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SCIENCE OPPORTUNITIES ON THE VLT INTERFEROMETER

M. Schöller[1]

RESUMEN

El interferómetro del VLT está desde hace varios años en operaciones científicas, con nuevas oportunidades disponibles cada vez que nuevas instalaciones están siendo integradas. La mayor parte de estos pasos son fácilmente visibles, pero algunas posibilidades se presentan a partir de mejoras simples. Detallo el potencial científico del VLTI, dando una descripción de la infraestructura y los modos ofrecidos por los instrumentos. Luego examino las limitaciones fijadas por la accesibilidad del cielo, flujo del objeto en el espectro visible e infrarrojo, o la morfología del objeto, seguida por una discusión de qué información se puede extraer de las mediciones del VLTI. Finalizo con una perspectiva en las mejoras futuras del VLTI.

ABSTRACT

The VLT Interferometer is since several years in science operations, with new opportunities becoming available every time new facilities are being integrated. Most of these steps are easily visible, but some possibilities arise from simple improvements. I detail the scientific potential of the VLTI, giving an overview about the infrastructure and the modes offered by the instruments. I then examine limitations set on sky accessibility, object flux over the visible and infrared spectrum, or object morphology, followed by a discussion of what information can be extracted from VLTI measurements. I close with an outlook on future improvements to the VLTI.

Key Words: instrumentation: interferometers — techniques: interferometric

The Very Large Telescope Interferometer (VLTI) on Cerro Paranal (see Figure 1), about 80 km south of the city of Antofagasta in Northern Chile is without doubt the largest optical interferometer in the world (Schöller 2007; Haguenauer et al. 2008). It comprises a total of eight telescopes, four fixed 8.2 m Unit Telescopes (UTs) and four movable 1.8 m Auxiliary Telescopes (ATs), which can be installed on 30 stations. The four large telescopes are all equipped with the adaptive optics system MACAO, which is located in the Coudé rooms. The six baselines spanned by the UTs are between 47 and 130 m, while the ATs cover the range between 8 and 202 m.

The VLTI infrastructure is used to "put the light in the one place at the one time". It injects the image plane into the laboratory, makes the pupils coincide (e.g. with cold stops in MIDI), and ensures that variations of the optical path difference (OPD) are only atmospheric or even residuals of the atmosphere. A schematic overview is provided in Figure 2. The light collected by the telescopes is focused with the help of the adaptive optics or tip/tilt systems in the Coudé foci and then propagates collimated through light ducts to the underground delay line tunnel. This tunnel has a length of 140 m and is the home of six delay lines. The delay lines are used to ensure that the optical path length (the path traveled by the light from the star through each telescope to the beam combination instrument) is equalized for all

Fig. 1. The summit of Paranal in early 2005. The picture is dominated by the enclosures of UT1 to UT4 from left to right. In the background between UT3 and UT4 one can see the enclosure of the VLT Survey Telescope (VST). Flanking the VST in the foreground, the first two ATs can be seen. To the left of the ATs and at the far right of the picture, the small enclosures of the two test siderostats are visible. The white lids in the front to the left are covering some of the 30 station pits to which the ATs can be moved.

[1]European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany (mschoell@eso.org).

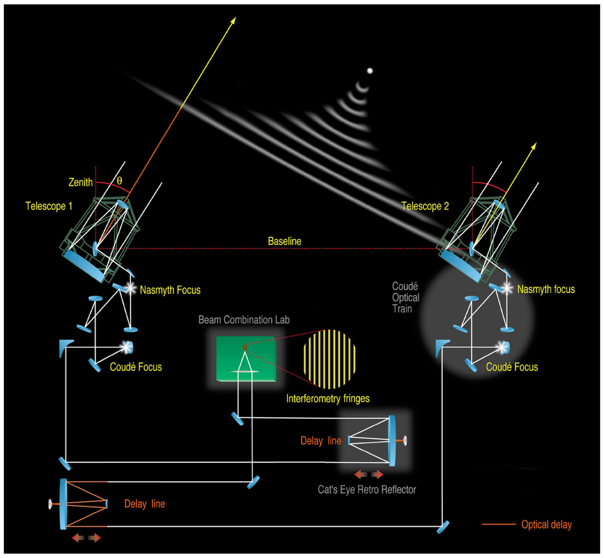

Fig. 2. Optical layout of the VLT Interferometer for two telescopes. The light is collected by the telescopes, transferred to the Coudé focus, and then sent through the delay line tunnel to the interferometric laboratory, where it is combined.

