EUROPEAN SOUTHERN OBSERVATORY

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Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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Scientific Objectives of the VLT Interferometer

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March 15, 2001

A. Executive Summary

Astronomers have long sought to improve the sensitivity and spatial resolution of their observations in order to see as far back in time and as sharply as possible. As the photon-collecting power scales as the telescope diameter D^2 and spatial resolution as D^{-1}, the solution of the problem has always been in the form of ever larger collecting-aperture telescopes. Unfortunately, although this solution did indeed increase dramatically the sensitivity of astronomical observations, it still was far from ideal in terms of spatial resolution owing to the negative effects of the earth's atmosphere. On the ground, the improvements were mainly due to finding the proper location where the seeing was best (California, Hawaii and Chile) and, more recently, to the technique of adaptive optics as shown schematically in Figure 1.

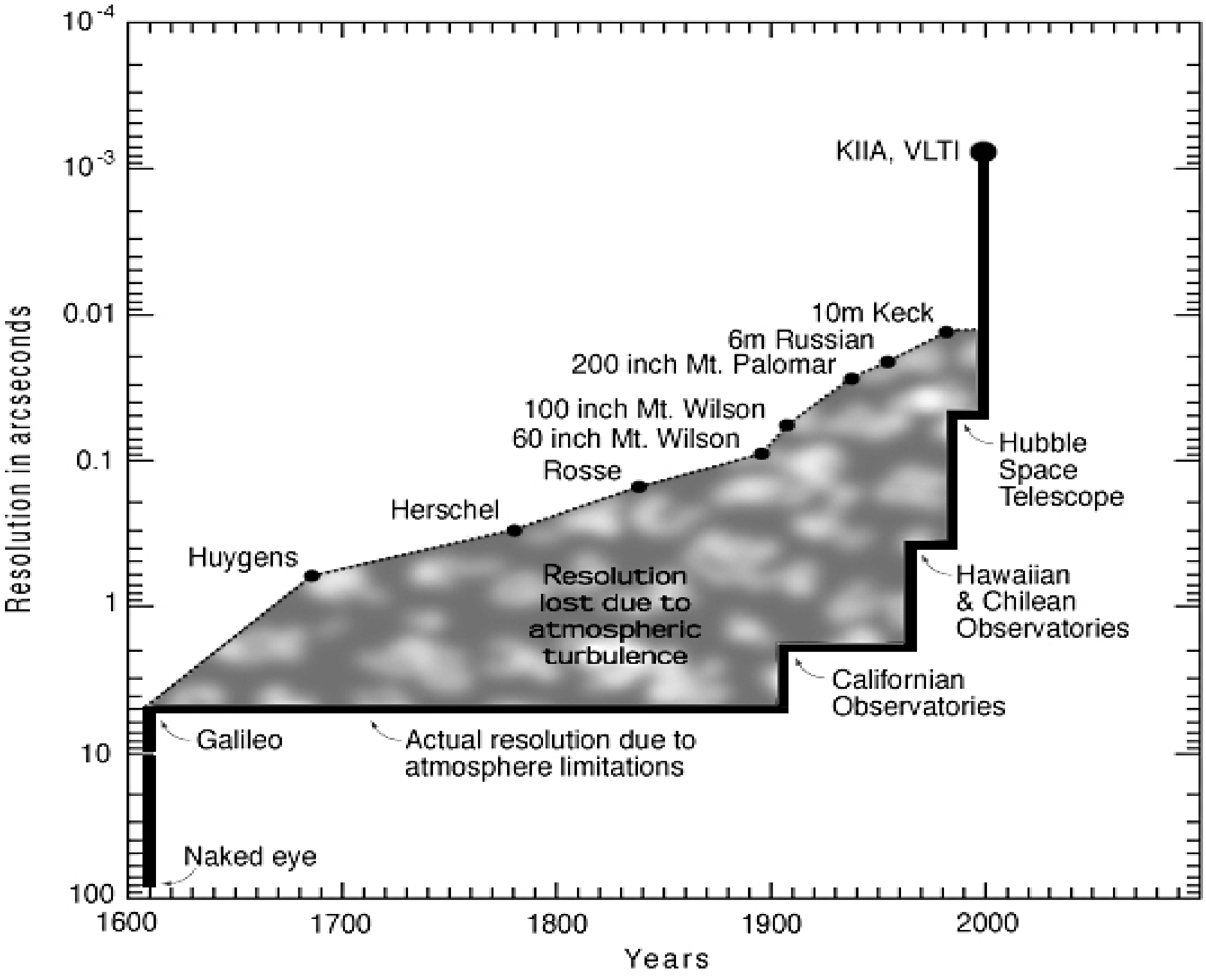

Figure 1. Spatial resolution as a function of historical time since Galileo. Adapted from P. Bely (ESA SCI(96)7, 1996).

Apart from the development of a ~100m diameter telescope, the foreseeable breakthroughs in optical/IR resolution in the near future are essentially only two: operating in space (HST and, in the future, NGST) and aperture synthesis interferometry. In essence, even going to space with a simple filled aperture telescope of 6m diameter (NGST) still does not approach the potential of the latter technique even on the ground. This is especially true in the infrared at 2.2 µ where very high sensitivity can be coupled to very high angular resolution of ~1 milliarcseconds (mas).

Because of these considerations, interferometry has 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 come on-line in the next few years. 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.

Table 1. Current Ground-based Optical Long Baseline Interferometer Projects

Program (Nation)	No. of Simultaneous Baselines (ultimate)	Maximum Baseline [m]	Telescope Diameter [m]	Status or Year of First Fringes
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 (USA)	1	100	0.45	Operational
CHARA (USA)	10	350	1.00	2000
KIIA (USA)	1/6/15[1]	75/180[2]	10/1.8	2001
VLTI (EUR)	6/3/21[1]	128/200[2]	8 /1.8	2001
LBT(USA/I/D)[4]	1	20	8.4	2005
MAGELLAN (USA)	1	20	6.5	>2005

Notes:
[1]) beam combination: main / auxiliary / hybrid
[2]) between main / auxiliary telescopes
[3]) heterodyne, to be changed into a homodyne interferometer
[4]) monolithic array

It has always been ESO's aim to operate the VLT in an interferometric mode which allows the coherent combination of stellar light beams collected by the four 8m diameter telescopes (UT) and by several smaller 1.8m diameter auxiliary telescopes (AT). Thus, the VLTI has the unique advantage of being the only large telescope facility together with the LBT designed from the very start as an interferometer. This means that it will have three main characteristics that are unprecedented for this type of array:

1) very high precision visibilities (up to $\Delta V/V=10^{-4}$) for moderately bright sources,
2) excellent UV coverage (a synthesized beam of 1-2 mas FWHM at 2μ),
3) very high sensitivity to faint sources (down to K~20 with a brighter reference).

Of course, it has to be realised that, in practice, these capabilities will be acquired over a period of time in various phases starting with the easiest to implement and progressing to ever more demanding capabilities. The dates listed in Table 1 represent the start of operations in the various facilities with the most basic of capabilities. In general, these phases can be broken down into the following periods:

Phase 1: two- beam combination to measure fringe visibility leading to the amplitude of the object’s Fourier transform. This phase usually includes the gradual development of additional capabilities leading to a significant improvement in sensitivity like on-source fringe tracking and wave-front reconstruction using adaptive optics (AO) techniques. In this phase, earth rotation and relocation of telescopes over a grid of different positions ensure a reasonable coverage of the (u,v) plane in order to obtain a well behaved point spread function for moderately bright objects (K~14). These capabilities allow one to reconstruct several components of the object’s Fourier transform and, by fitting to a few-parameter model, to invert the transform and extract useful astronomical information at resolutions of several mas for simple objects with the main arrays and moderate spectral resolutions in the 1-20μ range.

Phase 2: maintaining equal optical paths in the two beams to within a fraction of a wavelength or co-phasing the interferometer. Fringes can be tracked on a bright reference star, allowing long integrations on the fainter target source located an atmospheric coherence length away (~1’ at K). This allows phase-referenced imaging of sources of brightness up to K~20 with the UT (main array,VIMA) and very accurate astrometry with precisions up to 10 microarcseconds (μas) with a dual beam instrument such as PRIMA for the VLTI with the AT (auxiliary array, VISA). This phase will follow the first by a few years for the VLTI.

Phase 3: combining beams from more than three telescopes, ideally up to eight for a measurement of visibilities on 28 baselines simultaneously yielding a closure phase for 21 triangles. This would determine the exact fringe position as a measure of the phase of the Fourier transform of the object’s brightness distribution. Combined with the visibility measurements, this allows, in principle, model-independent reconstruction of an image of the object. This phase requires developing a complex 8-way beam combiner and using many delay lines implying an advanced sophistication in the management of many highly complex and extremely sensitive components working simultaneously. The final outcome is an instrument capable of generating images on suitable sources of a few tens to a few hundred non-zero intensity mas spatial resolution elements or as many as the number of independent measurements in the (u,v) plane. This phase might also include more sophisticated AO techniques to allow expansion into the visible range and higher spatial and spectral resolutions.

Phase 4: enlarging the instantaneous field of view of the array from a single telescope Airy disk (~0.1-1") to several arcseconds as required for imaging of complex extended sources such as a dense cluster of stars. This can be accomplished with a Fizeau-type interferometer with homothetic mapping over a large field. Attaining this capability, in essence, would place the VLTI at the pinnacle of human achievement in its attempt to resolve or distinguish very faint and distant astronomical objects as shown in Figure 1.

ESO is defining and prioritising the key science drivers for each phase of the program 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. As already evident from the position of VLTI in Figure 1 with respect to all other facilities currently available, the kind of data which interferometry will access is so far beyond our current experience that it is inherently difficult to specify a definitive science justification. Indeed, much of the prospects are more in the nature of the unexpected. Although optical interferometry carries within it the potential to revolutionise whole areas of astronomy, it suffers currently from the difficulty to exactly foresee the details of the revolution. No one yet has peered into the very core of an AGN, for example, as the VLTI surely will and one can only speculate by engaging in risky extrapolations as to what one might find there. This is especially true since interferometric performance is still not well understood for a large class of sources which are extended on the scale of a few Airy disks.

In any case, it is still relatively straightforward to foresee, at least in general terms and on the basis of the expected VLTI performance parameters just described, the areas of research where VLTI is most suited to providing the kind of potential breakthroughs that we currently require in order to better understand our universe. Although the VLTI targets are mainly located in our relatively local universe due to the limitations in sensitivity inherent in high spectral and spatial resolution interferometry even with large telescopes, the impact of these breakthroughs on our knowledge of the furthest reaches of the observable universe cannot be underestimated. This is especially true when one considers that much of the universe consists of stars and fundamental information on stellar formation, the IMF, binarity, ages and distances are crucial in unravelling the mysteries of galaxy and structure formation, the reionization of the IGM by the first stars etc.

These research areas are the following:

1) The structure and composition of the outer solar system.
2) The mass function of low mass stars, brown dwarfs (BD) and planets.
3) The direct detection and imaging of extra-solar planets.
4) The formation mechanism of stars and planetary systems.
5) The formation of star clusters and their evolution.
6) The surface structure of stars.
7) The accurate distance to galactic Cepheids, the Large Magellanic Cloud and globular clusters.
8) The baryonic composition of the galaxy's spheroid.
9) The physical mechanisms responsible for stellar pulsation, mass loss and dust formation in stellar envelopes and evolution to the Planetary Nebula and White Dwarf stages.
10) The structure and evolution of stellar and galactic nuclear accretion disks and associated features (jets, dust torii, NarrowLine Regions, Broad Line Regions etc).
11) The nature of the Milky Way nucleus surrounding the central black hole (BH).
12) Interacting binary evolution and mass transfer mechanisms.
13) The structure of the circum-stellar environment of stellar BH and neutron stars.

14) The evolution of the expanding shells of novae and supernovae and their interaction with the interstellar medium and its chemical enrichment.
15) The mass distribution of the galaxy beyond the solar circle.
16) The internal dynamics of star clusters and tidal interactions with the galactic potential.

In the next sections, some of these areas are described in more detail in order to give the reader a flavour of the kind of science that the VLTI can actually accomplish simply on the basis of our current but limited knowledge of where astronomy is going to lead in the next decade with facilities such as this one. Naturally, as the VLTI evolves in this time interval through the four development phases briefly outlined above, the quality and volume of information to be garnered in most areas will grow allowing fainter, more distant and/or more complex objects to be studied with greater accuracy.

