First Scientific Results from the VLT Interferometer*

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ABSTRACT

The VLT interferometer has been operating since the time of first fringes in March 2001 with a pair of 40 cm diameter siderostats at baselines of 16 and 66m and a pair of 8m diameter telescopes (UT1 and UT3) with a baseline of 102m using the test camera VINCI operating in the K band. A fair fraction of its commissioning time has been devoted to observing a number of objects of scientific interest around the southern sky bright enough to allow high precision visibilities to be obtained on a routine basis. A large number of stellar sources with correlated magnitudes brighter than K~6 and K~3 with the 8m and 40cm telescopes respectively have been observed over this time period with limited u,v plane coverage. In this paper, the most interesting results on sources never observed before at these spatial resolutions and on known sources for which the VLTI data allow the establishment of tighter constraints on theoretical models will be reviewed.

Keywords: VLTI, stars, η Car, R Aqr, Cepheids, Ψ Phoenicis, S Ori, science

INTRODUCTION

Since the corresponding times of first fringes in March and October of last year, the configuration we have been using is shown schematically in Figure 1. In particular, this means the use of the UT1 and UT3 8m telescopes on a 103m roughly NE-SW baseline both equipped with Coude' optics and tip/tilt sensors and 2 40cm diameter siderostats on 16 and 66m baselines oriented almost orthogonally as shown in Figure 1. In the 120m long delay line tunnel, 3 60m long stroke delay lines allow access to most of the available AT stations and the required tracking and OPD compensation. In the beam combination laboratory, pupil plane combination of the two beams is implemented by means of the test instrument VINCI operating in the K band at 2.2μ. The whole system together with its scientific objectives is described in greater detail in this conference and on the ESO web site: http://www.eso.org/projects/vlti/.

The currently achieved delay line precision is remarkable: flatness of rails better than 25μm over 65m, an absolute position accuracy of the carriages of ~30μm and a relative position error of ~20nm RMS over 50ms. It is this phenomenal precision and stability that makes the VLTI possible and unique.

FIRST RESULTS

First fringes with the siderostats were obtained March 17, 2001 and with UT1 and 3 on October 30, 2001. Technical commissioning is ongoing with highest priority. During natural pauses, observations of scientifically interesting sources take place. An internal science group decides on sources to be observed and the list is approved by the project manager responsible for commissioning. All scientifically interesting data taken in the period from March 17, 2001 to June 28, 2002 have been released to the community and are currently available from the ESO archive: http://www.eso.org/projects/vlti/instru/vinci/vinci_data_sets.html

About 35 ESO community scientists have availed themselves of the opportunity and are presently working on data taken so far. Data release is expected about every 3 months. VINCI and the siderostats have also been made available in service mode to the community on a shared risk basis starting on October 1, 2002 (Period 70). The deadline was April 3, 2002 and 40 proposals were received by that date. The same combination will also be made available for Period 71.

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The total number of objects measured so far is 140 (most of them repeatedly), 57 for the first time. The breakdown is the following: 1 AGN, 1 W-R star, 1 LBV, 1 symbiotic nova, 1 S star, 3 Cepheids, 3 YSO, 3 emission line stars, 3 shell stars (IR excess), 6 C stars, 10 MS dwarfs, 12 Spectroscopic binaries, 39 Late-type giants, and 56 Miras.

