Science opportunities with AMBER, the near-IR VLTI instrument

Andrea Richichi[*a], Thomas Blöcker[b], Renaud Foy[c], Didier Fraix-Burnet[d], Bruno Lopez[e],

Fabien Malbet[d], Philippe Stee[e], Oskar Von Der Lühe[f], and Gerd Weigelt[b]

[a]European Southern Observatory, Karl-Schwarzschildstr. 2, D-85748 Garching b.M., Germany

[b]Max-Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

[c]Centre de Recherche Astronomique, 9 av. Charles André, F-69561 Saint Genis-Laval Cedex, France

[d]Laboratoire d'Astrophysique de l'Observatoire, BP 53, F-38041 Grenoble cedex, France

[e]Observatoire de la Côte d'Azur, BP 4229, F-06304 Nice Cedex 04, France

[f]Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, D-79104 Freiburg, Germany

ABSTRACT

AMBER is the near-IR instrument for the VLTI, which will offer the possibility of combining two or three beams from either the 8 meter VLT main telescopes or the 1.8 meter auxiliary telescopes. With spectral dispersion up to 10,000, high visibility accuracy and the ability to obtain closure phases, AMBER will offer the means to perform high quality interferometric measurements in the 1-2.5 micron range initially, with later extensions to other portions of the spectrum. These design characteristics, coupled to the VLT interferometer potential, open up the access to investigations of several classes of objects, from stellar to extragalactic astronomy. We will review the projected performance in terms of sensitivity and angular resolution, and illustrate the potential applications in some key research areas. In particular, we will present the work of the AMBER Science Group, which is evaluating simulated data of source models and interferometric outputs for the purpose of defining the criteria for observations.

Keywords: VLTI, Near-Infrared, AGN, Exoplanets, AGB stars, T Tauri stars, Be stars

1. INTRODUCTION

AMBER is the near-IR instrument for the VLTI, built by a consortium of European institutes and to receive first light in 2002. Details on the instrument project, its design, projected performance and operation can be found in a number of papers[1,2,3,4] as well as in several contributions to these proceedings[5,6,7,8,9]. To summarize, the main characteristics of the instrument are: operation in the 1 to 2.5µm range; the ability to combine more than 2 beams (three are foreseen, and the design allows the extension to more), providing in principle closure phase; different levels of spectral resolution, up to ≈10,000; a fiber-optic spatial filter, allowing high visibility accuracy. The instrument is designed to be used at the ESO VLT Interferometer[10] (VLTI), which will provide combination of two or more telescopes of 1.8 m or 8 m diameter (AT and UT respectively), with a wide range of baselines up to 200 m. An adaptive-optics system will be provided for use with the 8m telescopes[10,11,12], while in a later phase of the project a dual-feed facility (PRIMA[10,12]) will provide the possibility for off-axis fringe tracking and astrometry.

All these factors combined, together with the fact that the VLTI will be the first and only large interferometric facility in the southern hemisphere and that it will be located at an excellent site, provide the potential for an extensive use of AMBER in many diverse fields of astronomy, from stars to extrasolar planets to galaxies. In fact, the number of observing programs that could potentially be carried out with AMBER is so large, that it is important to examine in advance their relative

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[*] On leave from Osservatorio Astrofisico di Arcetri, Italy

benefits, the required configurations of instrument and interferometer, and their weight in terms of observing time. This is particularly true in the first phases of operation, when it will be important to address ground-breaking topics as far as possible, while paying attention to an efficient use of the VLTI at the same time.

For this reason, a Science Group (SGR) was established by the AMBER consortium, with the following aims: to define the astrophysical scope of AMBER; to participate in the design of AMBER and advice on technical choices; to analyse the impact of AMBER design on science; to participate in the definition of integration and commissioning; to select a list of key programs, and establish for each a list of targets; to suggest a schedule of observations during guaranteed time. In this contribution, we report on the work of SGR and in particular we present aspects related to the last two points in the above list.

2. OBSERVING WITH AMBER

In this section we present some considerations on the limits of angular resolution, baseline coverage, and sensitivity, that are useful to identify the research areas in which AMBER can play an important role and define its scientific potential.

Angular resolution is set by the maximum available baseline, which is about 200 meters for the ATs and about 130 meters for the UTs. Accordingly, the limit will be about 2 milliarcsecond (mas) for the ATs, and about 3 mas for the UTs, in the K band. These values must be roughly halved for the J-band. Of course, the actual resolution will depend also on the signal-to-noise ratio (SNR) available, which is in turn a function of the source brightness, as well as of many factors mentioned below. Under conditions of very high SNR, it is in principle feasible to obtain higher resolutions than the broad limit given above. This applies in particular to cases in which a source model is available and determinations of the visibility before the first zero are sufficient to constraint the size of the object (for instance, angular diameters and binary stars). Reversely, conditions of low SNR (for instance, for very faint sources), will limit the actual maximum resolution to values which can be substantially lower than the figures mentioned above.

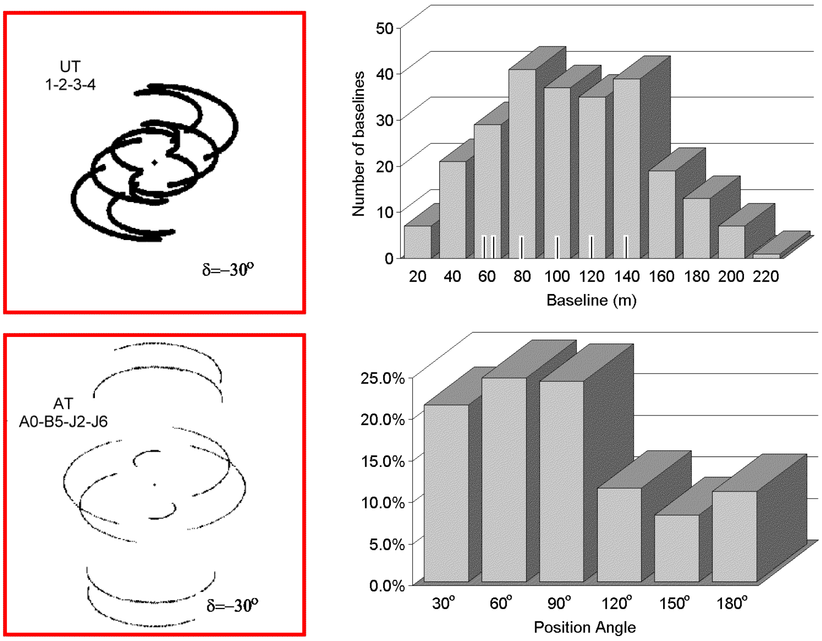

Figure 1. Left panels: examples of *u-v* coverage. Right panels: distribution of baseline lengths and position angles. The histograms are for the ATs only. The UT baseline bins are marked by the small segments.

