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Astrophysical potential of the AMBER/VLTI instrument

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ABSTRACT

AMBER is the near-infrared instrument of the Very Large Telescope Interferometer (VLTI). With a spectral resolution up to 10000 in the 1.2-2.4 micron wavelength range, AMBER will offer the possibility to combine 3 beams from the VLTI array either 8-m or 1.8m telescopes. The instrument has been designed to bring high precision measurement and high sensitivity and therefore opens the way to new domain of investigation in stellar physics and for the first time access to extragalactic sources. We show how the performance of the instrument can apply in these different astrophysical fields. We present the work of the Science Group and the AMBER consortium who defined precise astrophysical goals for the first years of operation.

Keywords: astronomy, interferometry, optical, infrared, astrophysics, large telescopes

1. AMBER FEATURES AND MAIN SCIENTIFIC DRIVERS

AMBER is a near-infrared spectrograph that can combine up to three beams from any telescopes of the same size in the *Very Large Telescope Interferometer*.¹ The instrument will produce:

- squared visibilities measured in the *J*, *H*, and *K* bands [1-2.5 μm]
- closure phases if used in 3-telescope configuration
- differential visibility amplitudes and phases thanks to the spectral resolution of 35, 1000 or 10000.

More details on the actual implementation are given in Petrov et al..²

The technical specifications of AMBER have been derived from the following scientific drivers:

- Imaging the environment of young stellar objects (YSOs): access to a wide range of spatial frequencies and to closure phases in order to get parametric images. The limiting magnitudes with the auxiliary 1.8-m telescopes (ATs) must be much fainter than $K = 6$.
- Study of the close surroundings of active galactic nuclei (AGN): the limiting magnitude with the unit 8-m telescopes (UTs) must be fainter than $K = 11$.
- Detection of the flux of hot extra-solar Jupiters: the ultimate visibility precision must reach 10^{-4} rad at least for the differential phase. This request is a goal and not a specification, since we know it will be difficult to reach and because it depends on the final instrument stability as well as the sensitivity of the refraction index of the air to temperature and humidity which both depend on the site.

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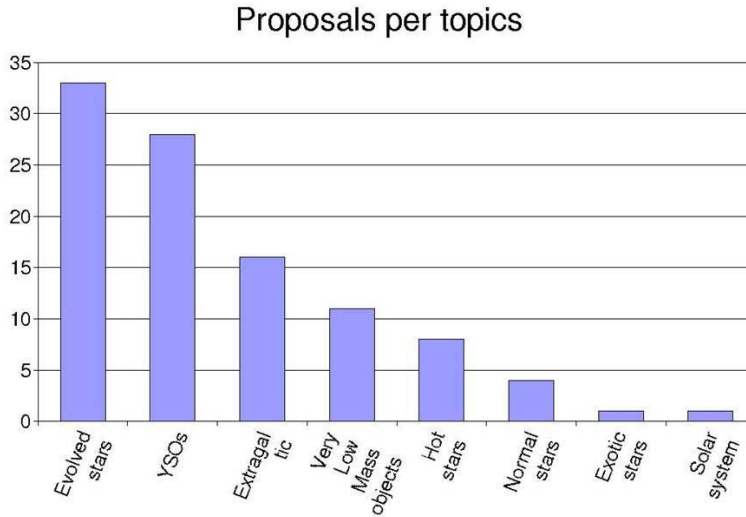


Figure 1: Results from the AMBER internal call for proposal.

Table 1: Spectral configurations requested by the AMBER consortium

Low resolution	Medium resolution		High resolution		
67%	49%		35%		
JHK-LR	JH-MR	HK-MR	J-HR	H-HR	K-HR
67%	21%	26%	13%	7%	13%

- Studies of circumstellar envelopes in particular for stars in their late stages of evolution: the spectral resolution must reach 10000, with a medium resolution around 1000.

We issued a preliminary call for ideas within the AMBER consortium in order to prepare the observations with AMBER. The results of this call give an impression of what astronomers would like to do with AMBER. The AMBER consortium includes researchers from 5 institutes: LAOG (Grenoble, France), MPIfR (Bonn, Germany), OAA (Arcetri, Italy), OCA and UNSA (Nice, France) and some additional individuals. We received a total of 102 proposals. Figure 1 shows the numbers of proposals per category of object: late and early stages of stellar evolution, studies of extragalactic objects, observations of very low-mass objects including hot exoplanets and several classes of stellar astrophysics.

