SCIENCE WITH THE VLT/VLTI

A New Start for the VLTI

*ISAC – Interferometry Science Advisory Committee**

1. Introduction

It has always been ESO's aim to operate the VLT in an interferometric mode (VLTI) which allows the coherent combination of stellar light beams collected by the four 8-m telescopes (UTs) and by several smaller auxiliary telescopes (ATs). In December 1993, in response to financial difficulties, the ESO Council decided to postpone implementation of the VLTI, Coudé trains and associated adaptive optics for all the UTs but included provisions for continuing technological and development programmes devoted to the aim of reintroducing these capabilities at the earliest possible date (see *The Messenger* No. 74, December 1993). In July 1994, the ESO Council approved a revised VLTI implementation plan to provide at least the VLT interferometric sub-array (VISA) consisting of three ATs by the year 2003 and, provided additional funds could be obtained, integration of the UTs by 2006.

The desirability of carrying out the full VLTI programme as originally envisaged at the earliest possible moment has not, however, diminished, especially in view of VLTI's exceptional capabilities and resulting potential for new and exciting discoveries. In recent years, interferometric projects have begun to play a central role in ground-based high-resolution astronomy, and numerous instruments have been completed or are in the process of construction (see Table 1 for a summary of the present situation in this regard). Several large-aperture interferometers will probably come on-line near the turn of the century. The impending presence of these new instruments represents an important incentive both for clarifying the scientific cases for various VLTI implementation plans and for ensuring VLTI's competitiveness in the international context over the next 10–20 years.

The complexity and ambitious scope of VLTI mean that its astrophysical repercussions are difficult to define fully, even for many of its most vocal supporters. However, the primary scientific issues that it seeks to address are well defined, although there remains a need to present these coherently to the wider community in order to justify the significant resources which the project requires. Another pressing need is to develop an implementation plan that will optimally exploit the various technological stages of the project and ensure their compatibility with a vigorous, yet realistic and timely, astrophysical programme.

In order to study these issues and to establish a clear set of guiding principles for the development of VLTI, a new Interferometry Science Advisory Committee (ISAC) was established in April 1995. This committee has met twice to review the present technical status of VLTI, its scientific rationale as elaborated by past advisory panels (ESO VLT Reports 59 and 65), and the present recovery plans. The committee has now begun to define and prioritise the key science drivers for the programme and the technical specifications that flow from them. This article briefly presents these science goals as they currently stand. The list is not meant to be frozen or complete, but rather is intended to stimulate community reflection and comment. The preliminary recommendations of the committee are discussed in the last section of this article.

To provide a forum for the discussion of the ideas presented here, ESO has decided to host a workshop on "Science with the VLTI", in Garching on June 18–21 of this year (see *The Messenger* No. 82 and the announcement in this issue). It is hoped that this will allow the whole of the ESO community to further refine the concepts outlined in this article and to make a case for any capability or role omitted here.

2. Science Goals

2.1 Extrasolar planets

Searches for extrasolar planets have started to assume centre stage both in the professional arena and in the public perception of astronomy. The recent detection of a planet orbiting 51 Peg (Mayor & Queloz, 1995) has generated much interest, and it is widely believed that more giant gaseous planets around solar-type stars can be found by precise radial-velocity and astrometric surveys. Both these methods are indirect, in that they measure the motion of the star around the barycentre of the star-planet system. While radial velocity searches could soon become a very efficient method to detect exoplanets, they have a serious drawback: they cannot determine separately the planetary mass and its orbital inclination; only M sin i is measurable. In contrast, astrometric observations give M directly. Of course, in planetary systems which are viewed "pole-on", astrometry provides the only way to detect reflex motion.

The VLTI has the potential to be an extremely powerful instrument for precise narrow-angle astrometry. For instance, the atmospheric limit for determining the separation vector between two stars which are 10″ apart is about 10 μas for a half-hour integration. Realising this potential is a challenging but solvable task. It requires monitoring the baseline vector inside the interferometer with ~ 50 μm precision and measuring the differential delay between the two stars with ~ 0.005 μm precision. Implementing an astrometric mode in VLTI with these capabilities would enable us to detect Sun-Jupiter systems out to a distance of 1 kpc and small planets (10 Earth masses) around the closest stars.

The following observing strategy could be adopted for the VLTI astrometry programme: a list of ~ 200 target stars would be observed in the near infrared with VISA. These stars must be bright enough for fringe tracking (K ≤ 12), which will allow the astrometric reference sources to be relatively faint (K ≤17) and ensure that references for phasing can be found for almost any object of interest. The integration time would be half an hour per star per night. With thirty observations of each target star over ten years, this would require a total commitment of 300 nights on VISA spread over a decade. The data for each star would be used to solve for relative parallax and proper motion, with any residuals indicating the presence of planets. In practice, one would use two or three different astrometric reference stars for each target to remove ambiguities from the motions of the reference stars themselves.

The target list would include candidate planetary systems found from radial velocity searches, for which VLTI could determine the inclination and thus the planetary mass. The list could also include candidates from a large-scale astrometric survey such as the GAIA project, a mission proposed within the Horizon 2000+ programme of ESA. In the GAIA data, which should also have a

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precision of ~ 10 μas, albeit over much wider angles, planets would be revealed by conspicuous residuals in the astrometric fit, but the mission lifetime and temporal sampling would generally not be adequate to determine planetary orbits.

While observations of candidate exoplanets would make the VLTI programme quite efficient, the target list should also include a survey of other "interesting" objects. Examples are the closest stars, for which the VLTI can detect planets with lower masses than can radial velocity searches, IR-excess stars like β Pic, and pre-main-sequence objects in low-mass star forming regions and in Orion. The astrometric mode of the VLTI would thus open new vistas in the study of the formation and evolution of planetary systems. It could also provide an input list for even more ambitious space interferometry projects aimed at spectroscopic investigations of extrasolar giant and Earth-like planets. One such project, DARWIN, is also under study as a cornerstone mission within Horizon 2000+.