A second important factor that characterizes the performance of an interferometer is the number of available baselines, which in turn define the coverage of the *u-v* plane. For a simple spherically symmetric object (for instance, a stellar disk at a first approximation) one single point in the *u-v* plane will be sufficient to determine its size. For an object such as a binary star, two points will be required to determine angular separation and position angle. For increasingly complicated objects, more points will be necessary. In the case of VLTI, the large number of stations for the ATs and the availability of four UTs located in a non-redundant way, provides a very rich scenario of possible baselines. Altogether, 254 independent baselines are possible, corresponding to 3025 closure phases. In Figure 1 we provide a quick overview of the available baseline coverage. In the figure, the left panels illustrate the (future) case of 4-telescope combination, for the UTs and for some AT stations. The right panels show the distribution of baseline lengths and position angles (at the zenith, without rotation), which can be seen to be relatively smooth and without gaps. Of course, a practical limit is set by the fact that only a few of the baselines are available simultaneously, since there are currently only 3 delay lines in the VLTI (although in principle extensions are possible in the future). The management of the large number of baselines in connection to the requirements of different observing programs, as well as to the constraints imposed by design factors, is discussed in detail by Schöller[14]. Here we want to stress the fact that AMBER will permit the combination of 3 beams (with the possibility of later extensions). In this latter case, not only the efficiency of observations will be significantly boosted (3 baselines instead of 1 can be measured simultaneously), but also closure phase will be possible. This will provide the key to actual imaging, not possible with 2-beam interferometers.

Table 1. AMBER K magnitude limits for various configurations.

Mode	Int. time	Disp.	2UT	2AT
High precision	0.01s	R=5	11.3	8.0
High sensitivity	0.1s	R=5	13.2	9.9
Fringe Tracking	4h	R=5	17.0	12.1
Fringe Tracking	4h	$R=10^2$	16.5	11.6
Fringe Tracking	4h	$R=10^3$	15.0	11.1
Fringe Tracking	4h	$R=10^4$	14.2	9.6

Finally, for what concerns the limits in sensitivity, these depend on a large number of factors. Some of these are relatively well identified by the design of AMBER (for instance, transmission efficiency, fiber coupling, detector characteristics etc.), while many others are more difficult to characterize at this time: for instance the quality of fringe tracking and adaptive optics correction. A discussion of the expected performance of AMBER is given elsewhere[7], and here we restrict ourselves to presenting a summary of some key numbers in Table 1.

3. AMBER SCIENCE DRIVERS

In this section, we provide a brief introduction to some research areas which will be tackled by AMBER, and which have been investigated for this purpose by the SGR. Given the available space, it is not possible to present many details, and we limit ourselves to a brief summary the current understanding of each class of objects, including the results of some selected high angular resolution observations, and to highlight the contribution that will be possible with AMBER. More detailed analysis of most of the topics of this paper are given in individual contributions elsewhere in these proceedings[15,16,17,18,19,20]. For the same reason of space, we have been forced to leave out several other research areas, where AMBER will also offer the potential for innovative investigations. These include for instance investigations of solar system objects, low-mass stars, Cepheids, microlensing, the galactic center, nearby galaxies. A large research area in which AMBER and the VLTI can make substantial contributions is that of binary stars[21].

We should also mention that many authors have already investigated the science opportunities which will be opened by the next large interferometers such as VLTI and Keck, and that several publications already exist on many of the subjects covered by this contribution. In particular, we refer the reader to the proceedings of an ESO Symposium[22], which provides an excellent overview of many scientific topics in connection with the VLTI, in many cases with the wavelength ranges and sensitivity limits which are very similar to those soon to become available with AMBER.

3.1. Hot Exoplanets

At present, there are about 20 stars with a candidate exoplanet, as inferred from radial velocity measurements. The direct detection of exoplanets is considered one of the hot topics for modern astronomy, and one which is attracting many efforts. In the absence of a specific astrometric capability, AMBER alone is not in a position to detect directly the reflex motion of the central star in these systems (note however that with the addition of the PRIMA facility this should become possible later). However, Lopez and Petrov[23] have described how it will be possible to detect the planet by its effect on the phase and visibility of the system. An alternative method relying on an accurate calibration of the visibility has also been proposed[24]. We summarize here briefly the potential of AMBER in this area, while a more detailed discussion is given elsewhere[20].

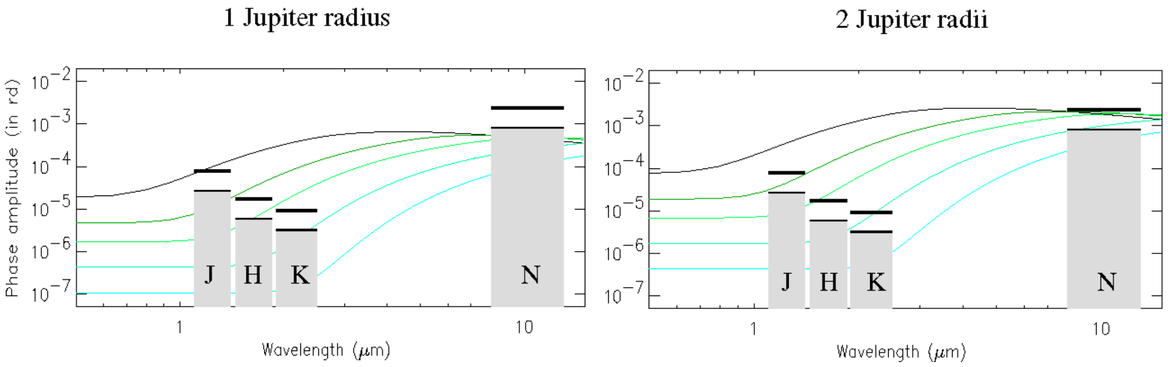

Figure 2. Phase variation for a solar-type star due to a hot planet. The lines represent the phase shift induced by a planet orbiting at distances between 0.03 AU (top) and 0.4 AU (bottom). The horizontal bars are the detection limit in 0.5 (top) and 5 (bottom) hours.

