Harvesting Scientific Results with the VLTI

THE ESO VERY LARGE TELESCOPE INTERFEROMETER (VLTI) HAS BEEN INCLUDED FOR THE FIRST TIME IN THE OFFICIAL CALL FOR PROPOSALS REQUESTING ESO TELESCOPES FOR THE PERIOD STARTING IN APRIL 2004. THIS MARKS THE OFFICIAL START OF PUBLIC INTERFEROMETRIC OBSERVATIONS OPEN TO THE COMMUNITY. IT IS THE START OF A NEW APPROACH TO INTERFEROMETRY AS A STANDARD ASTRONOMICAL TECHNIQUE, AND A POINT OF PRIDE AND SATISFACTION FOR ALL THE PEOPLE WHO HAVE BEEN WORKING WITH THIS CHALLENGING GOAL FOR MANY YEARS. BUT IT SHOULD NOT BE FORGOTTEN THAT THE VLTI HAS ALREADY LOGGED OVER TWO YEARS OF INTENSIVE COMMISSIONING, AS WELL AS SOME INITIAL SCIENCE DEMONSTRATION RUNS. OVER 16,000 OBSERVATIONS OF HUNDREDS OF OBJECTS HAVE BEEN COLLECTED AND ARE AVAILABLE PUBLICLY OVER THE ESO ARCHIVE ON THE WEB. IN 2003, THE FIRST SCIENTIFIC RESULTS OF THIS REMARKABLE EFFORT HAVE APPEARED. ALREADY MORE THAN A DOZEN PAPERS BASED ON VLTI DATA HAVE BEEN SUBMITTED OR ACCEPTED BY REFEREED JOURNALS, WITH A SIMILAR VOLUME OF CONTRIBUTIONS TO WORKSHOPS AND CONFERENCES OF A SCIENTIFIC NATURE. WE PROVIDE HERE AN OVERVIEW OF THIS EARLY SCIENTIFIC PRODUCTION OF THE VLTI, RANGING FROM THE DETERMINATION OF FUNDAMENTAL PARAMETERS OF MANY CLASSES OF STARS TO THE FIRST INTERFEROMETRIC MEASUREMENT OF THE INNER REGIONS OF THE NUCLEUS OF THE SEYFERT GALAXY NGC 1068.

ANDREA RICHICHI AND FRANCESCO PARESCE (ESO)

WHAT DOES A BOTANICAL GARDEN share with astronomy? Not much at first glance, granted. But in Munich you find a wonderful example of the former, and many professionals of the latter. Strolling through the century-old trees and the colourful flowerbeds of the Botanischer Garten, one wonders how different plants display different growth patterns. The bamboo grows 30 centimeters per day in the tropical jungle, and at the other extreme the canadian white cedar (*Thuja occidentalis*) takes one and half century to reach a height of 10 centimeters. Then the thought strikes us: is it not the same with astronomical research? Some ideas produce wonderful results almost immediately, while some others have to wait patiently for decades before becoming accepted. And of course, some ideas never succeed at all.

If the ESO Very Large Telescope Interferometer (VLTI) were a plant, it would be indeed a strange mix. Its first seed was planted about twenty years ago when European astronomers started to be fascinated by the idea of creating a quadruplet of four identical giant telescopes and combining them interferometrically. A visionary concept that took decades of engineering feats to become reality. One by one the four VLT telescopes were erected, changing forever the skyline of Cerro Paranal. As the giant mirrors swept the skies, the first incredible images began to open new opportunities for astronomers around the world.

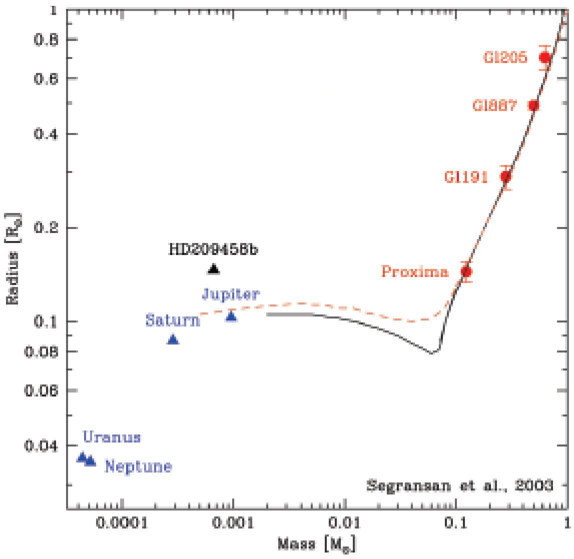
But underground, in tunnels and isolated rooms, other activities continued as ESO astronomers and engineers assembled hundreds of mirrors, fine mechanical mounts, and scores of computers: the skeleton of the most powerful interferometer was growing rapidly. Finally, in March 2001, the VLTI saw its first fringes. From that moment, the growth has been definitely bamboo-like. Every few months, or even every few weeks, a new bud has been added, a new branch has been spawned. Even the astronomers and engineers in the VLTI group have trouble sometimes keeping up with the news from one side or the other of the ocean, be it the addition of a new delay line or the inauguration of a new baseline.

Table 1. Statistics of the VINCI commissioning observations (up to August 2003). A total of 321 independent objects have been observed.

Year	Number of OBs	Total number of files	Number of nights	Volume (Gb)
2001	4827	19308	206	25.2
2002	4966	19864	235	35.9
2003	6125	24500	180	56
Total	15918	63672	621	117.2

As 2003 comes to an end, more than two years of patient commissioning with the test instrument VINCI have been completed, accumulating over 16,000 observations of hundreds of stars and making them available publicly to the whole community (see Table 1). The small siderostat test telescopes have been the workhorses of this enormous effort, but the Unit Telescopes (UTs) have been used as well and are ready to be offered publicly. The first VLTI scientific instrument, MIDI, has been opened to the community starting from Period 73, while the second one, AMBER, is completed and awaiting shipment from Europe. Schools and workshops have been organized around

Figure 1: Radii and masses of the four very-low-mass stars now observed with the VLTI, GJ 205, GJ 887, GJ 191 (also known as "Kapteyn's star") and Proxima Centauri (red filled circles; with error bars). For comparison, the masses and radii of the Solar System planets (blue triangles) and of HD 209458 B (black triangle) are also shown. The two curves represent theoretical models for stars of two different ages (400 million years - red dashed curve; 5 billion years - black fully drawn curve). The VLTI results are from Sègransan et al. (2003), the models from Baraffe et al. (1998).



the VLTI, with several students choosing it as the basis of their scientific career in their thesis and dissertations.

Amidst all this enthusiastic flowering, more than a few remained skeptical. Was interferometry really worth the effort? Where was the long-awaited scientific production? When would we see the first papers? Solid questions, which have now received a solid answer. This year, the first publications have appeared, and not just one or two as one might expect from a facility which after all is just emerging from commissioning of its basic systems. In 2003, more than a dozen papers based on VLTI data have been submitted or accepted by refereed journals with a similar volume of contributions to workshops and conferences of a scientific nature.

