Recent Astrophysical Results from the VLTI

We present a review of recent astrophysical results based on data obtained with the ESO Very Large Telescope Interferometer (VLTI). The very first VLTI results have already been reviewed by Richichi & Paresce (2003). Remarkably, the first scientific results from the mid-infrared instrument MIDI, which emerge from science demonstration and guaranteed time observations, already cover a very broad range of astrophysical topics. These topics include active galactic nuclei, young stellar objects and protoplanetary discs, the environments of hot stars, as well as evolved stars and their envelopes.

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Observations with the ESO VLT Interferometer started with the achievement of First Fringes in March 2001, which employed the test siderostats and the commissioning instrument VINCI. Since then, the VLTI instrumentation has been constantly expanded, and scientific observations have continuously been carried out using the instrumentation that had been available at any given time. A report on the technical status of the VLT Interferometer was for instance presented by Glindemann et al. (2004). A huge number of scientifically interesting VINCI data were secured between March 2001 and September 2004 within commissioning and early shared risk programmes, and all of these VINCI data are publicly available[1]. Early MIDI observations in the framework of science demonstration and guaranteed time programmes have been conducted since 2003. The data based on MIDI science demonstration programmes are also publicly available[2]. The MIDI instrument has been offered to the whole astronomical community for general programmes since ESO period P73 (observations starting in April 2004). First science demonstration and guaranteed time observations using the near-infrared phase closure instrument AMBER were conducted in October and December 2004.

The first refereed publications based on data obtained with the VLTI appeared in the year 2003. A review of the very first VLTI results was presented by Richichi & Paresce (December 2003). Since then many new results have been published that are based on data obtained with VLTI instruments. The ESO telescope bibliography lists for the years 2003 and 2004 a total of 21 refereed publications directly using ESO data, which were obtained with the VLTI instruments VINCI and MIDI (see Table 1). These data were taken within VINCI commissioning, VINCI shared risk, MIDI science demonstration, and MIDI guaranteed time programmes. These publications are listed in the references below. Also listed are 11 additional publications that appeared in 2005 or that are in press, and that qualify to be included in the ESO telescope bibliography. Here, we review these scientific results, concentrating on those that were published after the review of first VLTI results by Richichi & Paresce (2003). We put a particular emphasis on the results emerging from MIDI science demonstration and guaranteed time programmes (Jaffe et al. 2004; Leinert et al. 2004; van Boekel et al. 2004; Chesneau et al. 2005 a, b, c; Ohnaka et al. 2005). Recently, Richichi et al. (2005) presented an updated version of CHARM (catalogue for high angular resolution measurements), a catalogue that lists high angular resolution measurements in general, including results from the VLTI.

The VLTI results reviewed in this article illustrate that the VLT Interferometer provides excellent opportunities to address a broad range of important astrophysical topics. With the large collecting areas of the 8 m VLT Unit Telescopes, VLT Interferometry is not limited to the brightest stars, as most interferometric facilities so far, but can be used to study relatively faint sources. Results obtained so far include already, for instance, studies of the innermost cores of Active Galactic Nuclei (AGN) harbouring supermassive black holes, the origins of stars such as our sun and the formation of protoplanetary discs, fundamental parameters of stars in evolutionary stages such as our sun, the evolution and fate of stars and their mass-loss to the circumstellar environment, the environment of hot stars, and distance estimates based on measurements of Cepheid pulsations.

Remarkably, several of the publications reviewed here include results that were obtained by combing observations using different instruments and facilities. For instance, Chesneau et al. (2005a) combined observations obtained with MIDI, optical spectra taken with the HEROS instrument, and infrared spectra from the 1.6 m Brazilian telescope. Kervella et al. (2003b), Pijpers et al. (2003), and di Folco (2004) combined VINCI data with asteroseismic observations. Boboltz & Wittkowski (2005) conducted coordinated near-infrared (VINCI) and radio (VLBA) interferometry. Woodruff et al. (2004) combined VINCI observations with near-infrared speckle observations. Wittkowski et al. (2004) combined VINCI interferometry with available spectrophotometry. These examples show that interfer-

[1] *www.eso.org/projects/vlti/instru/vinci/vinci_data_sets.html*
[2] *www.eso.org/projects/vlti/instru/midi/midi_data_sets.html*

Year	VINCI	MIDI	Total
2003	6	–	6
2004	12	3	15
2005 (so far)	8	4	11
	26	7	32

Table 1: Refereed publications based on data obtained with VLTI instruments. Source: ESO Telescope Bibliography.

ometry, and in particular VLT Interferometry, is becoming a very useful complementary tool for general astrophysics among the many tools that are available to the astronomical community. It can be expected that more synergies between observations with the VLTI and external instruments and facilities will emerge, ultimately also including ALMA and OWL.

Galactic Nuclei

VLTI observations of Active Galactic Nuclei (AGN) with MIDI started soon after the instrument was ready for scientific observations with two UTs: the first interferometric spectrum of the famous Seyfert II galaxy NGC 1068 was obtained during science demonstration time in June 2003. A second set of MIDI measurements were carried out in November 2003. Also in November 2003, the first near infrared *K*-band long-baseline interferometric observations of NGC 1068 succeeded, which employed the VINCI instrument after adaptive optics wavefront correction (MACAO). The first successful MIDI observation of the second brightest galactic nucleus, that of the Circinus galaxy, became possible in February 2004. Two more measurements with baseline UT2–UT3 were obtained during guaranteed time in June.

