: fit of HT Lupi's SED. Our model is displayed by the bold red line, the dark blue line is the Spitzer spectrum and the other points represent the visible, NIR, IRAS and mm photometry. *Right*: modelling or the visibility profile (upper panel) and closure phase (lower panel). The data and error bars are displayed in black (or in blue for the recently acquired short baseline data). The dashed and dotted line are the visibility profiles of our model along the minor and major axis. the triangles are the visibility profile of our model taking into account the baselines orientation.

successfully reproduces the SED and long baseline interferometric data, but has to be refined further to fit our recently acquired short baseline data.

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Discussion

Alycia Weinberger: Could you describe whether the uncertainties on the visibilities include all calibration uncertainties that is, is the absolute level of the visibilities reliable at the level of the error bars shown?

Fabien Anthonioz: Shortly, yes. More presisely, all the instrumental and atmospheric biases are calibrated by intertwining the science target between different calibrators (as explained in the last paragraph of the section 2). For more information about PIONIER (including the calibration), I warmly recommend the paper from Lebouquin *et al.* 2011.