B. Specific Objectives

Solar System

Solar system studies provide information on a wide variety of important topics such as the dynamical and chemical evolution of the Sun and its proto-planetary system, the physical processes leading to the formation of the planets and satellites and the initial conditions of the primordial solar nebula. Imaging the surfaces of asteroids and planetesimals will yield important information on surface composition and bombardment history as well as be useful to guide the selection of candidates for visits with space probes for in-situ observations and sampling. There are more than 500 minor planets known with K < 10 and with diameters > 8 mas. A significant fraction of these is known or suspected to be composed of two or more “pieces’. The angular resolution of the VLTI will allow us to clearly separate these components and to follow their relative orbital motion. Mass determinations will become possible and we will gain insight on the physical processes at work in the formation and destruction of asteroids.

Of particular interest currently are objects such as comets, Kuiper belt objects and outer satellites that have escaped differentiation effects due to external or internal heating and that can, therefore, provide crucial information on the earliest stages of planetary formation.

The typical angular size of a comet nucleus at a heliocentric distance of 1 AU where activity is most interesting and brightness close to maximum is of order 10-15 mas. Observations in the 10-20μ region where penetration of cometary nuclear dust is most effective and with moderate spectral resolution would yield the size and shape of the nucleus. In the best cases, it would also yield the positions of the hot spots, the rotation period and the polar axis as well. Synergy between VLTI imaging of the nuclear region, simultaneous AO imaging of the outer gaseous envelope and high resolution UVES spectra of the coma and nuclear gases allows an unprecedented global view into the structure of the comet and the physical mechanisms responsible for its evolution. The good UV coverage and flexibility of the VISA array make it the ideal instrument for this task.

For the higher sensitivity required for the fainter trans-neptunian objects whose angular diameter may be only of order 3-4 mas, the VIMA array with an external reference for fringe tracking and wavefront correction will be better suited. Here, the shape of the object and its possible variation in time due to projection effects will be the interesting parameters never before measured. The presence or absence of companions would also yield very exciting new information on the dynamical history of these objects and a first measure of the collision rate in the outer reaches of the solar system.

Although space probes are clearly preferable when they are actually there, they are not always available when most needed. In these cases, the VLTI will fill in the gaps in coverage by, for example, imaging the rapidly changing surface of Io in search of new volcanic activity or by probing the surface of Titan in the near IR atmospheric windows. These windows allow one to search for features that might be the signatures of altitude and possible compositional variations. The VISA array would resolve Io with 100 pixels along its equator where the maximum of volcanic activity occurs. The volcanoes have typical sizes of ~12 mas at 5μ and brightness of M~6-7, features easily resolved with the MIDI instrument once its sensitivity is extended this wavelength range.

Very high resolution imaging of the "quasi" trans-neptunian objects Pluto, Charon and Triton fall into a similar category. In some cases, the target itself can be used for fringe tracking but in others there will certainly be a need for an external reference whose presence at some point is made likelier if not certain by the large proper motion of the target, an advantage most other astronomical objects lack.

Extra-solar Planets and Proto-planetary Disks

Since 1995, at least 50 objects classified as planets have been unambiguously detected (see compilation in http://www.obspm.fr/encycl/catalog.html) orbiting around nearby solar-like stars. Although there have been some doubts raised as to the reality of some of them, especially 51 Peg, subsequent even more refined observations have swept away all remaining doubts. As techniques get better, accuracy improves and surveys get more telescope time, this number is bound to increase dramatically.

Already, the statistics of the current searches indicates that planets are found around a few % of the nearby solar- like stars. Since all of the discoveries so far, except Lalande 21185, have been made by means of the reflex velocity (RV) technique, the derived mass of the planet is always a lower limit and the true value will depend on the unknown inclination i of the orbit. This uncertainty disappears for the reflex motion technique used in precision astrometry as planned for the VLTI PRIMA facility.

This is a crucial point since current controversies swirl around the very definition of a planet versus a BD or even a low mass star and this depends entirely on the mass of the object. The latest "planet" discovered around HD168443, for example, has an implied msini of 17 M_J ($1M_J$ = Jupiter mass = 0.001 $M_\odot$) and, therefore, may not be a planet at all but a brown dwarf (BD) since the upper mass limits for planets is ~13 M_J. Below this mass, objects never burn deuterium nor generate significant energy from any nuclear reactions. This limit, however, is only empirically determined by the observed mass function which currently looks like that shown in Figure 2 and clearly suggests a distinction between the occurrence probability of objects above or below this limit. But this function depends crucially on getting the masses right and the sini term definitely prevents this. Only by performing astrometry on these objects will one get a compelling answer to the question of what is a planet as opposed to a BD. Already, Hipparcos- determined masses of some of the objects in question have shown, in almost all cases, that their masses were underestimated.

Indeed, several formation mechanisms giving rise to a variety of objects (planets, BD or low mass stars) of very different masses are being currently considered:
1) direct fragmentation of a collapsing, rotating interstellar cloud,
2) gravitational instability in an equilibrium disk which has condensed out of the collapse,
3) multiple fragmentation and capture in a system of major and minor fragments and,
4) accretion of solid particles in a disk to form a solid core of a few to 10 earth masses (the gas giant cores of the currently popular planet formation paradigm) followed by rapid accretion of the gaseous envelope.
The formation phase in any of these scenarios might be followed by inward orbital migration due to interaction with the massive accretion disk and consequent loss of angular momentum.

The planets we are observing now are certainly not anything like those in our own solar system. This is mainly due to the strong observational bias still present in the peculiarities of the RV technique that favours detection of large planets in orbits very near the parent star that give rise to the highest velocities. This effect is clearly evident in Figure 3 that shows the orbital star-planet separation in AU plotted against the planetary mass. The positions of a number of stars, BD, and planets observed with the RV technique are plotted with the uncertainty in mass due to the sini term. Planetary symbols represent the solar planets. The observation limits corresponding to radial velocity precisions of 250, 10 and 3 m/s are shown running inclined towards the right while the narrow-angle astrometric limits of 10 and 50 μas run inclined towards the left (only objects to the right of these lines are detectable at these limits).

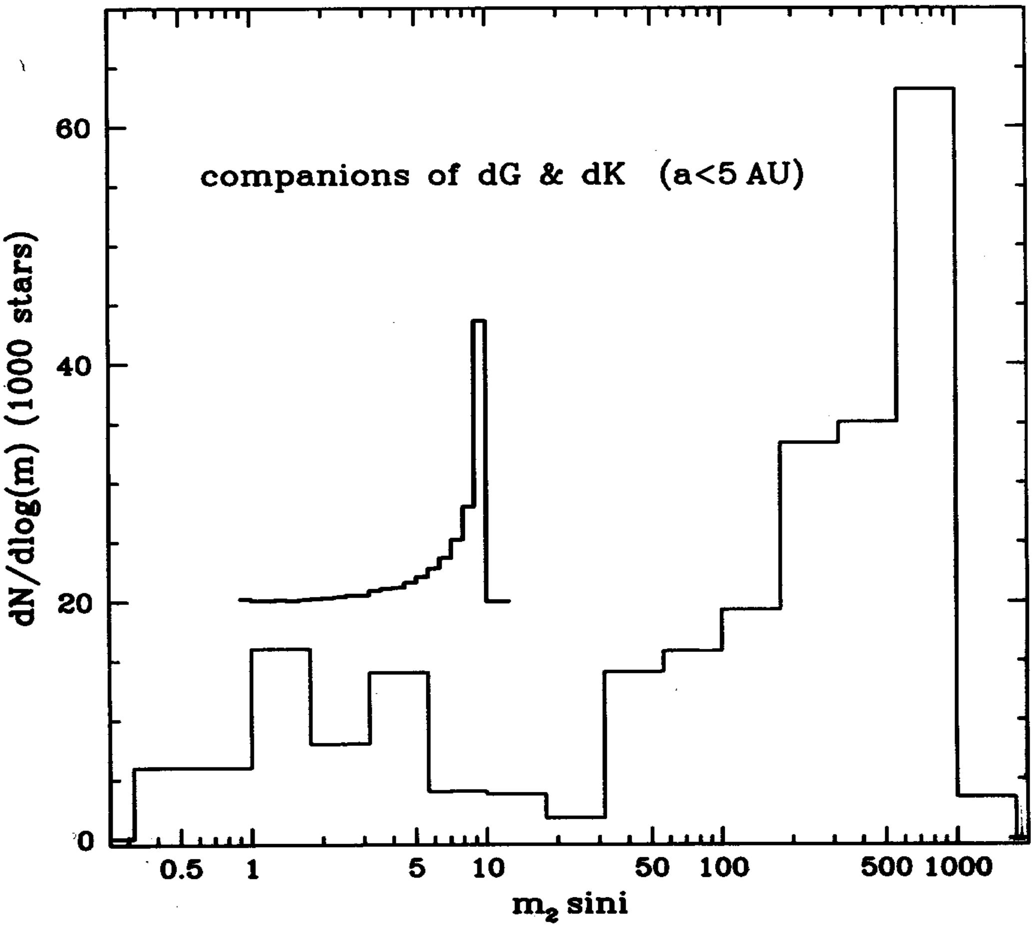

Figure 2. Mass function of extrasolar planets in units of Jupiter mass detected so far out of ~1000 stars from Queloz (ESA SP-451, 2000)

It is evident how the two techniques are complementary to each other. The RV technique is particularly sensitive to close-in massive planets around stars at any distance but only those whose spectra is particularly rich in absorption lines that can be used to determine the radial velocity to the exquisite precision required. In contrast, the astrometry technique favours the intermediate mass planets orbiting at larger separations. Both techniques still have a wide region of overlap, however, that can be conveniently exploited to get to a unique determination of its mass.

Two issues are particularly clear from an inspection of Figure 3. First, the mass uncertainty of the RV method is large enough to move, in principle, most objects from one category to another. For example, most objects classified as BD could well be stars. That they actually turned out to be so after an Hipparcos distance calibration did not bode well for the sample statistics. But some planets could also move to the BD category. Second, it is clear that only by observing the same objects with the astrometric mode of the VLTI can one be sure of the precise mass. Since most planets detected so far by the RV method are located at a distance of 10-20 pc, the 10 μas VLTI limit comfortably allows this measurement for most of the known extra-solar planets.

It is already clear that planets far different from our own exist in abundance and the theories of planetary formation will have to be substantially revised or expanded to account for them. Pinning down the details of any of these mechanisms will clearly require substantially better observational techniques to uncover new planets and especially to completely characterise them physically and chemically. Consequently, two crucial steps need to be carried out as soon as possible:

1) use the VLTI to enlarge substantially the sample of stars searched for planets to include Pre Main Sequence (PMS), early-type Main Sequence (MS) and low mass stars that the RV technique cannot cover at all so that we

are not restricted to the nearby solar- like stars which can only represent a very thin cross section of the planetary zoo and

2) perform very high precision astrometry and high spectral resolution direct imaging of the planets and the gaseous and dust disks out of which they are most likely to form and on which they will impress their peculiar dynamical signatures.