The Circinus nucleus is over three times closer and ten times less luminous than NGC 1068. The analysis of the data shows that the central dust structure is well resolved at 10 μm even with a 43 m baseline. Nevertheless, due to the small distance, its physical size is only 1 pc diameter. The observed visibilities as a function of projected baseline orientation hint at a much flatter dust distribution than that observed in NGC 1068 (see below).

For the purpose of this overview, however, we focus on the discussion of the VLTI results of NGC 1068 since they best demonstrate the wealth of information which already has been provided by the VLTI. A first account of the MIDI observations of NGC 1068 was published by Jaffe et al. (2004). On the basis of the interferometric spectra covering the range 8 μm < λ < 13 μm taken with 78 m and 42 m baseline, respectively, the authors argue that two central components are discernible: a well resolved, warm (T = 320 K) component of 3 pc diameter which is geometrically thick ($h/r \simeq 0.6$), and a very compact hot (T > 800 K) component, which is marginally resolved along the source axis. The SiO absorption feature increases in depth when using higher spatial resolution, i.e. longer baseline, suggesting that the central hot component suffers strong dust extinction equivalent to A_V > 50. The model is visualized in Figure 1 (top).

A natural interpretation of these findings identifies the 320 K component with the AGN-heated dusty torus expected in the cores of Seyfert galaxies, while the embedded hot component represents the wall of the funnel which is heated almost to the dust sublimation temperature and confines the well studied outflows along the source axis of NGC 1068. Additional support for this picture comes from radio continuum observations with the VLBA presented by Gallimore et al. (2004): Superimposing their map of the central component S1 on the MIDI model (Figure 1 bottom) shows that the disc-like radio source coincides in size with the hot component. Presumably, in the radio continuum we observe free-free emission of the ionized gas within the funnel which is continuously released from the walls and eventually feeds the central accretion disc. It is intriguing to identify the increased height of the radio continuum source at its outer parts with the ionized gas which has just been “eaten away” from the funnel walls by the intense UV radiation from the central engine.

At the same time, Wittkowski et al. (2004) presented the first *K*-band long-baseline interferometric measurement of the nucleus of NGC 1068 (see above). A squared visibility amplitude of 16.3 ± 4.3 % was measured for NGC 1068 at a baseline length of 46 m. This value corresponds to a FWHM of the *K*-band intensity distribution of 5.0 ± 0.5 mas if it consists of a single Gaussian component. Taking into account *K*-band speckle interferometry observations up to a baseline of 6 m (Wittkowski et al. 1998), a multi-component model is suggested for the intensity distribution where a part of the flux originates from scales clearly smaller than 5 mas (< 0.4 pc), and another part of the flux from larger scales. Figure 2 shows the measured VLTI/VINCI *K*-band visibility together with possible visibility models. For illustration, two different two-component visibility curves are shown which are consistent with both, the VLTI/VINCI visibility measurement at a baseline of 46 m, and the speckle observations up to a baseline of 6 m. These models consist of a 0.1 mas or 3 mas compact core, respectively, plus a more extended component.

Taking the MIDI and VINCI results of NGC 1068 together, there remains a completely open question: How are the compact components at 2 and 10 μm related to each other? Without an accurate (relative) astrometry (to about 1 mas) available yet, we are left to speculations based on indirect arguments. From the depth of the SiO feature one infers a *K*-Band extinction toward the hot MIDI component of A_K > 12. One possible explanation is a very porous dust torus which occasionally leaves holes of low extinction toward its hot centre. The compact *K*-band component could then represent a direct view to the central source or the inner part of the funnel viewed through such a hole. Alternatively, the *K*-band component could be located somewhat above the torus plane: in this case it is very unlikely that dust can be heated to > 1 200 K (unless the UV radiation from the central source is extremely collimated). More probably, the *K*-band light is then scattered by dust clouds above the torus.

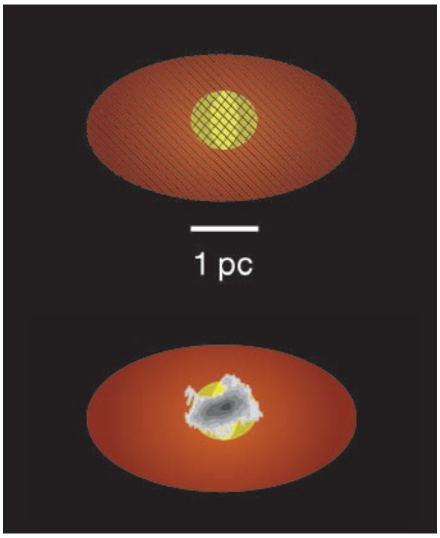

Figure 1: Top panel: Model dust distribution in the nucleus of NGC 1068 as inferred from the MIDI observations (North is at top, East to the right). A compact hot component (yellow) is embedded into the well resolved warm component (red). Hatching indicates the depth of the SiO absorption. Bottom panel: The VLBA radio continuum map at 5 GHz of the S1 component in NGC 1068 (from Gallimore et al 2004.) superimposed on the model. Note the widening of the radio component at its western edge.