While these indirect methods will certainly yield a wealth of data about extrasolar planetary systems, the direct detection of photons originating from the planet itself would enable more detailed astrophysical studies. Examples include determining the chemical composition and temperature of the planets through spectroscopy, and studying surface structure and rotation by analysing the lightcurve. However, in the visible and near-IR regimes it is prohibitively difficult to detect planets against the glare of the parent star. The only chance lies in the mid-infrared, where the contrast is reduced by several orders of magnitude. In the 10 and 20 μm atmospheric windows, the thermal emission of a planet depends strongly on its temperature (for example, at 10 μm the Earth is brighter than Jupiter). Simple sensitivity calculations show that Jupiter at a distance of 10 pc would not be detectable against the thermal background in a reasonable time with an Earth-based (and therefore uncooled) 8-m telescope. It should be kept in mind, however, that other planetary systems may be very different from ours. In particular, other giant planets may be warmed by internal heating, which is stronger in planets that are younger or more massive. Planets may also be warmed by strong irradiation, either because the parent star has an early spectral type or because the orbit is small (as in the case of 51 Peg). There may be a realistic chance of detecting such warm giant planets in the solar neighbourhood with the VLTI at 10 or 20 μm, provided their temperature is at least 400 K. Suitable candidate objects for such an ambitious project, which would require several hours of integration time with the full array of four 8-m telescopes, could be drawn from the astrometric survey list.

2.2 Low mass stars and brown dwarfs

Ninety percent of stars in our Galaxy are less massive than the Sun. Despite this fact, the properties of stars with low or very low masses are far less certain than those of their more massive counterparts. For instance, establishing an observational mass-luminosity relationship for stars with masses smaller than 0.3 $M_\odot$, is still an active field of research (Henry & McCarthy 1993). Similarly, observations are still unable to significantly constrain the lower end of the mass spectrum that is produced by the star formation process.

Even less well understood are substellar objects: the elusive brown dwarfs. It seems that, after a long and eventful search, the question of their existence has recently been settled by clear detections (Rebolo et al., 1995; Nakajima et al., 1995). Of course, this result opens a new field of study for this latest class of cosmic objects which will finally allow theory to be related to observations. Unfortunately, this relation is rather indirect because the classical observables of a brown dwarf (broad-band photometry and spectrum) are determined by its very thin atmosphere, while its physical status depends mostly on the age and mass.

Progress in understanding low-mass stars and brown dwarfs clearly requires a method for determining masses. The first step is to perform radial velocity surveys of large samples of low-mass stars in search of spectroscopic binaries. However, while these surveys provide fundamental statistical results (Duquennoy & Mayor, 1991), they can only yield masses for each component if combined with direct imaging measurements. Duquennoy et al. (1995) have recently discussed the impact of the VLT and VLTI on such a programme. In particular, they show that the combination of high-precision (~ 15 m/s) radial velocity data with parallaxes provided by Hipparcos and angular separations from VISA would allow the determination of masses of very low mass stars with a precision at the percent level. Even the mass of a suspected 0.03 $M_\odot$ brown dwarf companion could be estimated with ~ 5% accuracy, firmly establishing its sub-stellar nature and allowing one to test evolution scenarios for these still mysterious objects.

2.3 Star formation and early stellar evolution

Young stellar objects (YSOs) exhibit a large variety of different phenomena, such as infrared excesses, luminosity variations and highly collimated jets with velocities of several hundred km/s. These phenomena suggest the presence of a circumstellar accretion disk and strong magnetic fields. Understanding the inner regions of YSOs, including their accretion disks and jets, is an important area of current research and is related to the question of how our own solar system formed. The similarity of some YSOs to AGNs, particularly the so-

TABLE 1. Current Ground-based Optical Long Baseline Interferometer (OLBI) Projects

Programme (Nation)	Number of simult. Baselines (ultimate)	Maximum Baseline [m]	Element diameter [m]	Year of operation
I2T (F)	1	140	0.27	operational
GI2T (F)	1	65	1.52	operational
ISI (USA)[3]	1	35	1.65	operational
COAST (GB)	3 (6)	100	0.40	operational
SUSI (AUS)	1	640	0.14	operational
IOTA (USA)	1 (3)	45	0.45	operational
NPOI (USA)	3 (6, 15)	250	0.35	operational
ASEPS-0 ITT (USA)	1	100	0.45	operational
CHARA (USA)	10	350	1.00	1997
KIIA (USA)	1 / 6 / 15[1]	75 / 180[2]	10 / 1.5	1998
LBT (USA/I)[4]	1	20	8	1999
VLTI (EUR)	6 / 3 / 6[1]	128 / 200[2]	8 / 1.8	2000

[1] Beam combination main / auxiliary / hybrid — [2] between main / auxiliary telescopes — [3] heterodyne, to be changed into a homodyne interferometer — [4] monolithic array. — (Last update: 02/01/96).