The key to this early successful exploitation has been the public release of all on-sky commissioning data of scientific interest. Every few months, a new release appears on the VLTI web page, listed by object observed as well as by night of observation. The data can be requested from the ESO archive and are usually delivered very quickly. With much of the commissioning tasks completed, the VLTI is beginning to be accessible to the community for open time observations. Already for period 73, 30 proposals for the MIDI instrument have been submitted on the basis of the standard ESOFORM package, and they will be reviewed by the OPC as any other proposal for ESO telescopes. As for all ESO instruments, a complex and extensive system of user support, data quality, and archiving has been developed also for the VLTI. Interferometry for all astronomers might have been a vision until now, but it has definitely become a reality on Paranal.

Fundamental stellar properties

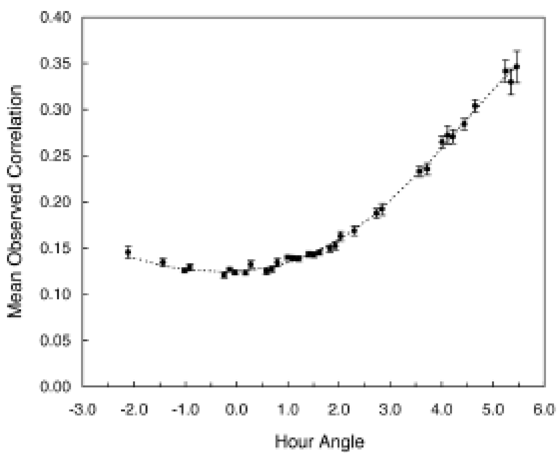
If astronomy has a peculiarity among modern scientific disciplines, it must be that it allows us to obtain insight and understanding of objects that we cannot ever subject to our direct scrutiny. From stars to nebulae, from black holes to active galaxies, we predict birth, evolution and death of a universe where distances are so immense that they defeat imagination. Come to think of it, the wonderful monument of our scientific knowledge rests on a system of pillars which is, after all, relatively simple: we have to build on fundamental blocks such as stellar masses, sizes, luminosities and chemical composition in order to derive almost everything else, from the properties of the newly found extrasolar planets to the energy liberated at the heart of the most distant quasars.

Interferometry is the key technique to measure some of these fundamental blocks. A recent review of its technical and scientific aspects provided by Monnier (2003) could be a helpful introduction for many interested readers. Typical angular size scales of the closest stars and their immediate circumstellar environment are on the order of a few milliarcseconds (mas), inaccessible at the diffraction limit of current single telescopes but easily resolvable with long-baseline interferometry. Stellar angular diameters, combined with measurements of bolometric fluxes, give model-independent effective temperatures. An accuracy of 50 K or less in T_{eff} is required, for example, to put significant constraints on the current theoretical models of late-type stars. This corresponds to an accuracy of 2% or better in the angular diameter.

The VLTI routinely achieves a precision well below the 1% level, and is ideally suited to expand our knowledge in this area, especially for main sequence stars where the data are very scarce. When combined with accurate parallaxes such as those from HIPPARCOS, angular diameters can be converted into linear diameters. Finally, when applied to binary stars, interferometry can measure the orbital motions in close pairs: together with spectroscopic radial velocities, this information leads to the determination of the masses and distances.

Angular diameters have traditionally constituted the primary targets of all interferometers, and at least in this respect the VLTI is no exception. Already from the first observations on both siderostats and UTs, several tens of stars have been observed with diameters susceptible to being resolved on the available baselines. Faithful to the commissioning mission, these stars encompassed a wide variety of types: from calibrator objects with a well-estimated diameter, to late-type giant stars, to solar analogues like α Centauri, to pulsating variables such as Miras and AGB stars. For many of these objects, the VLTI measurements

Figure 2: The correlation measurements obtained on Fomalhaut on the night of October 20, 2002, as a function of hour angle, i.e. of baseline projected length. The solid line is the best fit for a uniform-disc angular diameter of 2.086 mas (Davis et al. 2003).



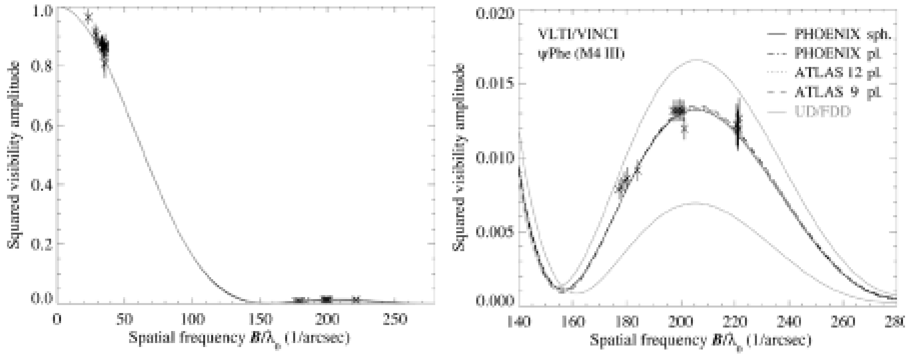


Figure 3: Measured squared visibility amplitudes of Psi Phe together with predictions by a (solid black line) spherical PHOENIX model atmosphere, (dashed-dotted line) plane-parallel PHOENIX model atmosphere, (dotted line) plane-parallel ATLAS 12 model atmosphere, (dashed line) plane-parallel ATLAS 9 model atmosphere. The models were constructed by comparison to spectrophotometry. The gray lines denote uniform disc and fully darkened disc models. The left panel shows the full range of the visibility function while the right panel is an enlargement of the low squared visibility amplitudes in the second lobe. From Wittkowski et al. (2003).

were the first ever obtained, given that the southern sky has remained so far largely untapped by interferometers as sensitive as the VLTI.

A notable achievement of the VLTI in this field has been the measurement of the angular diameter of several main sequence late-type stars, with spectral types between M0.5 and M5.5 (Sègransan et al. 2003). Other main sequence stars of earlier spectral types have also been measured by the VLTI: these include α Centauri A and B, Sirius, α Eridani, Procyon and τ Ceti. As opposed to giant stars, for which hundreds of direct angular diameter determinations exist by several techniques (Richichi & Percheron 2002), only a handful of angular diameters are available for main sequence stars, which are two orders of magnitude smaller. In particular for the coolest types, the VLTI result by Sègransan and his collaborators has already almost doubled the available statistics and the prospects look very promising with the forthcoming introduction of the AMBER instrument.