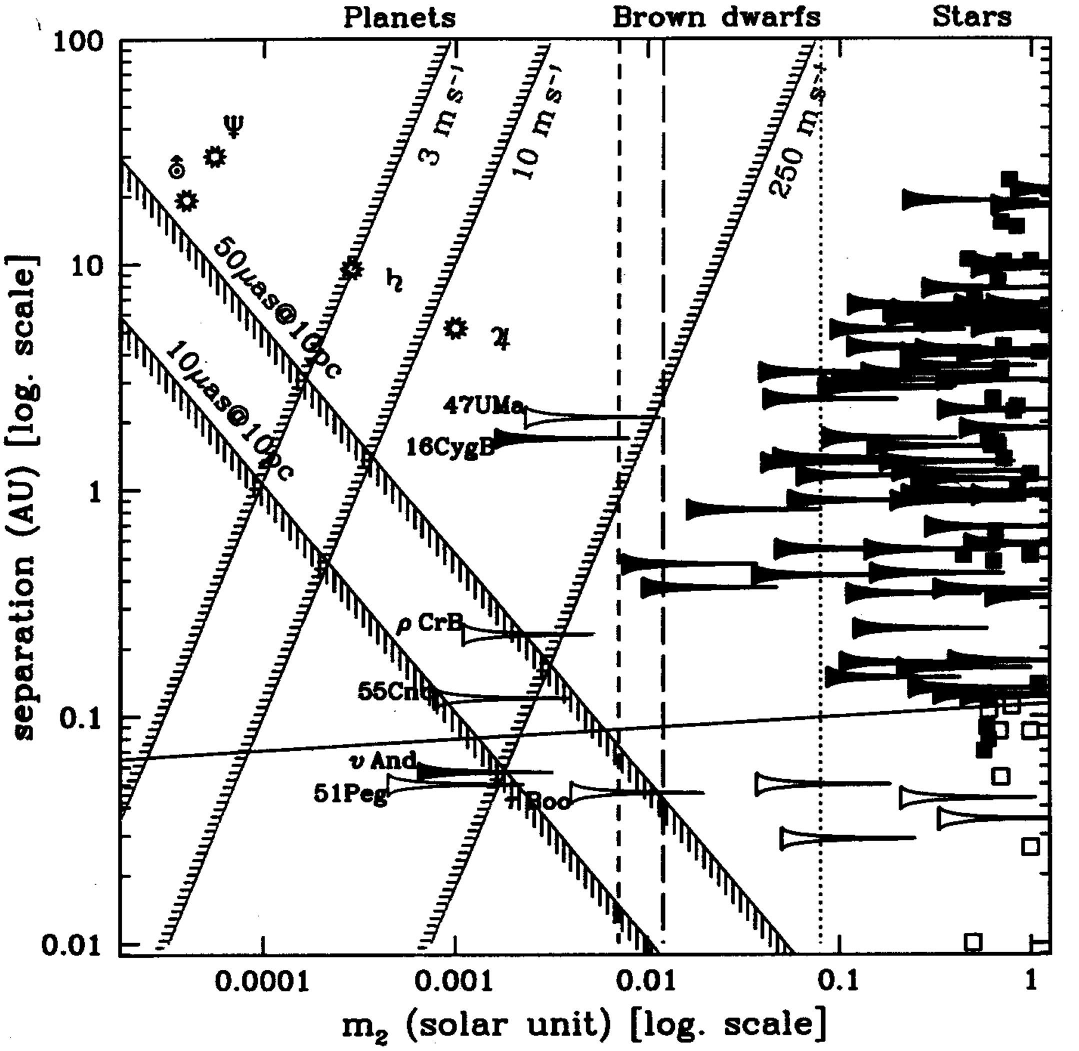

Figure 3. The mass-separation diagram for binaries with RV and astrometry limits from Mayor (2000).

The VLTI as presently designed can accomplish this ambitious but absolutely critical task by relying on its capability to support high precision phase referencing. This characteristic will be critical in order to perform the high precision, narrow angle astrometry required to reach the predicted atmospheric limit of 10 μas accuracy at Paranal. Attainment of this performance will allow the reflex motion induced by an orbiting planet on a star located at the distances shown in Figure 4.

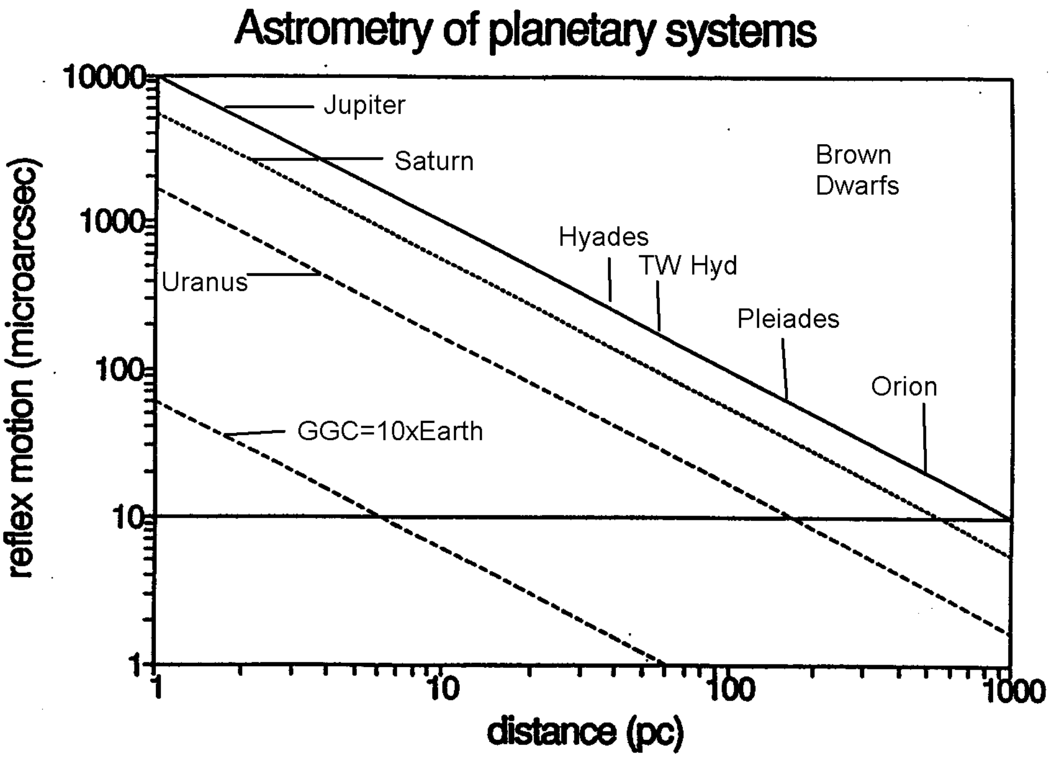

Figure 4. The expected astrometric reflex motion of objects of different masses as a function of distance. The VLTI is expected to measure reflex motions > 10 μas.

This figure shows how the VLTI in its astrometric mode would cope with a planet of a Jupiter, Saturn, Uranus or Gas Giant Core (GGC) of ~10 earth masses placed at either the Jupiter radius of 5 AU as expected for a solar-like star or closer for a cooler companion. Since the closest star forming regions (SFR) are located between ~50 (TW Hyd) and ~140 pc (Taurus-Auriga) from the Sun, the VLTI would be in the enviable position of easily finding Jupiter-sized planets around stars of any spectral type and, most significantly from the physical point of view, of any age up to the MS.

This capability would, in fact, allow the VLTI to explore, for the first time, both the precise time of formation and the subsequent evolution of planets in all PMS stages leading into and well up along the MS. Since VLTI astrometry is not limited to solar- type stars as is the RV technique, it can also quickly attack and resolve the burning issue related to the strongly implied possibility that the IR excess MS stars like Beta Pic, Fomalhaut and Vega have or have not already formed planets in their observed debris disks.

The VLTI, by exploiting its dual mode of operation with phase referencing, can, at the same time, probe in considerable detail not only the planet itself through its effect on the motion of the parent star but also the evolution and structure of the proto-planetary/proto-stellar disk from which it eventually must emerge and interact. This affords another unprecedented opportunity to finally understand and pin down the presently uncertain connection between the two phenomena. At the typical distance of the MS early type star IR excess disks, for example, the VLTI IR spatial resolution of a few mas ensures a clear probe of these disks down to the level of a few tenths of AU resolution at a few AU radii where most of the interaction between a possible planet and the edge of the small particle disk is expected to occur.

Direct detection of photons originating from extra-solar planets gives crucial information on these bodies that cannot be obtained with indirect methods. With direct spectroscopic and photometric observations it is, in principle, possible to determine size, temperature, chemical composition, atmospheric stratification, rotation rate, and the presence of surface features. Because of the faintness of extra-solar planets, and because of the large contrast between planet and parent star, such observations are extremely challenging.

With the VLTI equipped with spatial wave-front filters such as single mode optical fibers, the fringe amplitude can be measured with great precision. This can be used to make measurements of ``double stars" with large magnitude difference, such as star-planet systems. Gaseous planets have strong molecular absorption bands. Within the bands, the planet is dark, and the photo-center of the star-planet system is centered on the star itself. Outside the bands, the photo-center is shifted slightly towards the planet. This shift of the photo-center might be detectable as a wavelength-dependent phase shift with the VLTI.

Fundamental Stellar Parameters

In the standard homogeneous and isotropic FRW cosmology, the main observables such as the present mass density relative to the critical density, the cosmological constant, the Hubble parameter and the age of the universe are all inextricably linked to one another. While the first two have proved stubbornly resistant so far to accurate measurement, the latter are definitely on better observational footing. Thanks mainly to the HST key program, Ho has been determined to a formal two σ standard deviation error of 12 $\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$ or a 20% relative error. The age of the universe is limited by the age of the oldest stars in globular clusters to the range 10-17 Gyrs. These are still quite significant errors which prevent much better concordance on the proper cosmological model.

The critical observational challenge facing the VLTI today boils down to reducing the uncertainty on both these parameters from the presently cosmologically equivocal 25% to the unequivocal 10% or better level.

A similarly difficult situation exists for stellar masses whose determination is especially critical at the lower end of the MS as we mentioned in the previous paragraph and down into the BD regime even though 90% 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, just properly establishing an observational mass-luminosity (M-L) relationship for stars with masses smaller than 0.3 $M_\odot$ for different metallicities is still a very active field of research. Present observations are still unable to significantly constrain the lower end of the mass function (IMF) that is produced by the star formation process and the resultant uncertainty in its shape implies an uncertainty in galaxy masses of factors of 2-3 or more. Finally determining the size, shape and composition of the putative dark baryonic matter in the galaxy's spheroid is another important task made possible by accurate mass measurements.

The VLTI can provide such measurements even in the very first phases of operation by means of measurements of angular stellar and orbital diameters with very accurate visibilities. In general, the angular diameter of the uniformly illuminated disk of a star θ in mas obtained by a single-parameter fit to the calibrated visibility curve is related to the bolometric luminosity L in Watts/cm^2, effective temperature Te, linear radius R and mass M in solar units and distance d in pc of the star by the relations:

$$\theta^2 = 1.316\cdot 10^{11} L T_e^4 = 21.5\cdot\left(\frac{R}{d}\right)^2 = 21.5\cdot\left(\frac{M^\beta}{d}\right)^2 \qquad 1)$$

where β is the index of the mass-radius relation for the type of star in question ($\beta\sim 0.7$ for the main sequence at $\sim 1\ R_\odot$). Thus, at least in principle, an accurate measurement of θ and L coupled to knowledge of the distance d, yields the fundamental physical parameters of the star.

To be of greatest astrophysical significance today, θ needs to be determined to an accuracy of 1% or better for a significant sample of stars of all spectral types, luminosity classes, metallicity, ages etc. so that theoretical stellar models can be put to serious test at a precision at the 2σ level on T_e of +/- 50K or better. The ideal way to approach this problem is to apply this technique to stars already having good, high S/N spectra that can be compared to theoretical models. The best fit to the spectra yield values of T_e, g, [Fe/H], L, and rough values of M, and R through the relation $g=GM/R^2$. Interferometry yields much higher accuracy values of T_e, M and R (if d is known) that must be reconciled with the spectroscopic determinations by means of improved models. Parameters that are currently unconstrained especially in young and low mass stars such as the depth of convective regions and the mixing length as a function of spectral type would become finally amenable to precise measurement.

The calibration of T_e with spectral type is well established and reliable presently only for MS stars hotter than ~4500K and for giants hotter than ~3000K. For later-type stars this fundamental test of stellar models breaks down. Thus the T_e of cool stars on the MS, of chemically peculiar cool giants (Carbon stars, for example) and T_e variations with phase for Mira variables are some of the most pressing open issues in this area of research to which the VLTI is expected to contribute significantly.

Dynamical masses can be accurately determined by using the VLTI to resolve binary and multiple-component orbits. The basic observational material consists in the angular separation and position angle specifying the relative orientation of the components as a function of time and the period. Masses can then be determined from application of Kepler’s third law. Only a few dozen stars have accurate mass determinations currently but tens of thousands of stars are well known binaries so the potential of exploiting this technique is enormous. Moreover, the VLTI will have at least ten times the resolution of the very best speckle imaging techniques used presently so that the sample will grow exponentially (most stellar populations have binary fractions of order 50% or more).

The quality of the measurements depends critically on any auxiliary information available for each system. For a simple “visual” binary of known distance and measured period and orbital semi-major axis, only the sum of the stellar masses can be derived but the addition of the individual component semi-major axes obtained from a full orbital solution and the spectrum yields the individual masses and luminosities. Working up the ladder of information complexity, knowledge of the RV characteristics for the system as in single-lined binaries or for both components as in the double lined binaries then yield the masses independently of distance but with the sini degeneracy already discussed on p.7. Again, use of the VLTI eliminates all ambiguity. Application of this powerful technique is expected to provide the benefits described in more detail in the following paragraphs.

