IMAGING WITH AMBER/VLTI: THE CASE OF MICROJETS

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Abstract. The engine that powers pre-main-sequence micro-jets is still unknown and remains a fundamental open question in star formation. The engine can be located solely on the inner disk or in the interaction of the inner disk with the star. In order to ease interpretation problems, imaging the jet engine is the ideal probe to disentangle between the old models and shed evidence for new ones. In this paper, we analyse the feasability of imaging bright southern targets, and show that even at low SNR, accurate image reconstruction is still possible with high contrast. However, the small number of ATs requires a fast reconfigurable array.

Keywords: Amber, VLTI, PMS, microjets, image restoration

1. Introduction

The VLTI with its four movable ATs and four UTs has an enormous potential for interferometric imaging. The focal instrument AMBER, adds to the imaging capability moderate to very high spectral resolution. In particular at intermediate resolutions $R = 1\,000$ a broad spectral coverage is available allowing not only the combined study of of several spectral lines but also wavelength bootstrapping.

This paper addresses the issue of imaging with the VLTI in the context of pre-main-sequence (PMS) star micro-jets. Fundamental open questions remain in this region of astrophysics. In the literature models for the engine that powers the jet can be found. Those who present observational predictions lie in two classes: pure disk engines, and star-disk engines. These models share one property, because most of the mass is ejected in the inner disk or star-disk interface, jets are hollow. This property was noticed by (Garcia, 2002) to produce well defined visibility 'arms' in the spatial frequencies space, and therefore showed a context within which visibility measurements could be interpreted. A companion paper in these proceedings (Bacciotti et al., 2002) describes in detail this project as well as it's astrophysical context.

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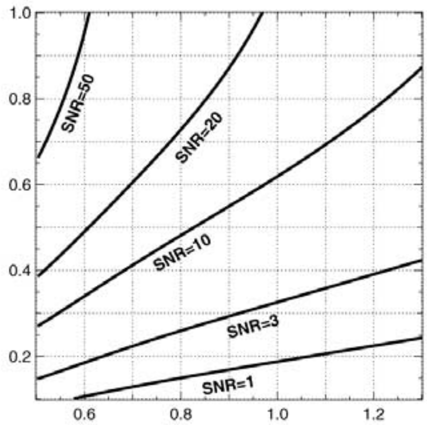

Figure 1. SNR isocurves, for RU Lupus, in V^2 – seeing space.

Here the next step is analyzed, namely if images can be produced by AMBER for such objects. With no a priori model for the object brightness distribution, images free us of the degeneracy often connected to model dependent data interpretation. AMBER/VLTI allows the recombination of 3 telescopes which provide, in addition to visibilities (V) or power spectra (V^2), phase closures. If enough spatial frequencies are obtained it will be possible to reconstruct an image. This allows one to identify the structure of the jet's engine without assuming a particular physical model. On the other hand for the relatively small number of AT's available the required spatial frequency coverage is obtained at the expense of moving some AT's around. In the next section we address the problem of signal to noise ratio obtained in one visibility measurement, then we introduce our image reconstruction algorithm and apply it to a PMS micro-jet, finally we end with the conclusions.

2. Signal to Noise Ratio Estimation

The brightest southern PMS harbouring a micro-jet is RU Lupus with $m_J = 8.6$. The Paβ emission line is probably the most interesting one, very near the star densities are expected to be high enough so that H recombination dominates emission. The line profile peaks at 2.5 times the continuum. We used a calculator written by Malbet (Malbet, 2000) to estimate the signal to noise ratio (SNR). The flux entering AMBER fibers critically depends on the Strehl ratio (SR). We computed the expected SR for the ATs assuming tip-tilt correction. Our star being very bright at visible is not limiting the AO compensation, the final SR is limited only by the seeing. We assumed that a fringe tracker was able to freeze the fringes for 1 minute, and that 30 such frames were obtained. We selected the medium resolution ($R = 1000$) configuration. Figure 1 shows the expected SNR per wavelength bin.

3. The Multi-Aperture Image Reconstruction Algorithm

MIRA (Multi-aperture Image Reconstruction Algorithm) is the imaging software devoted to optical interferometry data and currently under development at the JMMC (Jean-Marie Mariotti Center).