The conversion from angular diameters to linear sizes is straightforward thanks to the HIPPARCOS parallaxes for these nearby stars. However, the conversion to masses is more problematic, since these stars are single and no direct determination is possible. Some empirical calibration of the mass-radius relation exists for the lower main sequence (Delfosse et al. 2000), and can be used to convert the VLTI measurements into masses. A plot of this result as a function of the luminosity is shown in Fig. 1, together with the Solar System planets and the eclipsing planet HD 209458 B. The two curves represent theoretical models for stars of two different ages – calculated before the interferometric data became available (Baraffe et al. 2003).

These VLTI results show that the models are at present satisfactory but also that new challenges lie ahead. One might notice in Fig. 1, for example, the apparent discrepancy of HD 209458 B from the model. Furthermore, it can be appreciated that, for masses around 0.1 $M_\odot$, the relation between mass and luminosity is predicted to be quite flat and improved accuracies will be required. If this challenge can be met, the reward will consist in strong observational constraints on both atmosphere and interior physics. The mass range between 0.001 and 0.1 $M_\odot$ is particularly interesting since this is the realm of brown dwarfs and eventually of large planets. Objects in this range are too faint at the moment for the VLTI but will become accessible with off-axis phase-referencing provided by PRIMA.

The VLTI equipped with the VINCI test instrument has demonstrated an intrinsic accuracy well below the 1% level, and even higher standards are expected with the AMBER instrument. However, the accuracy in the fringe contrast is not the only factor in the quest for improved stellar diameters. On one hand, it is necessary to compare the fringe contrast of the science target with that of a calibrator star. In this case, the aim is to make sure that the calibrator diameter is so precisely known that no additional error is introduced but, unfortunately, this is often not the case at the level of precision attained by the VLTI. On the other hand, the angular diameter, be it of a tenuous giant or of a compact main sequence star, can only be as precise as our understanding of the stellar surface. Generally, we imagine the star as a disc of uniform brightness, but when the accuracy increases, then we must take into account phenomena such as limb-darkening.

On both counts, significant help comes from the VLTI commissioning efforts. An intense program of observations of calibrator stars coordinated by A. Richichi, I. Percheron and M. Wittkowski has been given high priority. An initial list of bright candidate calibrators for the VINCI instrument has been established based on both estimated diameters and existing previous measurements. A similar effort has been undertaken in parallel by the MIDI consortium for the specific needs of their instrument. A dedicated mini-workshop was held in Garching in January 2003 with about 30 attendees from ESO, the instrument consortia, and the community in general.

As a result, a list of potential VLTI calibrators has been made public, including almost 600 objects for both the VINCI and the MIDI instruments. Up to August 2003, 133 sources from this list have been observed successfully with VINCI. Fifty-two of these objects have more than 100 observations each on more than 3 baselines. The data are being analyzed by the pipeline and by specially developed global fitting programs aimed at computing the best solution to all calibrator observations on a nightly basis as well as over several nights (Percheron et al. 2003).

While this approach has, by necessity, the style of an automated large-scale processing, individual calibrator stars are also being measured accurately on a case by case basis. An example of this is given by the observations of Fomalhaut (α PsA), a bright star which, with its small angular diameter, lends itself well to being a calibrator for the hectometric VLTI baselines. During continued observations of this star over one night, J. Davis et al. followed the relative change of the fringe contrast as a function of time, i.e. of the change in the projected baseline due to Earth's rotation (see Fig. 2).

This particular kind of measurement does not require an external calibration, provided that the baseline is accurately known. An uncertainty term is introduced by the changing characteristics of the atmosphere which affects the interferometric contrast (particularly since a variety of zenith angles are sampled). Davis and collaborators, even after allowing a large increase in the error bars to take into account such adverse factors, obtained a precise limb-darkened angular diameter for Fomalhaut of 2.109 ±

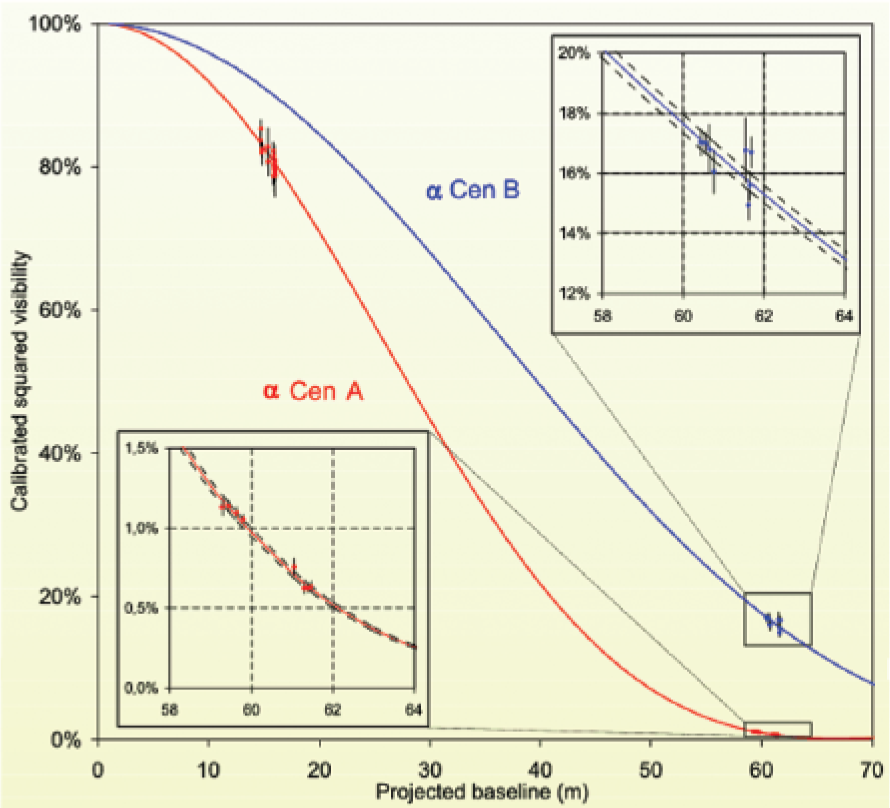


Figure 4: Overview of the α Cen A (red) and B (blue) squared visibilities and the corresponding best fit uniform disc (UD) models. Details of the lower visibility points are shown in the upper right (α Cen B) and lower left panels (α Cen A). The dashed lines represent the limits of the ± 1σ error. From Kervella et al. (2003).

0.013 mas, which confirms and improves the original measurement of this star by the intensity interferometer (2.10 ± 0.14 mas, Hanbury-Brown et al. 1974). Considering the recognized accuracy of that special interferometer, this is no small prize for the VLTI. In parallel, also an improved value of the effective temperature Teff=8819±67 K was obtained.