Stellar Distances

The biggest contribution (80%) to the quoted Ho uncertainty comes from the uncertainty in the distance to the LMC while 10% comes from the Cepheid P-L relation. In both cases, the error stems one way or the other from uncertainties in the physics of the nearby and LMC Cepheids. While determining P is relatively straightforward, obtaining L is quite less so. An ideal solution, of course, is to use Hipparcos parallaxes to nearby Cepheids to obtain the first step in the ladder independently. Unfortunately, this is not useful at the moment because the Hipparcos distance errors to the nearest Cepheids amount to 30% or more partly due to the fact that about 60% of these Cepheids turn out to be binaries.

A better way out of this dilemma is to actually use the VLTI to accurately measure a Cepheid diameter during its pulsation and, using simultaneous RV velocimetry, derive a distance by inverting equation 1, on p.10. VLTI can resolve the 20-25 nearby Cepheids within 1 Kpc and obtain diameter measurements of exquisite precision (+/- 0.25%) with 20-30 minute sequences over 2 pulsation periods in most cases. A simulation of this situation in the particular case of Zeta Geminorum assuming an expected pulsation amplitude of 15% of its average diameter typical for these objects is shown in Figure 5. The binaries among the sample can, of course, also be resolved with VLTI thus avoiding the Hipparcos problem.

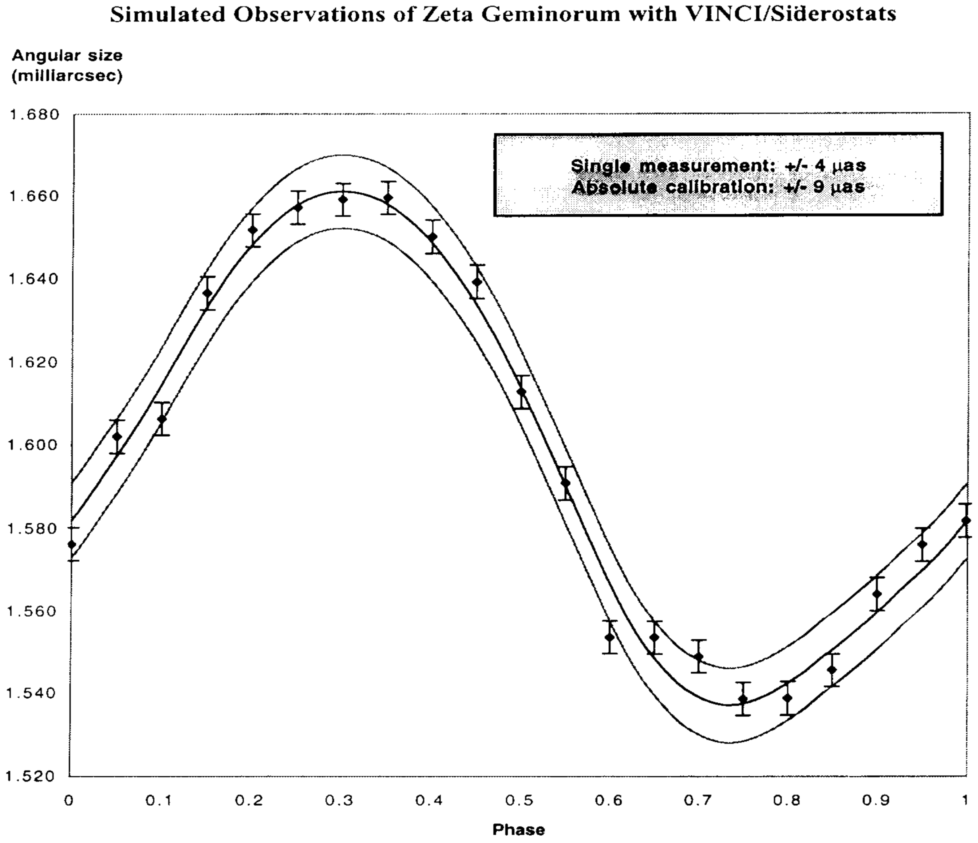

Figure 5. Zeta Geminorum expected pulsations from Kervella.

The conversion to distance can be made via the projection factor p that is model- and limb-darkening-dependent. Presently, one can expect the precision of knowledge of p to be ~1% or better which will then be the expected precision on the distance itself, a full order of magnitude better than required. Moreover, sampling of the star over many baseline orientations and pushing well beyond the first null will yield fundamental new insight into the pulsation mechanism and possible anisotropies in the envelope.

At the very edge of possibility for the VLTI in its astrometric mode in Phase 2, is resolving the orbit of a single-line spectroscopic binary in the LMC thus obtaining a true geometrical distance determination to this crucial step of the distance ladder. The expected precision of 50 µas corresponds to ~0.15 AU at the distance of the LMC so that an LMC system brighter than V~16 could be resolved with PRIMA if it is located within 20-30" from a bright reference source used to co-phase the interferometer.

Well-detached eclipsing binaries offer another very exciting way to get at the vexing problem of stellar distances. The shape of the alternate eclipses provides information on the fractional radii of the two stars with respect to the separation of the two centers. The light curve analysis provides the values of period, inclination and eccentricity. The RV curves together with this information give the linear size of the orbit and the radii of the two stars. Normally, this information is coupled to an estimate of the luminosity of and reddening to the system in order to derive a distance. Especially the reddening is uncertain enough to make the method somewhat unreliable. The interferometric measurement of the angular radius of one or both of the components via eq.1 on p.12, however, immediately yields the distance without recourse to an uncertain luminosity conversion. In principle this method should yield by far the best and most accurate distances in the next decade.

Stellar Masses.

A star's mass and chemical composition completely determine its structure and appearance and evolution from birth to death. The former is usually very difficult to determine directly and is normally inferred indirectly from its luminosity, composition and the theoretical M-L relation unless the object under study happens to be in a binary. Thus, an attack on the general problem of accurate mass determination depends crucially on a reliable calibration of the empirical M-L relation.

The first step is to perform radial velocity surveys of large samples of low-mass stars in search of spectroscopic binaries. These can and will be accomplished, for example, with the FEROS and HARPS instrument on La Silla. These surveys provide fundamental statistical results but alone can only yield masses for each component if combined with direct imaging measurements. The combination of high precision ~10-15 ms^{-1} radial velocity data with parallaxes provided by Hipparcos and angular separations from VLTI would allow the determination of masses of very low mass stars to precisions at the 1% level. Even the mass of a suspected 0.03 $M_{\odot}$ BD companion could be estimated with ~5% accuracy, firmly establishing its sub-stellar nature and allowing one to test evolution scenarios for these objects.

The importance of such precisions cannot be underestimated. Current theory predicts, for example variations between different metallicity and age models that require this type of accuracy or better. This is shown clearly in Figure 6 where expected M-L relations are plotted with old observational data and the new speckle imaging data on triple systems just becoming available.

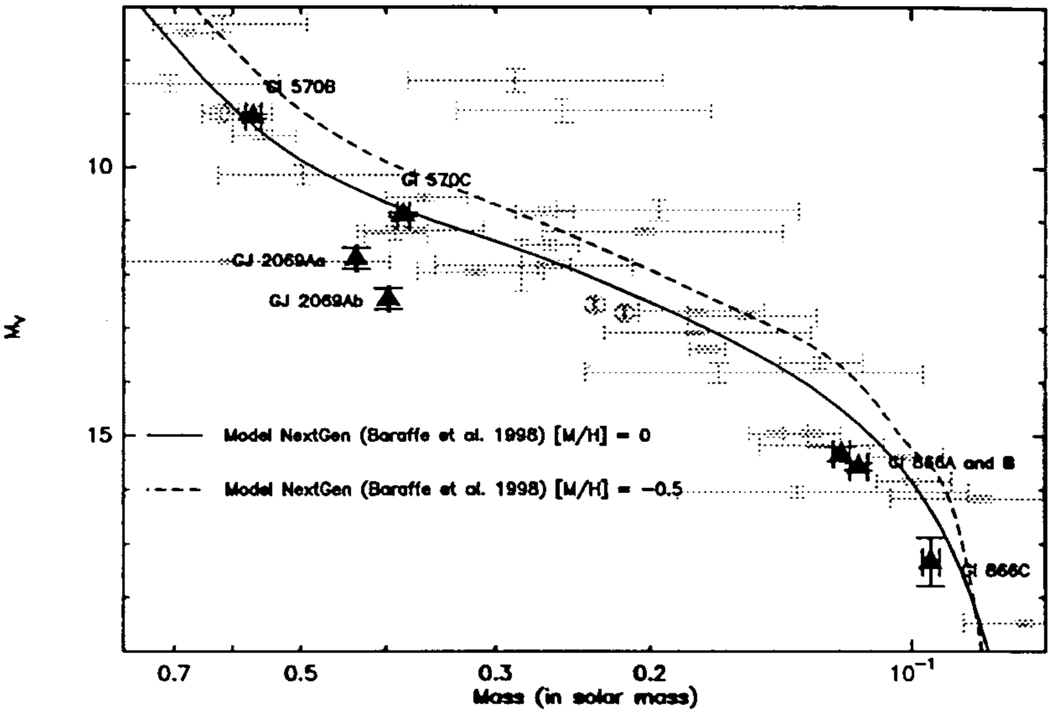

Figure 6. The observed and theoretical M-L relations for low mass stars from Delfosse et al., A&A, 350, 39, 1999. The model curves show the expected difference due to a metallicity change of half a dex. The points with dotted error bars are obtained with visual and interferometric pairs while the points with the solid bars are obtained with HST astrometry and AO imaging techniques.

Here one can easily judge how critical it will be for VLTI in the next few years to fill in such a diagram for a variety of low mass objects in different physical conditions in order to pin down the correct theory. Once this is accomplished for a wide range of stellar types and populations, the theoretically tested empirical M-L relations can be used to obtain an accurate census of stellar masses to derive the stellar IMF. This will be especially important to be able to tell whether or not the IMF is universal or if it depends on the stellar birth environment.

Exploiting the already existing body of information on double and single-lined spectroscopic binaries would be by itself a compelling project for the VLTI. Several hundred DL binaries have angular separations in the range easily covered by the VISA facility and these would immediately yield component masses and distances with a known orbital solution. Approximately 70% of the SL binaries known are resolvable with VISA and a

Hipparcos parallax would again suffice to derive good masses. High precision astrometry of the 50 or so known extra-solar planets would yield the orbital inclination and, therefore the mass of the planet directly. This would allow a far better understanding of the position and origin of the presently controversial dividing line between brown dwarfs and planets around 13 M_J whose origin is still unclear as already discussed on p.6.

Stellar Ages

The precise determination of the age of stars in globular clusters (GC) is particularly critical since the GC are the oldest identifiable objects in the universe and, as such, may have been among the first stellar systems to form after the big bang. This measurement would then yield a severe and compelling constraint on the age of the universe. Unfortunately, neither the absolute ages of GC stars nor the relative ages of GC has been resolved to the accuracies required. Current estimates range from a low of 10 to a high of 17 Gyr.

The main reason for these huge discrepancies lies in the very difficult task of determining accurate distances to the GC. Lately, a new method has been devised to measure the age of a GC via a deep Strömgren color-color diagram that is independent of distance and relatively insensitive to foreground absorption and can, in principle, yield absolute ages with an internal precision of 0.3 Gyr or better. The only disadvantage of this approach is that it relies heavily on the accuracy of the T_e-color scales of the theoretical isochrones used to fit the observed diagrams. Thus, currently available accuracies in these parameters limit the accuracy of the age determination to a few Gyr, still not significant enough to constrain cosmological and galaxy formation models.

The theoretical models used in this type of investigation rely critically on the color and T_e calibration of field population II (subdwarfs, turnoff and subgiant) stars with accurate parallax-based distances. The VLTI can easily resolve some of the nearest objects in this category and, as was discussed in an earlier section of this document, obtain very accurate T_e values (+/-25K) directly without appealing to any particular model. By measuring a variety of nearby halo objects this way in conjunction with accurate Strömgren colors, one can collapse the color-T_e errors to very low values and such as to allow very precise age determinations to the GC.

Binary Frequency

SFR offer a unique opportunity to investigate the early evolutionary stages of stars and their surrounding environment, with important implications on our understanding of the subsequent evolution on the main sequence. Among the many physical phenomena which are observed in SFR, an important role is played by the presence of binary stars.