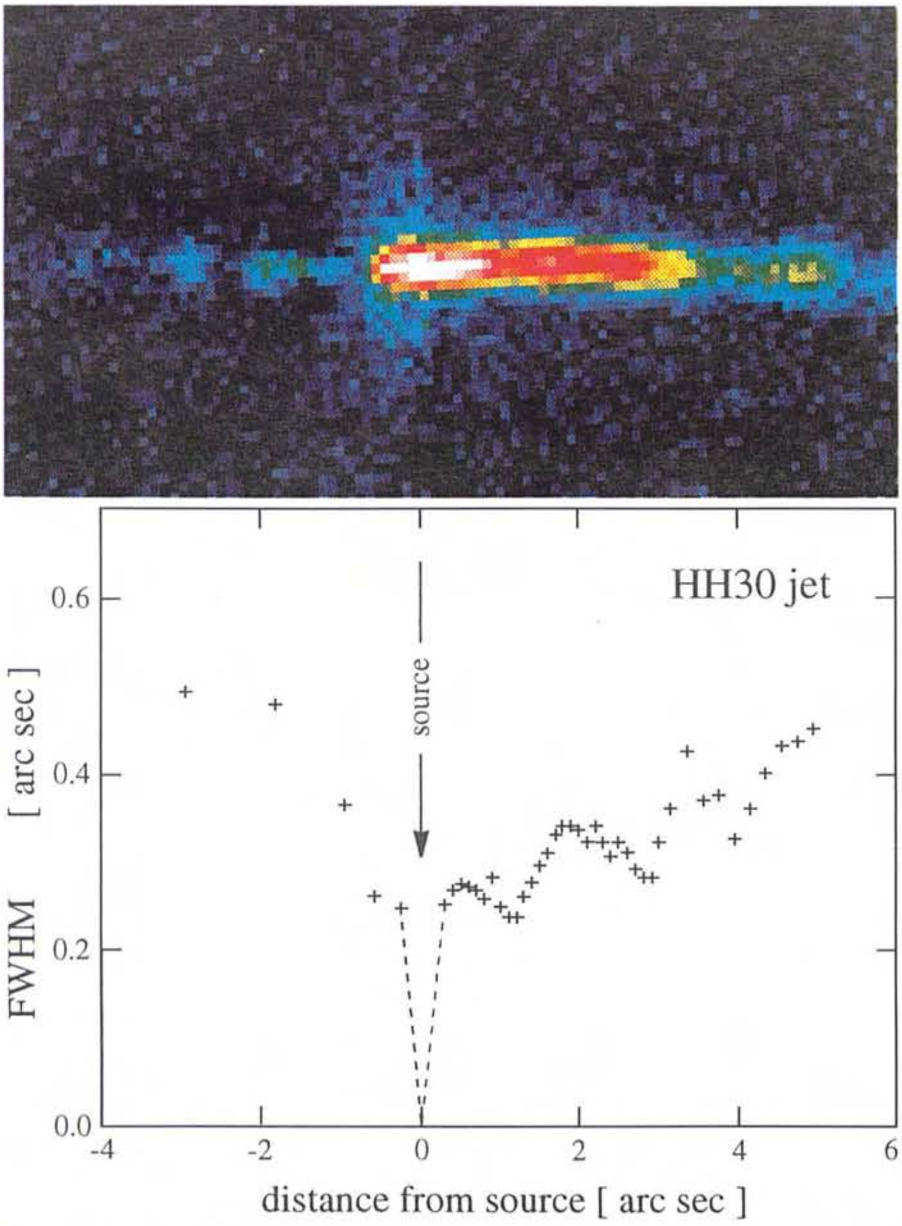

Figure 1: The top part shows a HST/WFC image of the bipolar jets from the HH 30 star in the [SII] 6716, 6731 lines (with the continuum contribution subtracted). The HH 30 star is not visible due to strong extinction in the circumstellar disk. The star is assumed to be located in the centre of the gap between the two jets (i.e. 0.3″ to the left of the very end of the brighter jet). In the lower part, the measured FWHM of the bipolar jets as a function of distance is shown. For the visible parts of the jet, average full opening angles of about 6 degrees (left part) and 2 degrees (right part) have been derived. However, for the invisible part of the jet, i.e. between the source and the first point of measurement the jet opening angle must be considerably larger (at least 50°) as indicated by the dashed line.

called classical T Tauri stars, means that progress in understanding the physics of star formation may have important implications for extragalactic astronomy.

A major programme for the VLTI is to study systematically the rich circumstellar environments of YSOs at a resolution of about 2 mas, which corresponds to 20–30 stellar radii (0.3 AU) for the nearest star-forming regions (*d* = 150 pc). The factor of twenty increase in resolution over HST provides access to the phenomena which occur in the inner regions around young stars and should provide important input to the theoretical models. However, even VLTI will not be able to resolve the innermost parts of the accretion disk, where material is presumably funnelled via magnetic fields onto the stellar surface and where other parts of the rotating magnetosphere accelerate and collimate the outflowing matter. Nevertheless, observing just outside these regions should allow meaningful extrapolations.

Very few direct studies of circumstellar disks have been performed so far, because this requires high resolution in the near- and mid-infrared domains. Important parameters yet to be determined include the morphology of circumstellar disks, the temperature distribution, the relative contributions from scattered stellar light and thermal disk emission, the disk chemical composition and the properties of dust grains.

In a few objects, minima in the broadband spectrum have been tentatively attributed to zones cleared by a planet or faint companion (Marsh & Mahoney, 1993), although different interpretations based on material properties are also possible. These gaps lie around 1 AU and would be detectable with the VLTI (Malbet & Bertout, 1995). The determination of visibility curves at 2 and 10 microns should indicate the interesting candidates; imaging will be required to study the phenomenon with its asymmetries due to the presence of the orbiting object. Generally, distribution of dust and gas, and of the spatial distribution of temperature can be measured and will clarify the initial conditions for possible subsequent planet formation.

The question of how YSO jets are accelerated and collimated should also be addressed with the VLTI. Although the innermost region will not be resolved, important constraints on models can be derived from observations beyond about 30 stellar radii. A start has been made with HST and ground-based telescopes, and studies of jet width as a function of radius show that at least some YSO jets have full opening angles of greater than 50° for small distances from the star. This behaviour, which is observed for of at least a few YSO jets, is illustrated in Figure 1 on the basis of a recent HST/WFC image of the bipolar jets from the HH 30-star in the [SII] 6716, 6731 lines (Ray and Mundt, 1996). The figure shows how drastically larger the opening angle of this YSO jet must be on small scales (i.e. within < 0.3″ or for < 50 AU from the star). A similar behaviour has been predicted by the theoretical models of Camenzind (1990) in which the jets are accelerated and collimated by rotating magnetospheres and in which one expects large jet opening angles for jet radii much smaller than the light cylinder, which is expected to have a radius of about 30 to 100 AU for typical rotation periods for T Tauri stars of a few days.

