Thermal infrared stellar interferometry using single-mode guided optics: first scientific results on IOTA

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Abstract

We report on first scientific observations of a few bright late type stars by direct long baseline interferometry in the thermal infrared (3.4 to 4.1 microns) obtained with the TISIS (Thermal Infrared Stellar Interferometric Set-up) experiment of the IOTA (Infrared and Optical Telescope Array) interferometer. Beam combination is provided by a single-mode fluoride glass coupler optimized for operation in that wavelength domain and yielding visibility measurements with 2% typical relative accuracy. First precise estimations of uniform disk diameters for α Orionis, α Herculis, o Ceti and R Leonis are presented in the L band. Very large increases (50 to 70%) in apparent angular diameters have been found for the 2 Mira stars o Ceti and R Leonis with respect to previous measurements obtained at shorter infrared wavelengths and same luminosity phase. Extended optically thin close-by dust shells characterized by Infrared Spatial Interferometer (ISI) measurements are not found to play a significant role in the observed L band intensity distribution. Gas properties are likely to have a greater impact at these wavelengths. Our o Ceti interferometric observations look indeed in good agreement with the presence of very extended circumstellar gas layers (mostly H_2O and SiO) derived from recent Infrared Space Observatory (ISO) thermal infrared spectral data.

1 Introduction

1.1 Interferometry using single-mode fibers

First stellar interferometric observations using a Fiber Linked Unit for Optical Recombination (the FLUOR set-up) were obtained in the K band at the McMath-Pierce solar telescope of the National Solar Observatory on Kitt Peak (Coudé du Foresto and Ridgway 1991). However, because of the short and unique baseline available (5.5 m) this configuration remained essentially a technology demonstrator, and an agreement was reached with the Harvard-Smithsonian Center for Astrophysics to move the unit to the Infrared and Optical Telescope Array (IOTA) on Mount Hopkins (Perrin 1996). The unit was then upgraded, differential dispersion has been nulled and polarizations are now matched in the two beams. It has been used as part of IOTA's instrumentation since 1996 and now routinely provides stellar interferograms on baselines ranging between 5 and 38 m, with an accuracy of 1% or better in the fringe visibility measurements.

1.2 Thermal infrared stellar interferometry

Direct interferometry in the thermal infrared is planned for both ground based observations, with the 10 micron interferometric mode of the VLT (through its mid-infrared focal instrument, called "MIDI", [Leinert et Graser 1998]), the 10 micron nulling mode on the Keck telescopes [Colavita et al. 1998], and for space based projects mostly dedicated to the characterization of extrasolar planets, such as DARWIN [Léger et al. 1996] or TPF [Angel et Woolf 1997]. High angular resolution in the mid-infrared is indeed required in various fields of astrophysics, from the observation and modeling of circumstellar dust shells around late type stars, the study of broad line regions of active galactic nuclei [Voit 1997], to the detection of key spectroscopic features in the atmosphere of extrasolar planets. Yet direct interferometry at wavelengths higher than 2.4 microns has been poorly demonstrated so far, and the problem of fringe calibration in the thermal regime has never been addressed.

In the thermal infrared, ground based interferometric stellar observations face indeed very specific technical difficulties, when compared to the ones encountered in the visible or at near infrared ($\lambda < 2.4\mu$m) wavelengths. The seeing is much better, the constraints on the optical surfaces are relaxed, but the interferometric signal is contaminated by an incoherent thermal background, that needs to be minimized, monitored, and properly subtracted in order to achieve high accuracy visibility measurements. Around 10 microns, the thermal background signal is several orders of magnitude higher than the stellar flux itself. The difficulties in the alignment of the optics and the lower efficiency of the detectors are also probably responsible for the lack of interferometric observations in the thermal regime. So far, the only scientific results derived from interferometric observations in the thermal infrared have been obtained by single aperture interferometry [McCarthy and Low 1975, McCarthy et al. 1977], and more recently through heterodyne interferometry at 11.15 μm [Danchi et al. 1994], studying dust shell properties of bright late type stars. Although it has a better adaptability to multitelescope recombination, this technique has a low sensitivity, limited by the narrow usable spectral bandwidth (about 6 GHz, i.e. a spectral resolution of about 5000 at 10 microns). Direct broadband interferometry between large telescopes using adaptive optics and/or spatial filtering for real time correction of atmospheric effects, as planned for instance for the MIDI instrument, should lead to higher sensitivity. The expected background noise limited magnitude in the N band on two 8m telescopes is about 5, without integration capability, and could in principle reach 12 with a fringe tracker [Leinert et Graser 1998].