Regarding limb-darkening, this important aspect of the stellar surface is quite difficult to measure directly. The main reason for this is that the change in the visibility curve introduced by limb-darkening, as opposed to a uniform or fully darkened disc, is noticeable mostly at the baseline frequencies after the first minimum, and then only marginally (see Fig. 3). As a consequence, very few measurements are available, but the VLTI is moving quickly to fill this gap. Already only one month after the first UT fringes, commissioning observations of the M4 giant star Psi Phe were obtained. Using the large sensitivity of these telescopes, as well as their long baseline, the visibility was accurately measured in the critical range beyond the first minimum. By combining these measurements with others at lower frequencies (for which the siderostats were sufficient), an accurate confirmation of the model-predicted strength of the limb-darkening effect for this star has been obtained by Wittkowski et al. (2003). The models were independently constructed by comparison to available spectrophotometry. They used a grid of stellar atmospheric models, and computed the corresponding visibilities, selecting the ones which best fit the VLTI data (see Fig. 3).

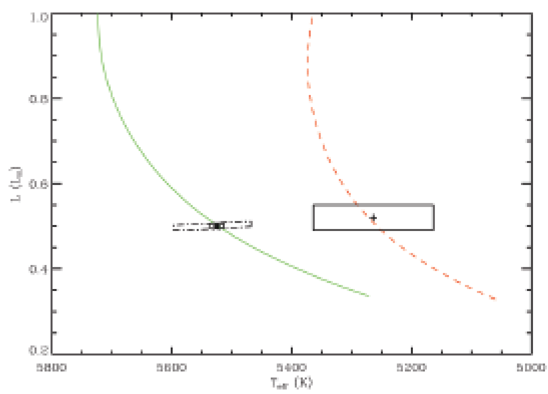
This is a delicate process, which must take into account issues of calibration and particularly the effect of the broad-band filter employed in VINCI, since visibility functions are strongly chromatic and the effect of limb-darkening varies across the band. Even several definitions of the angular diameter exist, and one must take care to be consistent between models and data. At the end of their analysis, the authors were able to determine a thickness of 6% of the atmospheric layer for this star, and derive a brand new set of its fundamental properties: T_{eff} = 3472 ± 125 K, radius = 86 ± 3 $R_{\odot}$, mass = 1.3 ± 0.2 $M_{\odot}$, log g = 0.68. These data constitute a valuable observational check for theoretical model predictions.

Clearly new similar measurements are needed to constrain the models but this should be no difficult task for the VLTI, with a large number of potential candidates available. These measurements constitute also an important precursor for studying stellar surface structure in more detail, including features such as surface spots. Studies of stellar surface structure require high-precision measurements of low-contrast fringes in the second and following lobes. Wittkowski et al. (2002) showed that a realistically modeled spot on a magnetically active star can likely be directly detected and its parameters constrained using squared visibility amplitudes and triple products obtained with the VLTI and the AMBER instrument.

An important new trend in the exploitation of accurate stellar diameters is represented by asteroseismology, and also in this area the VLTI has started off with important contributions. The outer layers of most stars, including our Sun, are constituted by ionised gas which is held in balance between the pull of gravity and the pressure of the enormous radiation emitted from the interior. These layers have their own characteristic frequency of oscillation under the influence of these forces and this frequency can be excited by mechanisms such as convection. As in a giant musical bell agitated by an invisible hand, the outer layers of these stars resonate in harmony, resulting in slow but regular shifts of their spectra.

These effects have been very well identified in our Sun, and are now beginning to be measured in some of the stars closest to us. In fact, theory predicts a whole system of characteristic frequen-

Figure 5: Location of τ Cet in the Hertzsprung-Russell diagram, according to the determination inferred from interferometry (left) and spectroscopy (right), with the associated uncertainty boxes. The solid and dashed lines correspond to two models of the star, with significantly different values of the scale of the mixing-length in the star. From Pijpers et al. (2003).



cies for each star, depending on mass, radius, temperature of the gas. Most importantly, they depend on details of their interior composition and energy production mechanisms. Like a fingerprint, the oscillation frequencies of each star are different from any other. Unfortunately, the number of parameters involved is so large that observations are often well consistent with several, significantly different models.

Now, long-baseline interferometry is coming to the rescue, and once again with its most basic and simplest type of measurement: the accurate determination of a stellar angular diameter. At least for nearby stars where accurate parallaxes are available, we can, thus, obtain the linear size and this is a precious piece of information for asteroseismologic modeling. In its debut year, the VLTI has already produced four papers with this important keyword. In some cases, the stars measured are very well known like α Cen, Sirius, and Procyon, and the corresponding results are certainly exciting for experts and casual readers alike.

We take here as illustrations of the VLTI contribution to this field, the well known stars α Cen A and B (Kervella et al., 2003) our closest stellar neighbour and the lesser known star τ Cet (Pijpers et al. 2003). The angular diameters of the two main components of the system, α Cen A and B, were measured using VINCI with a relative precision of 0.2% and 0.6% respectively. The measured uniform disc angular diameters for α CenA and B were 8.314 ± 0.016 and 5.856 ± 0.027 mas, respectively and limb darkened angular diameters of 8.511 ± 0.020 and 6.001 ± 0.034 mas, respectively (see Figure 4).

Particular care was taken in the calibration of these measurements considering that VINCI estimates the fringe visibility using a broadband K filter. Combining these values with the known parallax, the linear diameters of 1.224± 0.003 $D_\odot$ and 0.863 ± 0.005 $D_\odot$ were derived for the two components A and B, respectively. The measurement of α Cen A is the most precise photospheric angular size ever obtained by interferometry.

The measurements were compared to recent model diameters constrained by asteroseismic observations. The reported values are compatible with the most recently published masses for both stars.

If α Cen, the closest solar analogue, is slightly hotter and larger than our Sun, τ Cet provides an interesting bracketing comparison because it is slightly smaller and cooler than our Sun (spectral type G8, temperature approximately 5300 K). More interestingly, while the direct measurement by the VLTI resulted in a diameter largely in agreement with theory in the case of α Cen, in the case of τ Cet there appears to be a significant difference (see Fig. 5). The radius and effective temperature of this star estimated on the basis of its spectral and photometric characteristics are 0.87 ± 0.04 $R_\odot$ and 5264 ± 100 K respectively, while using VLTI data, Pijpers et al. (2003) obtained 0.773± 0.004 $R_\odot$ and 5525±12 K.

However, they also recognize that their estimate suffers from having only one single calibrator available, and that the actual uncertainty could be five times larger than the formal one. The difference between these results is shown in Fig. 5, which makes clear that the two sets of values correspond to models with significantly different assumptions on the initial hydrogen content and the scale of the mixing-length. Further observations by the VLTI, along with a more refined data analysis, are certainly desirable.