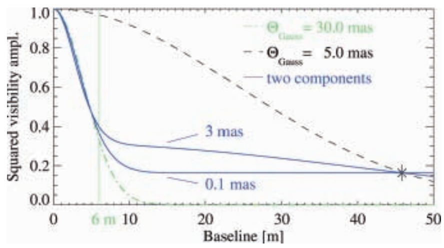

Figure 2: First *K*-band long-baseline interferometry of NGC 1068, obtained with VINCI. The VINCI visibility point at a baseline of 46 m indicates that part of the *K*-band flux originates from very small scales of less than 5 mas or 0.4 pc. Two possible two-component model visibility curves are shown which are consistent with this VINCI visibility measurement and with speckle observations up to a baseline of 6 m. These models consist of a 0.1 mas and 3 mas compact core, respectively, plus a more extended component. Based on Wittkowski et al. (2004b).

Pott et al. (this issue, page 43) describe in detail their program to study the stellar population close to our Galactic Centre. In particular, they describe the first successful MIDI observations of the dust enshrouded star IRS 3 located in the central lightyear of our Galaxy. Such studies aim at investigating the star formation history and the interaction of stars with their environment in the presence of tidal forces exerted by the gravitational potential of the central supermassive black hole.

In summary, it is obvious that already the first one and a half years of VLTI observations of galactic nuclei have provided completely new views into the cores of these still mysterious objects. New facilities like the phase-closure instrument AMBER or the external fringe tracking system FINITO will soon extend the VLTI capabilities to a level that interferometric observations of galactic nuclei will become both routine and the most important driver for our understanding of AGN physics.

Sizes and mineralogy of circumstellar discs around young Herbig Ae/Be stars

MIDI on the UTs was recently used to determine the characteristic sizes of Herbig Ae/Be star discs (Leinert et al. 2004) and their detailed dust properties (Van Boekel et al. 2004). The characteristic 10 µm sizes of the discs around seven Herbig Ae/Be stars turned out to be in the range of 1–10 AU and correlated with the slope of their SED between 10 and 25 µm (Figure 3). This correlation tends to give observational support even for such a limited sample to the hypothesis that Herbig Ae/Be star discs can be distinguished by whether they are flaring or non-flaring. In this context, one would expect, that as observed, the reddest objects should be larger since the flaring disc geometry exposes more distant material to direct illumination than the non-flaring geometry.

The detailed spectral shapes of three stars of this sample (HD 142527, HD 144432, and HD 163296) were then studied as a function of spatial scale in order to better understand the properties of circumstellar dust in these very young stars. It has been known for some time that most of the dust in discs around newborn stars is made up of silicates. In the natal cloud this dust is amorphous, i.e. the atoms and molecules that make up a dust grain are put together in a chaotic way, and the grains are fluffy and very small, typically about 10^{-4} mm in size. However, near the young star where the temperature and density are highest, the dust particles in the circumstellar disc tend to stick together so that the grains become larger. Moreover, the dust is heated by stellar radiation and this causes the molecules in the grains to re-arrange themselves in geometric (crystalline) patterns.

Accordingly, the expectation is that the dust in the disc regions that are closest to the star is soon transformed from "pristine" (small and amorphous) to "processed" (larger and crystalline) grains. Model calculations show that crystalline grains should be abundant in the inner part of the disc at the time of formation of the Earth. In fact, the meteorites in our own solar system are mainly composed of this kind of silicate. Spectral observations of silicate grains in the mid-infrared around 10 µm should tell whether they are "pristine" or "processed". Earlier observations of discs around young stars have shown a mixture of pristine and processed material to be present, but it was impossible to tell where the different grains resided in the disc.

Thanks to a hundred-fold increase in angular resolution with the VLTI and the highly sensitive MIDI instrument, detailed infrared spectra of the various regions of the protoplanetary discs around the three young Herbig Ae stars, only a few million years old, now show that the dust close to the star is much more processed than the dust in the outer disc regions. In one star (HD 142527) the dust is processed in the entire disc (Figure 4). In the central region of this disc, it is extremely processed, consistent with completely crystalline dust. In the other two stars (HD 144432 and HD 163296) the dust in the inner disc is fairly processed whereas the dust in the outer disc is nearly pristine (Figure 5).

An important conclusion from the VLTI observations is, therefore, that the building blocks for Earth-like planets are present in circumstellar discs from the very start. This is of great importance as it indicates that planets of the terrestrial type like the Earth are most probably quite common in planetary systems, also outside the solar system.

The present observations also have implications for the study of comets. Some – perhaps all – comets in the solar system do contain both amorphous and crystalline dust. Comets were definitely formed at large distances from the Sun, in the outer regions of the solar system where it has always been very cold. It is therefore not clear how processed dust grains may end up in comets. In one theory, processed dust is transported outward from the young Sun by turbulence in the rather dense circumsolar disc. Other theories claim that the processed dust in comets was produced locally in the cold regions over a much longer time, perhaps by shock waves or lightning bolts in the disc, or by frequent collisions between bigger fragments.

The MIDI observations now imply that the first theory is the most likely explanation for the presence of processed dust in comets. This also implies that the long-period comets that sometimes visit us from the outer reaches of our solar system are truly pristine bodies, dating back to an era when the Earth and the other planets had not yet been formed. Studies of such comets, especially when performed in-situ, will therefore provide direct access to the original material from which the solar system was formed.

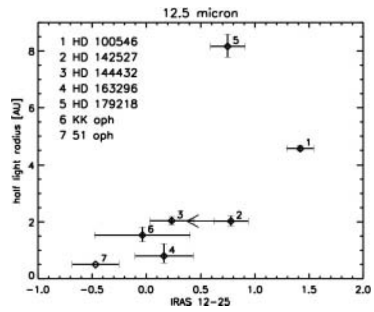

Figure 3: Correlation between the mid-IR spectral slope and the half light radius corresponding to the observed visibilities at 12.5 µm. The largest sources are those with the reddest mid IR SED. From Leinert et al. (2004).