1.3 Technical and scientific rationale for TISIS

Interferometric observations in the L band reported here with the "TISIS" (Thermal Infrared Stellar Interferometric Set-up) experiment constitute a first step towards such future 10 micron observations. Building up on the experience acquired with the FLUOR single-mode instrument, the aim of TISIS is threefold:

1. To face the specific problems of the thermal regime, under the less severe conditions of the 3.4-4.1 μm region. This allows to characterize both the intensity and time evolution of the thermal background, which should help define future observations and signal processing procedures.

2. To test single-mode components in the thermal infrared, characterizing on the sky their transmission, dispersion and -to some extent- polarization properties. The use of spatial filters proves to be very helpful in order to derive accurate visibility measurements, [Coudé du Foresto et Ridgway 1991, Perrin et al. 1998, Coudé du Foresto et al. 1998] and would be of great use for the VLTI mid-infrared instrument [Leinert et Graser 1998]. Spatial filtering is also very powerful to remove the high spatial frequency defects on the incoming wavefronts of a nulling interferometer, which considerably relaxes the constraints on the optics [Ollivier et Mariotti 1997, Mennesson et al. 1999c].

3. To study the close-by environment of bright late type stars. Observing in the L atmospheric window has its own scientific interest by looking at structures around 1000K, such as the inner edges of extended dust shells surrounding some Mira stars, as in the case of o Ceti or R Leo. The comparison of some Mira stars L band observations with quasi simultaneous interferometric measurements in J, H, K (with IOTA and PTI for instance) and N (ISI) bands are of particular interest. They should help characterize the very close-in atmospheric and dust shell intensity distribution around some of these stars. The monitoring of its evolution with luminosity phase should ultimately lead to a better understanding of the physical processes responsible for pulsations and mass loss phenomenae in these complex objects.

First two technical items were partly addressed in April 1998 with the first interferometric observations of α Bootis and α Herculis in the L band with the TISIS instrument [Mennesson et al. 1999a], showing the feasibility of accurate visibility measurements using single-mode guided optics in that spectral range. Further technical results have been obtained in December 1998 on a larger sample of stars [Mennesson et al. 1999b], and observations were this time background limited. Further on-going upgrades involve faster ($\simeq 1\,\mathrm{Hz}$) sky chopping and interferogram acquisition. We concentrate here on the third item, i.e. scientific results obtained so far.

2 L band uniform disk diameters measurements

Figure 1 gives visibility data, associate error bars and uniform disk fits for α Orionis, α Herculis, R Leonis, and o Ceti.

