ESO Workshop on Science with the VLT Interferometer

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Interferometry: From Fringe Science to Mainstream Astronomy

When the coherent combination of the four telescopes of the VLT was first discussed during the design phase of the observatory, interferometry seemed to be a small field with very specialised applications. However, the reports issued by ESO's two successive advisory groups on interferometry (ESO 1989, 1992) showed already the large potential of the VLTI for a broad range of astronomical problems. This became even more apparent during the ESO Workshop on "Science with the VLT", which took place in June 1994 (see Walsh and Danziger, 1995). Several contributions to this workshop were dedicated to the interferometric mode of the VLT, and many others discussed the use of the VLTI in the context of larger multi-instrument programmes. The strong interest in interferometry expressed by astronomers working in a wide variety of fields, and the necessity to build the VLTI within tight financial constraints and optimised for the most promising scientific programmes, prompted ESO to form a new Interferometry Science Advisory Committee in April 1995. The ISAC was charged with updating the science case for the VLTI and prioritising the technical options in order to maximise the astronomical return from the interferometer. A summary of this work has been published in a previous issue of *The Messenger* (Paresce et al., 1996). At the same time ISAC served as the Scientific Organising Committee for a workshop on "Science with the VLT Interferometer", which was held at ESO's Garching headquarters from June 18–21, 1996. This workshop was aimed at presenting in more detail the ideas and views of ISAC, at gathering new developments in astronomy since 1994 and their implications for the VLTI, and at soliciting input and comments from potential users on what they expected from the VLTI. In fact, "Science with the VLTI" was perhaps the most comprehensive overview ever of the scientific questions that can be addressed with ground-based interferometry. All speakers were asked to address explicitly the question of how their project would be carried out with the VLTI, and which capabilities would be required to accomplish the scientific goals. To provide all participants with a more thorough understanding of how astronomical goals translate into technical requirements, the first morning of the workshop was dedicated to four introductory tutorials on the fundamentals of interferometry and on the particulars of the VLTI. Many speakers who gave invited or contributed presentations during the following three and a half days came back to technical points raised in the tutorials. Indeed, almost all of them succeeded in making the connection between their aspirations and the harsh reality of instrumental limitations. In my view, this was among the great successes of the workshop: Mainstream astronomers have started to feel comfortable with talking about fringe tracking and visibility Calibration, just as if they were talking about photometric accuracy or signal-to-noise in a spectrum.

Opportunities for the VLTI, Old and New

As expressed by the choice of the title, the workshop's primary goal was a discussion of the scientific potential of the VLTI. It has been clear all the time since Michelson's and Pease's pioneering work that interferometry can be applied to a broad range of problems in stellar and Circumstellar astronomy. The capabilities of the VLTI, in particular its sensitivity and wavelength coverage, will substantially expand the range of problems that can be addressed with the instruments that are already operational. The high expectations of stellar astronomers was reflected by a large number of sessions dealing with stellar diameters and fundamental parameters of stars, imaging of stellar surfaces, binary star research, and the analysis of stellar populations and determination of proper motion in extremely crowded regions like globular clusters and the centre of the Galaxy. Observations of circumstellar matter, related to accretion or mass-loss phenomena, was another topic that received a lot of attention. Obtaining images of disks around pre-main-sequence objects is certainly one of the key scientific goals of the VLTI. Of equal importance are observations of dust disks around main-sequence stars, which range from β Pictoris-like objects down to the level of the zodiacal light in the solar system, a topic that is still good for more surprises. On the whole, however, we have a fairly clear picture of what we can expect from the VLTI for stellar astronomy, since there are well-developed models and theories that make clear predictions, and since some programmes can be direct follow-ups to current efforts at interferometers with smaller aperture. In contrast, observing extragalactic objects with optical and near-infrared interferometry means entering completely uncharted territory. This implies that predictions of the scientific return from the VLTI are much more uncertain; on the other hand, the potential for breakthroughs in long-standing important questions is very high. Measuring the sizes of the dusty tori that are at the core of unified theories of Active Galactic Nuclei, resolving the broad line region in nearby Seyfert galaxies, determining the importance of star formation for the energy balance in Seyfert nuclei, and studying the structure of galaxies at high redshift are exciting prospects for the VLTI. Stellar and extragalactic astronomy are the two pillars on which planning for the VLTI has always rested, but there is more. There are quite a few questions concerning small bodies in our own solar system which could potentially be addressed with the VLTI. The main issue here is in which cases fringe tracking on the object itself is possible, or how suitable reference objects can be found. Among the recent developments in astronomy, the detection of brown dwarfs and extrasolar planets stands out as an event that opens a completely new area where observations with the VLTI will probably have a large scientific impact. Interferometric astrometry is a powerful method to search for Jupiter-like planets out to nearly 1 kpc, and for planets with 10 Earth masses orbiting the nearest stars. The surprising detection of a giant planet in a very close orbit around 51 Peg has established a new class of objects, which may be sufficiently bright to be detected directly with the VLTI. The VLTI could thus become the first instrument to perform spectroscopy and photometry of some extrasolar planets, and therefore to determine their temperatures, composition, and rotation periods. Some flexibility is required, of course, to incorporate the technical requirements for these challenging observations into the development plan for the VLTI.