In Figure 2, it is shown how the phase is affected by the presence of an exoplanet with 1 and 2 Jupiter radii, respectively (a similar effect exists for the visibility). It can be noted that the effect is strongly wavelength-dependent. In particular, it can be seen that an exoplanet with an orbit ≤0.1 AU induces a phase-shift which can be potentially detected (i.e., with integration times ~1 hour) by AMBER at all its operating wavelengths. Indeed, it is fundamental to observe simultaneously at several wavelengths because the detection is based on the unique signature of this effect as a function of wavelength. In passing, it can be added that the determination would be additionally strengthened by observations in the thermal infrared with the MIDI instrument. The main difficulty of this method is that phase errors must be contained between 10^{-5} and 10^{-6} rad for the near-IR. This is very demanding, but not impossible to achieve, and the AMBER team has used this case as a strong argument to request that ESO implements a phase-inverter.

At this point we stress that while it is certainly important to obtain more exoplanet direct detections, as is the goal of astrometric interferometers, the next step will be to acquire some specific knowledge about their nature, for instance their spectrum. The approach that we propose for AMBER includes the possibility to extract such information, at least in principle: in fact, the wavelength signature of the phase-shift will be convolved with the spectrum of the host star and of the exoplanet. There are presently about 10 exoplanets candidates which are sufficiently hot for this method to work (i.e., ≤0.1AU). Of these, a few are accessible from Paranal, in particular some of the best ones, such as 51 Peg and υ And. On the other hand, we reckon that many more candidates will be known by the time we have first light we AMBER, because many radial velocity surveys are still being processed and some of them are specific to the southern emisphere.

3.2. Angular diameters and effective temperatures

The knowledge of the effective temperature of stars is of fundamental importance in astronomy for various reasons. Firstly, it provides a fundamental test for stellar models, involving aspects of stellar structure, composition and evolution. The effective temperature of a star, deduced from its measured angular diameter and bolometric flux, is completely independent from the distance to the star, and therefore it represents a powerful method to test theoretical models on a very large and varied number of stars. Secondly, the calibration of effective temperatures with spectral type (possibly complemented by luminosity class and chemical composition) is of fundamental importance for investigations involving stellar populations, and as such it finds extensive use in galactic and extragalactic studies. Finally, recent accurate parallax measurements, such as those obtained by the Hipparcos satellite, are beginning to permit a direct conversion of many angular diameters into linear sizes, opening a new point of view on stellar studies.

Empirically, it has long been established that the effective temperatures of spectral types similar to or hotter than solar can be well described by a simple temperature-color relation[25]: although based on relatively few measurements, this calibration seems very reliable and leads to accurate predictions. For spectral types K and cooler (T_{eff} ≤4500 K), however, the situation is more complex. Initial attempts to define a relationship between temperature and visual color indices were less successful for cooler stars, mainly because of the presence of broad molecular bands in the V, R and I filters. Instead, it was necessary to push studies of the diameters and photometric coverage for these stars into the near-infrared (NIR). Effort in this area has proceeded for the past 20 years both by lunar occultations[26,27] and by interferometry[28,29,30]. Measurements from different methods and authors agree on the effective temperature of giant stars down to about M8 (i.e., $T_{\rm eff}\approx 2900$ K). An example is given in Figure 3, adapted from Richichi et al.[27].

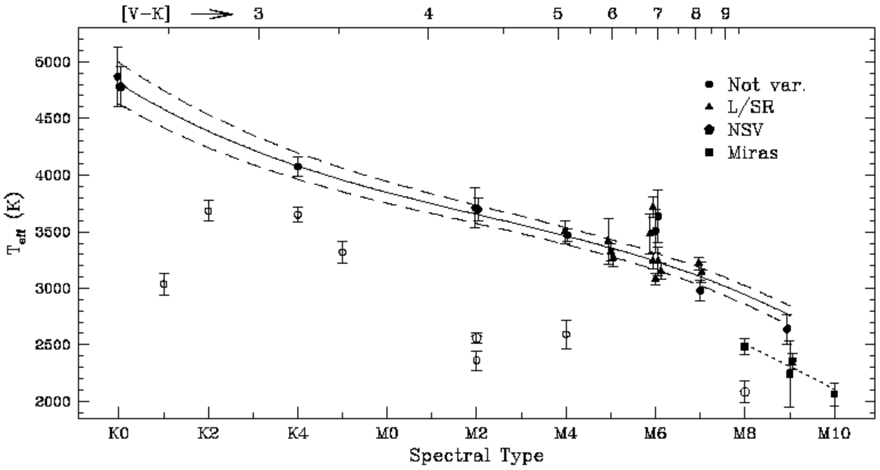

Figure 3. Effective temperature calibration for late-type giants derived by lunar occultations[27].

However, our direct observational knowledge is still scarce on several issues, either because the measurements are too few or absent, or because they are incomplete. In particular, the following topics are still relatively open:

- effective temperature of cool stars on the main sequence
- effective temperature of chemically peculiar cool giant stars (carbon stars as a prime category)
- temperature variations with phase for pulsating and long-period variables (Miras as a prime category)

Roughly speaking, for a given spectral type a main sequence star is 10 smaller, i.e. 100 times less luminous, than its giant counterpart. This means that for a set limiting resolution, an interferometer will need to be 10 times more sensitive to measure main sequence stars than for giants. Moreover, the fact that dwarfs are smaller implies that they have to be closer to be within a set resolution, i.e. there will be relatively few of them - although this effect is partly balanced by their being more abundant. In practice, up to very recently research in this field has been hampered by the fact that most interferometers did not have the necessary baseline length to resolve dwarf stars, and/or sensitivity. As a consequence, our knowledge of the effective temperature of main sequence stars has been limited to cases such as those of eclipsing binaries. These are relatively rare, and the corresponding $T_{\rm eff}$ calibration is well established and reliable only for Sun-like stars or hotter.

In the case of cool main sequence stars, our knowledge is much less satisfactory, in spite of the importance of this parameter for theoretical models[31]. Unfortunately, even with 200 meters baselines, no M dwarfs can be completely resolved in the near–IR. However, it has been shown[32] how the VLTI can make major contributions in this area, by studying with high visibility accuracy a number of stars which will be partially resolved. This study has shown that there should be about 160 stars where a 0.5% visibility accuracy should permit temperature estimates accurate to ≤5%. For this, it is important to use short wavelengths in the near-IR, and the availability of the J band in AMBER is therefore of primary importance.

For what concerns the issues of carbon stars and Miras, several measurements by lunar occultations[33,34], speckle interferometry (see for instance Sect.3.3), and long-baseline interferometry[35,36], have begun to measure angular diameters and circumstellar shells around this class of objects. In this sense, the situation is quite improved with respect to just ten years ago[37]. However, these measurements have also begun to reveal directly what has been known on the theoretical level for a long time, i.e. the fact that these objects vary their physical characteristics with time. In particular the issue is critical for Mira stars, which undergo pulsations with substantial variations in their temperatures and in the properties of their surface and near-stellar environment. As a result, it is becoming increasingly important to combine the high angular measurements with a frequent monitoring of the bolometric and spectral variability in these stars.