Asteroseismology predicts oscillation frequencies quite different for the two situations above: a peak at 3570 μHz and a frequency spacing of 173 μHz in the case favoured by the interferometric measurement, and 2950 μHz and 1148 μHz, respectively for the other case. High-accuracy spectroscopic measurements with an instrument like HARPS will be able soon to shed light on this discrepancy. In the future, high-accuracy interferometric and spectroscopic measurements will go hand in hand, and allow us to understand better the internal composition and energy transfer mechanisms of many more stars.

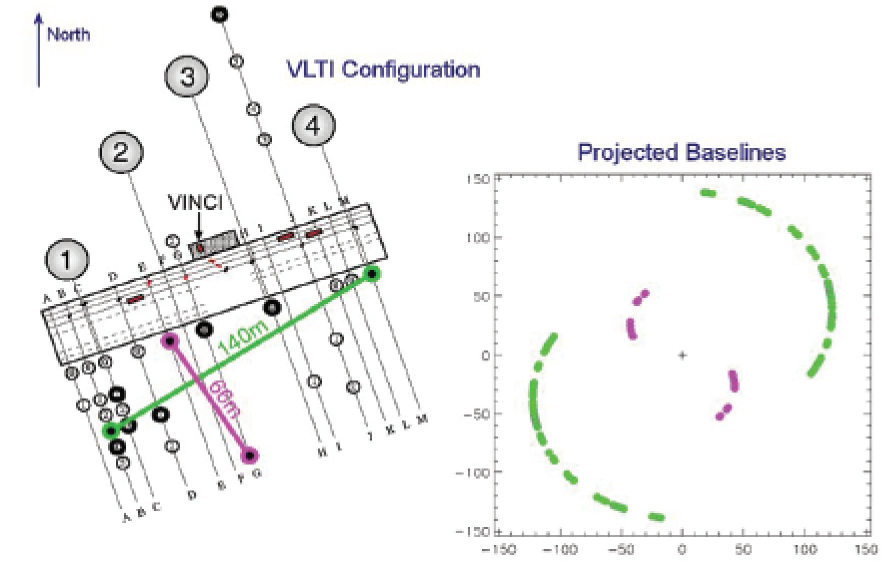


Figure 6: *VLTI ground baselines for Achernar observations and their corresponding projections onto the sky at different observing times. Left, scheme of VLTI baselines for the two pairs of siderostats used for Achernar observations. Colour magenta represents the 66 m (E0-G1; azimuth 147°, counted from North to East) and green the 140 m (B3-M0; 58°). Right, Corresponding baseline projections onto the sky (B_{proj}) as seen from the star. Note the very efficient Earth-rotation synthesis resulting in a nearly complete coverage in azimuth angles.*

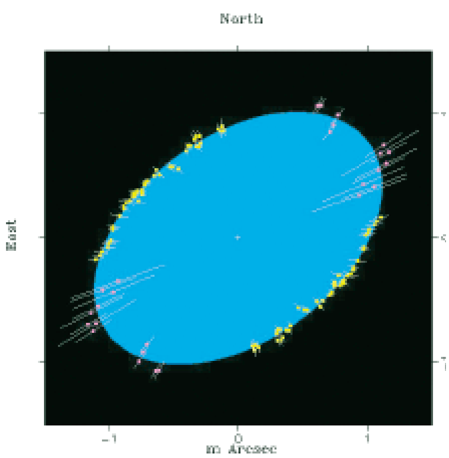


Figure 7: *Fit of an ellipse over the observed V^2 points of Achernar, translated to equivalent uniform disc angular diameters. Magenta points are for the 66 m baseline and yellow points are for the 140 m baseline. The fitted ellipse results in major axis 2a= 2.53 ± 0.06 milliarcsec, minor axis 2b= 1.62 ± 0.01 milliarcsec, and minor-axis orientation α_0=39°±1° (from North to East). The points distribution reveals an extremely oblate shape with a ratio 2a/2b = 1.56 ± 0.05. From Domiciano de Souza et al. (2003).*

New aspects of stellar research: Achernar and Eta Carinae

Stellar angular diameters may be considered the staple food of interferometry, but as sensitivity and accuracy increase new exciting results are produced even with this basic kind of measurement. We have seen that already in the case of more or less regular stars such as late-type giants and solar analogues, we are beginning to tackle interesting subjects such as limb-darkening and asteroseismology. However, when we move to less ordinary objects, interferometry is the key to open completely new doors. The VLTI is bringing facts, after many promises, also in this area, and as an example we take the recent results obtained on the fast rotating star Achernar, and the ultra-luminous star η Carinae.

Rotation is an intrinsic property of all stars, but for some classes of stars it can be a rather extreme phenomenon, with important consequences on the stellar structure. The most obvious is the geometrical deformation that results in a radius larger at the equator than at the poles. Another well established effect, known as gravity darkening or the von Zeipel effect, is that both the surface gravity and emitted flux decrease from the poles to the equator. Although well studied in the literature, such effects of rotation have rarely been directly tested against observations. The best candidates for such observational tests are represented by Be stars. A Be star is defined as a B type star that has presented episodic Balmer lines in emission, whose origin is attributed to a circumstellar envelope (CSE) ejected by the star itself. Physical mechanisms like non-radial pulsations, magnetic activity, or binarity have been invoked to explain CSE formation in Be stars in combination with their fundamental property of rapid rotation.

Struve's original vision of a critically rotating Roche star ejecting material from its equator has been discarded in the past by observing that Be stars rotate at most at 70% to 80% of their critical velocity (typically 500 km/s for a B0V star) a value not sufficient to explain the presence of discs. However, this statistically observed limit may be biased by the fact that close to or beyond such velocities the diagnosis of Doppler-broadened spectral lines fails to determine the rotation value due to gravity darkening. Only direct measures of Be star photospheres by interferometry can overcome the challenge of proving whether these objects rotate close to a few percent of their critical velocity or not. This will have a profound impact on the dynamical models for Be star disc formation due to rapid rotation combined with mechanisms like pulsation, radiation pressure of photospheric hot spots or expelled plasma by magnetic flares.