Interferometric Life Before (and Beyond) Imaging

As a result of the workshop, we have seen an expansion of the scientific agenda of the VLTI into new areas, and refined ideas about realistic observing programmes. As a consequence, it has been realised that much, perhaps most, of the science with the VLTI can be done without "imaging". For example, there is a lot of interest in detecting faint companions (stars at the bottom of the main sequence, brown dwarfs, giant planets) near much brighter stars. Several talks dealt with methods to do this, which involve using relative phase information, either the phase difference between two wavelength bands, or the phase difference between the primary star and a nearby reference (i.e., narrow-angle astrometry). These approaches are orders of magnitude more sensitive than synthesis imaging of the field around the primary using closure phase, and they require fewer telescopes (three are adequate, four are good). As a bonus, information on scales smaller than the resolution limit of the interferometer can be obtained. This compensates partly for the fact that the baselines of the VLTI are somewhat smaller than what one would ideally like to have. Another important point is the realisation that even in situations where synthesis imaging is the "best" method, much of the scientifically interesting information can be extracted from much more limited data, if adequate models are available. Recall, for example, the discovery of apparent superluminal motion in extragalactic radio sources, which involved fitting simple few-parameter models to data obtained with a VLBI "array" consisting of only two antennas (Whitney et al., 1971; it is very instructive to read this classical paper with 25 years of hindsight)! In many cases, a simple measurement of the size or overall geometry of an object contains much useful information. This has also been demonstrated by results from single-baseline optical interferometers, such as the I2T, GI2T and Mk III instruments, which show that the Hα emission region of Be stars has a disk-shaped geometry. Data of similar quality on T Tauri and β Pictoris disks, and on dust tori in Seyfert galaxies is exactly what we hope to get from the VLTI soon after "first fringes".