Owing to the small number of telescopes, optical interferometers are only able to measure very few Fourier frequencies at the same time and even less Fourier phases because of the lack of phase referencing capability at this time. Unless a large number of nights are spent to collect the data, optical/IR aperture synthesis imaging is much more challenging than what can be routinely done in radio-astronomy. The solution adopted in MIRA algorithm is to directly fit the phase closure and power spectrum data without explicitly rebuilding the missing Fourier phases (i.e. no explicit self calibration). The image reconstruction in MIRA is regularized in order to cope with missing data and to avoid artifacts due to the sparse/non-even sampling. Various kinds of regularization (entropy, generalized Tikhonov, ...) can be used by the algorithm. MIRA states the image reconstruction as an inverse problem solved by minimizing a so-called penalty function. Owing to the specific relationship between the object brightness distribution and the data (phase closures and power spectra), the penalty to minimize cannot be guaranteed to be convex. The problem is then very difficult to solve because global optimization is required to find the best solution among the multiple local minima. At this time, the VMLM-B non-linear constrained optimization algorithm (Thiébaut, 2002) is used in MIRA. Since VMLM-B is mainly a descent algorithm, it can only provide a local optimum. We therefore expect the results obtained with this preliminary version of MIRA to be somewhat worse than what is achievable when global optimization will be implemented.

4. Application to PMS's Micro-Jet

In order to assess the imaging capability of Amber/VLTI, we used an image of a micro-jet in Paβ computed with the model by (Garcia, 2001) (see Figure 2). In the simulation, at the wavelength of Paβ, the integrated brightness of the jet roughly equates to that of the PMS star. Nevertheless, since the jet covers a large area, the ratio of the mean jet brightness over a 0.643×0.643 marcsec^2 pixel divided by the star brightness is about 1/100 which is quite unfavorable. As a consequence, imaging of the micro-jet should require high quality data.

We simulated Amber/VLTI data of RU Lupus (phase closures and power spectra) for 6 different configurations involving 3 auxiliary telescopes (AT's, see Figure 2). In our simulations, we considered various SNR for the power spectra⋆: 100, 50, 20 and 10; we took the standard deviation of the noise of the phase closures

⋆ One limitation of these simulations is that the SNR was assumed independent of the value of V^2. As can be seen from Figure 1 this is not the case.

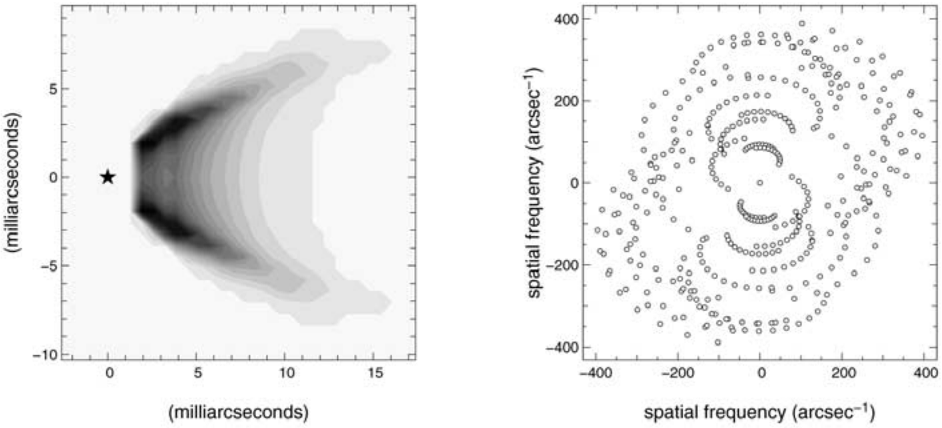

Figure 2. **Left:** Micro-jet emitted by a PMS. The *pixel* size is 0.643 marcsec. The point-like star contribution has been removed (to display the jet brightness distribution) and replaced by a star symbol. The isocontours are evenly spaced. **Right:** (u, v) coverage in our simulations. The configurations were J3-I1-K0, D1-J2-K0, C2-G2-K0, J2-I1-H0, D0-G1-K0, and G2-J1-B5.

to be $1/\mathrm{SNR}$ that is: 0.6, 1.1, 2.9 and 5.7 degrees respectively. Assuming that the star (RU Lupus) is observable in the ± 4 hours range from transit and that one measurement is obtained every 12 minutes**, we got 11 measurements per night. For the 6 simulated observing nights, the total number of measurements is 199 power spectra and 66 phase closures.

Using MIRA and starting the image restoration iterations with a point source, we reconstructed the images shown in Figure 3 for the various SNR considered. These results show that even for the lowest SNR: (i) the micro-jet can be detected and (ii) the open angle can be estimated. The main artifacts are due to the fact that we choose a very small pixel scale (0.643 marcsec) which is 4 times smaller than the resolution achieved by the largest of the bases in our configurations.