beams, while tracking the object. A variable curvature mirror (VCM) located in the Delay Line's cat's eye moves the pupil position in axial direction. The beams are combined in the interferometric laboratory in the two science instruments, MIDI and AMBER. During the commissioning phase, the test instrument VINCI was used. The near-infrared tip/tilt tracker IRIS allows to hold the beams at a given focal point and the fringe tracker FINITO stabilizes the optical path difference introduced by the atmosphere between up to three beams. The PRIMA dual feed facility (Delplancke 2008) completes the first phase of the VLTI.

Today, by the middle of 2009, all this hardware is installed and most of it is in operation. PRIMA has arrived in August 2008 and is currently undergoing extensive commissioning activities. Pictures of the telescopes and delay lines can be found in Figure 3. The transmission of the VLTI optics with a large number of reflections on very different optical surfaces depends on the exact configuration and wavelength band used. For single feed (i.e. not using PRIMA) and after the VLTI switchyard, the transmission is the lowest (>13%) in the J band on the UTs, and the highest in the N band (>38% on UTs and >42% on ATs). At the detector of the science instrument, the number of detected photons can be significantly lower, taking into account the Strehl ratio, the fact that part of the light is used for IRIS

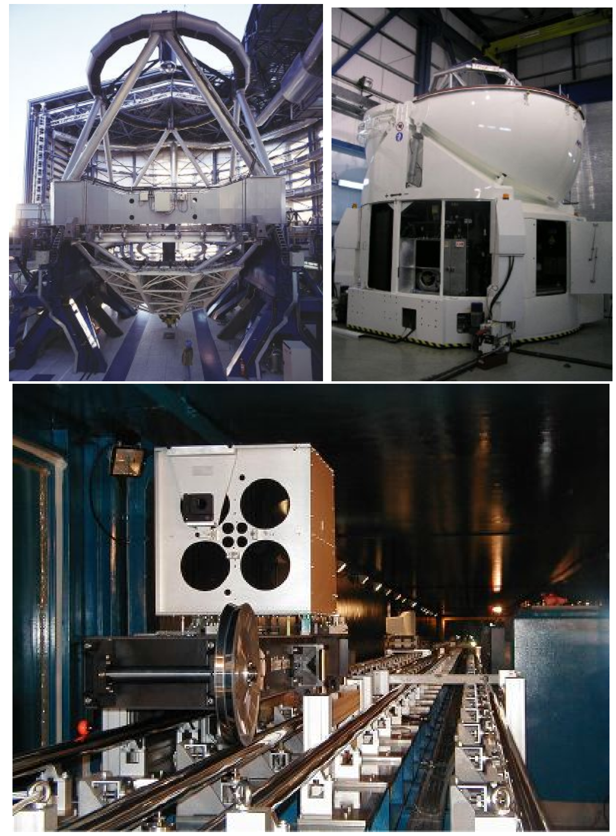

Fig. 3. Some of the VLTI hardware can be seen in this figure. In the top row are one of the Unit Telescopes and one Auxiliary Telescope (in the Paranal AT integration hall). The picture on the bottom shows one of the delay lines (with an optical alignment tool inserted in one of the optical paths).

and FINITO, injection into fibers, and a number of additional reflections.

Regular VLTI observations with the first scientific instrument, the mid-infrared instrument MIDI (Leinert et al. 2003), started in April 2004 on the 8.2 m Unit Telescopes (UTs). In October 2005, the near-infrared instrument AMBER (Petrov et al. 2007) started observations on three UTs simultaneously. Both instruments are in the meantime also available on the movable 1.8 m Auxiliary Telescopes (ATs), with four different configurations. These allow the observer to choose between four telescope triplets for AMBER and ten different baselines for MIDI. Pictures of both instruments are shown in Figure 4.