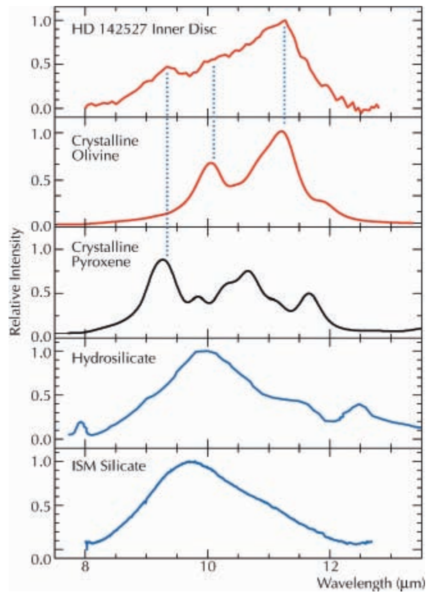

Figure 4: The mid-IR spectrum of the inner region of the protoplanetary disc around the young star HD 142527, as observed with MIDI (upper panel). Below it are shown laboratory spectra of two crystalline minerals as well as of an Interplanetary Dust Particle (IDP; captured in the Earth's upper atmosphere) with hydrated silicates and, at the bottom, a typical telescopic spectrum of dust grains in the interstellar space. The spectral "signatures" of crystalline pyroxene and olivine, i.e. peaks at wavelength 9.2 and 11.3 µm, respectively, are clearly visible in the spectrum of the inner stellar disc, demonstrating the presence of these species in that region of the disc. From Van Boekel et al. (2004).

Hot stars and their environment

Be stars are hot stars that exhibit Balmer lines in emission and free-free infrared excess, interpreted as due to a compact equatorial gaseous disc around these objects. Be stars are relatively frequent among the B-type objects. α Ara (HD 158427, B3Ve), which is one of the closest Be stars with an estimated distance of 74 pc (Hipparcos parallax) and an infrared excess among the highest of its class, has been chosen for the first MIDI observations of a Be star (Chesneau et al. 2005a). Surprisingly, α Ara could not be resolved with the 102 m projected baseline of the UT1 and UT3 telescopes, putting an upper limit to

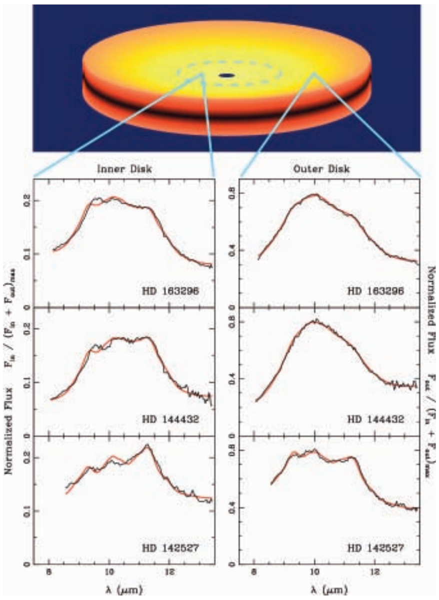

Figure 5: Schematic view of a circumstellar disc and the observed MIDI-spectra of the inner and outer regions of the discs around three young Herbig Ae stars, HD 163296, HD 144432 and HD 142527 (black lines). In all of them, there are clear spectral differences between the inner and outer regions, indicating a difference in mineralogy. The general broadening of the spectral "mountain" in the inner discs is a sign of larger grains and the spectral peak at wavelength 11.3 μm indicates the presence of crystalline silicates (cf Figure 4). Also shown are best-fit model spectra (red lines), based on mixtures of the mentioned mineral species. From Van Boekel et al. (2004).

the disc size in the *N*-band of the order of ϕ_{max} = 4 mas ± 1.5, i.e. 14 R_* at 74 pc and assuming R_* = 4.8$R_\odot$, based on the spectral type.

On the other hand, a high density of the disc is mandatory in order to reproduce the strong Balmer emission lines and the infrared excess. Optical spectra from the HEROS instrument, and infrared ones from the 1.6 m Brazilian telescope have been used together with the MIDI visibilities to constrain the system parameters. Using the circumstellar parameters from the SIMECA code, a good agreement was found with spectroscopic and interferometric data only if the disc is somehow truncated at about 25 R_*. The authors found variations of the hydrogen recombination line profiles and of the radial velocities of α Ara, and they argue that this may be an indication for a possible low-mass companion that could cause the truncation of the disc.

Using the stellar parameters from the model, i.e. a mass of 10 $M_\odot$, a 70 day period would give a radius of about 32 stellar radii, a value in agreement with the estimate based on the MIDI data for a disc truncated at 25 R_*, i.e. somewhat smaller than the companion orbit. Figure 6 shows a schematic view of the proposed model for the Be star α Ara and its circumstellar environment, including the possible unseen companion.

Previously, Domiciano de Souza et al. (2003) reported on VINCI observations of the rapidly rotating Be star Achernar. They found an oblateness of Achernar which exceeds theoretical predictions and, hence, puts new perspectives on our understanding of the Be phenomenon. α Ara presents a rotational velocity *v* sin *i* which is even larger than that of Achernar, and is, hence, likely to be very distorted, as well. The oblateness of the surface of α Ara can be studied with AMBER, and this will likely provide additional implications on the wind model.