This call for proposals also helped us to identify what type of configurations are usually requested:

- the majority of the proposals (81%) ask for AT time since these telescopes are relocatable and therefore allow a wide range (u, v) coverages.
- a large fraction of the proposals (26%) ask for UTs in order to observe objects which are faint, at a high spectral resolution or with very high precision.
- the time requested as a function of the spectral configuration is given in Table 1. The total percentage exceeds 100% because some proposals asked for several different configurations.
- It is interesting that 83% of the proposals ask for a 3-beam configuration mainly because it provides better observing efficiency with 3 simultaneous baselines and access to one closure phase.

In the following sections, we will describe some of the programs we would like to carry out with AMBER: observations of dust tori in AGN, the late stages of stellar evolution, the environment of hot stars and detection of hot Jupiters. Concerning the ejection and accretion phenomena in young stellar objects which was part of the presentation, the reader is invited to read the YSO review in this volume.³

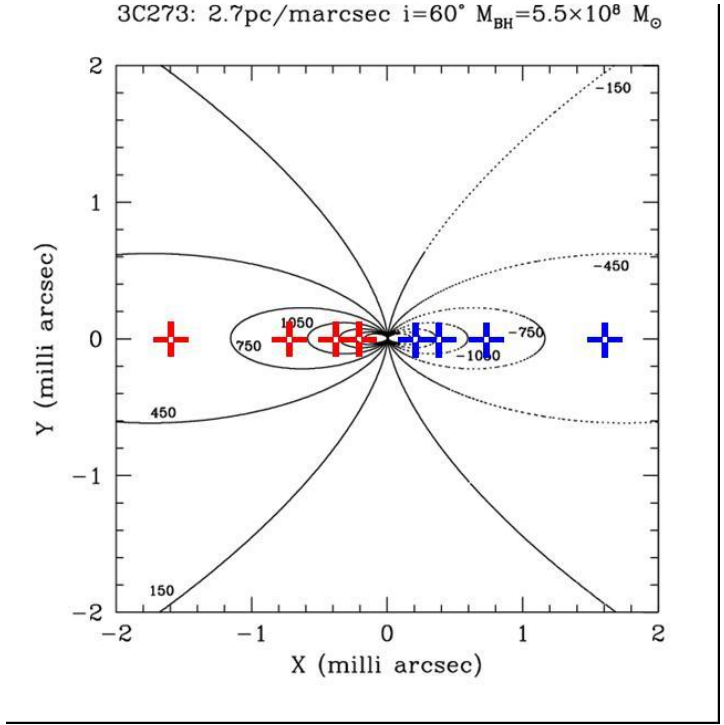
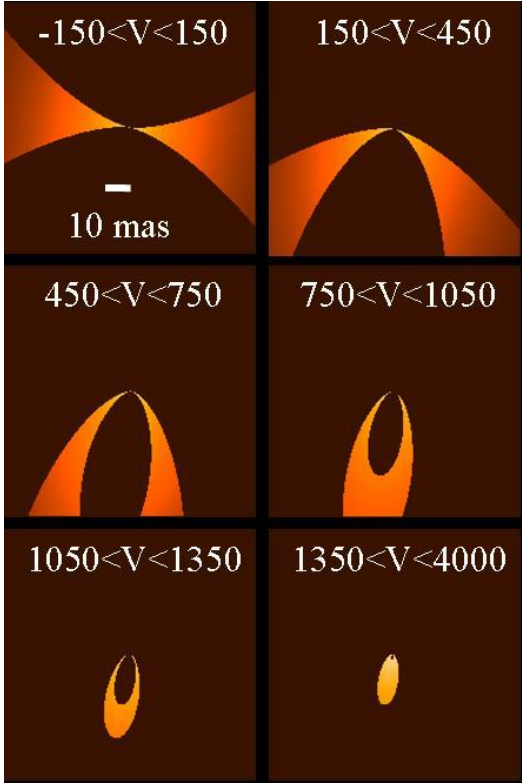


Figure 2. Left panel: Simulation of the nuclear gas disk for given velocity bin in the case of Centaurus A: BH mass $2 \times 10^8 M_{\odot}$ (Marconi et al.⁵). Right panel: Expected Velocity field of the famous quasar 3C273 (with an assumed BH mass of $5.5 \times 10^8 M_{\odot}$): the contours are isovelocity lines. Crosses mark photocenters in the velocity bins, as they can be seen in the BR γ emission line.