In the general context of stellar diameters, we should also stress that an advantage of the VLTI and AMBER will be also the geographical location, which will provide access to a large portion of the sky not covered by similar facilities.

3.3. Stars in late evolutionary stages

This topic has been traditionally one of the typical targets of high angular resolution techniques: on one side it includes sources with a wide range of characteristics, from the disks of late-type stars to circumstellar shells, and angular scales that can be accessed already with the moderate resolution offered by the diffraction limit of a large single telescope. On the other side, it is the key to a number of issues that are not yet completely understood on a theoretical level, or that need a constant observational input: for instance stellar pulsation, mass loss, dust properties, effective temperatures to name a few. So far, measurements of this kind have been possible by means of speckle interferometry (which was limited by angular resolution to the largest stars), by lunar occultations (limited to sources subject to this phenomenon), and by long-baseline interferometry with relatively small telescopes (limited to the brightest sources). With large intereferometers such as the VLTI, the step forward in this field will be dramatic, thanks to the long baselines and increased light-gathering power, but also to the specifications of accuracy, spectral dispersion, and limiting magnitude of AMBER. Finally, the possibility to obtain real imaging –by means of closure phases using 3 beams– will permit to understand better complex structures on small angular scales, such as asymmetric dust shells or surface features. In this wide research area, we take as a lead some examples extracted from recent high angular resolution results on a few sources, to illustrate the potential offered by AMBER and the VLTI.

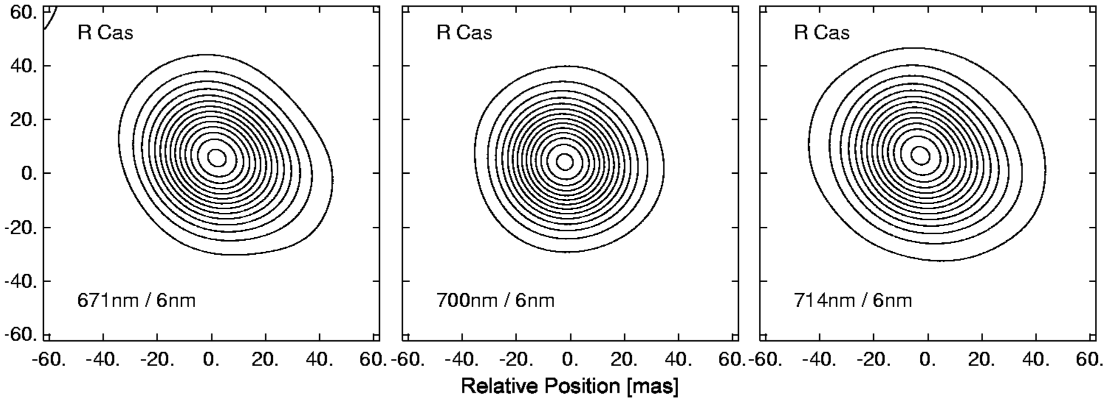

Fig. 4. Bispectrum speckle interferometry images[17] of R Cas with 30 mas resolution. In each panel the contour levels are plotted from 7 to 98% of peak intensity in steps of 7%.

Diffraction-limited bispectrum speckle interferometry of Mira stars with the 6 m telescope and other interferometric studies have shown that the stellar surfaces of Mira stars are much more complex than previously assumed. For example, the assymmetric image of R Cas shown in Fig. 4 has a size of 43x56 mas at the wavelength 714 nm[38,39]. This image suggests that unexpected high-contrast objects (hot spots or supergranulation for example) can be resolved on the disk of R Cas and other Mira stars with baselines of only 8 to 32 m. In addition to the speckle observations, infrared long-baseline interferometry with the IOTA and GI2T interferometers have very recently demonstrated, for example, that the stellar surfaces of R Leo and R Cas are not at all homogeneous[40,41]. These observations demonstrate that the resolution of infrared interferometers is high enough to resolve the disk of many Mira stars, to reveal photospheric asymmetries and surface structures, and to study the strong wavelength and phase dependence of the diameter. Theoretical studies show that accurate monochromatic diameter measurements can much improve our understanding of cool stellar atmospheres. Interferometric observations are required to test and improve theoretical Mira star models, to derive effective temperatures, and to study and explain the wavelength-dependent center-to-limb intensity variations and the surface structures.

Carbon stars are in an advanced stage of red giant evolution, and accordingly they are often heavily enshrouded by circumstellar dust. Their dust shells, therefore, represent an ideal diagnostic tool to study these late phases of stellar evolution. The VLTI will be able to resolve the surface structures and dust shells of many carbon stars. Bispectrum speckle interferometry observations[42,43] of the carbon star IRC +10216 obtained at the SAO 6m telescope between 1995 and 1998 illustrate the feasibility of such VLTI projects. This is the nearest (130 pc) and best-studied carbon star and one of the brightest infrared sources. The speckle observations have shown several compact components within a 0.2" radius, and followed their evolution over a period of few years. For instance, the separation of the two brightest components A (northern component) and B (southern component) increased from 191 mas (≈6 stellar radii) in 1995 to 265 mas in 1998. At the same time, component B is fading and the components C and D (eastern and western components) become brighter. Radiative transfer calculations show that the dominant component A is not the central star, but the southern lobe of a bipolar structure. The position of the central star is probably at or near the position of component B. If the star is at or near B, then the other components are likely to be located at the inner boundary of the dust shell. Without doubt, the VLTI will contribute significantly to our understanding of such far-evolved stars. For example, in the case of IRC +10216 more details on the dynamics of an evolving dust shell can be unveiled and the position of the central star can be determined much more precisely. IRC+10216-like dust-shell structures can be expected to be typical for the very end of the AGB evolution. VLTI observations of several of the nearest carbon stars will provide crucial details on the key issue of the metamorphosis of a red giant into a proto-planetary nebula.