MIDI and AMBER follow the established general operations scheme of the other VLT instruments, including the proposal form, OB preparation and execution, FITS data format, and science data archive.

TABLE 1

INSTRUMENT MODES OF THE VLTI SCIENCE INSTRUMENTATION

	Bands	Number of telescopes	Spectral resolution	Limiting magnitude (UTs/ATs/UTs+FINITO/ATs+FINITO)
AMBER	J, H, K	3	35, 1500, 12,000	7, 4, 1.5/5.1, 1.6, −/7, 7, 6/5, 5, 5
MIDI	N	2	30, 230	4, 2.8/0.7, 0.3

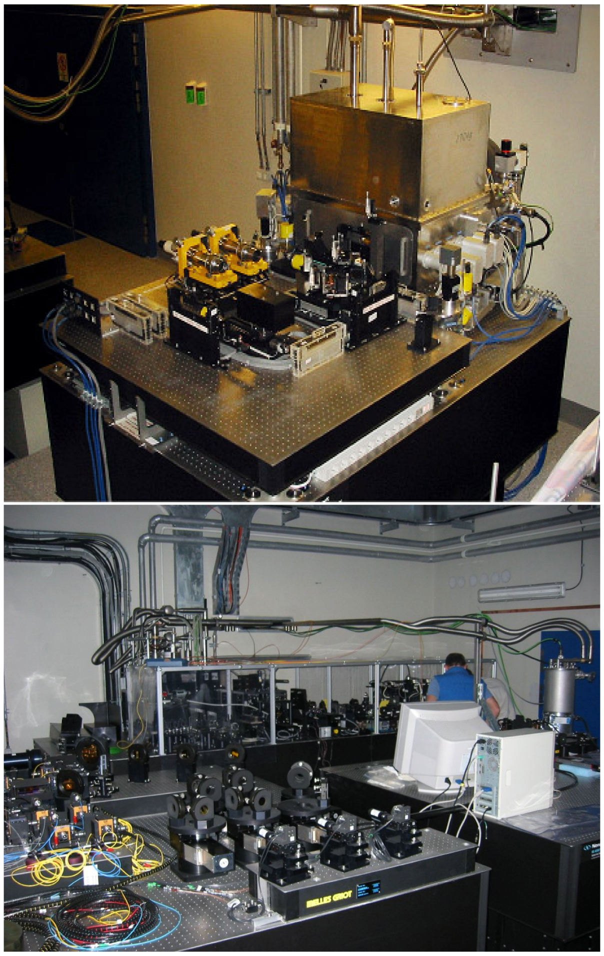

Fig. 4. MIDI (top) and AMBER (bottom) in the VLTI laboratory. The AMBER instrument is shown in the back of the image. The optics in the front belong to the fringe tracker FINITO.

Observations are performed in Visitor and Service Mode. Roughly 50% of the available time is used for science operations of the interferometer. The rest is used to improve the current system or to install new components. The characteristics of the science instruments, including their spectral coverage, number of telescopes combined, spectral resolution, and currently offered limiting magnitudes, can be found in Table 1. At $10\,\mu$m, a limiting magnitude of 4 corresponds to 1 Jy. A complete overview of the instruments and their capabilities can be found on the ESO instrumentation page under (`http://www.eso.org/sci/facilities/paranal/instruments/`).

Observing with the VLTI, the user faces several constraints, coming from the sensitivity of the various subsystems to atmospheric conditions, or from the site layout. The adaptive optics system MACAO has the following constraints: visual magnitude $1<\mathrm{m_V}<17$, seeing $< 1.5''$, coherence time $\tau_0 >$ 1.5 ms, airmass < 2, and natural guide star up to $57.5''$ from the science target. On the ATs, the guide star magnitude is currently $-1.7<\mathrm{m_V}<13.5$. The FINITO fringe tracker works under the following conditions: seeing $< 1.2''$, coherence time $\tau_0 >$ 2.5 ms, airmass < 1.5, a correlated magnitude $\mathrm{H}<7$ (UTs) or $\mathrm{H}<5$ (ATs), and a target visibility $V >$ 10%. Additionally, the size of the delay line tunnel and the location of the telescopes lead to pointing restrictions of the interferometer. Three examples can be found in Figure 5. To ease the preparation of the observations, ESO offers several tools on the exposure time calculator page (`http://www.eso.org/observing/etc/`). The visibility calculator VisCalc allows to estimate the visibility obtained with a given interferometer/instrument configuration, taking into account the limitations mentioned above. The calibrator selection tool CalVin is a front end to a database of carefully selected visibility calibrators.