2. DUST TORI AND SUPERMASSIVE BLACK HOLES IN ACTIVE GALACTIC NUCLEI

Active galactic nuclei can be divided into two categories depending on their observational properties. These two categories can be reconciled in the framework of a unified model where the central black hole and its accompanying accretion disk are surrounded by a torus of dust. Type 1 AGN are seen almost pole-on, whereas type 2 AGN are seen almost edge-on. The inner radii of the dusty tori are set by the dust sublimation

$$R_{\text{subl}} \sim 0.6 L_{45}^{0.5} \text{ pc} \quad \text{with} \quad L_{45} \text{ in units of } 10^{45} \text{ erg.s}^{-1} \quad (1)$$

Therefore the expected torus dimension is of the order of 1 pc, i.e. at 15 Mpc (distance of NGC1068) an angular distance of 13 mas, which is well within the capability of AMBER.

One of the first questions to be answered is “do dust tori actually exist?” and one of the first tasks is therefore to show direct evidence of their presence. If we are able to resolve this structure, as Granato et al.⁴ have predicted from their model, then we will try to constrain dust radiative transfer models by measuring the radius and by determining the inclination angle. Furthermore, if the signal-to-noise ratio is high enough, we could look for an eventual departure of the observations from the existing models and try to reconcile the data and the measures with different dust properties (i. e. large grains).

In order to probe scales which are smaller than the torus, we propose to try some extremely high, sub-mas resolution obtained by differential phase observations. In particular we will study the rotating disk around the central black hole. The visibility phase, which depends on the location of the photocenter of the object, will vary with the wavelength since it will track different part of the environment of the black hole as shown in the left part of Fig. 2.

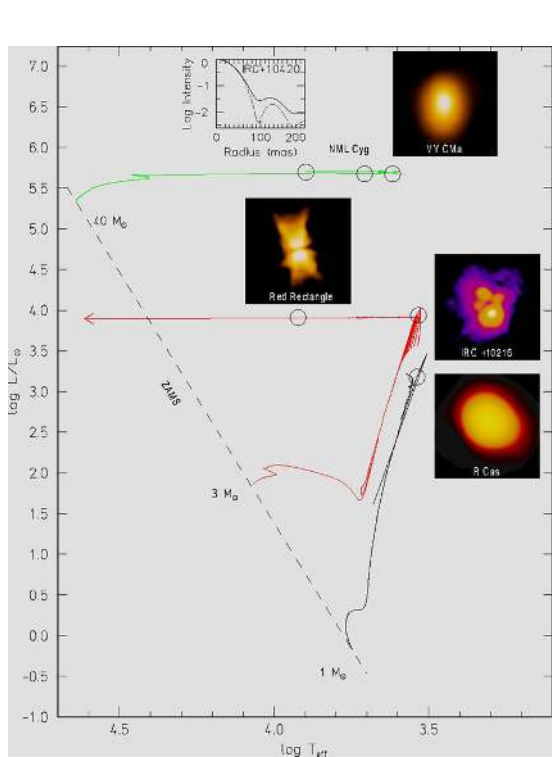


Figure 3. Late stages of stellar evolution. Left panel: Hertzsprung-Russell diagram where the targets are identified. Asymptotic Giant Branch (AGB): R Cas, IRC+10216, CIT3, CIT6; Protoplanetary Nebula Phase: Red Rectangle, Egg Nebula; Red Supergiant Branch (+ WR): NML Cyg, IRC+10420, VY CMa. Right panel: Model of IRC+10420 that fits the observation in speckle interferometry at smaller spatial frequencies and computation of the expected visibilities for a set of parameters.

If the disk is unresolved by the interferometer one can measure the differential phase and locate the photocenter at given wavelength bin with an accuracy as low as $1 - 10 \mu\text{as}$! One application is the study of the geometrical and kinematical structure of the BLR in Seyfert 1 galaxies and quasars. We should be able to resolve sizes down to a few 10 light days (typical sizes of BLR of Seyferts) and to eventually determine the BH mass from the BLR motion (if it rotates as a Keplerian disk).

Combining AMBER angular measurements with linear measurements obtained from *reflective mapping* will yield direct measure of the distance of the object and therefore give new and strong constraints on the global distance scale.

3. LATE STAGES OF STELLAR EVOLUTION

The late stages of stellar evolution provides us with a very interesting laboratory. More than 80% of the dust found in the interstellar medium comes from the mass loss at these stages of stellar evolution. The evolved objects are subject to strong stellar winds that lead to a partial obscuration, by dust absorption, of the visible light and therefore a reemission in the infrared domain.