The famous Luminous Blue Variable (LBV) η Car was recently studied by Chesneau et al. (2005b) by combining MIDI observations and adaptive optics measurements using NACO at the VLT. They reached a spatial resolution of 60–80 mas with deconvolved NACO images in the *L*-band. MIDI in interferometric mode provided a mean resolution of about 20 mas. Using this combination of MIDI and NACO observations, the authors were able to study the clumpiness of the nebula as well as to isolate the flux of the central star. The latter enabled them to constrain the spectral energy distribution (SED) of the central source by itself for the wavelength range from 2.2–13.5 μm.

Stars on the Asymptotic Giant Branch (AGB)

Interferometry is known to be a valuable tool for studying fundamental stellar parameters, the atmospheric structure, and the circumstellar environment of AGB and post-AGB stars. The spectro-interferometric capabilities of the VLTI instruments at near (AMBER) and mid-infrared (MIDI) wavelengths are expected to lead to new important insights into this stage of stellar evolution, and in particular into the atmospheric structure, the mass loss process, the formation of circumstellar envelopes, and the evolution of AGB stars toward planetary nebulae. Figure 7 shows a schematic diagram of a typical Mira variable and its surrounding environment. The various regions shown in this diagram can be probed by combining observations from various interferometric instruments and facilities in a multiwavelength study. In particular, mid-infrared interferometric observations are adequate for probing the outer atmosphere, i.e. the region between the top of the photosphere and the dust envelope where mass outflows are expected to be initiated, and the expanding dust shell.

Ohnaka et al. (2005) presented the results of the first mid-infrared interferometric observations of the Mira variable RR Sco with MIDI, coordinated with *K*-band observations using VINCI. The MIDI instrument has made it possible to measure the wavelength dependence of the visibility between 8 and 13 μm with a spectral resolution of ~ 30 (Figure 8, panel a). In this spectral region, a huge number of molecular lines due to H_2O and SiO are located, which allows one to directly study the parameters of the molecular gas in the outer atmosphere. Figure 8 (panel b) shows the obtained wavelength dependence of the angular diameter of

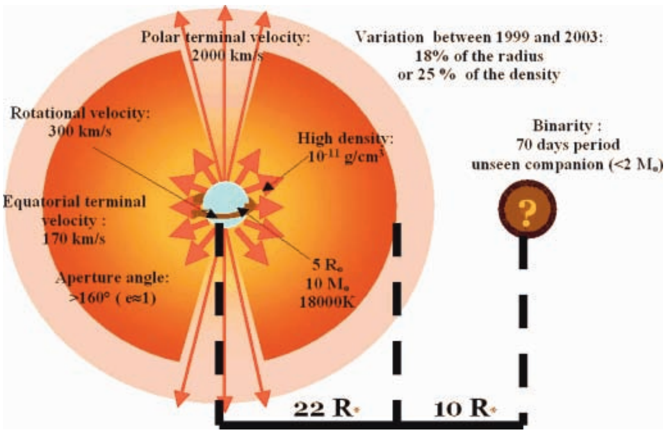

Figure 6: Schematic view of the proposed model for the Be star α Ara and its circumstellar environment. From Chesneau et al. (2005).

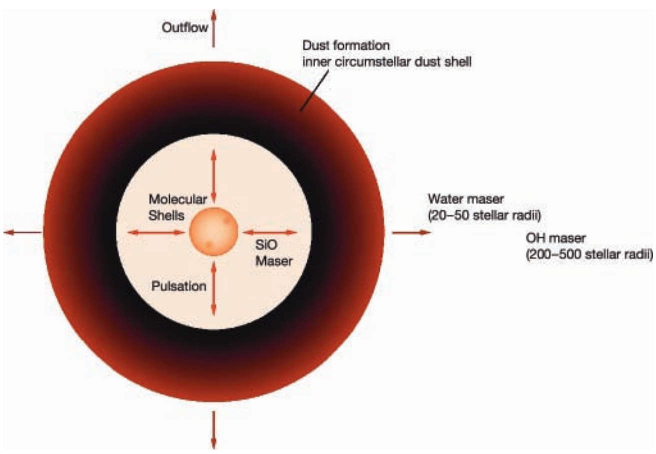

Figure 7: Schematic view of a Mira variable star.

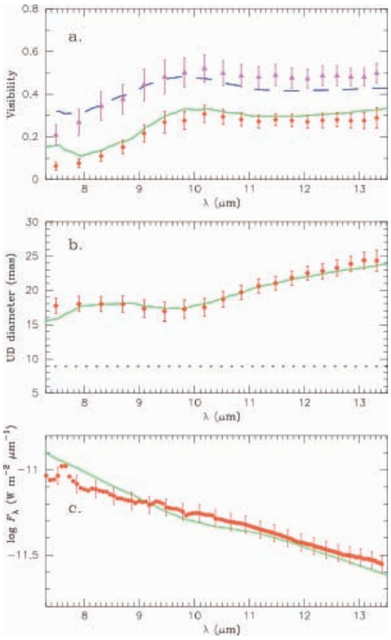

Figure 8: MIDI observations of the Mira variable RR Sco. Comparison between the visibility observed with MIDI (a), uniform-disc diameter (b), and spectrum (c) and those predicted by the best-fit model for RR Sco consisting of a warm H_2O + SiO envelope and an optically thin dust shell.
a: The diamonds and triangles represent the visibilities observed with projected baseline lengths of 99.9 m and 73.7 m, respectively, while the corresponding predicted visibilities are represented with the solid and dashed lines, respectively.
b: The filled diamonds represent the observed uniform-disc diameters, while the solid line represents the model prediction. The dotted line represents the continuum angular diameter estimated from the VINCI observation.
c: The filled circles represent the calibrated spectrum of RR Sco obtained from the MIDI observations. The solid line represents the spectrum predicted from the best-fit model. From Ohnaka et al. (2005).