The current picture is that, at least in the case of the Tau-Aur SFR, there is a higher frequency of binaries than observed on the main sequence in the same period range as shown in Figure 7. In this figure, the solid line represents the observed binary frequency for solar-type stars in the solar neighborhood, as derived by Duquennoy & Mayor by means of a statistically complete survey using radial velocities. The shaded areas represent the binary frequency observed by lunar occultation (cross pattern) and speckle interferometry (gray) among T Tau stars in the Tau-Aur SFR. An excess with respect to the main sequence is evident. It is noteworthy to stress that some spectroscopic binaries are also known, with periods in the $\approx$1-1000^d range. These kind of observations are particularly challenging, and a total of only 25 spectroscopic binaries are known or suspected over all SFRs, of which only a fraction has a confirmed solution.

This evidence has pushed theoreticians to improve models, or produce new ones, in order to reproduce the observed binary frequency. Many ideas have been developed for star formation mechanisms as discussed on p.7. Some of these models seem to hold enough potential for a realistic approximation of the observed binary frequency, however there is a wide range of parameters that needs to be constrained. For this reason, several quantities would be needed from observations. Among them are the frequency of binary systems with period, the distribution of eccentricities, the distribution of secondary masses, the presence of accretion disks and their correlation with the binary characteristics.

The main difficulty in extracting useful constraints for the current theoretical models from the available observations is in the limited database available. Only for Tau-Aur, the nearest (140 pc) among the relatively rich SFR and the best studied one, is there a sample with a significant statistical basis. Already in the second best-studied case, the Sco-Oph SFR at 160 pc, the available numbers are smaller and they become practically insufficient, either in terms of resolution achieved and/or of star sample, for all other SFR. Wider samples are needed to draw firmer conclusions about the reality of the observed binary excess. In particular, also for Taurus where the result seems more certain, it is difficult at present to ascertain whether the excess extends over the whole period range or not. The frequency of the spectroscopic binaries, which fall in the leftmost part of the histogram of Figure 7 seem consistent with that observed on the main sequence, but the statistics is too small to put a significant constraint.

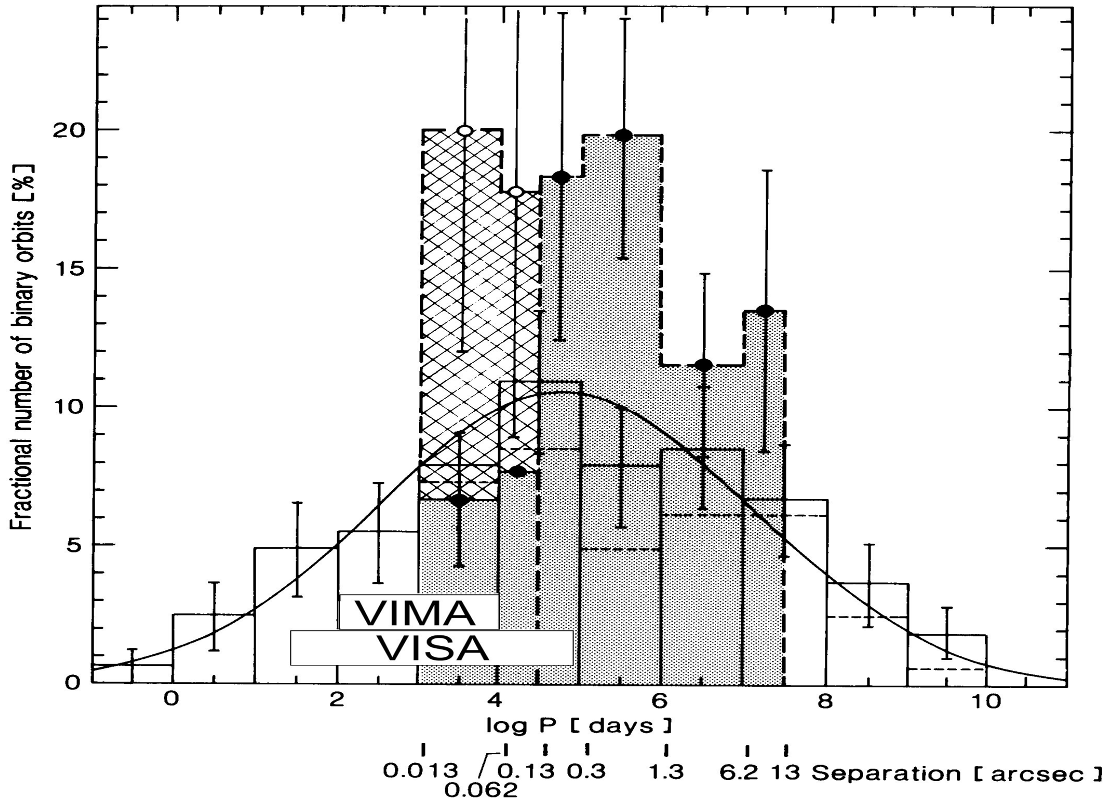

Figure 7. Binary frequency in the Tau-Aur star-forming region, adapted from Richichi et al., A&A, 287, 145, 1994.

The situation is complicated by the fact that in other SFR, notably the Orion association, current surveys provide a binary frequency which is fully consistent, in the measured separation/period range, with that on the main sequence. Whether this is due to a difference in the star-formation mechanisms at work in different SFR, and whether there is a correlation with the physical properties of the individual SFR (for instance, the stellar density or the presence of winds from hot OB stars), is an intriguing question that needs more data and from more SFR to be answered.

The VLTI maximum baselines will provide an angular resolution close to 2 mas. This is equivalent to 0.1 AU at the distance of the Tau-Aur SFR and 0.05 AU at the distance of the closest known SFR, the TW Hyd cluster. This is a significant step towards bridging the gap between the resolution currently available from high angular resolution methods, and the range of the spectroscopic binaries. The range which can be covered by the VLTI in the VISA/VIMA configurations is reported schematically in Figure 7. The sensitivity provided by the AT should be sufficient to cover the entire T Tau population in the Tau-Aur SFR.

The boost in angular resolution compared to what is currently available will allow the extension of this kind of studies to other, more distant SFR. An additional step of one decade in the separation/period range, means that histograms similar to those of Figure 7 can be produced for SFR which are 10 times more distant than Tau-Aur, i.e. out to 1-2Kpc. In turn, this means an improvement in the statistical basis of $\approx 10^2$ (including the effect of the galactic disk thickness and disregarding density effects within it). The apparent decrease in brightness of the T Tau stars in more distant SFRs should be largely balanced by using the UTs in place of the ATs.

The possibility to cover a wide wavelength range, at least for the relatively nearby SFR, from 1 to 10μm, as well as the possibility to investigate the sources with a choice of several spectral resolutions, will open the possibility to study in more detail and with a wider statistical significance the presence of infrared companions and circumstellar disks. The availability of many baselines will permit a quick access to complete solutions for binary pairs, and to investigations of complex structures such as disks. In particular, the possibility to combine the light from three telescopes at a time included for instance in the AMBER instrument will speed up the time required to complete surveys of binary stars, doing away with the need to relocate telescopes to obtain independent baseline projections.

The increased angular resolution will allow a measurement of actual orbital motions, at least in the most favorable cases. At the distance of the Tau-Aur SFR, an orbital period of one year corresponds to an orbit diameter of about 14 mas, and significant changes of the companion's position should be detectable in a matter of a few days using the PRIMA astrometric facility. Alternatively, it will be possible to detect orbital motions for much wider systems on time scales of months. The key to this capability is the high accuracy of the VLTI instruments VINCI and AMBER to achieve relative precisions at $\leq 10^{-3}$ in the visibilities. This will permit to extend the actual resolution well beyond the theoretical diffraction limit of the baseline.

AGB and Post-AGB stars

All stars with initial masses less than ~8 $M_\odot$ 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} $M_\odot yr^{-1}$ and expansion velocities of 5-30 kms^{-1}. The locations of the main structures constituting a typical AGB atmosphere are shown schematically in Figure 8. The VLTI resolution in the near IR of ~ 1 mas corresponds to a linear projected resolution of 1AU at 1Kpc.

AGB stars are characterized by a low effective temperature and a dense, slowly expanding stellar wind. The density in the extended atmosphere of the star is high enough for molecules to condense into solid dust particles. For low mass loss rates, the dust remains optically thin and the stellar photosphere remains visible. This is no longer the case for mass loss rates exceeding about 10^{-5} $M_\odot$/yr. The radiation of these dust-enshrouded stars is emitted at mid- and far IR wavelengths. These high mass loss rates cause the envelope of the star to be rapidly removed, effectively terminating AGB evolution and causing the white dwarf to emerge. Therefore AGB evolution cannot be understood without a reliable description of mass loss as a function of stellar properties and as a function of time.

A simple but basic measurement of the radius of an AGB star would allow critical tests of the dynamical model atmospheres that have been developed in the past few years. This test will be even more constraining if the stellar radius is measured at different wavelengths in the IR, since these spectral regions probe different layers of the atmosphere.

Current ideas concerning the physical mechanism causing AGB mass loss involve a complicated interplay between stellar pulsation and the condensation of dust in the inner parts of the wind. There is a well established observational link between the mass loss rate and stellar pulsation, but so far theoretical calculations have only partially been successful in reproducing the mass loss rates observed for some well-studied cases. An important constraint on dust condensation models is the location where the dust actually forms. Mass loss sensitively depends on the dust condensation distance and is poorly known from observations. The measurement of the diameter of the dust shell shown in Figure 8 with VLTI for a range of stars with different properties would be a very powerful way to constrain possible dust condensation models.

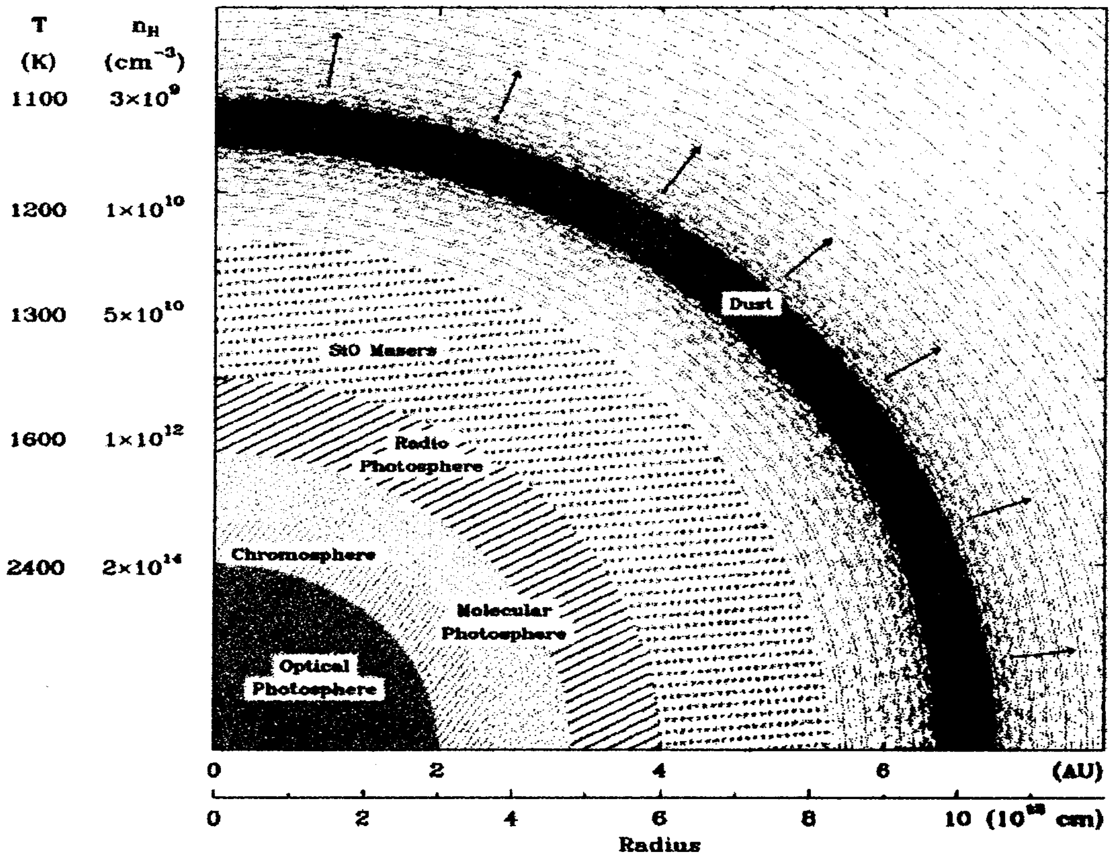

Figure 8. A schematic section of an AGB atmosphere with typical dimensions.