The VLTI can also investigate possible connections between variations of the central star and the formation of new knots in the jet. For a jet speed of 300 km/s, a new knot resulting from an outburst would move outwards and be detectable after a few days, allowing its proper motion to be accurately measured. This is similar to VLBI observations of QSO jets. The need to pursue these observations with high spectral resolution (R > 1000) and within 1–2 days because of the high proper motion of the knots (up to 1 mas/day) probably will require the inclusion of the UTs on the basis of current brightness estimates.

Measuring orbits of very close binaries would be another valuable science programme. High angular resolution is needed to produce accurate masses for lunar-occultation and spectroscopic bi-

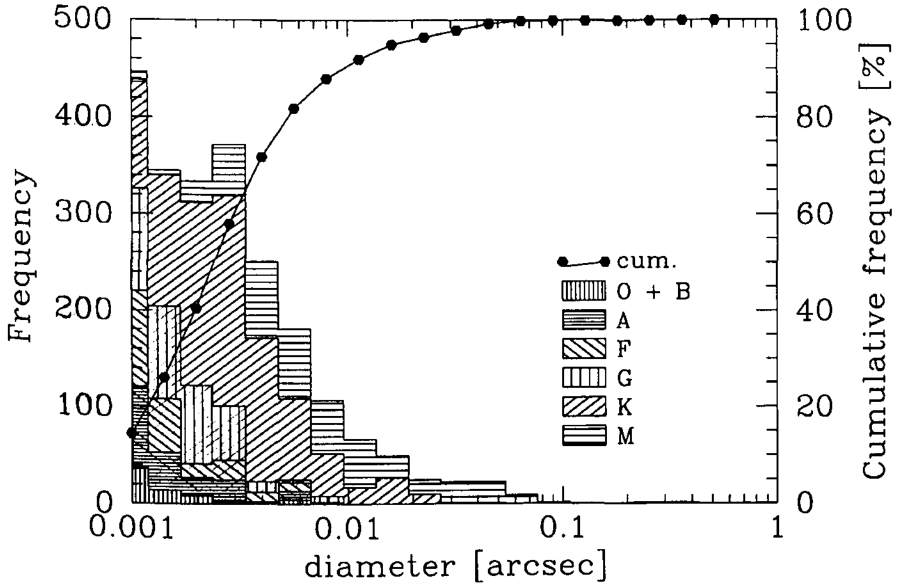

Figure 2: Histogram of CADARS (Catalogue of Apparent Diameters and Absolute Radii of Stars; Fracassini et al., 1988) stars with apparent diameters above 1 mas and declinations south of +40°. The solid line represents the cumulative frequency.

naries within a reasonable time: an orbit of 100 AU takes about 1000 years, but one of 4 AU will be completed in 8 years. Fortunately, the incidence of binaries among young stars is high (Reipurth & Zinnecker, 1993) and is probably close to 100% in some molecular clouds (Ghez et al., 1993; Leinert et al., 1993). Masses from binary orbits will finally provide urgently needed empirical checks on the evolutionary tracks used in interpreting the observations of young stars.

The key capabilities of VLTI in this field are its resolution, sensitivity and infrared response. There are many bright YSOs (V = 11–15, K = 6–9) which will make ideal targets. Once the first two ATs become available, a good first-light project would be to determine stellar masses from orbital motion and to search for new companions. Measuring visibilities at different wavelengths in the near- and mid-infrared bands will allow us to investigate the temperature and density distributions of the circumstellar material and search for gaps which might indicate the formation of planets. Finally, closure-phase imaging will be used to provide the detailed geometrical information needed to understand the fascinating phenomena mentioned above.

2.4 Stellar surface structure

A survey by von der Lühe et al. (1995) indicates that about 2000 stars with declinations less than 40° north have apparent diameters of one milli-arcsec and more and therefore are resolved to VLTI baselines in the NIR. Most of these stars are late-type giants. Some 50% have apparent diameters of 2.5 mas or more and will permit detailed studies of their surfaces. Figure 2 shows the histogram for the distribution of apparent diameters and spectral class.

The superior imaging capability of VLTI will make possible the study of physical characteristics of surface phenomena and their variation with time. Important surface phenomena are due to hydrodynamic and magnetohydrodynamic effects and result in large-scale convection cells in the outer convection zones and concentrations of magnetic fields. The study of convection through surface temperature and line-of-sight velocity variations provides clues to the fundamental properties of the convection zone. The temporal variation of active regions provides insight in the underlying dynamo processes which generate magnetic fields in stars.

Figure 3 shows the interferometric signal (visibility magnitude) which can be expected for a relatively quiet (solar-type) and an active star. It is important to notice that the signatures in the visibility functions occur at high angular frequencies and have small magnitudes. Only structures on active giants will probably be well resolved by VLTI. Although the target sources are bright (most stars have visual magnitudes between 2 and 8), the low visibility signal and the high spectral resolution required to perform measurements of velocities and Zeeman profiles will make necessary the use of the UTs.

The detection of surface features on cool giants and supergiants using large single telescopes has been one of the most important successes of interferometric imaging (Buscher et al., 1990; Wilson et al., 1992). The best-studied example is Betelgeuse. The image