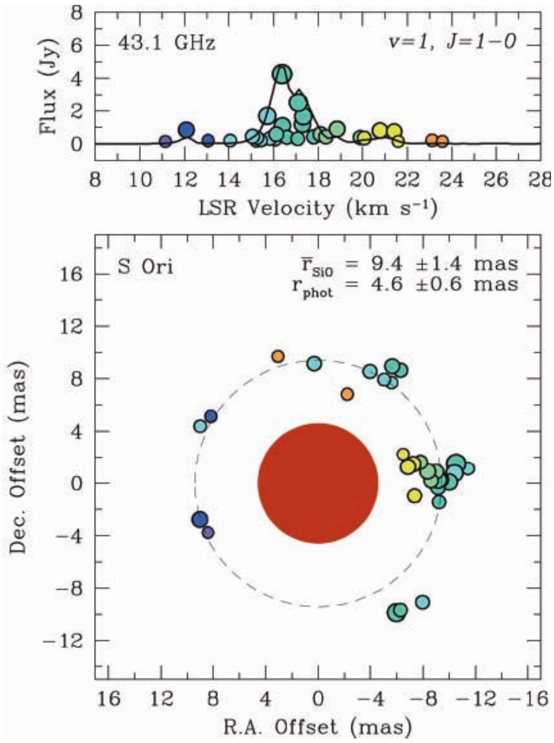

Figure 9: First-ever coordinated observations between ESO's VLTI and NRAO's VLBA: SiO maser emissions toward the Mira variable S Ori measured with the VLBA, together with the near-infrared diameter measured quasi simultaneously with the VLTI (red stellar disc). From Boboltz & Wittkowski (2005).

RR Sco. The angular diameter of 15–24 mas between 8 and 13 μm is significantly larger than the *K*-band diameter of 10.2 mas measured using VINCI, only three weeks after the MIDI observations. This wavelength dependence of the observed angular diameter of RR Sco can be interpreted in terms of the presence of a warm molecular envelope and an expanding dust shell. Ohnaka et al. (2005) derived physical parameters of these components using the *N*-band visibilities and the spectrum obtained with MIDI together with the *K*-band visibility measured with VINCI as observational constraints. Their model calculations show that optically thick emission from the H_2O + SiO envelope extending to ~ 2.3 stellar radii with a temperature of 1400 K makes the apparent mid-infrared diameter much larger than the near-infrared angular diameter. The increase of the angular diameter longward of 10 μm can be explained by the presence of an optically thin dust shell consisting of corundum and silicate with an inner radius at 7–8 stellar radii.

Additional insights into the conditions of the molecular gas in the outer atmospheres and circumstellar environment of AGB stars can be achieved by measuring and mapping the maser radiation that some of these molecules emit. Boboltz & Wittkowski (2005) conducted concurrent observations of the Mira variable S Ori as part of a program intended to exploit the power of long baseline interferometry at infrared and radio wavelengths to study the photospheres and nearby circumstellar envelopes of evolved stars. Figure 9 shows the results of the first-ever coordinated observations between NRAO's VLBA (Very Long Baseline Array) and ESO's VLTI. The VLBA was used to observe the 43 GHz SiO maser emission (represented by the circles color-coded in bins of radial velocity) concurrent with near-infrared *K*-band VINCI observations of the stellar photosphere (represented by the red disc in the centre of the distribution). The SiO masers were found to lie at a distance of about 1.7 stellar radii or 1.5 AU. With concurrent observations such as these, parameters of the circumstellar gas, as traced by the SiO masers, can be related to the star itself at a particular phase in its pulsation cycle. Such measurements can be used to constrain models of stellar pulsation, envelope chemistry, maser generation, and stellar evolution.

Fundamental parameters, most importantly radii and effective temperatures, of the photospheres of the central cool giant stars themselves have been frequently obtained with interferometric and other high angular resolution techniques, thanks to the favorable brightness and size of these stars. Richichi and Roccatagliata (2005) recently conducted new accurate measurements of the angular diameter of the cool giant Aldebaran using near-infrared interferometric and lunar occultation techniques. They discuss explanations for the elusiveness of a common angular diameter value which includes temporal variations as well as a dependence of the stellar diameter on wavelength.

Through the direct measurement of the centre-to-limb intensity variation (CLV) across stellar discs and their close environments, interferometry also probes the vertical temperature profile, the chemical composition, and horizontal inhomogeneities. Limb-darkening studies have already been accomplished for a relatively small number of star using different interferometric facilities. Wittkowski et al. (2004) presented the first limb-darkening observation that was obtained with the VLTI. Using the VINCI instrument, they measured *K*-band visibilities of the M4 giant *ψ* Phe in the first and second lobe of the visibility function. These observations were found to be consistent with predictions by PHOENIX and ATLAS model atmospheres, the parameters for which were constrained by comparison to available spectrophotometry and theoretical stellar evolutionary tracks.

For cool pulsating Mira stars, the CLVs are expected to be more complex than for non-pulsating M giants due to the effects of molecular layers close to the continuum-forming layers. Broad-band CLVs may appear as Gaussian-shaped or multi-component functions. Woodruff et al. (2004) and Fedele et al.