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Towards the end of the AGB, stars develop a 'superwind', a phase of extremely high mass loss rate, sometimes exceeding 10^{-3} $M_{\odot}$/yr. This phase obviously cannot last very long: typically a few 100 years. The very dense shells produced during this event are observed as the star is a post-AGB star and evolves to higher Te. Remarkably, the geometry of all post-AGB dust envelopes observed so far are axisymmetric, and this must reflect the geometry of the AGB wind in the last few 100 years before it left the AGB. This axisymmetry bears the seed of the beautiful shapes of evolved planetary nebulae (PN), that emerge as the star begins to ionize its AGB ejecta. Little is known about the large-scale structure of AGB winds just before they stop losing mass. The VLTI interferometer will be well suited to study the geometry of the dust shells produced by high mass loss AGB stars. For instance, the 10μ spectral region of oxygen-rich AGB stars contains the Si-O vibrational resonance, which is in absorption and probes a large range in optical depth (and hence distance) in the dust shell. These observations will determine the distribution of the dust with unprecedented detail and will tell us if the shells are spherical or not.

In summary, the most important questions that can be addressed by the VLTI are:

1) 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.
2) 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?
3) What molecules are depleted in the dust formation region?
4) How does dust formation depend on the phase of the pulsation and on the chemical composition of the star?

The mid IR region is ideal for studying dust formation near AGB stars and the accompanying depletion of atoms and molecules. The VLTI, with its 8-m apertures and 10-20 μ capability, is uniquely suited to extending this work to faint and distant objects with high 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 μ. The layers above the photosphere in which dust forms may extend to about 10 stellar radii, which are several tens of mas at distances of 0.5-1 Kpc and easily accessible to VLTI. Direct imaging of the stellar disk will also be possible, so limb darkening and distortions 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 as in the case of the Cepheids discussed on p.12.

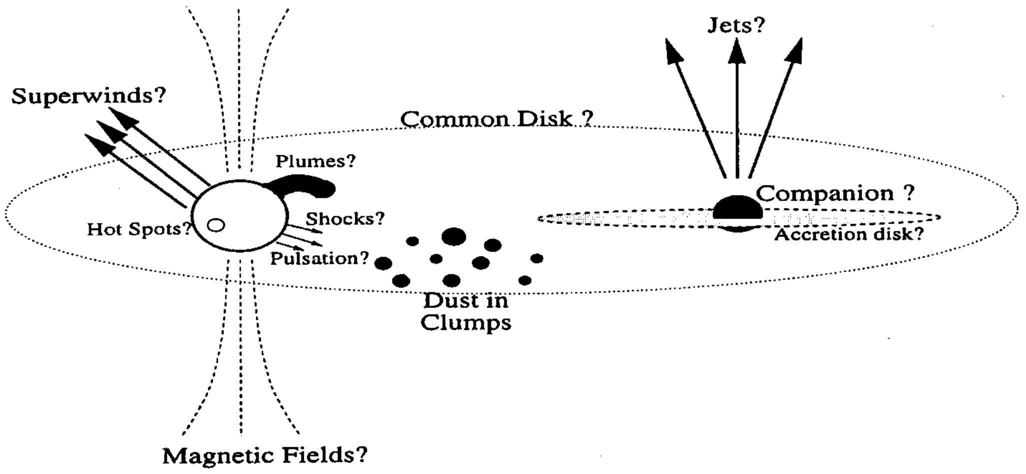

Figure 9. Schematic drawing of the circum-stellar environment of an AGB star. For a distance of 200 pc, the stellar radius drawn here would have an angular size of 10-20 mas.

The mid IR is the obvious wavelength region for studying post-AGB stars with the VLTI. Many post-AGB candidates were discovered in the IRAS point source catalogue to show warm dust (500 K) and turned out to be binaries. The most famous example of such an object is the Red Rectangle discovered by ground-based optical observations and speckle intyerferometry. 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. A possible scenario for the circum-binary envelope and related structures and their location around the object that VLTI will be able to probe in detail is shown in Figure 9. Hot spots in CV-like variables are another very fruitful avenue of research for VLTI considering that some of the best targets are located within 100 pc.

Be stars

Be stars show Hα emission that is strongly variable and usually double-peaked. They are also known to be rapid rotators, which suggests that the emission arises in a circum-stellar disk of ejected matter. Although this idea has not been universally accepted, recent optical interferometry has now confirmed that Be star envelopes are indeed flattened.

Models which assume a disk geometry have been successful in describing the winds of Be stars, but the only theoretical mechanism for disk formation consists in assuming 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. Moreover, the important variable character of Be stars (short-, middle- and long-term) is not well understood. Indeed different mechanisms could give the same observed results. Fortunately, one can show that the analysis of the interferometic data through the different variation cycles allows the determination of the correct processes.

The VLTI at optical and infrared wavelengths is very well suited to resolving the disk structure of Be stars and monitoring time variability. In particular, due to the fact that they are rapid rotators and to the presence of significant wind emission, their disks have very different photo-centers in the lines or continuum. 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) 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 program demands a good spectral resolution (R=10000 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 large apertures of the VLTI will be vital to achieve high spectral resolution maps in a few nights.

Young stars in the PMS phase and their accretion disks

The vast majority of young stars are observed to have a disk-like distribution of material during part of, or sometimes their entire PMS life. This disk, believed to be the location where planets are born, dissipates on a time-scale of about 400 Myrs, as evidenced by ISO observations of young stars and by the impact record of the Moon in our own solar system. We know from observations of exo-planets that the early phase of a planetary system is a very dynamic period in which planets can migrate and large bodies are continuously formed and collisionally destroyed. These processes modify the composition of gas and dust in the disk, and change the spatial distribution of material. Direct observations of the circum-stellar environment of young stars are urgently needed in order to better understand this crucial period in the evolution of proto-planetary systems, and make a link with the history of our Solar system as recorded by planets, asteroids, comets, the Kuiper belt and Oort cloud, and interplanetary dust.

The distribution of material surrounding young stars is a hotly debated issue. The trouble is that the spectral energy distribution is not unique in constraining the geometry of the circum-stellar material. Disk models as well as spherical dust shell models are equally successful in describing the infrared emission from young stars. The sub-millimeter interferometric maps have shown that the cold dust and gas are in a disk-like geometry, but the data have not been conclusive yet when it comes to the near-IR and mid-IR spectral region, due to a lack of spatial resolution. This will change with the commissioning of VLTI and its first science observations. We will be able to settle the case for disks, haloes, or a combination of both.

A direct measurement of the size of a disk constrains the density structure and the nature of the dust in the disk. Since the temperature of dust is a function of grain size, the simultaneous measurement of the temperature and location of the dust will set limits on the average size of the particles. The grain size distribution is believed to be a sensitive indicator of the degree of processing that has taken place in the disk. In addition, the measurement of disk size at several wavelengths (combining near-IR, mid-IR and sub-mm ALMA measurements) will constrain the geometry of the disk and test disk models with and without flaring outer disks.

The spectral capabilities of VLTI will allow us to measure the location of several dust components, such as the warm amorphous silicates, the crystalline silicates and the Polycyclic Aromatic Hydrocarbons (PAHs). Analysis of ISO data suggests that the PAHs observed in some Herbig Ae/Be stars are, in fact, located in the flaring outer part of the disk, but this needs confirmation from direct imaging with VLTI.

Young stars also 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 strong magnetic fields. Understanding the inner regions of proto-stars, 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 young stars to AGN, particularly the so-called classical T-Tauri stars, means that progress in understanding the physics of star formation may have important implications for extra-galactic astronomy. A currently popular model of the very inner regions of a PMS star might look something like that shown in Figure 10 while that of the outer regions probably look something like that shown in Figure 11.

A major program for the VLTI is to study systematically the rich circum-stellar environments of young stars at a resolution of about 2 mas, which corresponds to ~10 stellar radii (0.1 AU) for the nearest star-forming region (d = 50pc). 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. Although even VLTI will not be able to resolve the innermost parts of the accretion disk shown in Figure 10, 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, observing just outside these regions as shown in Figure 11 should allow meaningful extrapolations.

Very few direct studies of circum-stellar disks have been performed so far, because this requires high resolution in the near- and mid IR domains. Important parameters yet to be determined include the morphology of circum-stellar 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.

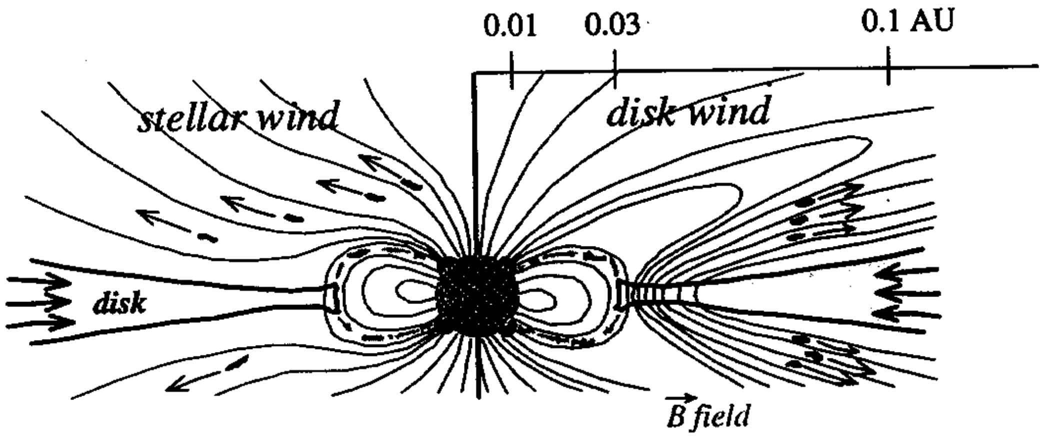

Figure 10. A schematic cross-section of the inner disk and wind of a proto-star from a model of Camenzind. The VLTI working in the near IR with the longest baselines would just reach this inner region in the nearest SFR at ~50 pc.

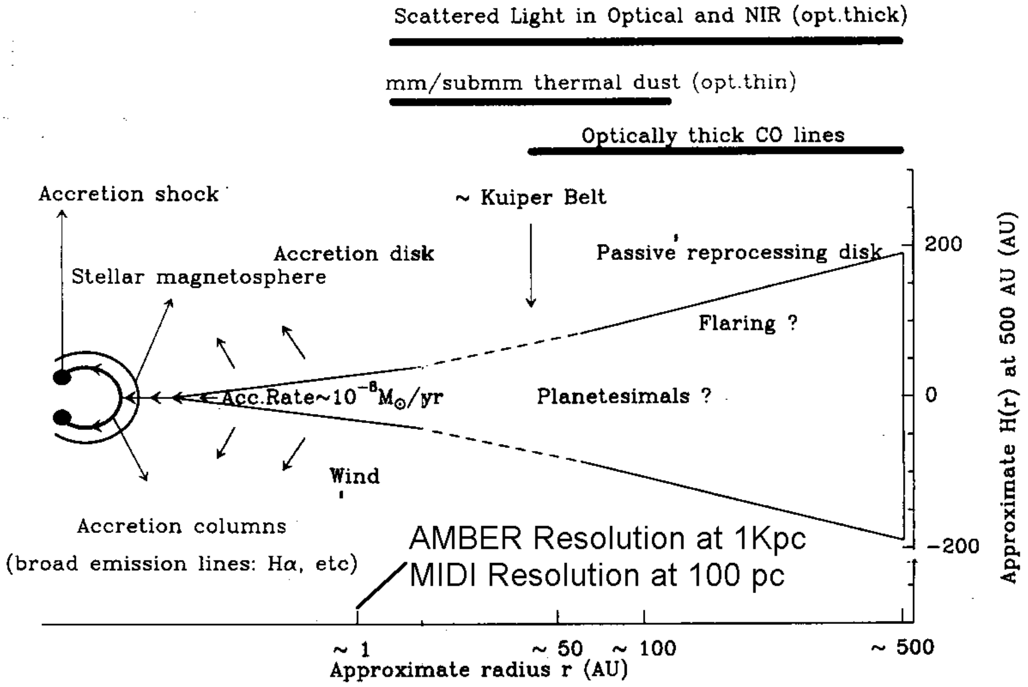

Figure 11. Schematic diagram of the outer regions of the accretion disk around a proto-star adapted from Lopez. Expected VLTI linear resolutions at 2 and 10μ are shown.