5. Conclusions

We have shown that it is possible to obtain an image of the close surroundings of PMS's with no a priori (real imaging) and sufficient resolution ($\sim$ 0.1 AU at 140 pc) with VLTI/Amber instrument. Our simulations demonstrate that 6 configurations (6 observing nights) with SNR ~ 10 (i.e. using 3 AT's) is sufficient to recover an image of the jet good enough to measure its opening angle.

It should be noted that these results were obtained from a preliminary version of MIRA the image reconstruction software under development by one of us (ET)

** At this point we are not allowing for reference calibration. In the considerable wavelength coverage of J–H, we however expect that the continuum is unresolved and can serve as a proper calibrator.

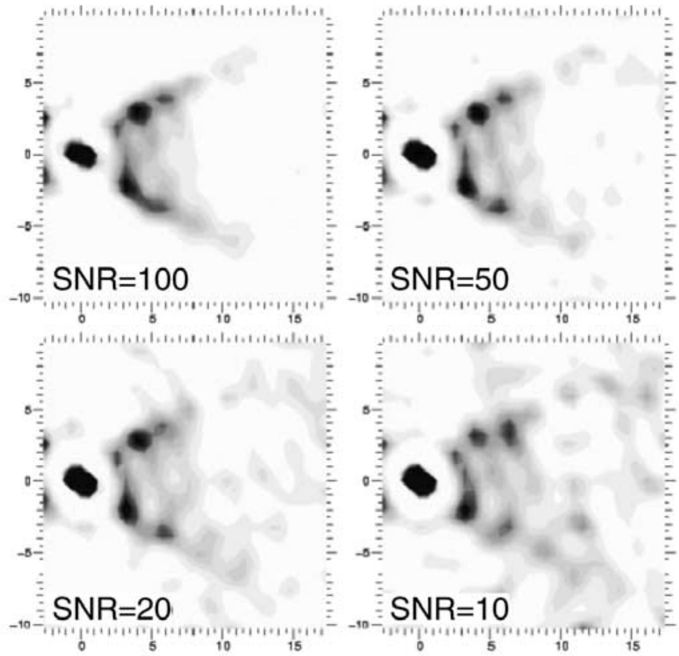

Figure 3. Reconstructions achieved from data with different signal to noise ratios (SNR). Intensities have been clipped to display the jet brightness distribution, the PMS star therefore appears as a saturated area at coordinates (0, 0).

within the framework of JMMC. In particular the current version of the algorithm lacks of global optimization capability (i.e. only a local optimum image is recovered not the best one over all possible images). Our derived requirements in terms of sufficient SNR and (u, v) coverage may therefore be rather pessimistic. With global optimization, the algorithm could cope with much worse data (lower SNR and/or more sparse (u, v) coverage resulting in substantially less observing time). Optimization of telescope configurations could also reduce the number of required observing nights.

Nevertheless, in order to recover worthwhile images with VLTI, some basic rules must be followed: (1) since the object is unknown (which is likely at the spatial resolution achieved by VLTI), no a priori brightness distribution can be used in the image reconstruction process and (u, v) coverage must be as uniform as possible; (2) even if some Fourier interpolation/extrapolation is allowed thanks to the constraints and the regularization, the maximum baseline extension $B_{\rm max}$ is related to the effective spatial resolution: $\Delta\Omega \simeq \lambda/B_{\rm max}$ whereas the mean (u, v) sampling $\Delta B/\lambda$ is related to the reconstructed field of view: $\Omega \simeq \lambda/\Delta B$; the number of interferometric measurements needed to reconstruct an image (with no a priori) will therefore be about $(\Omega/\Delta\Omega)^2 \simeq (B_{\rm max}/\Delta B)^2$. Image reconstruction will always require a not so small number of different interferometric configurations (with a small number, let us say 3 or 4, of telescopes) requiring several observing nights.

Another point to not forget is that at the small spatial scales achieved by interferometry, the observed object is more likely to be variable. This add the requirement that all the observations (of the same object) be made within the shortest time as possible (no longer than a few days), i.e. the telescope configuration should be changed every night. At this time, optical interferometers only have a small number of telescopes (says 3 or 4), imaging objects at the spatial resolutions achievable by these instruments therefore requires a versatile array of telescopes that are easy/fast to reconfigure.

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