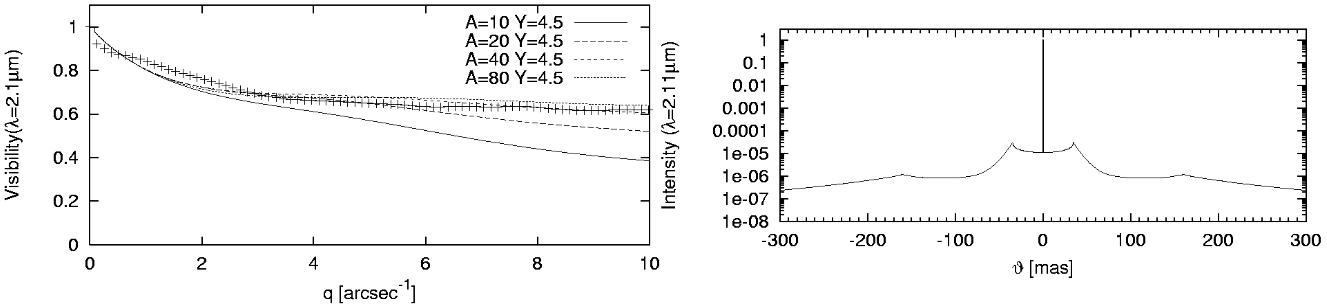

Figure 5. Left: IRC+10420 K-band observed visibility function[21], and visibilities for a superwind model with density enhancements of different amplitudes A. Right: Model intensity distribution[44].

The surface structures and dust shells of a large number of supergiants can be studied with the VLTI with unprecedented resolution. For example, the massive supergiant IRC +10420 is unique for the study of stellar evolution since it is the only object which is believed to be currently observed in its rapid transition from the red supergiant stage to the Wolf-Rayet phase. Its spectral type changed from F8 in 1973 to mid–A at present, corresponding to an effective temperature increase of 1000–2000 K within only 25 years. Speckle observations of IRC +10420 were carried out in the K band with 73 mas resolution[21], yielding a detailed insight into the inner structure of this source. The central star contributes ≈60% and the dust shell ≈40% to the total flux (see Figure 5). This has stimulated an effort on the theoretical understanding of the radiative transfer, and a two-component dust shell has been proposed to explain the observations. Without going into the details, for which we refer to the original papers[16,44], we note that the authors conclude that the next step to discriminate between different model parameters will be to obtain data with baselines of 100 meters or more, and possibly at more than one wavelength. In this respect, AMBER is well suited to push further our understanding of these and similar sources.

3.4. Be Stars

These stars are B stars which show at least part of the time strong emission lines due to the presence of a gas envelope. The observational data is very abundant. The optical/infrared and the ultraviolet observations of Be stars have been widely interpreted as being the evidence for the existence of two quite distinct regions in the circumstellar envelopes of these objects. The optical emission lines and the infrared excess are most probably produced in a dense rotating equatorial region, often called "equatorial disc". The asymmetric UV lines seem to be formed in a much more rarefied region which expands above and below the equatorial disc with velocities that may reach 1500 km/s, also called the "polar wind". An important aspect of this traditional picture is that the equatorial region would be characterized by a very low radial expansion. However some observational features complicate this scenario. Since long it is known that the wings of H_α in Be stars may be broader than the projected rotational velocity. As in certain cases velocities up to a thousand km/s are seen, turbulent motions can be ruled out. Electron scattering would require quite high temperatures in order to explain such great velocities. On the other hand the intensity of the UV resonance lines of CIV is roughly correlated to V/R variations, indicating that the two regions are somehow linked. In addition the equivalent widths and the edge velocities of the CIV doublet (and possibly also NV and SiIV) are correlated with *v sin*i). This would suggest that the geometry of the "high-velocity region" is also flattened towards the equator. The emission lines shapes and intensity strongly vary with time. A schematic illustration is given in the sketches of Figure 6.

Be stars have been very often observed by optical interferometers because they are bright, present a complex structure and have optical envelopes with the typical angular size of a few mas which can be resolved only with baselines of a few decameters. In fact it is high angular resolution observations in the visible with the Mk III and GI2T interferometer that definitively proved that Be stars envelopes are not spherical. Far infrared images reveal extended envelopes. Variable X-ray emission is often present and sometimes its variations show some regularity. Binarity is frequent but does not seem able to be used as an explanation in all cases. The light often shows clear and sometime stable polarization directions. The position angles of the major axis of the circumstellar envelope measured by interferometry are in agreement with the disk orientation determined from polarization data and also with the result from radio observations for ψ Per. It means that there is no misalignement between the larger scale envelope from the radio observation ($\approx 100R_*$), the intermediate scale from H_α emission ($\approx 10\ R_*$) and the inner regions where the polarization is produced. An important result is coming from the agreement between the position angles of the circumstellar disks derived from the interferometric measurements and those coming from the polarimetric data. For all cases the polarization angle is perpendicular to the major axis which rules out envelope that are both optically and geometrically thick since they produce polarization parallel to the plane of the disk.

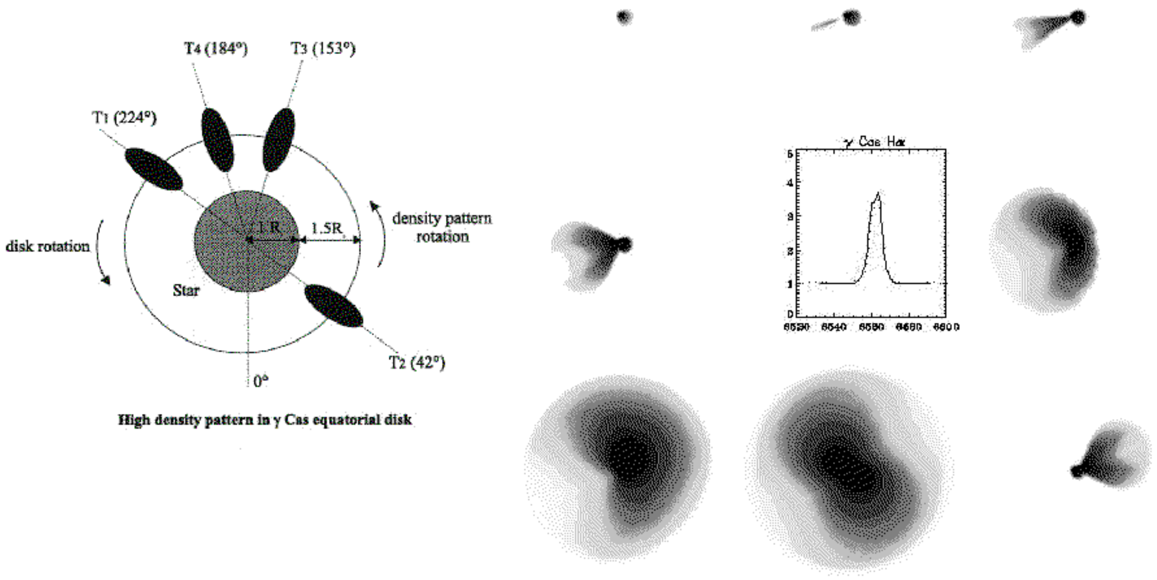

Figure 6. Schematic reprentation of the Be phenomenon, and the resulting brightness distributions and line profiles.