Since the first astrophysical paper based on data from the VLTI was published in 2003, there have been more than 100 refereed publications coming from the VLTI. This comprises more than half of the output of refereed papers from optical interferometers that operated during the last six years. These articles cover topics from stellar diameters to active galactic nuclei. Overviews about the VLTI science results can be found in Richichi & Paresce (2003) and Wittkowski et al. (2005).

In the following, I am listing a few techniques which illustrate the potential of VLTI for hot star research, focusing on AMBER. Exact stellar diame-

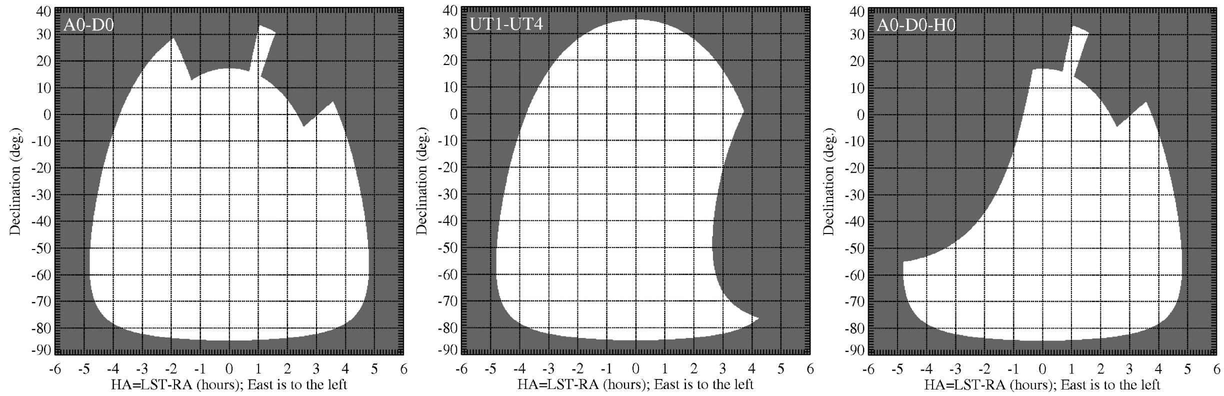

Fig. 5. Observing constraints for three different telescope configurations due to telescopes shadowing (left), baseline length limitation (middle), and a combination of both (right). Courtesy M. Wittkowski.

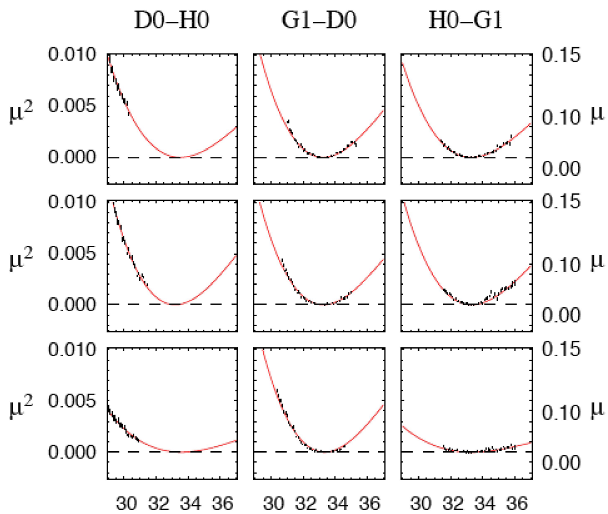

Fig. 6. K band squared visibility curves of V3879 Sgr for three different baselines and observations at three different hour angles.