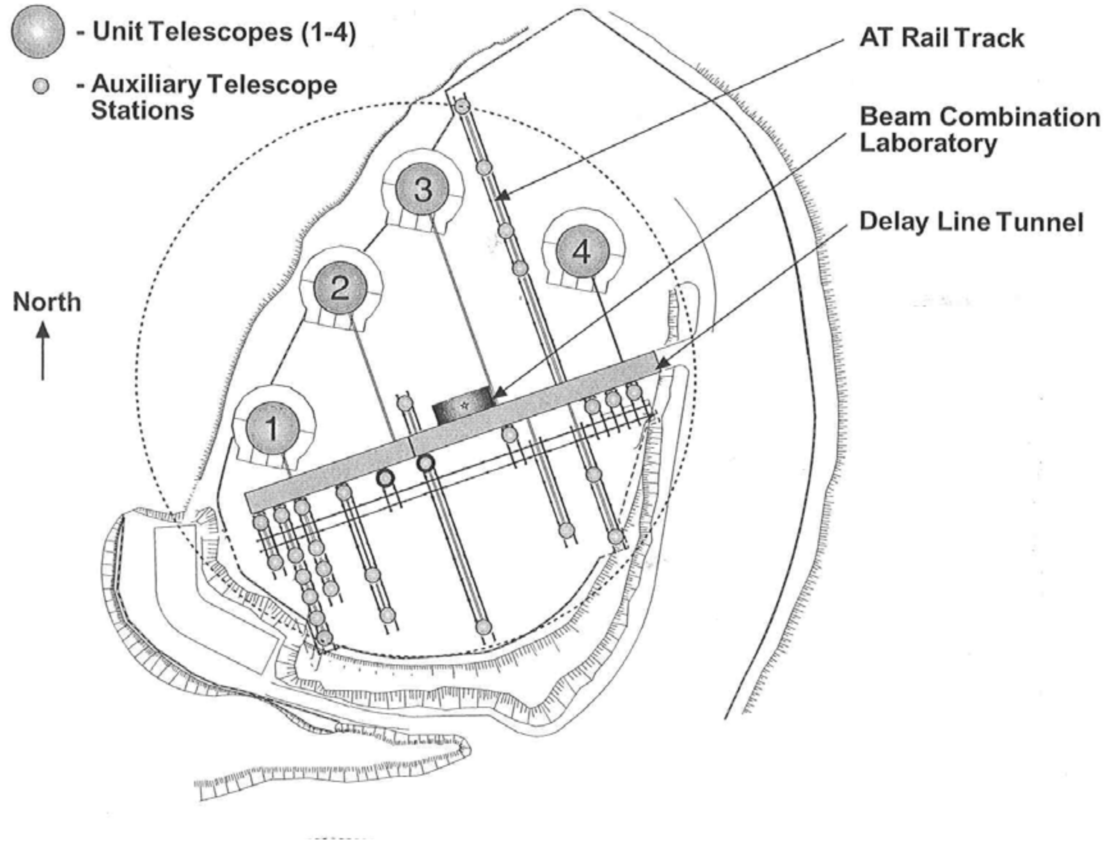

Figure 1. Schematic layout of the VLT Interferometer facility on Cerro Paranal. The dotted circle has a diameter of 200m for scale. The small circles indicate the auxiliary telescope (AT) and siderostat stations. The original siderostat positions with a 16m almost E-W baseline are marked in bold relief. The current positions correspond to the W siderostat remaining where it is and the E siderostat moved to the most Southerly station on the same track for a 66m almost N-S baseline.

CEPHEIDS

The Cepheids are used to obtain a distance determination as precise as 1% or better by accurately measuring the variation of the star's diameter through the full pulsation cycle. The corresponding measurements of the radial velocity variations yield the distance to the object since both the physical and the angular sizes of the motion are determined simultaneously. Observations of the Cepheid Zeta Gem (K=2.1, D~2.2mas, d=360pc, P=10d), for example, have shown that the required observing precision to track the pulsation has been achieved (1.78 +/-0.02 mas) and that all that remains to be done is to follow the 10d period to extract the distance (see Figure 2). Results obtained on other Cepheids are the following. Beta Dor gave a diameter of 2.07 +/- 0.09 mas near maximum and L Car 3.16 +/- 0.05 mas also near maximum.

K velocimetry is limited mainly by the projection factor which is model and limb darkening dependent. Currently, the precision with which this parameter can be obtained is ~ 1% which corresponds approximately to the final accuracy on the distance. Sampling over many baseline orientations and beyond the first null for limb darkening effects should push this accuracy down to ~0.1%. With these accuracies, the anchor of the distance ladder that is based mainly on the Cepheids will take a huge leap forward in usefulness and confidence.