In order to push further our understanding of the Be phenomenon, it is desirable to realize one or more of these goals:

- Measure the photospheric diameters: needs baselines up to 200 meters
- Study the connection between the disk and the photosphere: needs high precision visibility measurements
- Study the rotation in the disk: needs high spectral resolution and phase measurements
- Measure the size of "one-armed" structure in the disk and follow its rotation. Is it connected to the star? This calls for spectral and spatial resolution
- Study details on the photosphere, i.e NRP versus magnetism: needs large baselines, spectral resolution and a polarimetric device as well
- Detect stellar ejections: needs spectral, spatial and time resolution
- Make direct images at different wavelengths in narrow bands: needs spectral, spatial, time resolution and phase closure.

Many of the features required by these observations will be available with AMBER, in particular the potential to obtain phase closure and thus form images. In parallel to the observations however, we stress that also advancements in the models must be pursued. These are needed to reproduce visibility curves and intensity maps, and also to define in advance which are the "strategical" spatial frequencies that can put very strong constraints on the various model parameters, thus optimizing the observation efficiency.

3.5. Star forming regions

The study of young stellar objects(YSO) is a field for which AMBER is particularly well suited, for several reasons: many young stars are relatively bright, especially in the near-IR, and they provide an excellent opportunity for fringe-tracking and they do not require a wide field of view. In addition, there is a wide range of scientific investigations that can be carried out at various levels of accuracy, sensitivity and spectral resolution. Some examples include: detection and study of circumstellar disks, young binaries (as well as the correlation/anticorrelation between these two features), jets. The gain in spatial resolution in SFRs will permit a big leap in the knowledge of star formation processes. The closest known SFR is the Taurus–Auriga cloud which lies at 140 pc. A spatial resolution of 0.7" corresponds to 100 AU. Therefore with the VLTI, we will be able to resolve details at the scale of ≤1 AU, therefore probing the inner part of the circumstellar region of young stars. This spatial resolution is already achievable today with a facility like the Palomar Testbed Interferometer (PTI), but with much lower sensitivity. Up to now, fringes have been detected only on one YSO (FU Ori, K=4.5). At somewhat lower resolution, also on about 20 Herbig Ae/Be stars with the IOTA interferometer (H ≤6). Therefore AMBER with the VLTI will increase the sensitivity cell both with the ATs and the UTs: with a limiting magnitude of K=10 for fringe detection without off-axis fringe tracking on the ATs, the VLTI will be able to study 80% of the sample of known YSOs and therefore open an era were statistical studies can be performed.

One of the major step in the star formation field that will allow AMBER is the study of circumstellar material around young stars at the sub-AU scale, as a continuation of current investigations[45,46] with the present interferometers and a limited sensitivity. In the case of FU Ori, the standard model for disk accretion is compatible with the first observations, but in the case of AB Aur, both the binary and accretion disks scenari failed to interpret the visibility data. In order to progress in this area, we need to increase the number of spatial frequencies in order to better sample the *u–v* plane and to perform spectral measurements to disentangle the relation infrared excess and the visibility points obtained. This will be easily done with the ATs for the brightest objects, but requires UTs for the faintest objects. The long-term goal is to obtain the brightness profile of the matter around the stars in order to constrain the disk/binary model. An interesting application is that we should be able to deduce from our interferometric measurements and from spectroscopic diagnosis, the origin of the turbulent viscosity in the disk. AMBER with its spectral resolution will permit both the observations the double–peaked features of lines emitted in the disk which are explained by the presence of a keplerian disk[47], and the variation with the spatial frequencies. It will be interesting to measure the visibility along the lines, or better the phase differential variation between the continuum and the lines. Although we have not yet computed the needed SNR and visibility accuracy, we foresee that it will only be possible on the brightest YSOs with the UTs.

Another example of fundamental importance to understand the mechanisms of star formation is the diversity of binary systems encountered in SFRs in connection with the initial conditions in the parent molecular cloud, and the relation to the evolution of the stars on the main sequence, possibly with the presence of a planetary system. Speckle and lunar occultation investigations at the beginning of the present decade have shown that for the Taurus SFR there was a definite excess of binaries over what is expected on the basis of main-sequence stars. However, the techniques permitted to investigate only an incomplete range of separations. We refer the reader to Fig. 5 in the work by Richichi et al.[48] for a graphical illustration. AMBER will provide a definitive step ahead by permitting to extend the separation coverage, and especially by permitting us a complete survey (the result of lunar occultation was strongly biased in this sense). More importantly, AMBER will permit us to obtain similar results also for other, more distant SFRs. In fact, studies conducted on the Orion SFR (much denser and younger) have shown that in that case the binary frequency is consistent with the main sequence one. It would be of great importance to extend this to other SFRs, to increase the statistics and include several different situations of age, stellar density, etc. In the Taurus SFR there are about 150 T Tauri stars with a magnitude K <10. If we assume a limit of 17 by the use of UTs, AMBER can give us the means to conduct surveys on SFRs up to 25 times more distant than Taurus (i.e., ≤4 kpc), with a linear resolution equivalent to that obtained currently by the larger telescopes in Taurus. This would increase the statistics by ≈1000. It is important to note that this kind of measurement does not require a very high accuracy in the visibility, nor a detailed *u–v* coverage. The use of ATs will be sufficient (and indeed desirable for the longer baseline) for the nearby SFRs, but in order to extend the study to more distant ones it will be necessary to use UTs.

Another important feature of YSOs is the presence of powerful ejection of matter generally in the form of stellar wind and bipolar jets. Important constrains on jet models can be derived with AMBER from observations beyond 0.3 AU (20-30 stellar radii). These jets have been observed already with HST and ground-based telescope[49], but never at the spatial resolution that will be provided by the VLTI. These observations shows that the opening angle on scales smaller than 0.3 arcseconds (<50 AU) must be larger than 50º. If confirmed by the VLTI, this will permit to constrain the different jet models and even rule-out some of them. Moreover, AMBER is able to measure the proper motions of jet knots with time (up to 1 mas/day) thanks to its high spectral capability (R > 1000). From the current brightness estimates this program will probably require the UTs.