The VLTI – a Community Instrument

At this point, it might be useful to recall that the VLTI is unique among the world's interferometer projects insofar as it has been conceived within the framework of a large observatory, and with a broad community of users in mind. In contrast to the situation at all operational interferometers, the typical observer using the VLTI will not be a member of the highly specialised team that built the instrument, but rather an astronomer who needs data at milliarcsecond resolution to complement his or her work with other methods. This concept of the VLTI as a community instrument will certainly enhance its scientific output, since it can capture the imagination of users from all fields of astronomy, observers and theorists alike. The broad range of topics covered at the workshop is an encouraging indication that this process is already well on its way. However, additional ideas for applications of the VLTI are very welcome, especially in the areas of extragalactic astronomy and cosmology. Here, as in other fields, it must always be kept in mind that interferometry on its own will rarely lead to substantial progress; its real power lies in the unique capability to test predictions that have been formulated on the basis of observational work at lower angular resolution and theoretical modelling. Many projects therefore require the combination of data from the VLTI and more traditional techniques (spectroscopy, photometry, adaptive optics imaging, etc.); "one-stop shopping" at ESO will facilitate the planning of such observations tremendously. Open access to the VLTI will also ensure that programmes of all sizes can be carried out, from a snapshot of a single target (e.g., measurement of the diameter of a particular star as a function of wavelength) to long-term monitoring of large samples (e.g., astrometric surveys for low-mass companions), with detailed studies of individual key objects (such as 51Peg, αOri, βPic, the Galactic centre, NGC1068) ranging somewhere in between. While setting the scientific agenda for the VLTI is one important task for ESO's user community, the equally important technical development is another. In spite of many advances in the key technologies of beam combiner design, detectors, laser metrology, vibration suppression, and instrument control, astronomical interferometry is still difficult. The workshop saw several debates among the specialists about the merits of different instrumental concepts, and about the accuracy of detailed predictions of their performance. It appears unavoidable that the VLTI will have to support both astronomical research and development of interferometric techniques, with a fairly large share of technical aspects for quite a while to come. Fortunately, ESO can rely on a number of institutes and observatories with experience in interferometry and related areas for building the "focal plane" instrumentation of the VLTI, beam combiners and fringe detectors. In short: to realise the full potential of the VLTI, ESO must draw on the astronomical *and* technical expertise available in the European astronomical community.

The Next Steps for the VLTI

Now that we have formulated our dreams about the science we want to do with the VLTI, we have to turn back to the question how we can make these dreams come true. The first important task ahead is the formulation of a prioritised instrumentation plan with realistic goals. The astronomical programmes call for instruments covering the whole wavelength range from 0.5 to 20 µm; some require simultaneous operation in two widely separated wavelength bands for fringe tracking and data taking. Monitoring programmes take a lot of observing time and thus need the auxiliary telescopes. To image complex objects, the auxiliary telescopes have to be combined with the four 8-m UTs, which is possible only if a sufficient number of delay lines is available. Off-source fringe tracking calls for dual star feeds and additional differential delay lines. Narrow-angle astrometry needs extremely precise metrology on top of that. The sensitivity in the visible and near-IR depends strongly on the availability and quality of adaptive optics. It is clear that we cannot get all of this from the beginning. Making the right choices about a sufficiently capable, but at the same time affordable and technically viable, "first-light" configuration will be crucial for the health of the VLTI programme. At the same time, a plan has to be drawn up how to phase in additional instruments and capabilities. In this process the balance has to be kept between relatively simple, low-cost instruments, more capable and versatile, but also more complex and more expensive solutions, and specialised techniques optimised for a single key application. The workshop proceedings will be of invaluable help for this purpose, since they will give us a good idea about the technical requirements for each scientific project. This mapping from the space of possible instrumental configurations into the space of astronomical problems that can be tackled should form the basis for discussions between astronomers and engineers about the detailed implementation plan for the VLTI. Where the mapping is still incomplete – for example in the area of solar system research – further feasibility studies are highly desirable. In parallel to the technical planning, observing strategies for short observations and for long-term programmes have to be prepared. This involves an understanding of operational aspects like calibration procedures and scheduling requirements. These issues are more complex for the VLTI than for a single telescope, because visibility measurements are strongly influenced by "dirty" atmospheric and instrumental effects, and because of the peculiarities of aperture synthesis. Some observing programmes require special preparatory work. An example is the systematic search for random associations of high-redshift galaxies and quasars with suitable foreground stars that can be used as references for fringe tracking. While planning for the VLTI is a complex process by itself, we must not forget that it is strongly influenced by outside events. Financial aspects and unexpected astronomical discoveries aside, the progress made by other interferometer projects on the ground and in space, and developments in the area of adaptive optics are the two most important factors that change the boundary conditions for the VLTI. A number of interferometers with comparatively small aperture are already producing data or will come into operation very soon. In addition, instruments with sensitivity comparable to the VLTI (the Keck, LBT, and Magellan interferometers) may see first light soon after the VLTI. And finally, plans for interferometric space missions have been on the drawing board for quite a while. With that many contenders in the starting blocks, the competitiveness of the VLTI will depend critically on timing during all stages of its implementation. And because of its strong influence on the sensitivity, the availability of adaptive optics is an extremely important factor in this calculation.