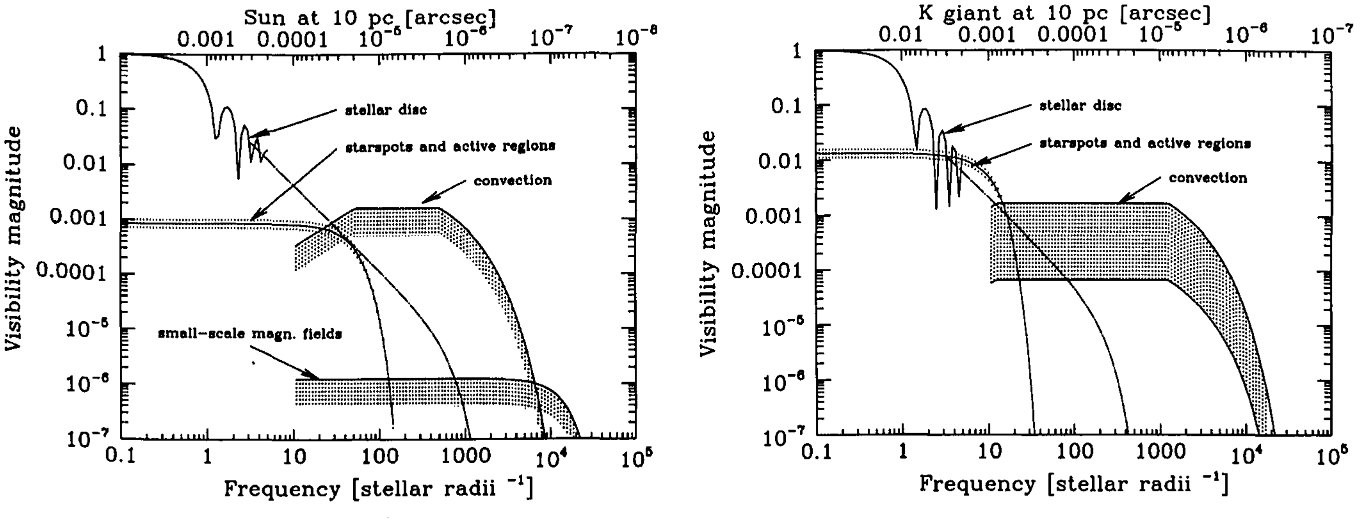

Figure 3: Distribution of visibility magnitude for a quiet (solar-type) star (left) and for an active giant (right). The phenomena shown are convection, active regions (starspots and plages) and small-scale magnetic fields. The large contribution at low frequencies is due to the sharp edge of the stellar disk. Angular frequencies are given in units of "inverse stellar radii." The corresponding scale in arcsec is shown on the top for the Sun at 10 pc (left) and for a K giant with 24 $R_\odot$ (right).

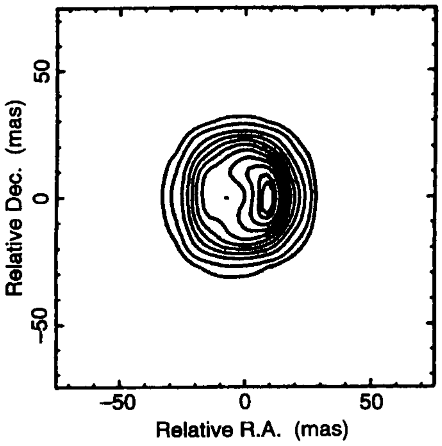

Figure 4: Image of the M2 lab supergiant Betelgeuse at 710 nm obtained using optical interferometry with the 4.2-m WHT (adapted from Buscher et al., 1990). This maximum-entropy reconstruction shows a single bright feature that is offset from the centre of an otherwise uniform disk. It represents the first resolved image of a star apart from the sun, and shows a convective hotspot. This type of feature has recently been rediscovered by HST at ultraviolet wavelengths. The large apparent size of Betelgeuse means that it is one of the few stars than can be resolved with HST. VLTI, with its 100-m baseline, will suffer no such limitations and offers the prospect both of investigating stars such as Betelgeuse at much higher spatial resolution, and of extending surface studies to more distant populations and less extended stellar types. Contours are plotted at 5, 10, 20, 30, . . . 90, 95 % of the peak intensity. Note the scale of the axes – this is the one of the largest stars in the sky (in terms of apparent size).

shown in Figure 4 is typical of those now being regularly obtained, which show a small number of bright unresolved features containing typically 5–15 % of the stellar flux superimposed on an otherwise uniform disk. The relationship, if any, between these features and the well-documented mass loss and variability of Betelgeuse is at present unclear.

These surface features, which appear as bright "hotspots" of emission, are probably the result of large-scale convective upwellings of material from hotter regions of the stellar interior (Schwarzschild, 1975). Their number, evolution timescale and brightness are certainly all consistent with such an hypothesis, but their detection has raised a number of further questions that will likely be amenable to large interferometers like the VLTI. For this reason, cool evolved stars are among the most promising targets for pilot interferometric observations. A brief summary of the possible science goals for such observations are listed below:

Frequency of occurrence. Although now imaged on a handful of massive M supergiants, there is growing evidence that surface inhomogeneities are also present on Mira-type long-period variables, i.e., stars of much lower masses (Tuthill et al., 1994; Haniff et al., 1995). Limitations on the resolving power currently attainable from the ground mean that only the nearest and most luminous sources have been observed. The primary goal of an interferometric survey of the local neighbourhood will be to determine the frequency of occurrence of these hotspots as a function of type and luminosity class.

Evolutionary timescale. One of the most useful diagnostics in the study of surface inhomogeneities will be the precise determination of their evolutionary timescales. Predictions exist for convective models, (Schwarzschild, 1975) but there has been little effort to monitor these stellar surfaces using high-resolution imaging methods. A dedicated interferometer offers the possibility of such a programme.

Multiplicity. Current ground-based studies of stellar hotspots have been constrained by the limited resolutions of monolithic telescopes. In this sense, observations have only been able to place limits on the sizes and multiplicities of the hotspots seen on these targets. Once again, predictions for these properties exist for a number of models, implying that significant progress could be made if observations at much higher spatial resolution were available.

Location. Another useful diagnostic for elucidating the physical mechanism responsible for surface features will be the identification of the precise radial depth at which they occur. Because of the abundance of molecular and atomic species in cool stellar atmospheres, spectrally resolved measurements provide useful information as to the radial stratification of the stellar atmosphere, and so it should be possible, in principle, to map out the vertical locations of the surface inhomogeneities.

Mass loss. Perhaps the most exciting prospect lies in tying together the observed surface features with the prodigious mass loss and variability of cool giants and supergiants. Mass loss from cool stars remains a very poorly understood area, and interferometric observations offer the prospect of imaging circumstellar dust very close to the stellar surface, of monitoring the photospheric radius directly, and of directly relating spatially resolved images with photometric and polarimetric variability.