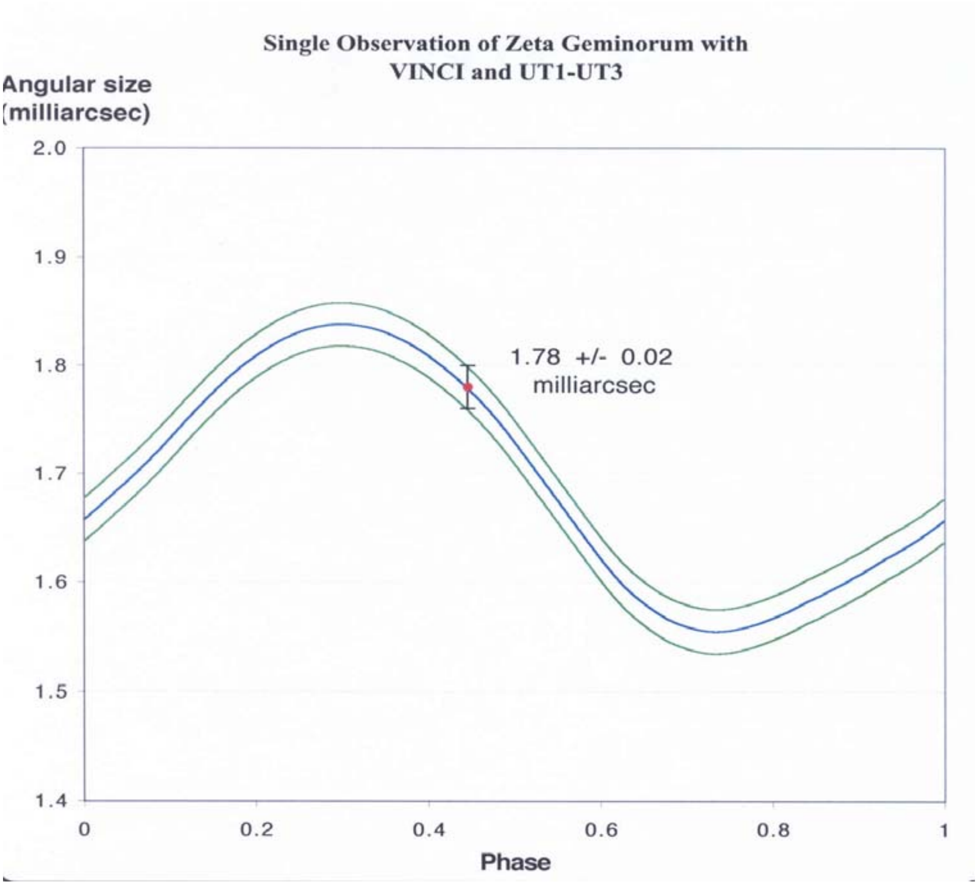

Figure 2. Results obtained so far with VINCI and the siderostats on Paranal on the Cepheid Zeta Gem. The curves represent the expected diameter variations.

ETA CARINAE AND R AQUARII

Eta Car is a Luminous Blue Variable of $L \sim 5 \cdot 10^6 L_\odot$ located at at a distance of ~ 2.3 kpc. It is thought to be a binary with a primary mass of $> 90 M_\odot$ and a secondary mass of $< 30 M_\odot$. The systems semi-major axis of ~9AU corresponds to 4milliarcseconds at its distance. The line spectrum of the stellar wind shows a 5.5 yr cyclic variability and a mass loss rate of $\sim 10^{-3} M_\odot yr^{-1}$ is inferred. The primary dominates the NIR spectrum and the primary's surface is most probably obscured by the very dense optically thick wind. The observing situation is shown schematically in Figure 3 where, superimposed on an HST picture of the LBV, the resolution and field of view of the VLTI is indicated.

Eta Car was observed with the Siderostats and VINCI with the 3 different baseline lengths and orientations shown in Figure 1 during four nights. The Unit Telescopes UT1 and UT3 which span a baseline of 102m with excellent results as the measured visibilities were all > 10% and relatively easy to measure. The measured visibilities with their error bars at the appropriate spatial frequencies are shown in Figure 4. The measurements are described in greater detail in Kervella et al., 2002.