3.6. Stellar surfaces

As discussed briefly in Sect. 3.2, stellar angular diameters are a topic of broad interest. In this context, a special remark should be made on the fact that stellar disks are in reality not uniform. Apart from the well–known effect of limb darkening, a variety of surface structures are present, and can be revealed provided that sufficient angular resolution is available. A discussion of this topic, with specific reference to the possibilites opened up by interferometry in general and by the VLTI in particular, has been given recently by Von der Lühe[50]. An example of the kind of visibility effects due to different surface features in a model K giant star is given in Figure 7.

It can be appreciated that the effects on the visibility are quite small. At present, it has been possible to investigate the surface structure only for a few stars (most of them peculiar, see also Sect. 3.3), and then only with very few resolution elements on the stellar disk. As a result, our direct knowledge of the surface structure is at present essentially non-existent, with the exclusion of interesting results obtained by alternative indirect methods on special classes of stars[51].

However the situation could change with the availability of milliarcsecond resolution, coupled to high visibility accuracy, and high spectral resolution. Von der Lühe[50] has shown how all these features combined should permit to obtain first direct assessment of the magnitude of starspots and active regions in several favourable cases of giant cool stars. AMBER and the VLTI should make all the required observational capabilities available.

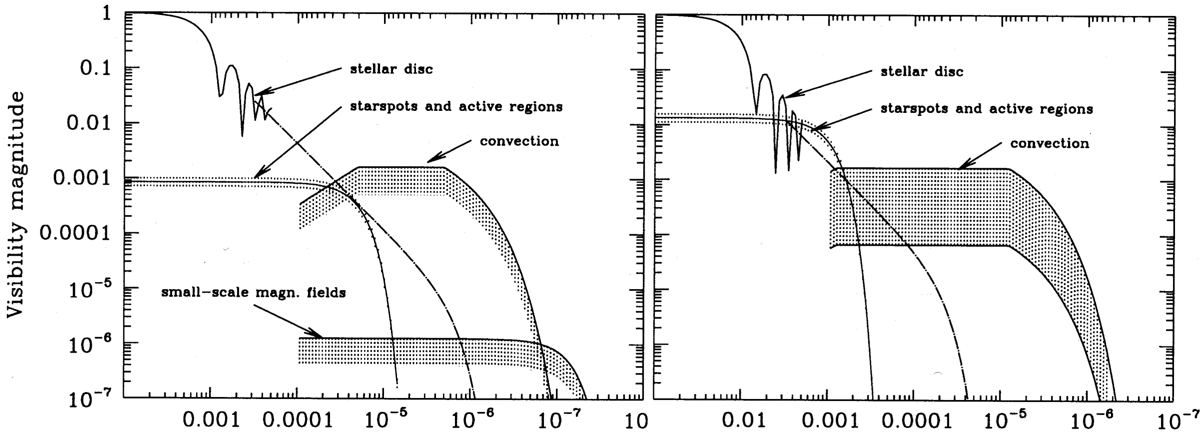

Figure 7. Surface structure visibility effects for a Sun-like (left) and a K giant star (right). The abscissae are marked in arcseconds, for a distance of 10 pc. Adapted from Von der Lühe[50].

3.7. AGN

AGNs are another target of high interest for AMBER, with a potential for very interesting results but with demanding requirements on the instrument. If we restrict ourselves to the brightest candidates, there are about a dozen objects which are accessible from Paranal. In particular, SGR has conducted some investigation in four specific cases: 3C 273, M87, 3C 279, NGC 1068. The following investigations could be possible with AMBER:

- to measure the characteristic inner size of the dust torus, by measuring about 15 visibility points in different directions using super synthesis;
- to locate and follow individual knots in the jet, even when they are beyond the resolution limit. Even if two knots are not separated spectroscopically, combining $V(\lambda)$ and $\phi(\lambda)$ will permit to separate the knot and to estimate its size, distance to the core and radial velocity;
- to measure the photocenter displacement through the Broad Line Region in near-infrared lines should allow to resolve it and to characterize its size and kinematics.

In addition, AGNs pose the problem of a suitable source for fringe-tracking. We should note that 3C 273 has a magnitude of K=9.7 referring to the nucleus as measured in a 3" aperture, but based on present models it can be assumed that most of this nuclear light comes indeed from the AGN source, with relatively little contribution from the host galaxy. In the case of NGC 1068, the inner core has been measured adaptive optics[52], as well as by speckle interferometry[53]. The results show a core brightness which is bright enough for fringe tracking even at the resolution of a UT. The statistics of AGNs on which such a measurement is possible is not assessed yet, but conceivably one can hope to find only less than a dozen candidates which are sufficiently bright and close. The central source, if bright enough, should be useful to this purpose, since it is effectively unresolved and concentrates most of the emission. However, the matter is still subject to some speculations since the precise characteristics of sesntivity and fringe contrast as a function of magnitude are not precisely established yet. The use of UTs is mandatory for these sources. More than the exact magnitude limit, it is important for this kind of studies to obtain a reasonable level of imaging, since the level of complexity expected in the inner regions is relatively high. At the same time, it is anticipated that the necessary accuracy required in the visibility is not too stringent, at the level of 1%.

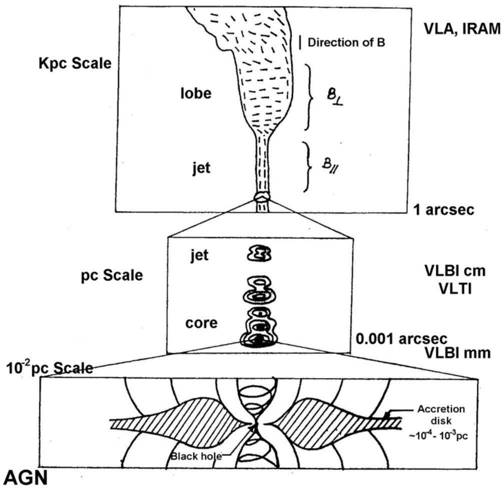

Figure 8. A schematic picture of an AGN, see text for discussion.

A schematized picture of a model AGN is illustrated in Figure 8, and it includes the central region extended over typical scales $\approx 10^{-2}$ pc, an intermediate region with the inner part of the jet extended over about 1 pc, and finally the outer jet extended over about 1 Kpc. The central source remains unresolved, but AMBER can detect in the near-IR the jet on the 1Kpc scale even at large distances, and the jet on the 1 pc scale in some favorable cases. To study this, we have made a model of the pc-scale jet/core region for 3C 273, and we have simulated its visibility for UT1/UT2 observations[15]. The result is that the model gives rise to a visibility with a strong modulation, i.e. even a coarse accuracy (≈10%) would provide significative constraints on the model. The Kpc-jet would be in principle an easier target that could be detected to much larger distances (thus increasing dramatically the number of candidates), although in this case a sensible decrease in the surface brightness would be expected.