As well as the main areas listed above, one should not forget more mundane, but equally important, problems that could be addressed by the VLTI. These include precise angular diameter measurements, which lead to effective temperature, and studies of the atmospheric structure. All the questions raised here can be addressed by a combination of programmes: (i) detailed studies of selected sources, (ii) monitoring of selected sources every month, and (iii) a survey of the local neighbourhood. In many instances, interferometric data will provide the first direct measurements with which to confront — and perhaps overturn — existing theories.

2.5 Be stars

Be stars show Hα emission that is strongly variable and usually double-peaked. They are also known to be rapid rotators, which led Struve (1931) to suggest that the emission arises in a circumstellar disk of ejected matter. This model has not been universally accepted (Doazan, 1987), but optical interferometry has now confirmed that Be star envelopes are indeed flattened (Mourard et al., 1989; Quirrenbach et al., 1993, 1994; Stee et al., 1995).

Ad hoc models which assume a disk geometry have been successful in describing the winds of Be stars (e.g., Marlborough, 1987), but a theoretical mechanism for disk formation only came through the work of Bjorkman & Cassinelli (1993). They showed that Coriolis forces in the radiation-driven wind of a rapidly rotating star will force the flow of gas towards the equatorial plane and create a very thin, dense disk. Many questions remain unsolved, however. This model underestimates the amount of matter in the disk by a factor of about 100 and predicts a disk opening angle which is much smaller than that derived from the statistics of shell stars. Also, the important variable character of Be stars (short-, middle- and long-term) is not understood. Indeed different mechanisms could give the same classical measurements. Fortunately, one can show that the analysis of the interferometric data through the different variation cycles allows the determination of the correct processes.

VLTI at optical and infrared wavelengths is very well suited to resolving the disk structure of Be stars and monitoring time variability. There are more than 100 Be stars brighter than 6th magnitude and they have already been well studied by classical techniques (spectroscopy, photometry, polarimetry). Interferometry brings new constraints on the size and morphology of the disk (including velocity and density fields), on the central star itself (radius, ellipticity, surface activity and limb-darkening – see Cidale & Vázquez, 1995) and on the effects of a binary companion.

Be stars make good targets for long-baseline interferometers, thanks to the simultaneous presence of a point-like continuum source (the central star) and a resolved structure (the emitting envelope). The programme demands a good spectral resolution (R=10,000 in the visible and R=100–1000 in the near-IR). Moderate (*u*, *v*) coverage is sufficient because the geometry is simple – even without images, and strong constraints can be placed on the physical processes involved in the Be phenomenon. The

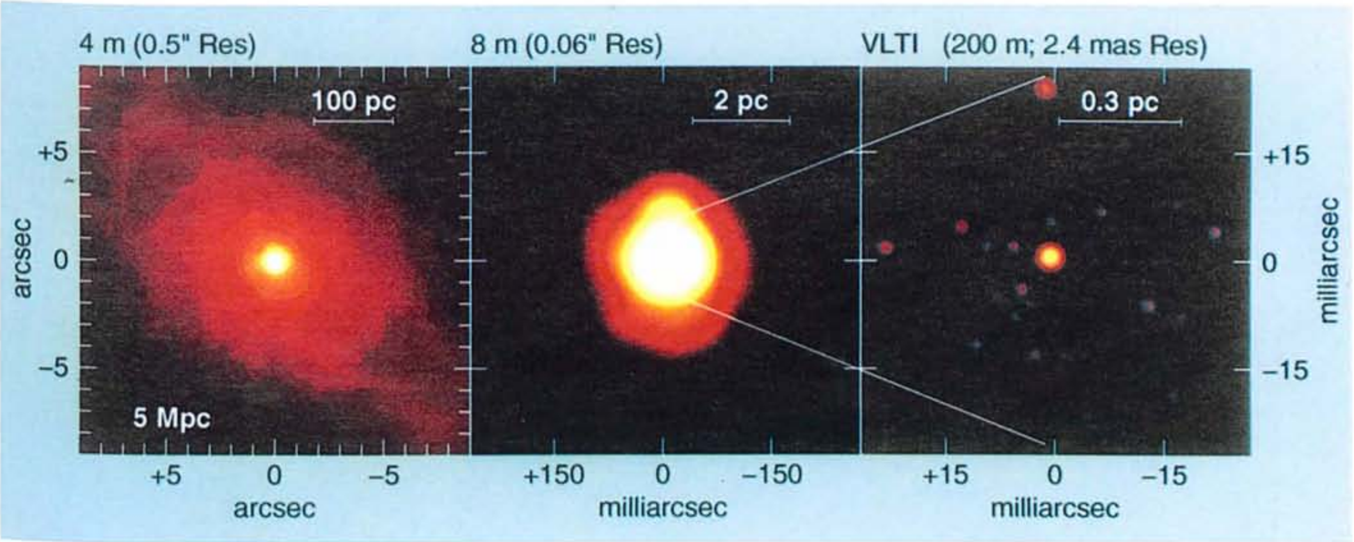

Figure 5: Simulated 2.2 μm imager of an active galaxy at a distance of 5 Mpc, when observed at three different spatial resolutions. Left: 0.5 arcsec resolution (adapted from a SHARP/NTT image of NGC 1068). Middle: 0.06 arcsec resolution (adaptive optics on a UT). Right: 0.003 arcsec resolution (VLTI). The galaxy is assumed to contain a point-like AGN surrounded by a star cluster. From Genzel et al. (1995).

large apertures of the VLTI will be vital to achieve high spectral resolution maps in a few nights.

2.6 AGB stars

All stars with initial masses $\leq 8M_{\odot}$ end their lives on the Asymptotic Giant Branch. An AGB star consists of a degenerate C/O core surrounded by a very extended convective atmosphere from which mass is lost via a dense and dusty outflow at rates of 10^{-8} to 10^{-4} $M_{\odot}$/yr and expansion velocities of 5–30 km/s. The mass-loss mechanism in AGB stars is poorly understood. It is believed to be related to the slow pulsations and the formation of dust, which is subsequently pushed out by radiation pressure. Improving our understanding of the physical mechanisms that drive this process is important because mass loss dominates AGB evolution and also because AGB stars play an important role in the chemical evolution of galaxies by returning gas and dust to the ISM.