Less straightforward is the interpretation of the measurements. The visibility curve shows a fairly rapid decline from 1 to less than 0.5 on projected baselines of 0 to 20m. At longer baselines the visibility still decreases, but more gradually. This behaviour can not be well explained in terms of a model with one component. Simple experiments in which we try to fit the visibilities with simple geometrical light distributions (a uniform disk, a gaussian, a ring) all show the same basic result: we can fit the short baseline data with certain model parameters, and we can also fit the long baseline data with certain *other* model parameters. However, it is *not* possible to fit the data on *all* baselines with any of these geometries, the best fit of any of the "models" to the short baseline data does not come anywhere near the long baseline points, and vice versa.

To fit the data on the short and long baselines simultaneously, a model with (at least) 2 spatially distinct components is needed. The VLTI measurements can be fit with a combination of 2 uniform disks. A single uniform disk that fits the long (~90m) baseline points hopelessly misses the short (15m) and intermediate (65m) baseline points. This example nicely illustrates the importance of having data on multiple baselines that span a large range in spatial scales probed.

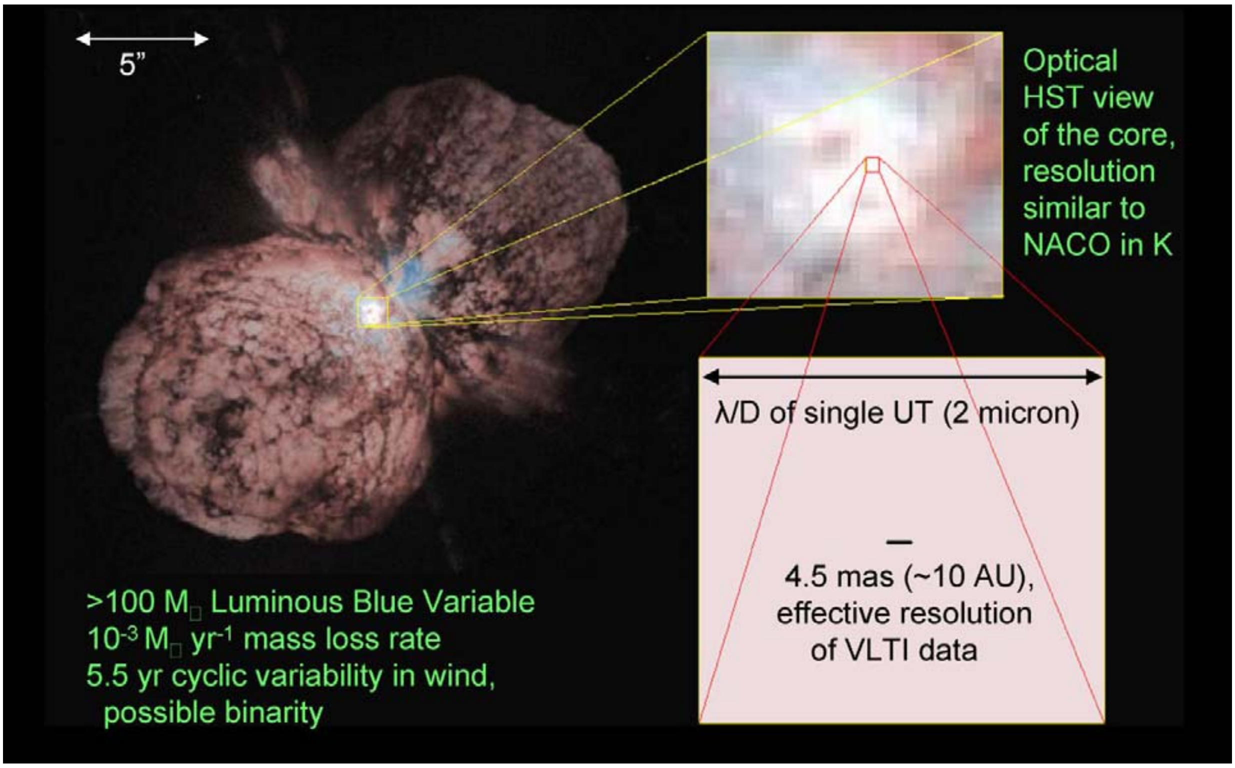

Figure 3. A schematic view of the VLTI's field of view and resolution in the sky at the position of Eta Car. The image is from HST in the optical band.