ter measurements are very difficult with the VLTI, since both AMBER and MIDI provide absolute visibility accuracies on the order of only 5%. Le Bouquin et al. (2008) used the spectral coverage of AMBER to identify at which wavelength the visibility goes through zero, thus turning the visibility calibration problem into a wavelength calibration problem (Figure 6). With this they obtained a diameter of 7.56 ± 0.025 milliarcsec for V3879 Sgr, i.e. an accuracy better than 0.5%. Malbet et al. (2007) used color differential visibilities to determine the size of the wind in MWC 297. Figure 7 illustrates the change of visibility with wavelength over the Brγ line, showing clearly the larger size of the region being responsible for the absorption line, compared to the continuum. Le Bouquin et al. (2009a) used color differential phases to find signatures of a rotating photosphere in the spectra of Fomalhaut. Since the photo centers of the blueshifted and redshifted part of a rotating object are on slightly different positions in the sky, a baseline perpendicular to the angle spanned between these parts will give a characteristic S profile (see Figure 8). They were able to show that the stellar rotation axis is perpendicular to the disk found in other studies. Millour et al. (2007) used all available measurables (color differential visibility, color differential phase, and closure phase) to define a model of γ^2 Vel (Figure 9). Finally, both Kraus et al. (2009) and Le Bouquin et al. (2009b) presented images obtained from data collected at the VLTI (see Figure 10). This requires a larger investment of telescope time, but also luck, since several AT configurations have to be used over several nights, with good weather and atmospheric conditions.

There are several upgrades envisioned for the VLTI in the near and far future. Once PRIMA is fully commissioned, it will offer three different modes. PRIMA will enable the two science instruments MIDI and AMBER to observe faint targets, if a bright off-axis star is available for fringe tracking. Furthermore, both AMBER and MIDI will have access to referenced phases, measured between the science target and a nearby reference star. Finally, PRIMA itself with its two fringe tracking units allows for narrow angle astrometry between two stars within a $1'$ field. Currently, an upgraded tip/tilt system is installed on the ATs, which will result in a better limiting magnitude for the guide stars and more robustness over a wide range of seeing conditions. On the UTs, vibration sources are removed or damped (especially the closed cycle coolers on instruments) and an additional and improved vibration tracking system is under study. The ATs will

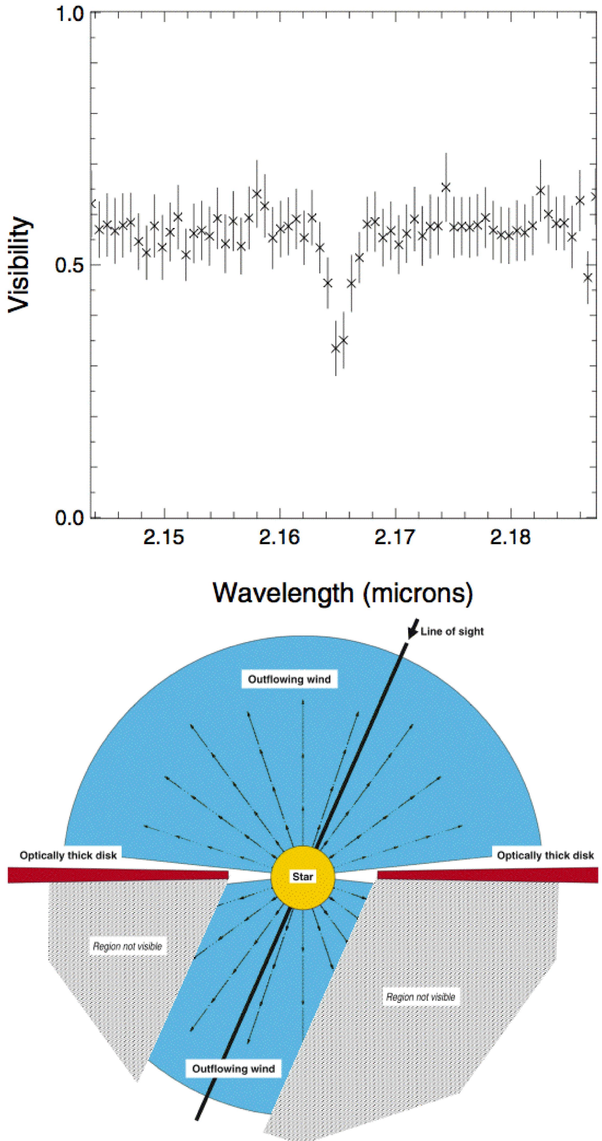

Fig. 7. Top: Visibility of MWC 297 over the Brγ line. Bottom: The resulting disk and wind model for this object.