Questions that may be addressed are: (i) Where does the dust form in the extended atmosphere? If it forms too far away from the photosphere the mass-loss rate resulting from radiation pressure on the dust grains is insufficient to explain the observations. (ii) What is the role of the pulsations in the mass loss process? Is the star distorted due to the large convective motions in the envelope? (iii) What molecules are depleted in the dust formation region? (iv) How does dust formation depend on the phase of the pulsation and on the chemical composition of the star?

Several theoretical studies have highlighted the potential of mid-infrared interferometry for studying AGB envelopes and addressing some of these issues (Lorenz-Martins et al., 1995; Winters et al., 1995; Ivezic & Elitzur, 1996). The mid-infrared region is ideal for studying dust formation near AGB stars and the accompanying depletion of atoms and molecules. A start has been made by Danchi et al. (1994) using the Infrared Spatial Interferometer, which has two 1.65-metre apertures (see Table 1). Their measurements, made at 10 μm using baselines up to 13 m, allowed a detailed study of the inner radii for 13 of the brightest late-type stars. The VLTI, with its 8-m apertures and 10–20 μm capability, is uniquely suited to extending this work to fainter and more distant objects and with higher spectral resolution. For example, the location and properties of the silicate dust can be studied by measuring the change in size of the object as a function of wavelength through the silicate features at 9.7 and 18 microns (Lorenz-Martins et al., 1995). The layers above the photosphere in which dust forms may extend to about 10 stellar radii, which is several tens of milliarcsec at distances of 500–1000 pc and easily accessible to VLTI. Direct imaging of the stellar disk will also be possible, so limb darkening and distortions from sphericity can be measured. If an AGB star is imaged throughout a pulsation cycle and if simultaneous radial velocity data are taken, the distance can be measured.

The mid-infrared also is the obvious wavelength region for studying post-AGB stars. Many post-AGB candidates were discovered in the IRAS point source catalogue to show warm dust (500 K) and turn out to be binaries. The most famous example of such an object is the Red Rectangle (see Van Winckel et al., 1995). It appears that mass loss on the AGB can be affected by the presence of an unseen companion, with mass being stored in a circum-binary disk. It is currently unclear whether these disks are stable and how they affect the further evolution of the object and the formation of a planetary nebula. The disks should be a few to several tens of AU in size, which means they can be resolved by VLTI at a distance of 500 pc.

2.7 The Galactic centre

The central 0.1 pc of our Galaxy will be an important target for VLTI at wavelengths from 2 to 10 μm The resolution of the VLTI at 2 μm is about 2 mas, which at the Galactic centre corresponds to 15 AU or about 1500 times the Schwarzschild radius of a 10^6 $M_{\odot}$, black hole. The first and most important goal will be to test for the presence of a central massive black hole by measuring the three-dimensional velocity field of the star cluster centred on IRS 16. The current astrometric programme at the NTT (Eckart et al., 1995) could be continued with higher precision and radial velocities could be determined at very small distances from the centre of the star cluster, where observations with single telescopes are limited by crowding.

Another very important goal for the VLTI will be detailed observations of the infrared sources close to the position of SgrA*. It is presently unclear whether any of the objects found at 2.2 μm is the true counterpart of the compact radio source. The study of a potential IR counterpart of SgrA* would give completely new insights into the vicinity of the central object of our Galaxy, and could perhaps give us a direct view of the putative accretion disk. In addition, the high angular resolution of the VLTI will enable us to obtain infrared spectra of individual stars in the very crowded Galactic centre region. It will thus be possible to make a census of the stellar population in this area, to check whether there is ongoing star for-

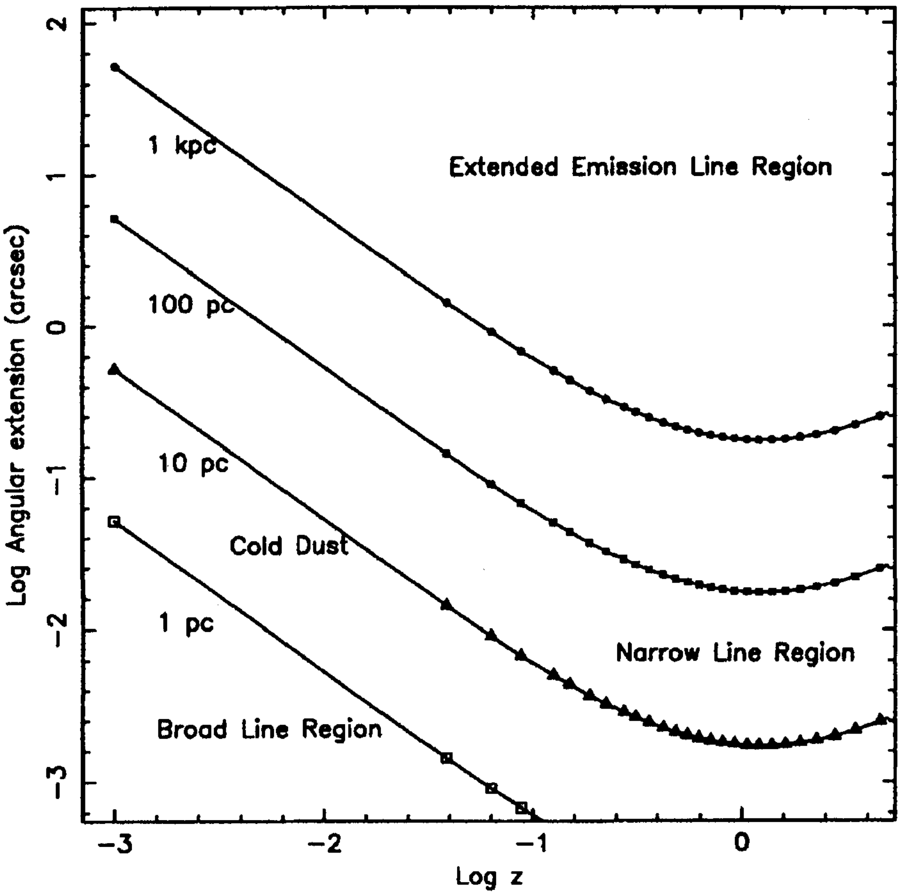

Figure 6: Angular extension as a function of redshift for regions with linear sizes of 1 pc (open squares), 10 pc (open triangles), 100 pc (filled squares) and 1 kpc (open circles). The calculations assumed H_0 = 75 km/s/Mpc and q_0 = 0.5. The difference in look-back time between adjacent symbols is constant and equal to about 0.5 Gyr.