A reasonable fit to the data can be obtained with a combination of a "small" uniform disk of 4.2 and a "large" one of 30 milliarcsecond diameter, both contributing roughly half of the total flux at 2 μm. At 2.3 kpc these correspond to linear sizes of roughly 10 and 70 AU. Even though the simple uniform disks do not represent a genuine physical model of the source, they are a good indication of the light distribution. A real physical model that reproduces the observed visibilities must contain both the small and the large component, with emission spatial scales that can not be much different from uniform disks.

A physical interpretation of the two components is that the small (10 AU) component we see is the optical depth=1 surface of the optically thick stellar wind. In a 10^{-3} $M_{\odot}yr^{-1}$ stellar wind, the main opacity source in the outer wind is electron scattering. The VLTI measurements suggest that the average photon in the wind of the primary in the Eta Car system is scattered for the last time at roughly 5 AU from the central engine. The "extended" (70 AU) component must be some form of "circumbinary" matter, possibly a dusty disk. Whereas determining the exact shape of the light distribution in this component requires a much more detailed study, the size of this component cannot be dramatically different from the 70 AU used in the toy model.

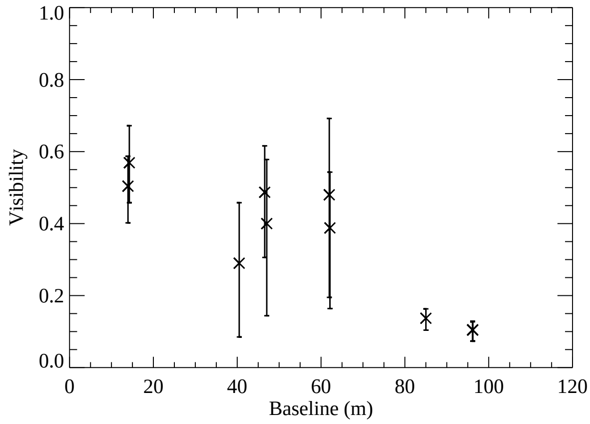

Figure 4. Visibilities determined with the VLTI and VINCI for Eta Car in the K band.

A similar study is ongoing on the symbiotic nova R Aquarii whose diameter is being monitored carefully to detect variations due to the Mira's 387d pulsations. Measurements taken at different times cluster around the value of 16.13mas as expected for a typical Mira of this type. The variations of the visibilities in time will be carefully monitored for signs of the possible hot white dwarf secondary.

THE STELLAR INTENSITY PROFILE OF THE M4III GIANT ψPHOENICIS

VLTI measurements of visibility amplitudes beyond the first minimum of the visibility function succeeded already during the VLTI commissioning phase on the resolved giant star Ψ Phoenicis using the near-infrared K-band two-beam commissioning instrument VINCI. Here, the capability to synthesize baselines of different lengths was used for the first time with the VLTI. High visibility values obtained in October 2001 on a 16m baseline using the VLTI test siderostats were combined with low visibility values beyond the first minimum of the visibility function obtained on Nov. 1 and 2, 2001 on a 102m baseline using the 8.2m diameter VLTI Unit Telescopes. Figure 5 shows the measured squared visibility amplitude values together with the three model curves used. The lower and upper solid lines indicate the fully darkened disk and uniform disk models, respectively. The dashed line indicates the Kurucz model atmosphere assumption. These observations are described in more detail in the context of interferometric measurements of stellar intensity profiles by Wittkowski and Hummel in these proceedings.

VLTI measurements will soon be able to constrain model atmospheres with a very high accuracy. This is of high importance for an observational verification of the models, in addition to measurements of stellar spectra. Ultimately, stellar surfaces may likely be imaged in much more detail including the mapping of special features like hot spots. These data can then be used to constrain hydrodynamic calculations of stellar convection including magnetic fields by observations of the sizes, intensities, and time variability of spots.