We can identify three classes of interesting targets (see Fig. 3):

- Asymptotic Giant Branch (AGB): R Cas, IRC+10216, CIT3, CIT6;
- Protoplanetary Nebula Phase: Red Rectangle, Egg Nebula;
- Red Supergiant Branch (+ WR): NML Cyg, IRC+10420.

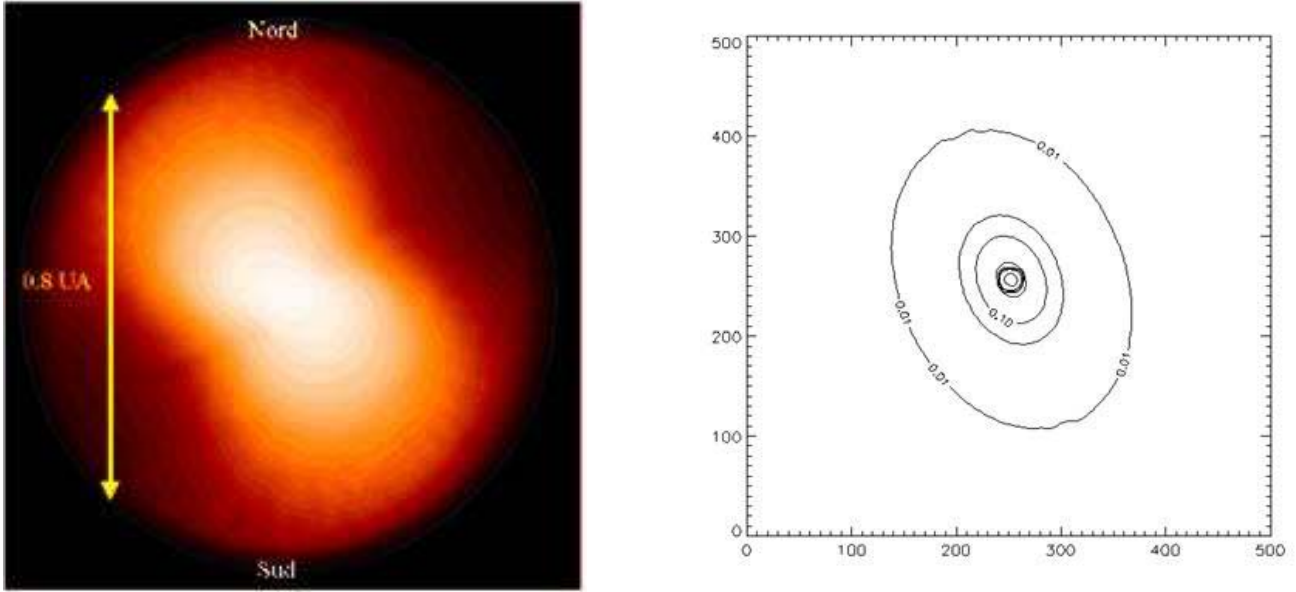


Figure 4: Maps derived from models of Be stars (left: in the continuum, right: in the line). After Stee et al.⁷

In this paper, an interesting example is IRC+10420. Blöcker et al.⁶ have demonstrated that a particular set of parameters of a superwind model can fit the observation at small spatial frequencies (from speckle interferometry). However, at high spatial frequency (typical baseline of 50m or 100m in the near-infrared) the set of parameters can lead to very different predicted visibility amplitudes. Therefore AMBER would be a good instrument for constraining wind models (in that case with an inner dust shell radius of 35 mas and an additional superwind radius of 135 mas). In addition one is able to derive the inner radius for the superwind ($r = 135$ mas).

4. ENVIRONMENT OF HOT STARS

Hot stars such as Be or B[e] stars, which exhibit strong emission in the hydrogen lines, are believed to be surrounded by a large circumstellar rotating envelope that has been revealed in the $H\alpha$ line by the GI2T interferometer with its 30,000 spectral resolution.⁸ Models⁷ have been developed to interpret in a global way the spectral energy distribution, the shape of spectral lines together with the variation of the visibility with the baseline and with the variation of the differential visibility amplitude and phase with the wavelength. Be stars have also been the test case used to demonstrate experimentally that the differential phase can yield interferometer on structure 200 to 1000 times smaller than the interferometer resolution limit.