mation in the vicinity of the Galactic centre, and to search for "peculiar" stars, which may be the remnants of stellar collisions. Observations at 10 μm would also reveal the distribution of warm dust associated with SgrA*.

Observing the Galactic centre is quite a challenging task for the VLTI because of the high density of sources. Hybrid configurations formed by combining the UTs with the ATs will give good coverage of the (*u*, *v*) plane, in particular when the technique of multi-frequency synthesis is employed. The focal plane instruments needed for observations of the Galactic centre are (i) an instrument for the mid-infrared with spectral resolution R ≈ 200, and (ii) a near-infrared instrument with R ≈ 2000. For the investigation of SgrA*, polarimetric capabilities would be very valuable.

2.8 Active Galactic Nuclei

AGNs are thought to be powered by accretion onto a massive black hole. For reasons that are not understood, but are probably related to the way galaxies form, there are many more AGN at high redshifts than locally. The space density of high-luminosity AGN at $z \sim 2$ is 100–1000 times greater than at the present epoch.

Although our understanding of the AGN phenomenon has increased dramatically, major fundamental issues remain unsettled. These include the precise mechanisms involved in feeding the central black hole, the relationship between AGN activity and ultraluminous starbursts, and the reason why some AGN in elliptical galaxies are radio loud (but not those in spirals). The relationship between members of the AGN zoo, ranging from the brightest quasars to barely-active Seyfert galaxies, is not understood.

There has been much debate on the relation between radio-loud quasars and radio galaxies (for a review see Antonucci, 1993). It could be that these objects are intrinsically similar but with differences that can be related either to their evolution, their environment or their orientation to our line of sight. The third possibility is currently the most favoured. In this scenario, the bright nucleus is surrounded by an obscuring torus of dust and gas, resulting in twin beams of continuum emission. If our line of sight falls along one of these beams then we see a quasar, otherwise the object appears as a radio galaxy.

A similar explanation can be applied to Seyferts, in which double cone-shaped emission has been observed directly. In Seyfert 1 galaxies, the Broad Line Region (BLR) can be seen in emission lines, but in Seyfert 2s our line of sight to the nucleus is obscured by the torus, making the BLR undetectable except in scattered light. One way to investigate the unified model directly is to image the very central part of the active nucleus.

Infrared imaging of the central regions is clearly important for our understanding of AGN. Dust near the nucleus will be heated by the UV flux from the central engine and there is good evidence that most, if not all, the infrared emission from AGN comes from heated dust (see Barvainis, 1992). The size of the emitting region is quite small. For example it is $5h_{75}^{-1}$ pc or 0.16″±0.04 (1 σ) in NGC 4151 (Neugebauer et al., 1990) at 10 μm.

About 20–30 nearby Seyfert galaxies are bright enough to be used as references for fringe tracking. For these, the central parsec will be probed in the optical and infrared. It is also useful to probe larger scales in more distant objects, to trace any cosmological evolution. Figure 5 shows simulated images of a typical AGN observed at different angular resolutions and Figure 6 shows how the angular sizes of the relevant regions scale with redshift.

If fringe tracking cannot be done on the object itself, a nearby reference star can be used. It is thus important to search for new objects (radio selected or by-products of planned surveys) located near bright stars. The overall impact of VLTI in extragalactic astronomy will depend on the sky coverage. Calculations for the adaptive optics system on a unit telescope in the visible predict a sky coverage of about 1% (Théodore et al., 1994). This increases by a factor of 4–5 if the correction is done in the near infrared and becomes even greater in the mid-infrared. A catalogue of bright stars in the near infrared is needed to search efficiently for observable objects.

3. Conclusion

On the basis of the above science goals, ISAC reached a clear consensus as to the appropriate phasing of capabilities that would minimise costs and maximise possible scientific benefits both in the short and long term. The recommendations are:

1. That the VLTI should be brought into operation as soon as possible.

2. That the development of VLTI should proceed in sequenced phases of increasing complexity, leading to the full implementation of the VLTI as endorsed by previous committees.

3. That the earliest phases should focus on:

(a) the near- and mid-infrared regimes (1–5 μm and 10–20 μm),

(b) the provision of single-mode instruments (i.e., a beam-combining instrument which covers a field of view equal to the extent of the Airy disk of an individual telescope of the array) for both of these wavelength regimes,

(c) the implementation of a narrow-angle astrometric capability in the near infrared,

(d) the deployment of three 1.8-m ATs with low-order adaptive correction (i.e., tip and tilt),

(e) the incorporation, at the earliest time possible, of two UTs augmented with low-order adaptive correction (i.e., tip and tilt),

(f) the capability to operate with up to four array elements simultaneously so as to permit reliable phase retrieval and imaging using closure techniques.

4. That the later phases should allow:

(a) operation at shorter wavelengths,

(b) incorporation of higher levels of adaptive compensation,

(c) operation using all four UTs as well as the auxiliary array elements.

The reaction of the whole ESO community to the ideas outlined in this article is warmly encouraged, and indeed may be pivotal in better defining ESO's programme. Please feel free to contact any of the ISAC members listed here or send e-mail to isac@eso.org. We also invite everyone with an interest in the scientific potential of VLTI to attend the ESO Workshop in Garching on June 18–21 where we look forward to constructive feedback.

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