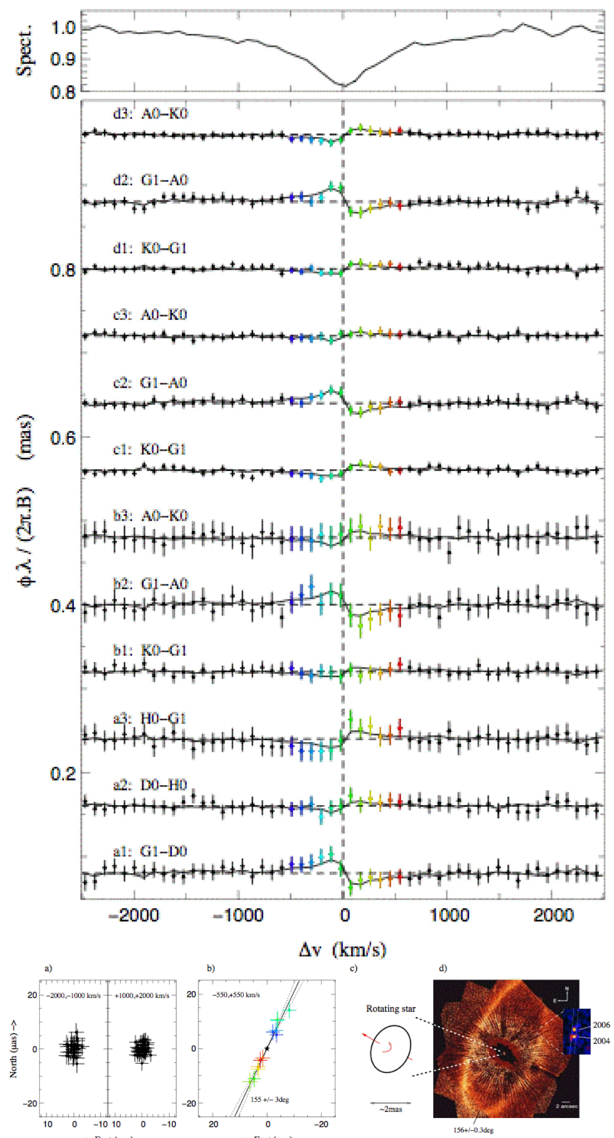

Fig. 8. Top: Spectrum (first line) and phases over the Brγ line for Fomalhaut, taken with medium spectral resolution on various baselines. Bottom: Astrometric positions for the continuum (left), over the Brγ line (middle), and the deduced rotation axis orientation (right) for Fomalhaut, compared to the debris disk and the planetary companion imaged in the visible by Kalas et al. (2008).

be offered in quadruplets, leading to more flexibility in operations, but also to a larger set of baselines and triplets available at any given time. Unfortunately, very short (8 m or 11 m) or longer ($\geq$120 m) baselines can currently not be realized with the ATs, since a pressure limit on the Delay Line VCM does not allow to reimage pupils for stations which are far away from the interferometric laboratory. Reductions of overheads, especially for bright targets will be achieved soon, which will also lead to improved calibrations. The ATs will be able to perform much better once an adaptive optics system will be installed. This system is currently under study and AT observations will benefit especially at shorter wavelengths, in the J and H bands. The second generation VLTI instrumentation is already on its way. MATISSE, a four way beam combiner operating in the mid IR in L, M, and N bands, and Gravity, a four way astrometric K band beam combiner, are in their preliminary design phases and are destined to