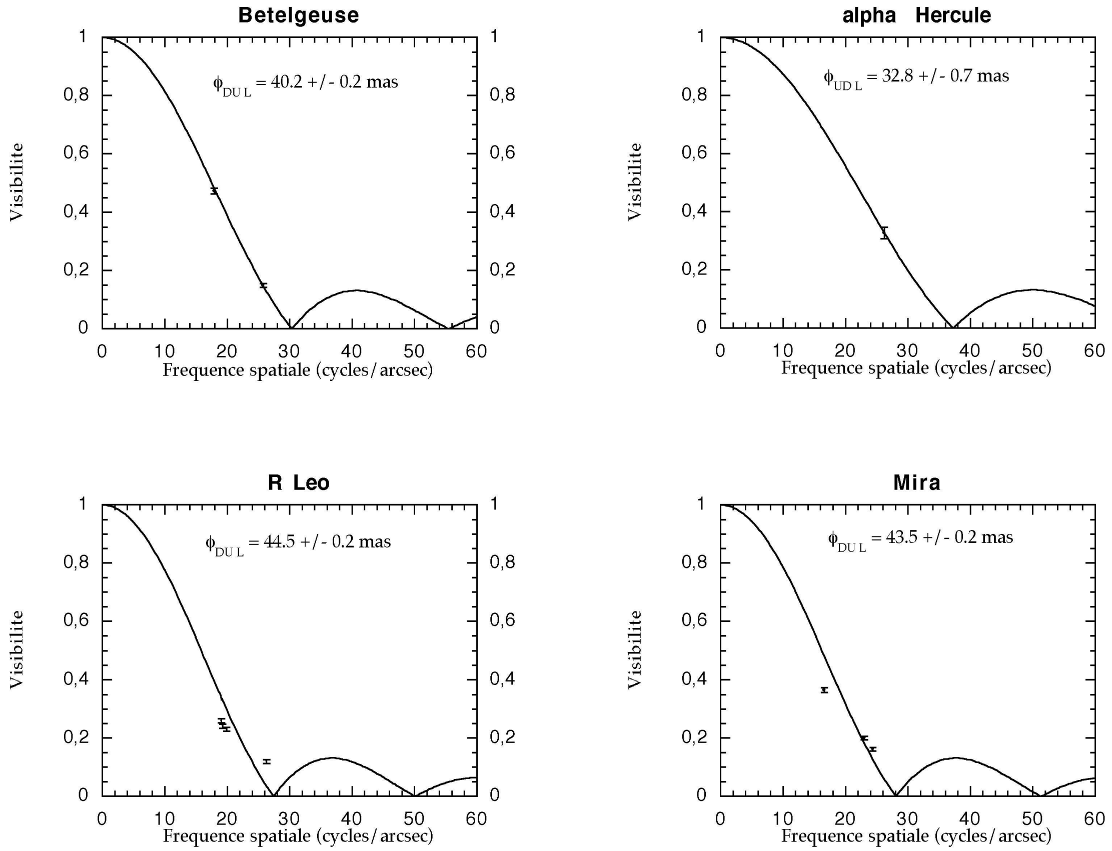

Figure 1: Fits of L band visibility measurements by uniform disk models

Table 1 synthesizes the observational results obtained so far with TISIS, and gives previous K band FLUOR measurements for comparison.

Variations in diameter are moderate in the case of α Ori and α Herculis, whereas o Ceti and R Leonis show much larger apparent sizes in L than in K, at about same luminosity phase and azimut.

Table 1: Sources successfully observed in the L band (3.4-4.1 microns). For the reference stars, uniform disk fit diameters used come from FLUOR K band observations, except in the case of α Tau, where lunar occultation data were available [Ridgway et al. 1982]. m_L is the stellar magnitude in L, D_L is the uniform disk diameter derived from TISIS observations in L, D_K the one measured in K with FLUOR [Perrin et al. 1998]. Phase stands for the visible luminosity phase at the time of L or K band observations, where relevant.

Star	Spectral type	m_L	D_L (mas)	phase	D_K (mas)	phase
α Boo	K1.5 III	-3.0	reference	-	20.20 ± 0.08	-
α Her	M5 Ib-II	-3.7	**32.8 ± 0.7**	-	**30.90 ± 0.02**	-
α Tau	K5 III	-3.0	reference	-	19.75 ± 0.11	-
R Leo	M8 IIIe	-3.2	**44.5 ± 0.2**	0.30	**30.68 ± 0.05**	0.28
β Peg	M2.5 II-III	-2.4	reference	-	16.19 ± 0.23	-
α Ori	M I	-4.4	**40.2 ± 0.2**	-	**44.2 ± 0.2**	-
o Ceti	M7 IIIe	-3.7	**43.5 ± 0.2**	0.98	**28.80 ± 0.1**	0.94
μ Gem	M3 III	-2.0	reference	-	13.5 ± 0.15	-

Table 2: Parameters of the dust shell best fitting the ISI 11.15 μm observations. r_0 designates the inner radius of the shell, T_0 the temperature at this location, and τ_{11} the optical depth at 11.15 microns.