4. CONCLUSIONS

We have reviewed some of the science opportunities which will be opened up by the availability of the near–IR beam combiner AMBER at the VLTI. This has been the subject of the work of a Science Group in the AMBER consortium, which has constituted the basis for this contribution. Without the possibility of being exhaustive in every field, we have provided examples of achievements by currently available high angular resolution techniques, and discussed the possibilities of the improved resolution and sensitivity offered with AMBER. Significant results should be possible in many diverse fields, from exoplanets to AGNs, from star forming regions to stars on the main sequence and in late stages of stellar evolution, from diameters and surface structures to binarity. Among the key features of AMBER will be the possibility to combine 3 beams, thus yileding closure phases, and a range of spectral resolutions, coupled to a design which has emphasized the need for high visibility accuracy.

Information on the AMBER project, including documents relative to SGR and science activities in AMBER, can be found at http://www.obs-nice.fr/amber/.

REFERENCES

1. R.G. Petrov, F. Malbet, A. Richichi, K.-H. Hofmann 1998, *The ESO Messenger*, 92, 11.

2. K.-H. Hofmann, R.G. Petrov., F. Malbet, A. Richichi, ASP "Astronomische Gesellschaft Jahrest." Heidelberg 1998
3. A. Richichi, F. Lisi, S. Gennari, C. Baffa, R.G. Petrov, K.-H. Hofmann, F. Malbet, " Telescopes, instruments and data processing for the astronomy of the 2000 ", S. Agata, 1999
4. A. Richichi, F. Malbet, K.-H. Hofmann, R.G. Petrov, Darwin and Astronomy, Stockholm, 1999
5. Petrov R., et al., SPIE Conference 4006-07, 2000
6. Robbe-Dubois S., et al., SPIE Conference 4006-07, 2000
7. Malbet F., Chelli A. , SPIE Conference 4006-27, 2000
8. Duvert G., et al., SPIE Conference 4006-25, 2000
9. Mouillet D., et al. SPIE Conference 4006-30, 2000
10. A. Glindemann et al. 1999, *The ESO Messenger*, 98, 2.
11. D. Bonaccini, F.J. Rigaut, G. Dudziak, G. Monnet 1998, Proc. SPIE Vol. 3353, p. 553
12. D. Bonaccini, F.J. Rigaut, A. Glindemann, G. Dudziak, J.-M. Mariotti, F. Paresce 1998, Proc. SPIE Vol. 3353, p. 224
13. Delplancke F., Leveque S.A., Glindemann A., SPIE Conference 4006-41, 2000
14. M. Schöller, SPIE Conference 4006-20, 2000
15. D. Fraix-Burnet, SPIE Conference 4006-16, 2000
16. T. Blöcker, K.-H. Hofmann, G. Weigelt, SPIE Conference 4006-19, 2000
17. F. Malbet, J.-L. Monin, SPIE Conference 4006-28, 2000
18. D. Mouillet, J.C. Augereau, A.M. Lagrange, F. Malbet, SPIE Conference 4006-29, 2000
19. D. Segransan, et al. SPIE Conference 4006-31, 2000
20. Lopez, B., Petrov, R. SPIE Conference 4006-47, 2000
21. A. Richichi, C. Leinert, SPIE Conference 4006-33, 2000
22. Proceedings of the ESO Workhsop on "*Science with the VLT Interferometer*", F. Paresce (ed.), Springer, 1997
23. Lopez, B., Petrov, R. 1999, The VLT Opening Symposium, in press.
24. Coudè du Foresto V. et al. 1999, The VLT Opening Symposium, in press.
25. Barnes T.G., Evans D.S. 1976, MNRAS 174, 489
26. Ridgway S.T., Joyce R.R., White N.M., Wing R.F. 1980, ApJ 235, 126
27. Richichi, A., Fabbroni, L., Ragland, S., Scholz, M. 1999, A&A, 344, 511.
28. Di Benedetto G., Rabbia Y. 1987, A&A 188, 144
29. Dyck H.M., Benson J.A., van Belle G.T., Ridgway S.T. 1996, AJ 111, 1705
30. Perrin G., Coudè du Foresto V., Ridgway S.T., et al., 1998, A&A 331, 619
31. M.S. Bessell, G.S. Stringfellow, ARA&A 31, 443 (1993)
32. A. J. Booth, J. Davis, M. Bessell, "*Science with the VLT Interferometer*", F. Paresce (ed.), Springer, 1997, p. 333
33. Di Giacomo, A., Richichi, A., Lisi, F., Calamai, G. 1991, A&A, 249, 397.
34. Richichi, A., et al. 1995, A&A, 301, 439.
35. G.T. van Belle, H.M. Dyck, J.A. Benson, M.G. Lacasse, 1996, AJ, 112, 2147.
36. H.M. Dyck, G.T. van Belle, J.A. Benson, 1996, AJ, 112, 294-300.
37. Richichi, A., Lisi, F., Calamai, G. 1991, A&A, 241, 131.
38. Weigelt, G., Balega, Y., Hofmann, K.-H., Scholz, M., 1996, A&A 316, L21
39. Hofmann, K.-H., Balega, Y., Scholz, M., Weigelt, G., 2000, A&A 353, 1016
40. Perrin et al. 1999, A&A 345, 221
41. Weigelt et al. 2000, SPIE Conference 4006-74
42. Weigelt, G., Balega, Y., Blöcker, T., Fleischer, A. J., Osterbart, R., Winters, J. M. A&A 333, L51 (1998)
43. Osterbart R., Balega Y., Blöcker T., Men'shchikov A., Weigelt G. 2000, A&A, in press
44. Blöcker et al. 1999, A&A 348, 805
45. Malbet et al. 1998, ApJ 507, L149
46. Millan–Gabet et al. 1999, ApJ 513, L131
47. Hartmann & Kenyon 1985, ApJ 299, 462
48. Richichi A., Leinert Ch., Jameson, R., Zinnecker H. 1994, A&A 287, 145
49. Ray & Mundt 1996, ApJ 468, L103
50. O. von der Lühe, "*Science with the VLT Interferometer*", F. Paresce (ed.), Springer, 1997, p. 304
51. Schuessler M., Caligari P., Ferriz-Mas A., Solanki S. K., Stix, M. A&A 314, 503 (1996).
52. Rouan et al. 1998, A&A 339, 687.
53. M. Wittkowski, Y. Balega, T. Beckert, W.J. Duschl, K.-H. Hofmann, G. Weigelt, A&A 329, L45 (1998)