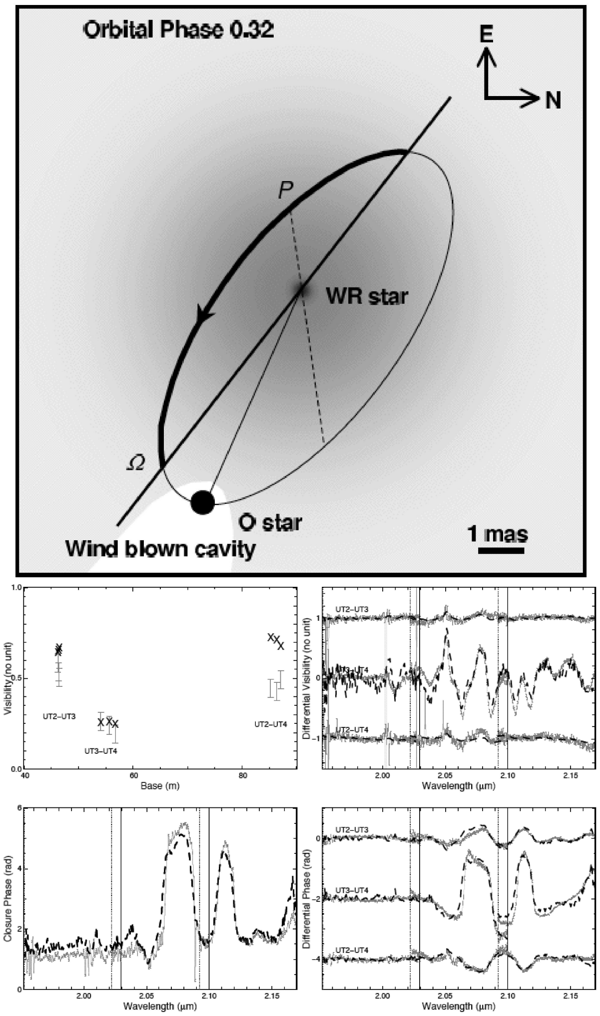

Fig. 9. Top: Model of the WR+O binary star γ^2 Vel. Bottom: Visibility values vs. baseline (upper left), and measured and modeled color differential visibility (upper right), closure phase (lower left), and color differential phase (lower right), all plotted vs. wavelength.

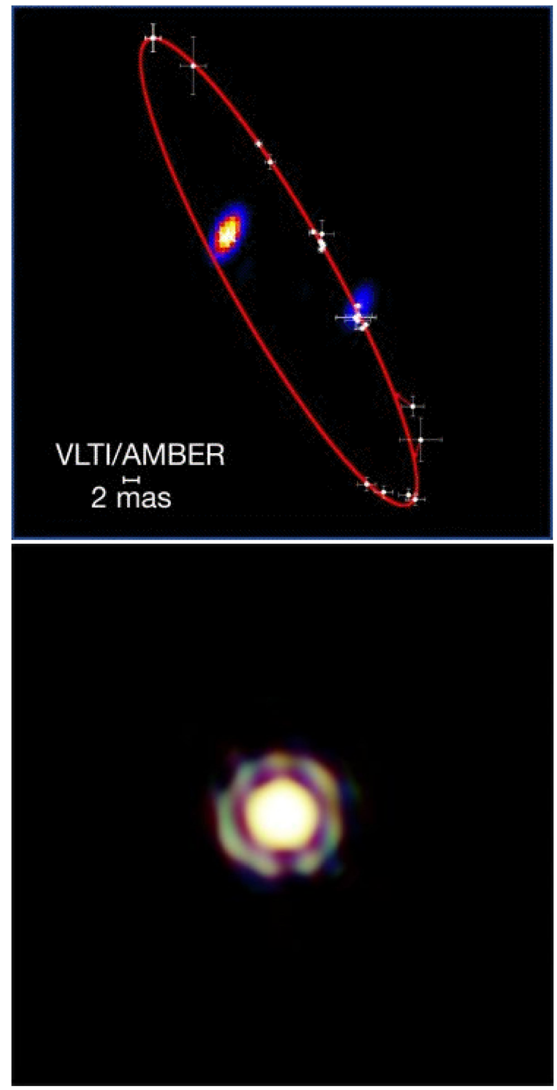

Fig. 10. Images obtained with the VLTI. Top: θ^1 Ori C overlayed with its orbit. Bottom: T Lep color composite image in the H band.

be installed in the VLTI laboratory in 2013. VSI, a six way beam combiner operating in the near IR, will very likely start its preliminary design phase in early 2010 and reach Paranal in 2014. While there is space for additional ATs and delay lines, no funding has been secured so far.

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