Star	Phase	r_0 in "	r_0/r_*	T_0 in K	τ_{11}
α Ori	-	1.0	46	400	$6.5\ 10^{-3}$
α Her	-	0.25	18	520	$1.6\ 10^{-2}$
R Leo	min	0.07	2.7	790	0.1
o Ceti	max	0.06	3.0	1280	0.14
	min	0.06	3.0	1060	0.14

3 Possible interpretations of o Ceti and R Leonis data

3.1 Dust shell thermal emission

As can be seen in Table 2, there is a striking apparent correlation between our data and the dust shell properties derived from ISI observations [Danchi et al. 1994]. ISI measurements indeed indicate cold and somehow distant inner dust shell regions for α Ori and α Herculis, then a priori invisible in L. Conversely, circumstellar dust shells of R Leo and Mira are expected to have close and hot enough inner radii to be possibly detected in L. The first natural idea is then to invoke dust thermal emission to interprete L band data.

We have used a code developed at the observatoire of Cote d'Azur [Lopez et al. 1994] in order to simulate radiative transfer through axisymmetrical circumstellar dust shells and fit the o Ceti and R Leonis data. At a given wavelength, the energy radiated by the stellar

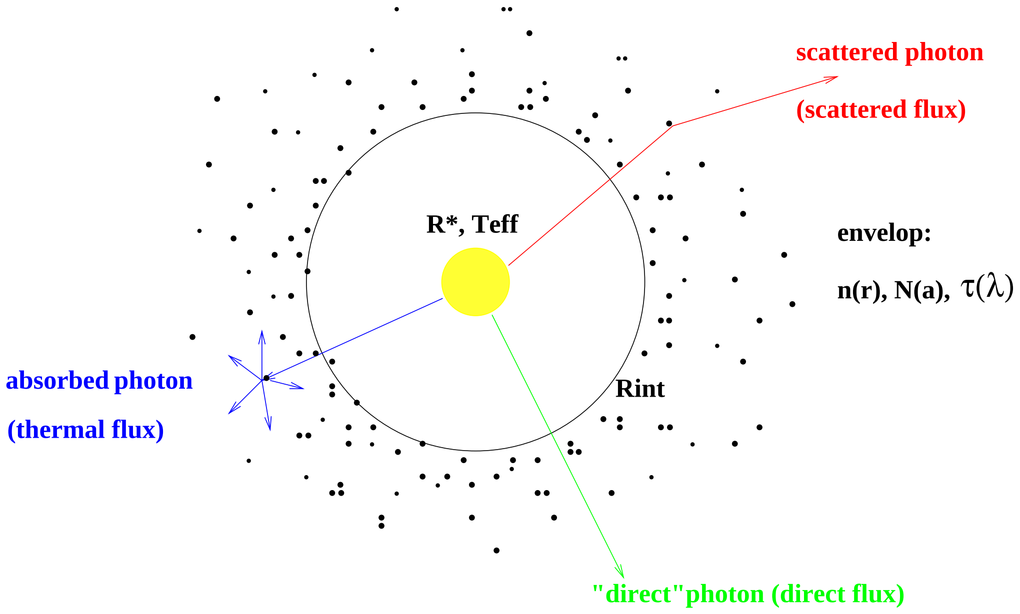

Figure 2: Principle and main parameters of radiative transfer code used to model L band data.