The VLTI and Beyond

It will still take a few years until the VLTI becomes operational, and even longer before its full potential gets realised with the combination of the four 8-m telescopes using high-order adaptive optics. Nevertheless, a look ahead into the more distant future should be useful. It appears that the VLTI will be close to the limit of what can be done sensibly from the ground. Other instruments will have somewhat longer baselines, or better *uv* coverage, but it is difficult to envisage an affordable way of obtaining significantly more sensitivity, accuracy, wavelength flexibility or sky coverage than provided by the VLTI. On the other hand, interferometry from above the atmosphere looks very promising. Space is quiet, empty, and cold. In the absence of atmospheric fluctuations, the coherent integration time on any point in the sky is only limited by the observing time available, giving an enormous boost to sensitivity even with moderate (1-m-class) apertures. At $\lambda \gtrsim$ 2.5 µm, the advantage of space is even larger, because the whole telescope can be radiatively cooled to a temperature of 40 K or so. The undistorted wavefront facilitates the calibration of the visibilities and makes advanced techniques for high-contrast observations feasible. Interferometer concepts based on “free flyers” – where each telescope is mounted on an independent small satellite – make very long baselines possible and provide superb imaging quality because the *uv* plane can be covered effectively. Bearing all this in mind, it seems plausible that the next big step after the VLTI will be the leap into space. Should ESO play a role in this adventure? There are very good arguments for an ESO involvement in space interferometry. First, the VLTI offers unique opportunities for the development of instrumental concepts and techniques, which have to be tested on the ground before they can be incorporated into space missions. Second, the VLTI will play an important role in defining the key scientific topics that can be addressed with space-based interferometry. And third, the efficient use of a space facility will require a user community well trained in interferometric observations. It thus appears that some coordination between ESO and ESA could be beneficial for both sides. A panel discussion with representatives of both agencies that took place during the workshop was devoted to the question of how a joint effort in the area of interferometry could work. Differences between ESO and ESA in their member nations, organisational structure, and scientific communities to be served will have to be addressed in order to define the scope and terms of a fruitful collaboration. With ESO’s VLTI back on the track to fast implementation, and an interferometric cornerstone in ESA’s Horizon 2000+ programme, there is an enormous potential for a strong European role in the development of interferometry. Generating synergism between these programmes can only make them stronger. We can thus look forward to exciting opportunities, and to a rich harvest of astronomical results in the near future and in the decades to come. George Miley boldly predicted that the IAU will hold its third (!) symposium on “Optical Interferometry of AGN” in November 2010. I look forward to seeing his paper at that conference, and to many other results at the meetings that will be held on imaging of T Tauri disks, stellar surface features, spectroscopy of extrasolar planets . . .

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Simulations of VLTI/VISA Imaging Observations of Young Stellar Objects at 2.2 µm

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1. Introduction

The study of star and planet formation is one of the most exciting science goals of the VLT Interferometer. Circumstellar disks related to star and planet formation are believed to be a common feature of both young and main-sequence stars in different stages of development (e.g. Beckwith & Sargent, 1993, Backman & Paresce, 1993).

The search for direct evidence of disks around young stellar objects has been successful only recently (McCaughrean et al., 1996), although their presence has been inferred indirectly for more than a decade. Direct detection was possible only with high angular resolution observing techniques, in particular with the HST. However, much higher resolution than available with HST is needed in order to probe the structure of these disks and to test current models which predict gaps and traces of planetesimals.

In an effort to understand the science performance of the VLTI, we have studied the potential of the VISA mode to do this kind of observations by computer simulations. Our main concern is the synthesis capability of various VISA configurations. To limit the large variety of parameters, we have concentrated here on the study of a limited sample of disk morphologies at high angular resolution. We used the CalTech VLBI software package (Pearson, 1991) for our simulations.

2. Source Models

To make the computations more realistic we used disk parameters as derived from HST observations. The simulated object is located at 440 pc and corresponds to disk 182–332 of McCaughrean et al. (1996), with the exception that the declination is –30°. At this distance,