In a few objects, minima in the broadband spectrum have been tentatively attributed to zones cleared by a planet or faint companion, although different interpretations based on material properties also are possible. These gaps lie around 1AU and would be detectable with the VLTI, as shown in Figure 11. The determination of visibility curves at 2 and 10μ should indicate the interesting candidates but imaging will be required to study the phenomenon with its asymmetries due to the presence of the orbiting object. Generally, the distribution of dust and gas and the spatial distribution of temperature can be measured and will clarify the initial conditions for possible planet formation.

The question of how proto-stellar jets are accelerated and collimated should also be addressed with the VLTI. Important constraints on models can be derived from observations beyond about 10 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 proto-stellar jets have full opening angles of greater than 50° for small distances from the star. A similar behaviour has been predicted by theoretical models in which the jets are accelerated and collimated by rotating magnetospheres and in which one expects large jet opening angles for 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 UT on the basis of current brightness estimates.

Stellar surfaces

About 2000 stars with declinations less than 40° N are thought to have apparent diameters of one mas or more and therefore are resolved to VLTI baselines in the near IR. Most of these stars are late type giants. Some 50% of these have apparent diameters of 2.5 mas or more and will permit detailed studies of their surfaces.

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 magneto-hydrodynamic 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 that generate magnetic fields in stars.

The signatures in the visibility functions which can be expected for a relatively quiet (solar-type) and an active star occur at high angular frequencies and have small magnitudes. The VLTI will be able to resolve well structures on active giants. 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, possibly in the future, Zeeman profiles will make necessary the use of the UT.

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. 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. 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. 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.

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, but there has been little effort to monitor these stellar surfaces using high-resolution imaging methods. A dedicated interferometer such as VLTI offers the possibility of such a program. 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.

Another useful diagnostic for elucidating the physical mechanism responsible for surface features will be 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.

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 circum-stellar 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.

The mass distribution in the galactic halo and globular clusters

Proper motions measured with VLTI coupled to radial velocities of objects in the halo will yield very interesting constraints on the galaxy’s mass distribution outside the solar circle and the dynamics of globular clusters. The halo can, in principle, be probed out to galacto-centric distances of 230 Kpc by measuring the ~10 μas proper motions of the Leo I and II dwarf galaxies. Since the luminous and especially dark matter distribution in the halo is very poorly constrained presently, this would certainly represent a significant breakthrough by itself. The dynamics through proper motions of galactic globular clusters (GC) around the galaxy will also probe the bulge and the inner halo and shed light on the important issue of how the Milky Way (MW) was formed.

Similarly, precise measurements of the proper motions of stars in GC will provide essential information on the distance to the nearest GC and, thus, on their age. Since stars in GC are the oldest stellar population in the galaxy, their age is a strong constraint as a firm lower limit on the currently very uncertain age of the universe and on models of galaxy formation. Another important issue is related to the way GC dissolve into the halo by evaporation due to internal relaxation and tidal interaction with the bulge and disk of the MW. It is suspected currently that the presently observable population of GC is only a pale remnant of the original complement of stars that has dissolved into the halo and now makes up a fair fraction of halo objects. How this process occurs and at what rate is a basic question that is not yet understood despite its obvious importance. Measurements of the dynamics of the stars in tidal tails around the dissolving clusters will be crucial in this task.

The internal dynamics of dense GC is a subject not yet explored fully due to the difficulties of observing objects in the very crowded cores (1 star/pc^3). The phenomenon of core collapse well understood now theoretically needs to be put on a much firmer observational basis with precise measurements of the dynamics of stars in the core of nearby GC such as NGC 104, M15, NGC 6397 and M4. These measurements will provide essential insights into mass segregation, binary fractions and velocity anisotropies that affect core collapse and the subsequent evolution of the cluster. In all cases, the only way to distinguish foreground and background objects from low mass cluster members is through their proper motions. This allows an optimum determination of the mass function in the critical stellar-substellar transition region.

A proper dynamical study of the stars in the most massive GC like Omega Cen and nearby dwarf galaxies like the Sagittarius with its associated GC M55 gives vital information on the currently very popular question of how the MW halo was assembled and when. There is considerable evidence on the basis of chemical and morphological data already that the former may represent the core of a dwarf galaxy that was accreted in the past by the MW in the process of building up the halo. This intriguing hypothesis can be studied in some detail with the VLTI that can determine precise orbits for the stars.

The Galactic Center

The central 0.1 pc of our Galaxy will be an important target for VLTI at wavelengths from 2 to 10µ. The resolution of the VLTI at 2µ corresponds to 15AU at the galactic center.or about 1500 times the Schwarzschild radius of a 10^6 $M_\odot$ BH. The first and most important goal will be to test for the presence of a central massive BH by measuring the three-dimensional velocity field of the star cluster centered on IRS16. The current limits for the enclosed mass as a function of distance from Sgr A* are shown in Figure 12 together with a number of possible theoretical models of the mass distribution.

High precision proper motion and radial velocities can be determined by VLTI at very small distances from the center of the star cluster, where observations with single telescopes are limited by crowding. Recent measurements have provided good evidence for the presence of a massive BH but the observational uncertainties still limit knowledge of the physical properties of the enclosed mass. The VLTI will be able to probe the 3D space motions of stars in the nuclear cluster down to 10^{-4} pc of the central source or approximately two orders of magnitude better than now as can be seen from Figure 12. This data will certainly provide very precise information on the central mass without the a-priori assumption of isotropic motions. High precision astrometry with PRIMA might even go so far as to probe the central BH to a few times its Schwarzschild radius ($2.5*10^{-7}$ pc).

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 2.2µ 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 center region. It will thus be possible to make a census of the stellar population in this area, to check whether there is ongoing star formation in the vicinity of the galactic center, and to search for ``peculiar" stars, which may be the remnants of stellar collisions. Observations at 10μ would also reveal the distribution of warm dust associated with SgrA*.

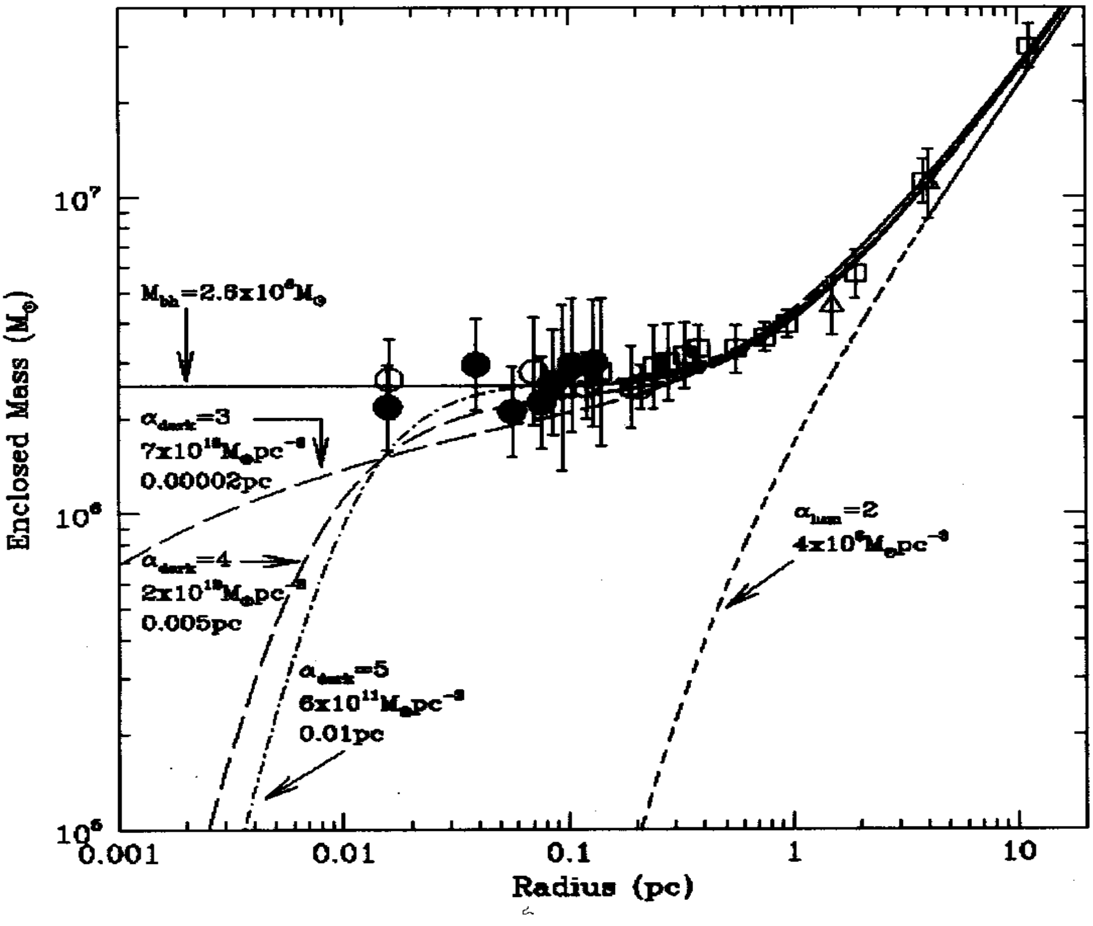

Figure 12. Enclosed mass around SgrA* as a function of projected distance from Ghez et al. 1998. The models correspond to power law dark clusters made up of stellar remnants, BD or even elementary particles with various values of the index alpha. Currently such models with alpha > 3 cannot be ruled out.

Observing the galactic center is quite a challenging task for the VLTI because of the high density of sources and the small field of view. Hybrid configurations formed by combining the UTs with the AT will give good coverage of the (u,v) plane, in particular when the technique of multi-frequency synthesis is employed. The arrays location in the southern hemisphere is another significant advantage of the VLTI in the study of the galactic center.

Galactic gravitational lensing

The phenomenon of gravitational lensing, or multiple splitting of the image of a distant source in the gravitational field of an intervening object (a star, a galaxy, or a galaxy cluster), is perhaps one of the more spectacular manifestations of the astronomically detectable effects of general relativity.

Gravitational lensing by low mass lenses of galactic objects, which can be detected by measuring the intensity variation of a macro-image made of any number of unresolved micro-images. The splitting power of a compact lens of the order of a solar mass and located within a few Kpc from us is only sufficient to separate the source images by about 1 mas. Therefore, the observations of such events up until now could only follow the photometric variations of the composite macro-image. Microlensing of source stars in the galactic bulge, or the LMC, by the stars (or possible other compact objects) in our Galaxy are observed by photometric surveys like MACHO, EROS or OGLE.

The interpretative work of the photometric data alone required auxiliary knowledge, or assumptions, about the spatial and mass distributions of populations of potential lenses in the Galaxy, in order to determine the mass of and the distance to the lens. The availability of a sensitive high-resolution interferometers like the VLTI will allow access to the microlens images themselves (see figure 13 for a typical example) and so directly to the lens mass and to its distance, without any additional assumption except the source distance. The VLTI will be sensitive enough to reach most of the microlensing events occurring at magnitude 15 or 16 with some ``bright'' events at magnitude 13. Moreover, as most existing microlensing surveys are focused in the direction of the galactic center and of the Magellanic Clouds, the VLTI is very well located geographically to react to survey alerts and to observe events at their peaks.

The microlensing image would appear at a given moment of time as in figure 13 for a source located in the galactic bulge lensed by a 10 $M_{\odot}$ BH located at mid-distance and passing as close as 1 mas from the source. The background source is split by the lens (usually too faint to be seen) into two images more or less elongated, and of different intensities. Both intensities are larger than the initial source intensity. The total image intensity, the value measured by the photometric surveys, increases as the lens passes closer to the source line of sight. The maximum amplification depends on the lens mass, on the effective distance to the lens and on the angular distance between the lens and the source. The event duration depends on the relative angular velocity of the source and the lens. The maximum of the photometric curve corresponds to the closest image pair and to the lowest intensity difference between the two images. The images, the original source direction and the lens are aligned in any case.

From the timed photometric curve, only the Einstein radius r_E can be retrieved. If in addition, the image separation can be determined by interferometry at only one point of the trajectory, the angular velocity can be determined. And knowing the distance to the source, the actual lens mass and distance can be obtained. In a first approximation, from the point of view of interferometry, the microlensed image of a star can be considered as a very close double star. Indeed, the distant source star is usually not resolved by the individual telescopes and only marginally by the interferometer. The elongation of each image due to the lensing effect being equal to the total intensity amplification which can reach 10 or more can be resolved by the interferometer in some cases.