(2005) presented *K*-band VINCI observations of the prototype Mira stars *o* Cet and R Leo, respectively. These measurements at post-maximum stellar phases indicate *K*-band CLVs which are clearly different from a uniform disc profile already in the first lobe of the visibility function. The measured visibility values were found to be consistent with predictions by recent self-excited dynamic Mira model atmospheres (Ireland et al. 2004 and references therein; Scholz & Wood 2004, private communication) that include molecular shells close to continuum-forming layers. Figure 10 shows as an example the comparison of the VINCI observation of the Mira stars R Leo (Fedele et al. 2005) with the predictions by the dynamic model atmospheres mentioned above.

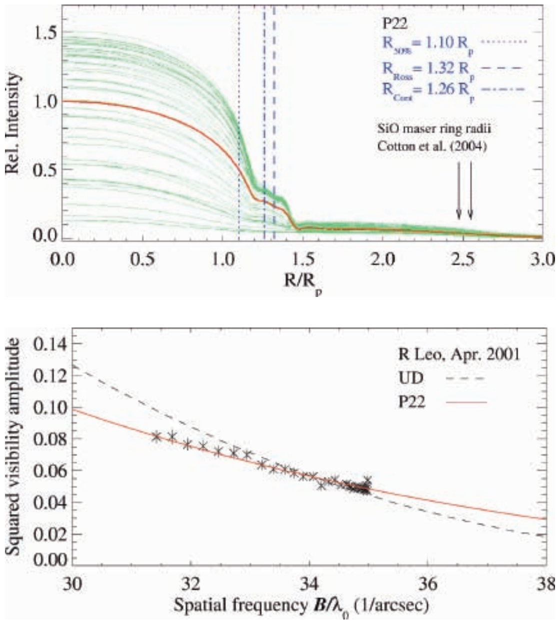

Figure 10: VINCI observations of the *K*-band intensity profile of the Mira variable R Leo and comparison to dynamic model atmosphere predictions (Ireland et al. 2004 and references therein; Scholz & Wood, private communication). The top panel shows the CLV prediction by model P22 (green lines: monochromatic CLVs; red line: filter-averaged CLV), and the bottom panel shows the corresponding visibility curve (red line) compared to the measured R Leo visibility values. Also indicated in the top panel are the mean positions of the SiO maser shells observed by Cotton et al. (2004). Based on Fedele et al. (2005).

Post-AGB stars

Further steps towards our better understanding of the stellar mass loss process are interferometric measurements of post-AGB stars. One of the basic unknowns in the study of late-type stars is the mechanism by which spherically symmetric AGB stars evolve to form axisymmetric planetary nebulae (PNe). Antoniucci et al. (2005) presented the first detection of the envelope which surrounds the post-AGB binary source HR 4049 by *K*-band VINCI observations. They report on a physical size of the envelope in the near-infrared *K*-band of about 15 AU (Gaussian FWHM). These measurements provide information on the geometry of the emitting region and cover a range of position angles of about 60 deg. They show that there is only a slight variation of the size with position angle covered within this range. These observations are, thus, consistent with a spherical envelope at this distance from the stellar source, while an asymmetric envelope cannot be completely ruled out due to the limitation in azimuth range, spatial frequency, and wavelength range. Further investigations using the near-infrared instrument AMBER can reveal the geometry of this near-infrared component in more detail, and MIDI observations can add information on cooler dust at larger distances from the stellar surface.

Chesneau et al. (2005c) very recently presented MIDI observations of the circumstellar environment of the massive OH/IR star OH26.5+0.6. This source is assumed to be at the tip of the AGB phase, and to have entered the superwind stage only about 200 years ago. The emission of the dusty envelope, appeared to be resolved by a single UT. The MIDI acquisition image taken at 8.7 µm exhibited clearly an asymmetry of the envelope of this star. In interferometric mode, no fringes were detected. The authors argue that this failure to detect fringes, caused by an over-resolved size of the source at this wavelengh range, gives additional constraints on the opacities of the inner regions of the dust shell or close vicinity of the star.

Cepheid pulsations and distance estimates

For almost a century, Cepheid variable stars have occupied a central role in distance determinations. This is thanks to the existence of the Period-Luminosity ($P - L$) relation $M = a \log P + b$ which relates the logarithm of the variability period P of a Cepheid to its absolute mean magnitude M. This relation is the basis of the extragalactic distance scale, but its calibration is still uncertain at a $\Delta M = \pm\, 0.10$ mag level. This uncertainty can be overcome by an independent estimate of the distance to a sufficient number of nearby Cepheids. Trigonometric parallaxes are generally too uncertain to provide strong enough constraints, and an alternative is provided by the Baade-Wesselink (BW) method. Its basic principle is to compare the linear and angular size variation of a pulsating star, in order to derive its distance through a simple division. Interferometry allows one to measure directly the angular diameter variation during the pulsation cycle, while the linear size variation can be obtained by high resolution spectroscopy (through the integration of the radial velocity curve). As described and reviewed in detail by Kervella et al. (ESO Messenger, 2004), the VINCI observations of 7 southern Cepheids (Kervella et al. 2004c) allowed the calibration of the zero point of the $P - L$ relation using interferometric BW distance measurements. The resulting zero point value is identical to the one obtained using a large number of Hipparcos parallaxes by Lanoix et al. (1999). This encouraging result strengthens confidence that no large bias is present on the $P - L$ calibration (Kervella et al. 2004b). Additionally, the VINCI measurements provided new calibrations of the Cepheid Period-Radius and Surface brightness-Color relations (Kervella et al. 2004a), two important relations to constrain theoretical models of Cepheids.