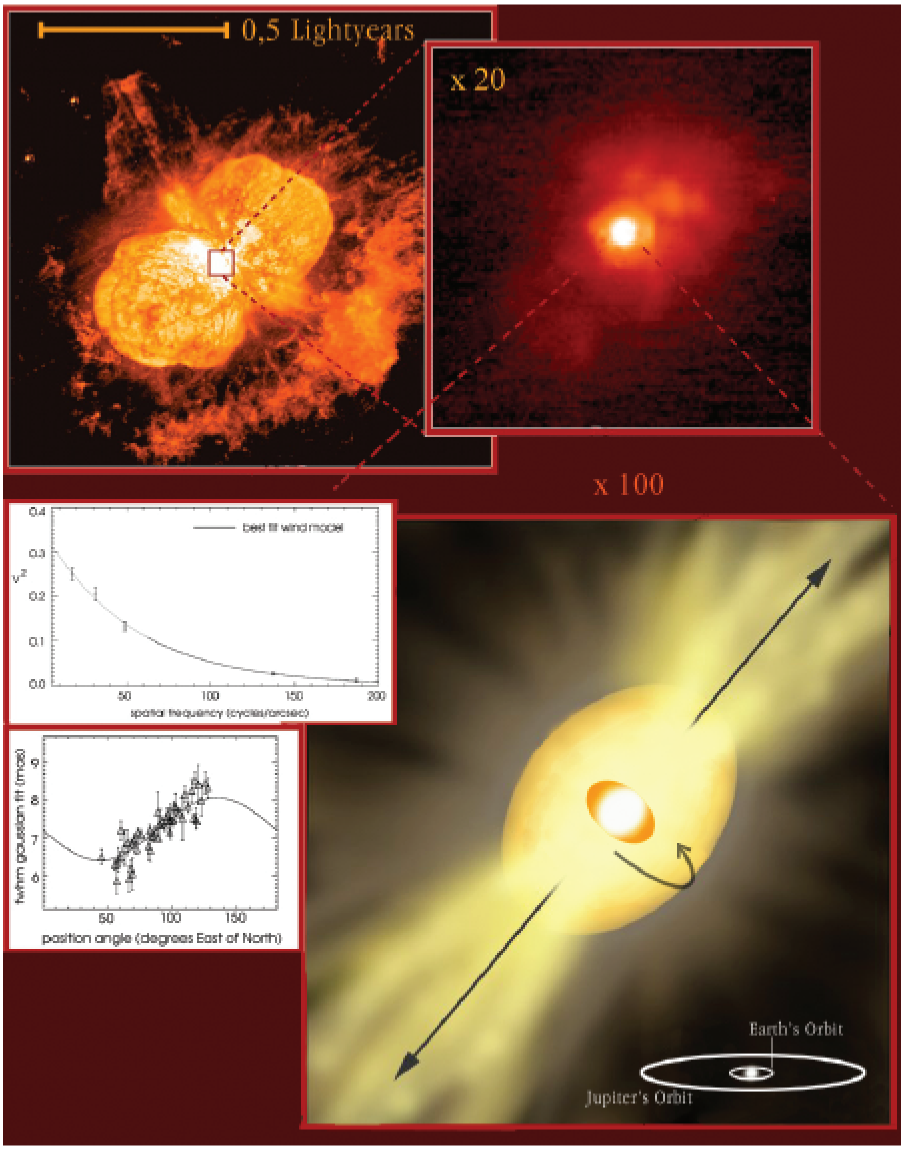


Figure 8: Zoom into the η Carinae nebula. Top left: WFPC2 image (Morse et al. 1998). Top right: NACO observations at 2 μm. Centre left : VINCI data reveal an object with size 5 mas. This is not the photosphere of the star, but the radius at which the stellar wind becomes opaque. Bottom left: VINCI data, converted to an effective diameter, plotted against the position angle of the baseline. Bottom right: the diameter change with position angle implies that the object is elongated; the orientation is the same as that of the large-scale nebula shown in the top left panel. Courtesy R. Van Boekel.

The southern star Achernar (α Eridani, spectral type B3Vpe) is the brightest Be star in the sky and, therefore, a perfect target for the VLTI and the siderostats. It also represents a convenient object to test the validity of the concepts briefly described above. A recent paper by Domiciano de Souza et al. (2003) describes VLTI observations of this star and exciting new results. Dedicated observations of Achernar were carried out from 11 September to 21 December 2002, with quasi-uniform time coverage using the siderostats. Two interferometric baselines (66 m and 140 m) were used (Fig. 6 left). Their orientations are almost perpendicular to each other giving an excellent configuration for the detection of stellar asymmetries. Moreover, Earth rotation produced an efficient synthesis effect (Fig. 6 right).

Analysis of the processed data gives the results summarized in Fig.7 which reveal an extremely oblate shape from the distribution of equivalent UD diameter values on an ellipse. The results of this fit are: major axis 2a=2.53±0.06 mas, minor axis 2b=1.62±0.01 mas and minor-axis orientation α_0=39°±1°. Note that the

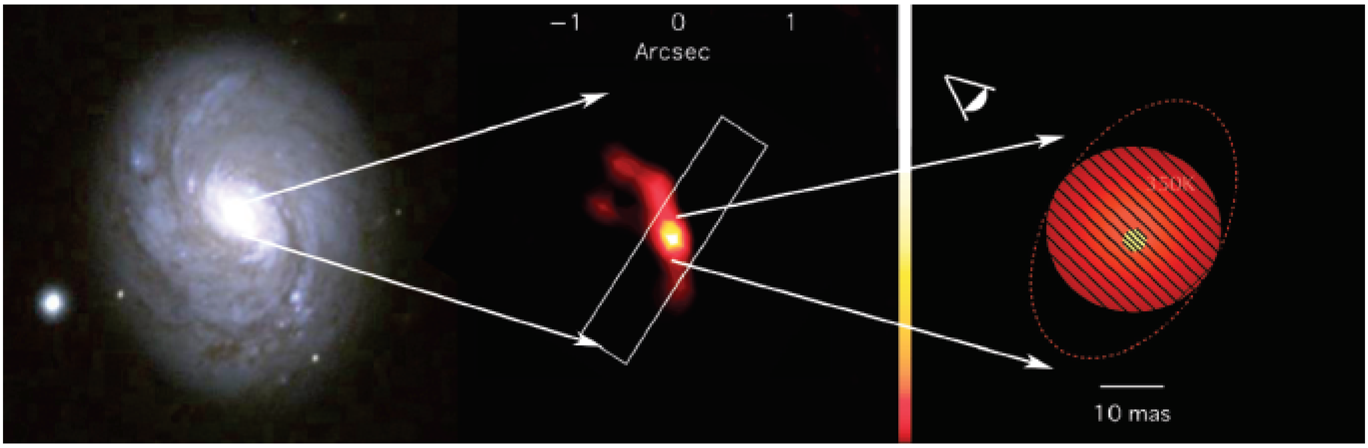


Figure 9: Left: 3.4 × 3.4 arcmin optical image of NGC 1068, (NOAO/AURA/NSF). Centre: non-interferometric acquisition image of NGC 1068 taken by MIDI with a 8.7 micron filter, showing the structures on arcsec scales. Also shown are the position of the spectroscopic slit used in the interferometric observations and the directions of North (toward top left) and East (toward bottom left) on the sky. The projected baseline was essentially North/South and the fringe spacing in this direction was 26.3 mas at 10 micron wavelength. Right: sketch of the dust structure in the nucleus of NGC 1068, as derived from modeling the MIDI observations. It contains a central hot component (T > 800 K, yellow) which is significantly smaller than the interferometric beam, and a much-larger well-resolved warm component (T=330 K, red) of diameter 33±5 mas, corresponding to 2.8 pc at the distance of NGC 1068. From Jaffe et al (2003).

corresponding ratio 2a/2b=1.56±0.05 determines the equivalent star oblateness only in a first-order UD approximation. It can be shown that, in the particular case of Achernar, the observed asymmetry of Achernar reflects its true photospheric distortion with a negligible CSE contribution. Under this assumption, and using the Hipparcos distance (*d*=143.8±3.6 light-years), an equatorial radius Req = 12.0 ± 0.4 $R_\odot$ and a maximum polar radius equal to 7.7 ± 0.2 $R_\odot$ can be derived from the equivalent UD measurements. From simple geometrical considerations, the actual polar radius R_{pol} will be smaller than for polar inclinations $i < 90°$, while R_{eq} is independent of *i*.