As a double star, the image can easily and simply be modeled with only two parameters: the star separation and the intensity ratio. The intensity ratio can be directly deduced from the photometric curves. Thus, only one parameter remains and can be very accurately determined by interferometric visibility or astrometric measurements even under the interferometer theoretical resolution limit. With a 100 m baseline interferometer, a separation of 10 arcsec to a reference star, an integration time of 30 min (to average the perturbing atmospheric effects), and a metrology accurate at the 5 nm level, one can reach a distance accuracy measurement of 10 μas achievable with PRIMA.

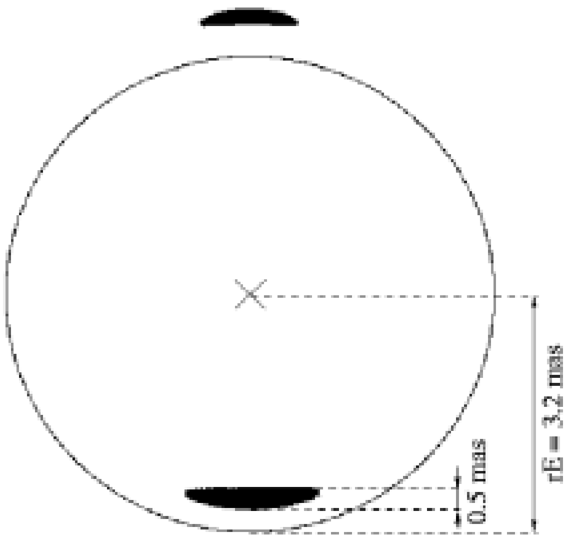

Figure 13: Elongation of the two background source images at the closest point, with an initial source diameter of 0.5 mas, a 10 $M_\odot$ BH passing at mid-distance from a galactic bulge source at 8 Kpc distance and at 1 mas angularly from Delplancke et al. 2001.

In both cases (visibility or astrometric measurements), the measurements will then be performed several times at intervals of days or weeks in order to obtain the time curve of the microlensing event. This facility will bring two main advantages: the possibility to observe fainter objects (gain of about 3 on the limiting magnitude) and the astrometric capability.

AGN

Active galaxies have compact nuclei that can be so luminous that they outshine a whole galaxy. These cosmological beacons are so bright that they can be seen out to the earliest 5% of the age of the universe. These objects are unique laboratories for testing models of early galaxy evolution. There is much evidence that these active galaxies contain massive BH, the central engine of the physical processes that give rise to a large number of energetic phenomena. The most important questions in this area include the relation of the AGN phenomenon to galaxy formation and the physics of the formation and evolution of the massive BH. A recent clue to answering these questions is the strong indication that a large fraction of all the galaxies contain massive BH and that the mass of the BH directly scales with the mass of the spheroid of the host galaxy.

The now canonical view of AGN is that they are powered by the exchange of gravitational energy for thermal energy in a compact accretion disk surrounding the BH. In the currently popular and attractive “unified” model of AGN, they are all surrounded by an optically thick obscuring torus whose orientation with respect to our line of sight determines whether we see the object as a Type I (Seyfert 1 or quasar) or Type II (Seyfert 2 or radio galaxy). A drawing of the unified model for the core of the AGN is shown in Figure 14. The inner accretion disk which feeds the massive BH directly is surrounded by the broad line region (BLR). In the BLR, dense compact clouds move at a high speed through a more tenuous medium giving rise to broad optical emission lines. The BLR is surrounded by the optically thick torus composed of dust and molecular and neutral gas. If the torus hides the central region from our view, the direct high energy phenomena associated with the nucleus are more difficult to observe. Then, the object does not show the broad lines and is classified as Type II. If the object is viewed sufficiently close to the polar axis as shown in Figure 14, a very bright nucleus is observed and the optical spectrum shows the broad lines. It will be classified as Type I.

Although this picture is capable of explaining a large number of observed physical characteristics of various classes of AGN, it is still unclear whether other mechanisms contribute to, or even, dominate over the scenario in which orientation and the putative torus play such a major role. It has even been argued that, in a subset of

AGN, the main power source is not a BH but supernova explosions produced within a central starburst region and that time variability may play a crucial role in the perceived differences between AGN. The important issues to be clarified are, therefore, whether dust tori in AGN exist at all and whether the physics of such tori can be constrained well enough that most of the differences between AGN can be understood completely.

As is quite apparent from Figure 14, high resolution imaging with the VLTI of the nearest AGN (Cen-A is at ~ 3.5Mpc) has a crucial role to play in this area especially with MIDI at 10 and 20μ. At these wavelengths, the view towards the heart of the galaxy is not hampered by extinction of dust in the galaxy and is not confused by stellar emission. The VLTI should, therefore, allow the unambiguous detection of dust tori and constrain their inner and outer radius and density and temperature structure. A number of models and geometries for obscuring tori have been proposed. The models range from extended 100 pc scale tori having moderate optical depths to much more compact ones with very high optical depths and, possibly, some with warped disks. All of these models can be severely constrained or eliminated easily by VLTI observations.

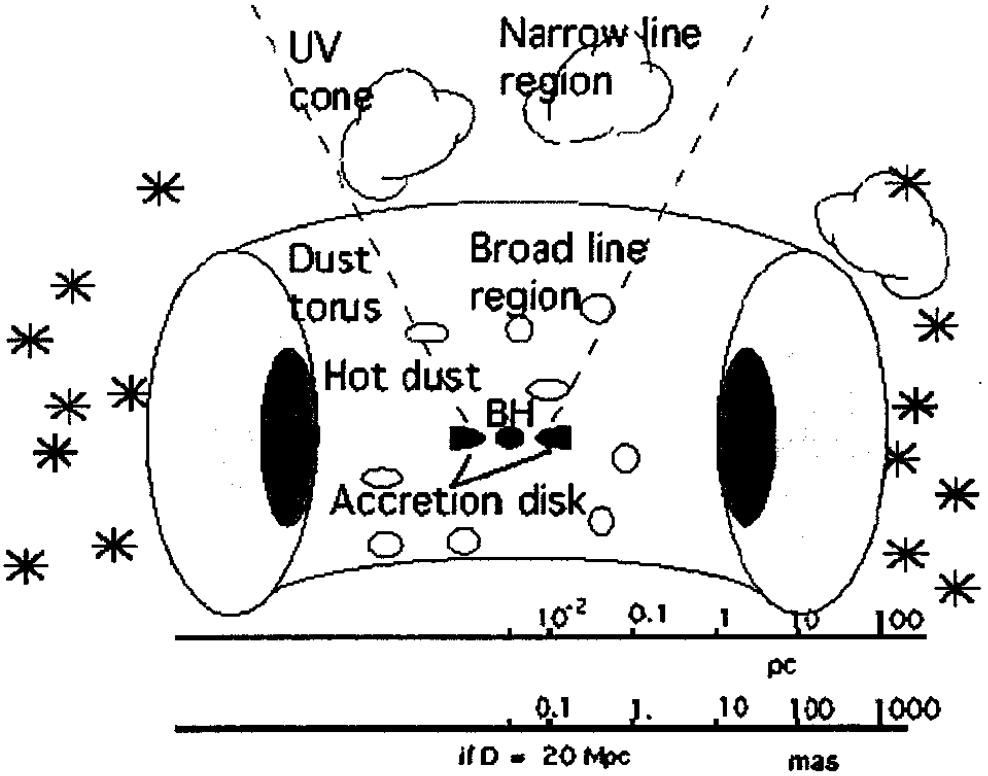

Figure 14. Drawing of the possible structure of the core of an AGN at 20 Mpc distance indicating several of the main components.

In any case, all of these ideas are still completely in the realm of speculation. No one has observed in the innermost core of an AGN so far and it should be stressed that there are still a number of serious theoretical difficulties with these models. Systematic observations with an instrument such as the VLTI will be able to establish the field on solid ground. Moreover, only an interferometer like VLTI can resolve the physical structures and motions within the BLR, between the dusty torus and the accretion disk of AGN. The intermediate region with the inner part of the jet extended over about 1pc and the outer part extended over ~ 1Kpc outside the obscured core will be easily accessible to IR imaging with AMBER and with moderate spectral resolution.

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~2 is 10^2-10^3 times greater than at the present epoch. 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 15 shows how the angular sizes of the relevant regions scale with redshift for VLTI spatial resolutions.

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. Calculations for the adaptive optics system on a unit telescope in the visible predict a sky coverage of about 1%.This number 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.

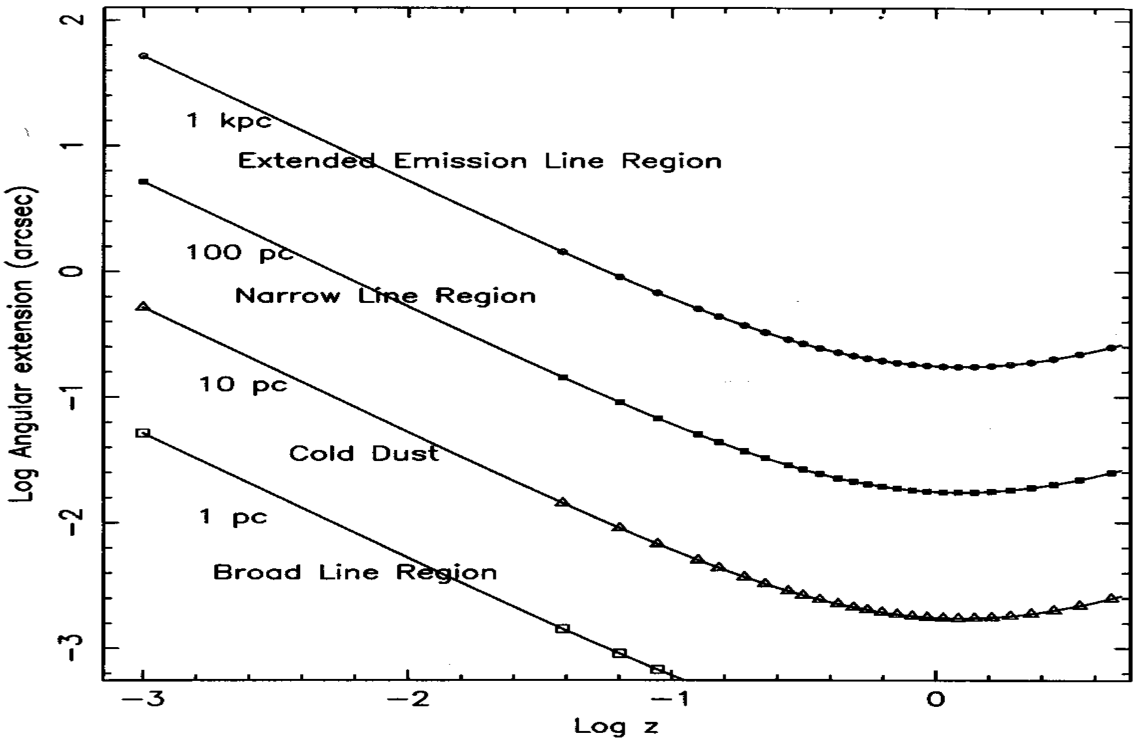

Figure 15. Angular extension as a function of redshift for regions with linear sizes of 1pc (open squares), 10pc (open triangles), 100pc (filled squares) and 1kpc (open circles). The calculations assumed Ho=75 km/s/Mpc and q=0.5. The difference in look-back time between adjacent symbols is constant and equal to about 0.5 Gyr.

Other research areas that the VLTI can contribute to significantly and deeper development of many of the topics covered in this document can be found in the proceedings of the ESO workshop “ Science with the VLTI”, ESO Astrophysics Symposia Series, ed. F.Paresce, Springer-Verlag, Berlin, 1997.

Acknowledgements

This document could not have been written without the fundamental scientific input of all the members of ESO’s Interferometry Science Advisory Committee who contributed in the early years to the establishment of the scientific objectives of the VLTI and to the success of its efforts to get VLTI restarted in 1996 after its near demise in 1993. Particular thanks are also due to Therese Encrenaz, George Miley, Andrea Richichi, Didier Queloz, Steve Ridgway, Francoise Delplancke, and Pierre Kervella for their help in defining the reasearch areas most appropriate for the VLTI and to Andreas Glindemann and Massimo Tarenghi for their continued support. Finally, a particular debt of gratitude is due to Jean Marie Mariotti whose noble example of dedication to and competence in the field of interferometry inspired many of the ideas in this document and infused the spirit of this new exciting endeavour.