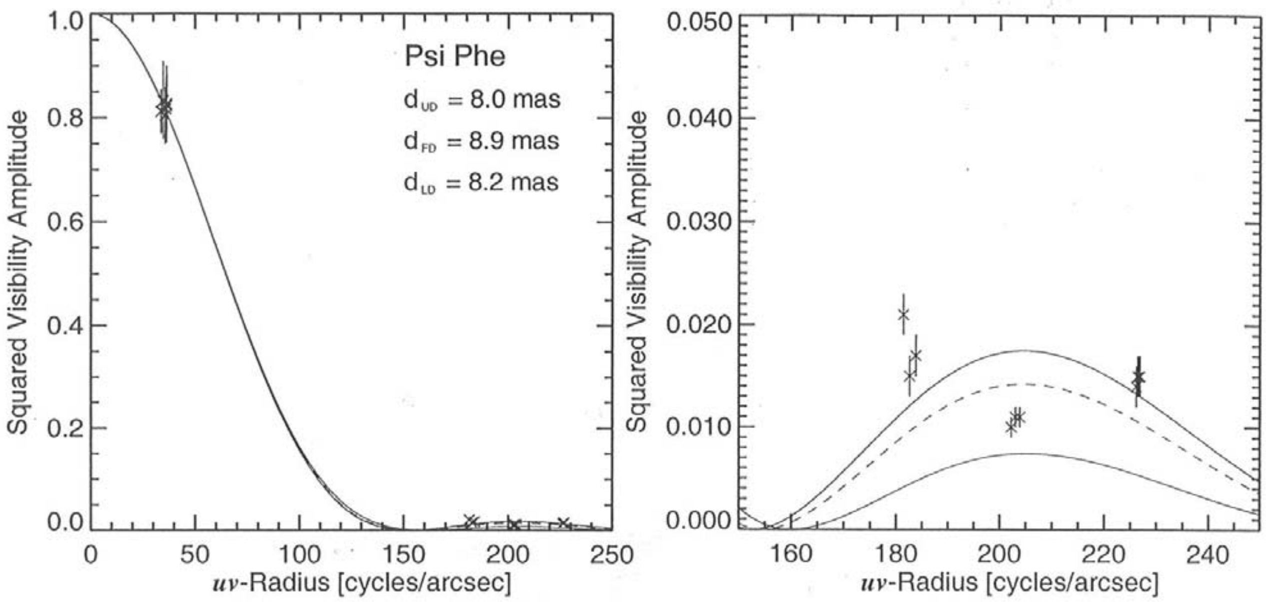

Figure 5: Visibility curve of ΨPhoenicis. The upper curve shows all measured squared visibility amplitude values, together with fits of a uniform disk (upper solid line), a fully darkened disk (lower solid line), and a limb darkened disk based on a Kurucz model atmosphere assumption (dashed line). The model fit is based only on the high values on the short baseline. The lower curve shows an enlargement of the low squared visibility amplitude values beyond the first minimum. These values allow us in principle to discriminate between these different models. The low values are currently affected by photon and detection biases. However, the internal accuracy, apart from the systematic bias terms, is of sufficient accuracy to distinguish the models.

OBSERVATIONS OF MIRA VARIABLES

VLTI observations of the famous red giant variable star Mira (o Cet) were obtained as part of the commissioning of the recently inaugurated ESO VLT Interferometer, in the period from October 23, 2001 to January 22, 2002 (photometic phases 0.12 to 0.38). Two small siderostat telescopes connected in a single 16m baseline were used, and several orientations and projected baselines were obtained thanks to Earth's rotation. The data were recorded in a K-band filter centered at 2.1μ. They resulted in high accuracy visibilities, over a range of about 20º in position angle. Fig. 6 provides an example of 2 nights of data. The quantity plotted is the equivalent diameter corresponding to the measured visibility in the hypothesis of a uniform stellar disc. This hypothesis is certainly inadequate in the case of Mira. In Fig. 7, we show that indeed an attempt to fit these data with a single uniform disc is impossible.

This is not surprising, since several observations in the past have shown that the star has asymmetries and/or more than a single spherical component. For example, the surrounding circumstellar dust has a significant effect on the measured visibilities, also depending on the wavelength of observation. What the observations collected so far -and shown here in a preliminary version- demonstrate, is that the VLTI data have a very good accuracy and stability, in spite of the very low fringe contrast of this large object (square visibilities are typically 5% on the 16m baseline). Clearly, further measurements with the VLTI are needed to complete the picture of this outstanding object. It is planned to resume observations of this object in autumn 2002, with a new set of baselines to explore also a wider range of azimuths.