Using an interferometry oriented code which includes radiation transfer and the von Zeipel law applied to Achernar in the Roche approximation, it was found that the commonly adopted Roche approximation (uniform rotation and centrally condensed mass) fails to explain Achernar's extreme oblateness. This result opens new perspectives in basic problems in stellar physics such as rotationally enhanced mass loss of Early-type stars. In addition to its intimate relation with magnetism and pulsation, rapid rotation thus provides a key to understanding the Be phenomenon, which is one of the outstanding non-resolved problems in theoretical astrophysics.

If energetic rotation is the key for a star such as Achernar, pure energy is the main keyword for the next object in the new flavour of angular diameters that the VLTI is biting into. With 5 • 10^6 $L_\odot$, η Carinae is the most luminous star known in the Galaxy; its initial mass must have been between 150 and 200 $M_\odot$. It loses mass at a prodigious rate (of order 10^{-3} $M_\odot$/year) in a 500 km/s wind. In an enormous eruption in the middle of the 19th century, several solar masses were ejected; the nature of this eruption is still not understood. The resultant debris now forms a large prolate nebulosity surrounding the star, with an elongation along a position angle of 135°. Clumps are found at all spatial scales; the strong inhomogeneities make it impossible to determine the mass loss rate from spectroscopy alone.

The highest-resolution observations of η Car from a single telescope are the VLT / NACO data, shown in the top right panel of Figure 8. They resolve much of the sub-arc second structure, but about 60% of the flux within the inner 1.5″ remains unresolved in a central object whose size must be smaller than 70 mas.

VLTI / VINCI observations clearly resolve this central object; its size can now be measured to be 5 mas at 2 μm corresponding to 10 AU at η Car's distance. This is clearly much larger than the stellar photosphere so that we must be observing the radius at which the stellar wind becomes opaque. The radiation is dominated by free-free emission and electron scattering; the radius of the surface is determined by the mass-loss rate and the wind clumping factor. The diameter measurement with the VLTI breaks the degeneracy between these two parameters in previous modeling efforts; mass loss rate and clumping factor can be derived separately from the combination of HST / STIS spectroscopy with the interferometric data.

A second important conclusion from the VLTI data is that the central object is not spherically symmetric (Figure 8, centre left panel). In fact, its major axis is aligned with that of the large-scale structure (Figure 8, bottom right panel). This alignment on all scales means that the 1840 outburst looks like a scaled-up version of the present-day wind, and that this wind is stronger along the poles than in the equatorial plane. This can be understood in the framework of radiation-driven winds from rapidly rotating stars: centrifugal forces favour mass-loss in the equatorial plane, but the radiation pressure in these massive stars is stronger in the polar regions because of the von Zeipel effect (the stronger gravity near the poles leads to a higher temperature).

For η Car, the von Zeipel effect is more important than the centrifugal levitation leading to a polar wind. The VLTI observations, thus, favour a model that interprets the morphology of η Car on all scales with a radiation-driven wind from a rapidly rotating star, and they have allowed us to more precisely determine the very high mass-loss rate from this object.

A New Window is Open: Interferometry of Extragalactic Objects

The few selected results presented so far are just highlights of the massive amount of observations accumulated by VINCI, the test instrument which was originally designed to test the VLTI at system level, and has instead operated almost continuously for over two years. Soon, the two facility instruments MIDI and AMBER will enable observations with an increased range of wavelengths, spectral dispersions and number of beam combinations. In fact, MIDI arrived on Paranal almost exactly one year ago, and having successfully achieved first fringes as well as having undergone a few commissioning runs, it is now offered for open observations in period 73 starting from April 2004. In the meantime, under a shared-risk basis, already some GTO and science demonstration observations have taken place.

The results are certainly impressive: from young stars, to evolved late-type objects, from the luminous star η Car previously described, to early-type emission line stars, dozens of targets have been observed. One should note that MIDI represents the first Michelson-type beam combiner operating at 10 microns ever to scan the skies in a routine fashion (ISI, another innovative and successful interferometer operating at these wavelengths is based on a different principle of beam combination using heterodyne technology). Add to that the fact that it is fed by the giant 8.2 m mirrors of the VLT, and it comes as little surprise that even these initial observations are rich in new results. Indeed, every object that MIDI is pointed towards represents a first timer for this kind of observation. It is certainly not too optimistic to expect that several new exciting discoveries will be made possible soon by MIDI.

Already now, new ground has been broken: the first 10 micron interferometric observation of an extragalactic source, NGC 1068. This result was one, but not the only, outcome of the first observations in the framework of the science demonstration program. This is a form of guaranteed time awarded to those partners who have made practical contributions to the VLTI, an open club where new members are always welcome. This represented an historical landmark for the whole field of interferometry, often regarded as a tool useful only for stellar research. Even more so, when one considers that almost simultaneously the Keck Interferometer, making use of their two 10 m telescopes equipped with adaptive optics, also obtained for the first time an interferometric observation of NGC 4151, an extragalactic source, in the near-infrared.

Both galaxies belong to the well-known category of active galactic nuclei (AGN), some of the most spectacular objects in the sky. AGNs display a plethora of very energetic phenomena: relativistic jets, broad and narrow emission lines, X-ray continuum and line emission, radio lobes all of which probably ultimately originate from the accretion of matter onto a central supermassive black hole. The varying relative importance of these phenomena results in a complex classification scheme which includes quasars, radio galaxies, BL Lac objects, Seyfert 1 and 2 galaxies etc. It is generally agreed that at least part of the observed diversity is caused by orientation effects: from certain viewpoints, circum-nuclear dust blocks the direct view of the central accretion disc and central jets. However, this model still remains to be demonstrated by direct observations, since the angular resolution provided by even the largest telescopes fails to resolve the dust geometry in even the nearest AGNs.

The first interferometric observation of NGC 1068, a Seyfert 2 AGN, by MIDI at the VLTI has probed the inner regions of this object with the unprecedented resolution of 30 mas. The combined spatial and spectral information reveals that the central dust distribution has a size of a few parsecs and contains an unresolved hot core, which might be the outer part of the accretion disc (see Fig. 9).