Very low mass stars and stellar evolution near the main sequence

The VLTI was used to precisely measure fundamental parameters of very low mass dwarf stars and of stars close to the main sequence (MS). During evolution after the main sequence, up to the subgiant and red giant stages, the stellar diameter increases enormously, up to several hundred times that of the present Sun. Even while the star is still close the the original MS, it inflates slowly. This means that the size of a given MS star is linked to its age. When combined with a theoretical stellar evolution model, a direct measurement of the size of a star therefore provides an estimate of its age.

Until recently, the mass-radius relation for very low mass stars was poorly constrained. The VINCI observations of four nearby M dwarfs using the 8 m telescopes UT1 and UT3 allowed the measurement of accurate angular sizes, and improved our knowledge of these faint stars (Ségransan et al. 2003). In particular, our nearest neighbour Proxima (M5.5V) was measured for the first time, with a very small radius of 0.145 $R_\odot$, only slightly bigger than Jupiter (0.103 $R_\odot$).

The angular diameters of a number of nearby dwarf stars were measured with high precision using VINCI, with the goal to establish their age based on numerical models of their evolution. The addition of the diameter as a constraint reduces dramatically the uncertainty of the evolutionary state of the star. For instance, the two components of our nearest neighbor, the binary star α Centauri, were resolved for the first time using VINCI (Kervella et al. 2003b). The 0.2 % accuracy of the angular diameter measurement of α Cen A is among the highest precisions ever achieved by interferometry. The numerical modeling of α Cen A and B and constraints from observed asteroseismic frequencies available in the literature reproduces the di-

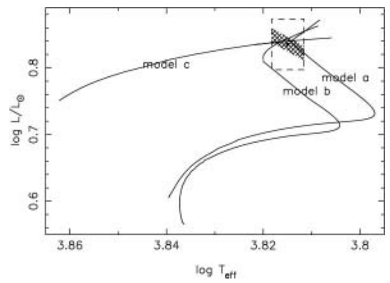

Figure 11: Evolutionary tracks in the Hertzsprung-Russel diagram of three models of Procyon A. The dashed rectangle delimits the classical uncertainty domain for luminosity and effective temperature, while the hatched area delimits the much reduced uncertainty when considering the interferometric radius. Model a is the most probable and indicates an age of 2.3 Gyr. From Kervella et al. (2004f).

ameters obtained by VLTI within their very small error bars.

The VINCI measurements of the bright stars Sirius A (Kervella et al. 2003a) and Procyon A (Kervella et al. 2004f) allowed the estimate of a very young age of 200–250 Myr for the dwarf Sirius, and an older age of 2.3 Gyr for the subgiant Procyon. Figure 11 shows as an example three evolutionary track models of Procyon. The interferometric constraint reduces considerably the uncertainty domain in the HR diagram, especially when coupled with asteroseismic observations. The age estimates based on the modeling of the interferometric data are confirmed by the cooling ages of the two white dwarfs that orbit Sirius A and Procyon A.

Similar modeling studies were also conducted for the debris disc stars α PsA, β Pic, ε Eri and τ Cet (Di Folco et al. 2004). These stars are MS or pre-main sequence stars with spectral type A to K presenting a far infrared excess, which has been commonly identified with circumstellar dust in optically thin discs. These discs are in turn often associated with planetary systems presumably already formed. The determination of the stellar ages is an essential information to study the evolution of the discs.

Diameter estimates of interferometric calibration stars

Interferometric measurements require the monitoring of the interferometric transfer function, which in turn is derived from observations of interferometric calibration stars. Usually those stars are selected as calibration stars that do not show any peculiar characteristics, and that have a well-known angular diameter and are as little resolved as possible. The need for well-known interferometric calibration stars has stimulated work aiming at measuring angular diameters of such candidates as well as establishing surface brightness-colour relations that allow the estimate of angular diameters based on known brightness and colour.

Richichi & Percheron (2005) recently described a massive ongoing effort, that was started in 2001, to accumulate observations on calibration stars with the aim of developing a VLTI-based system of high accuracy calibration stars. Observations of 191 calibration star candidates have been conducted with the VLTI and the near-infrared *K*-band commissioning instrument VINCI since March 2001, using six different siderostat and five different UT baselines. Based on angular diameters of these stars that have previously been available in the literature, the authors also discuss the evolution of the measured VLTI transfer function for the period 2001 to mid 2004. Work in progress aims at calculating a global VLTI-based solution that will determine uniquely new diameters of a subset of about 50 chosen calibration stars by minimizing the scatter of the residuals for each VLTI night under consideration.

Also, over the past two years, 16 new angular diameter measurements of nearby MS dwarfs and subgiants were obtained with the VINCI instrument, with the goal to calibrate the specific surface brightness-colour (SB) relations of these stars with high accuracy (Kervella et al. 2004e). The smallest dispersions are obtained for the visible-infrared based relations, in particular those based on the *B* and *K* magnitudes. These relations allow the prediction of very accurate (within 1 %) angular diameters of candidate calibration stars for long baseline interferometry.

The MIDI consortium has established a list of calibration stars for the MIDI instrument based on spectro-photometric observations of candidate stars and fitting of the data to atmosphere models (B. Stecklum, ESO calibrator workshop 2003; van Boekel et al., submitted).

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