In addition to Omicron Ceti itself, a number of about 15 other Mira type stars was observed during the VLTI/VINCI commissioning phase as well. One example is S Orionis. This object is a Mira star with a period of 414.3 days and a spectral type M6.5e-M9.5e. It shows a relatively strong variability amplitude of 4.5 mag and a V-K color of up to about 12-14 mag. This object was observed at a phase of its variability cycle with a V magnitude of about 12, and is thereby in the visual the faintest object that has so far been observed during the VLTI commissiong phase. This shows that the siderostat guiding is feasible down to at least this magnitude. S Orionis was found to have recently undergone a helium-shell flash possibly consistent with a strong period change. As a result, more detailed VLTI studies of the diameter and the atmosphere of this Mira star are planned for the near future. Figure 8 shows the visibility curve based on data obtained on January 4, 2001.

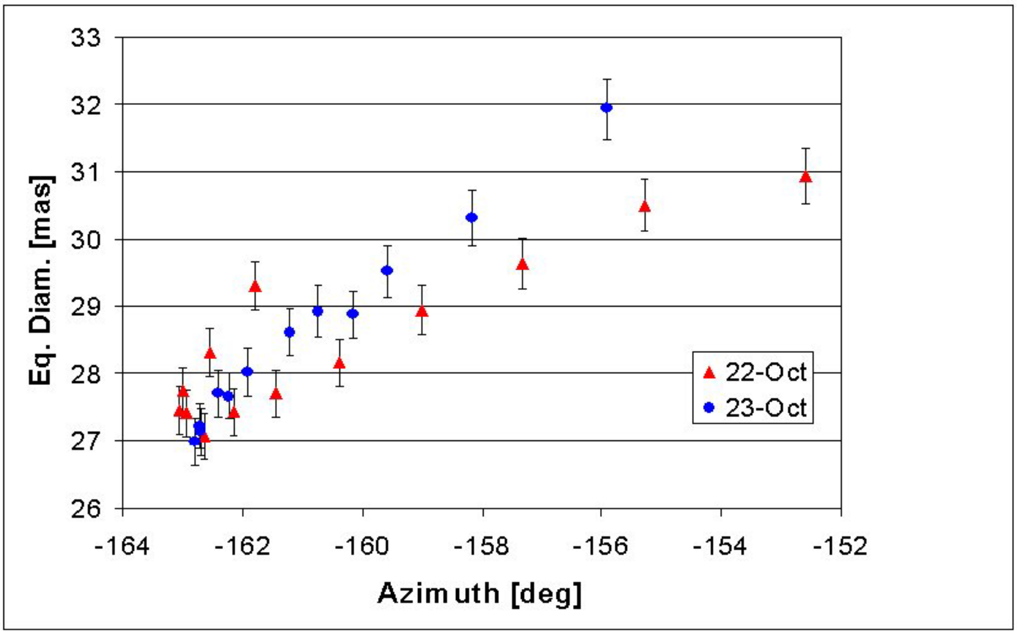

Figure 6. Measurements of Mira obtained throughout the nights of Oct 22 and 23, 2001. The visibility values have been converted to an equivalent angular diameter, under the assumption of a single uniform disc. Note the variation as a function of orientation of the baseline, indicative of asymmetry and/or presence of circumstellar emission.

FUTURE PROSPECTS

Future enhancements of the VLTI's capabilities will allow an enormous increase in the quantity and quality of the VLTI's scientific output. These will include, for next year (2003), the implementation of an axis fringe tracker Future enhancements of the VLTI's capabilities will allow an enormous increase in the quantity and quality of the VLTI's scientific output. These will include, for next year (2003), the implementation of an axis fringe tracker (FINITO), AO with MACAO on the UTs and an extension to the N band (10µ) with the MIDI instrument and 3-way simultaneous beam combination at J,H,K with AMBER. In addition, the first 3 ATs are expected to become operational in the next few years allowing 100% time coverage for interferometry. A little further down the line, phase referenced imaging and µas astrometry will be available thanks to the PRIMA facility now in an advanced planning stage.

Thus, the future looks bright for interferometry at Cerro Paranal. Thus, the entire community should make full use of this ground-breaking facility.