photosphere, considered as a blackbody with effective temperature T_{eff} and stellar radius R_*, is divided in N independent groups. N photons with this quantum of energy are then "shot" into the circumstellar dust shell according to an iterative Monte Carlo method. These photons are then either absorbed by a dust grain, or scattered by one or more grains, or do not interact at all with the envelop (figure 2). The overall observed flux is the summation of the three corresponding components: the thermally reemitted flux, the scattered flux and the attenuated stellar direct flux. The basic assumption of the code is the thermal equilibrium of the grains. The input parameters are the stellar radius, the stellar effective temperature, the envelop geometry and inner radius R_{int}, the optical depth τ at the observing wavelength λ, the grains density law n(r), size distribution N(a) and chemical nature, which determines refraction indices. Outputs are the overall spectrum from 0.1 to 1000 microns, and spatial intensity distribution at a given wavelength, from which visibility curves can be computed.

We first used the ISI circumstellar shells models fitting the 11.15 microns interfrometric data - and infrared low resolution spectra derived at same luminosity phase - for R Leonis [Danchi et al. 1994] and o Ceti [Lopez et al. 1997]. These models assume a fairly continuous dust production and expansion of the shell. Gas is coupled to the dust by collisional interaction, and dust grains outflow is driven by radiation pressure. In both cases, it was impossible to reproduce our K and L band data with these models. The dust shell is just too optically thin. Its thermal emission is too weak to cause the dramatic diameter increase observed between 2.2 and 3.7 microns. Alternative scenarios with confined and hot dust shell inner parts have also been tested, and fit better to the observations. Yet, such scenarios are rather unprobable since they would require grains to form and stay very close to the star, at distances where they are not supposed to condensate. This could either mean exotic grain composition, formation in locally colder convective regions or non grey behaviours.

Although other set of dust shell parameters remain to be explored, it looks very unlikely that dust thermal emission alone can account for the observed data.

3.2 Extended atmospheric molecular gas layers

The observed morphologic variations between K and L bands may in fact mostly be due to gas - and not dust - properties, i.e. strong absorptions or emissions due to extended molecular gas layers in the upper stellar atmosphere.

3.2.1 o Ceti

A recent model [Yamamura et al. 1999] has been developed to interprete o Ceti spectral data between 2.4 and 5.3 μm, also acquired close to its maximum (ϕ=0.99) with ISO/SWS. A very good fit to the observed spectrum is found with four spherically symmetric successive molecular gas layers on top of each other. These are namely H_2O (hot), SiO, H_2O (cold) and CO_2 layers with increasing distance from the star. The hot (2000 K) optically thick H_2O molecular layer extends out to two stellar radii. It is seen in emission in the 3.4-4 microns region, whereas the 2.6-3.3 radiation is absorbed by the subsequent cold (1200 K) H_2O layer, extending out to 2.3 stelalr radii .

Our K and L band data appear in very good agreement with this model. K band measurements would be mostly sensitive to the hotter inner part of the object, whereas L band measurements would rather see the outer extended part of this huge atmosphere.

Interferometric measurements in the 3-3.3 microns region would be a good observational test to this model. A substantially ($\simeq$ 15%) larger diameter than in the 3.4-4 microns region is expected because of absorption by the outer cold H_20 layer.

3.2.2 R Leonis

Photospheric pulsation and strong molecular scattering by H_2O and CO have been suggested to explain 1996 and 1997 FLUOR K band interferometric observations [Perrin et al. 1999].

These measurements were interpreted as a direct detection of the variation of the size of the photosphere of R Leonis from phase 0.24 to phase 0.28 generated by the pulsation of the star [Perrin et al. 1999] as shown in figure 3. Comparison with a uniform disk model yields a photospheric radius intermediate between that of fundamental and first overtone pulsators. High spatial frequency data acquired in 1997 display an excess of visibility that we interpreted as the possible signature of scattering by molecular species in the atmosphere, a scenario that has been found more compatible with data than limb brightening or convective spots on the stellar surface. If this hypothesis is correct, a direct effect is to yield lower values for the photospheric radius of 19 and 21 mas for each epoch, which would clearly make R Leonis a fundamental pulsator.