AMBER will perform the first interferometric observations in the near-infrared domain in particular in the $Pa\beta$ and $Br\gamma$ lines. But in addition AMBER will be able to measure the closure phase on any triplet of telescopes and therefore will in principle be able to feed raw data to image reconstruction algorithms in order to get images of the envelope either in the continuum or in velocity bins (see Fig. 4). Even before being able to reconstruct images, the measured closure phase will give information on the degree of symmetry of the envelope and will permit a detailed study of the envelope kinematics.

5. SIGNATURE OF HOT JUPITERS IN EXTRASOLAR PLANETARY SYSTEMS

AMBER has the capability to detect the direct signal from hot Jupiters (also called Pegasids) around main sequence stars. The prototype of these extrasolar systems is 51 Peg. These exoplanets have a spectrum which combines reflected star light, planet emission (with specific spectral feature) resulting from the reprocessing of the irradiating star light in a greenhouse atmosphere as well from heating processes of the planet alone (like for example an unfinished gravitational collapsing) with strong absorption features (see left part of Fig. 5). Therefore the exoplanet has a brightness ratio with its host star which varies with the wavelength.

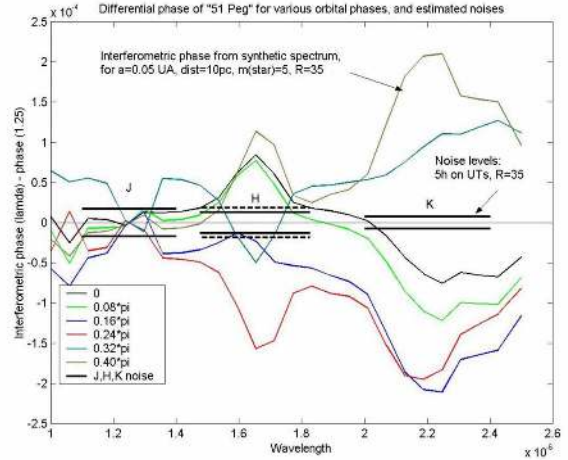
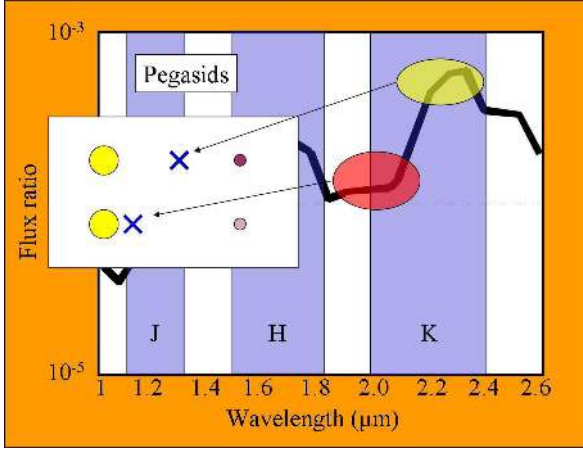


Figure 5. Signature of Pegasid exoplanets. Left part: spectrum of the planets (from Barman et al.⁹). Right part: expected differential phase in 5 hours of integration on the UTs compared to the expected error bars from AMBER.¹⁰

This results in a variation with wavelength of the phase of the star+planet visibility whose measurement at several orbital phases yields the planet spectrum (i.e. physical and chemical parameters of the atmosphere) as well as the orbital parameters and therefore the exact mass and inclination. Using synthetic spectra from Barman et al.,⁹ the differential phase expected from jupiter mass planets up to 0.2 a.u. away from their star is well above the computed photon, read out and background noise¹⁰ as illustrated in the right part of Fig. 5 for the 51 PegB planet. However, this corresponds to phases differences smaller than 10^4 radians. We have included in the design of the instrument elements that increase the probability to achieve such an extreme stability of the instrumental contribution to the differential phase.¹¹ All effects specific to the instrument can be kept lower than the photon noise if the calibration period is made short enough. A difficult problem is the variable differential OPD produced by the temperature, pressure and humidity variations in the air of the tunnels. If we fail to extract it from the recorded data itself, we can eliminate it using closure phase with three UTs. This closure phase can be made almost insensitive to detector and other detection expect by a modulation method.¹² The combination of this different SNR estimates and calibration methods convince us that the spectroscopy of Pegasids is an objective which can be pursued with a reasonable chance of success even if we want to stress that this extremely ambitious astrophysical program is at the limit of the instrument capacity.

6. CONCLUSION

In conclusion, we would like to emphasize that the AMBER gain in sensitivity, in spectral resolution, in visibility precision as well as in VLTI (u, v) coverage will undoubtedly lead to new results in stellar physics, exoplanetology and extragalactic domains.

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