A significant amount of the warm component is located in front of the hot component. The narrow versus wide hatching in Fig. 9 indicates that the silicate absorption towards the hot component is significantly larger than the (averaged) silicate absorption towards the warm dust. Although the observations clearly resolve the warm component along PA 58°, there is no spatial information available in the orthogonal direction: this uncertainty is indicated by the dashed ellipse. The displacement of the warm component by several mas relative to the hot core indicates that the current interferometric data allow for both components being not concentric.

These MIDI observations represent the first interferometric spectrum of an extragalactic source at IR wavelengths, and they reveal a deep absorption feature which appears significantly different from that seen in our galaxy. The 10 micron feature revealed in the interferometric spectrum provides, at a first interpretation, evidence for an alumino-silicate composition of the central dust (see Fig. 10). This is different from the olivine-type dust (commonly seen around stars in our Galaxy) feature that is revealed in non-interferometric, single telescope spectra. However, other more exotic interpretations such as the existence of PAHs compounds, cannot be yet completely excluded. Besides, the observations need to be complemented by more baselines to extend the coverage of position angles and resolutions. Such observations are being carried out as this article is being written, and hopefully we will soon hear more exciting news on this.

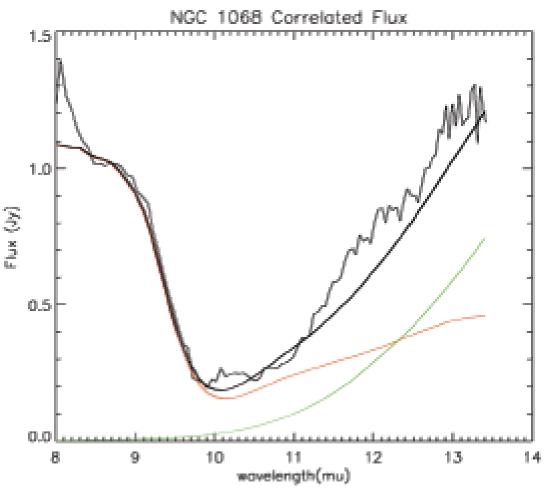


Figure 10: The interferometric spectrum of NGC 1068 showing the flux on scales of 30 milli-arcsec and smaller. The jagged line shows the data and the smooth line the best fitting two-component gaussian model described in Fig. 9. The red and green lines indicate the individual contributions of the "hot" and "warm" components, respectively. The dip near 10 micron is probably caused by alumino-silicate dust, as opposed to the olivine-type, silicate dust absorption noted in the same spectrum obtained without the interferometric combination. From Jaffe et al. (2003).

The future, not so far

The scientific results described above are only a selection of what has been achieved so far. Other data already available are currently being analyzed or waiting for additional complementary observations by the VLTI as well as by other instruments. Preliminary results have already been presented at a number of meetings and conferences, from national and international meetings to the XXV IAU General Assembly, from topical symposia to the recent MIDI workshop held last September. Astronomers will soon be able to make additional important steps in several areas, including stellar diameters, pulsation, circumstellar environments and binary stars.

Noteworthy are the results expected in the fields of pulsation, both among Cepheid stars and very evolved objects. The former are expected to permit a decisive improvement in the accuracy of the empirical period-luminosity relation for these important distance indicators, with important implications also at an extra-galactic level. Regarding the latter, pulsation and mass loss of evolved stars are a key to understanding important phenomena such as the late-stages of the evolution of stars like our Sun, and are also responsible for the chemical enrichment of the interstellar medium. Already a large number of observations have been collected by the VLTI for these kinds of objects.

This wealth of initial results attests to the fact that the VLTI is working well. This might come as no surprise for the many engineers and astronomers that dedicated so much effort through the years to its design and construction, but it certainly is comforting news to the large community that is longing for long baseline interferometry as a wide-ranging, user-friendly and reliable technique to be used by many new enthusiasts and not just a few black belts of applied opto-mechanics. Still, one should not forget that all this wealth comes from what has been until now a rather limited configuration of the VLTI. The majority of the first observations have been limited in sensitivity by the size of the small test siderostats, the lack of adaptive optics and of a fringe tracker. Flexibility has been severely limited by the lengthy relocation of the siderostats and by the number of delay lines (three) currently installed. Last but not least, the test instrument VINCI is equipped with a wide band *K* filter only.

All these limitations are being lifted as we write. The first two of four MACAO adaptive optics systems specific for the VLTI have been put into operation on the UTs, and the rest will follow in the course of next year. In parallel, the first 1.8 m Auxiliary Telescope (AT) has been accepted in Europe and is about to start its test period in Paranal. It will be soon be joined by the second AT in the course of 2004, while two more will follow later: together, the ATs will constitute an independent observatory on Paranal, fully dedicated to interferometry and quickly relocatable on a system of 30 stations. The FINITO fringe tracker is about to complete its commissioning on the mountain, and three more delay lines are ready to be added in the underground tunnel: the former will extend the sensitivity by permitting long integrations on faint objects, the latter will enable a much larger set of baseline combinations than has been possible until now. Finally, the two facility instruments AMBER and MIDI will offer a wavelength coverage which spans the *J, H, K* and *N* bands respectively, with various sets of spectral resolution up to 10,000.

With these additions, the VLTI will soon be a more complete facility, but its development will be by no means terminated. Second-generation instruments are being proposed, including the ESA-funded GENIE nulling interferometry demonstrator for DARWIN. The PRIMA facility, crucial for the observation of faint sources and for accurate narrow band astrometry through the use of off-axis reference sources, is planned to be integrated in about two years. It will extend the sensitivity limit of the VLTI well into the realm of extragalactic sources and permit the detection of the tiny gravitational pulls induced on stars by their orbiting planets. In the course of 2003, what was once a tiny seed timidly buried in hard ground, has finally grown and started producing its fruits. The harvesting has begun, and the prediction is that it will last many seasons.

Acknowledgements

If we can speak about VLTI results today, it is only thanks to the efforts of a large group of people in Europe and Chile. It is impossible to mention here all their names, and we hope we can be forgiven for this negligence. However, we take special pleasure in mentioning the former head of the Telescope Division, Massimo Tarenghi, who has defended the VLTI seed from the very first moment. Although he is now devoting himself to other projects, he still pays the occasional, unannounced surprise visit at the VLTI and still shows the same enthusiasm as ever. We would also like to mention by name the current members of the VLTI Science Group, on both sides of the Atlantic: Pascal Ballester, Emmanuel Di Folco, Emmanuel Galliano, Andreas Glindemann, Christian Hummel, Pierre Kervella, Sebastien Morel, Francesco Paresce, Isabelle Percheron, Fredrik Rantakyrö, Andrea Richichi, Markus Schöller, Martin Vannier, and Markus Wittkowski.

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