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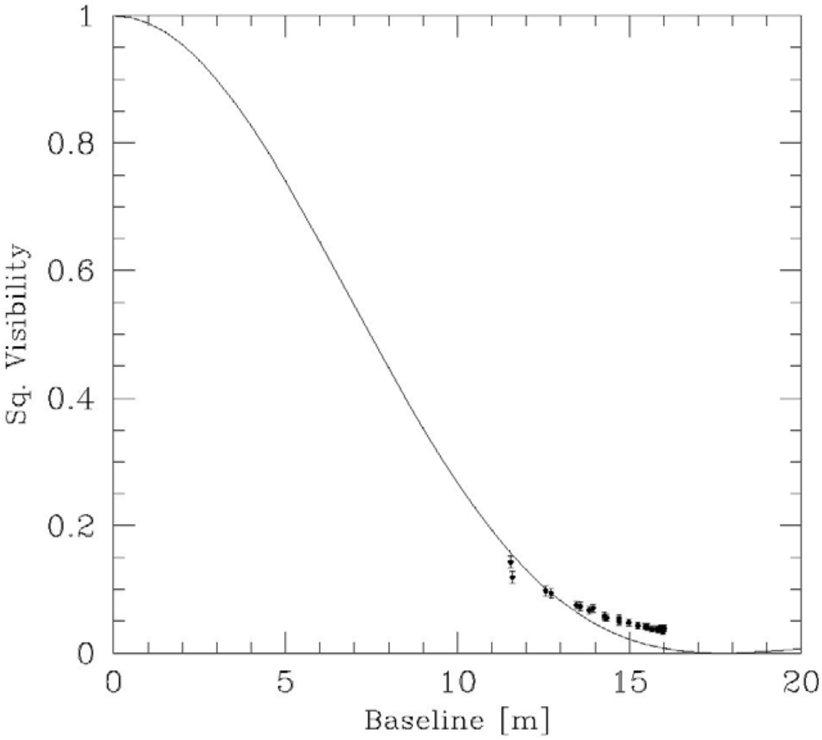

Figure 7. Same data of Fig. 6, plotted as a function of effective baseline length. A fit with a single uniform disc of 31 mas is also shown as a solid line. Clearly, the measurements are inconsistent with this simple model.

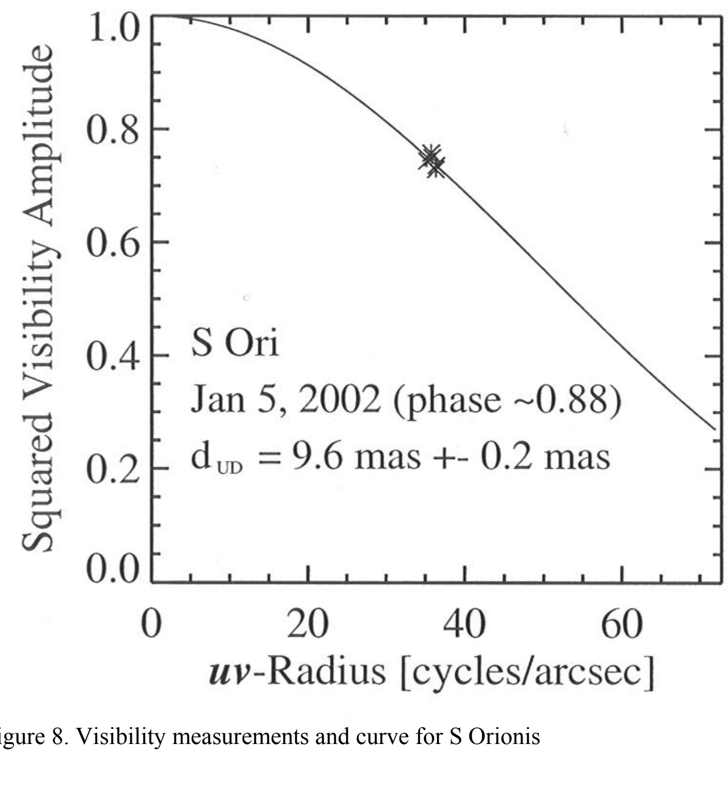

Figure 8. Visibility measurements and curve for S Orionis