If R Leonis also presents a very extended molecular gas layer, similar to that invoked for o Ceti, it would both confirm the signature of scattering by molecular species already infered

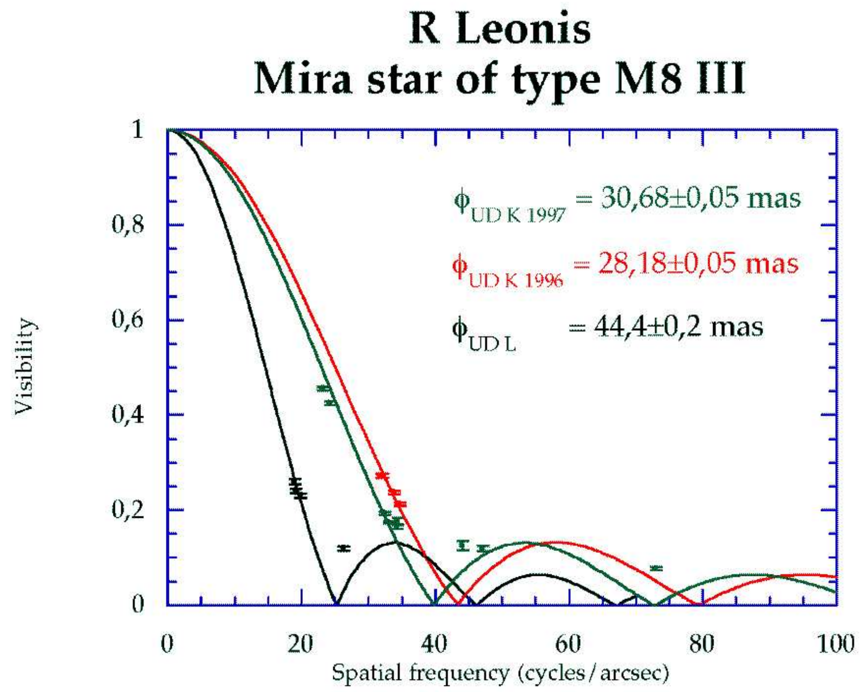

Figure 3: Fits of the 1996, 1997 and 1998 R Leonis data by uniform disk models. 1996 K band data consist in 3 points in the first lobe. 1997 K band data show a more resolved disk, with residual visibilities above the 10% level at high spatial frequencies. 1998 L band data show a much larger structure, possibly due to the inner dust shell thermal emission.

by FLUOR measurements, and explain our L band observations of a much more resolved object (figure 3). This would also corroborate the fact that R Leonis is a fundamental pulsator.

4 Conclusion

We have reported accurate observations of a few late type stars by long baseline direct interferometry in the near thermal infrared 3.4 to 4.1 microns region. Although they presently lack of sensitivity, these observations show the potential of interferometric measurements in that spectral range to constrain close-by circumstellar environments and pulsation regime, particularly in the case of Mira with extended atmospheres. Although further work is requested, there is strong indication, at least in the case of o Ceti, and also possibly R Leonis, that most of the 3-4 microns emission is dominated by very extended molecular layers rather than by dust shell thermal emission.

The L band region appears very attractive to constrain the geometry and properties of molecular gas layers in the upper atmosphere of Mira stars. It is indeed very rich in molecular spectral signatures, and sits in between the regions of maximal photospheric or dust emissions. Quasi-simultaneous interferometric observations at different wavelenghts, together with accurate spectro-photometric data look essential to ensure a good temporal follow-up of circumstellar intensity distribution around Mira stars. It would allow to test current atmospheric models and ultimately help in the understanding of pulsation and mass loss mechanisms in these complex objects. The new generation interferometric instruments to come within 2 years will certainly benefit from high spatio-spectral resolution and bring new and better understanding to the physics of Mira variables.

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