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Recent Scientific Results with the VLT Interferometer

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Abstract. During the extensive commissioning phase of the VLTI since first fringes in 2001, a number of observations were made to ascertain the VLTI's ability to produce scientifically compelling results even with the limited performance of the first test instruments. In this paper, I briefly describe the setting for these observations and some of the preliminary results of the on-going investigations.

Key words. Interferometry – High resolution – Stars

1. Introduction

The VLTI attained the first fringe milestone with the 40 cm diameter siderostats in March 2001 (ESO PR 23/01) and with the UT (UT1 and UT3) (ESO PR 06/01) in October 2001. The VLTI and its scientific objectives are described in detail in the ESO website http://www.eso.org/projects/vlti/. Since then a number of other significant milestones were passed including the inauguration of the Mid IR camera MIDI, the first true VLTI instrument, in December 2002.

In order to test and verify the VLTI facility from a scientific point of view a number of nights with as wide a combination of instrumental modes as possible were allocated to the observations of scientifically interesting celestial objects during the commissioning period. This policy was formalized by the issue of a call for proposals to the ESO astronomical community for shared risk science observations during periods P70 (October 1, 2002 – April 1, 2003) and P71 (April 1, 2003 – October 1, 2003) with VINCI, the $2\,\mu$ test camera and the 40cm diameter siderostats.

Allocated to this task in P70 were 150 hrs (~ 15 nights) of on source observing time. 40 proposals for a total of > 600 hrs were received which an ad hoc scientific review and a technical feasibility committee reduced down to 16 proposals covering a little more than the allocated time to account for contingencies.

A similar program was launched for Period 71 for the 150 hours allocated. 26 proposals were received for ~ 500 hours. This time the program was reviewed by the OPC in the standard ESO manner although the OPC had not yet adapted to the demanding requirements of reviewing interferometry proposals. 16 proposals were accepted in Category B for 270 hours but technical feasibility indicated that only 13

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proposals were feasible for a total of 230 hours.

2. First results

Both the P70 and P71 programs have yielded a vast assortment of interesting results that are being worked on actively by the community. Those that have progressed so far to referee review are the following:

- First radius measurements of very low mass stars with the VLTI, Segransan et al. 2003
- The diameters of Alpha Centauri A and B: a comparison of the asteroseismic and VLTI views, Kervella et al. 2003a
- The spinning-top Be star Achernar from VLTI-VINCI, 2003, Domiciano de Souza et al. 2003
- Calibration observations of Fomalhaut with the VLTI, Davis et al. 2003
- The interferometric diameter and internal structure of Sirius A, Kervella et al. 2003b
- Direct measurement of the size of the star Eta Carinae, Van Boekel et al. 2003

In the following paragraphs, I briefly describe some of the highlights of these results.

2.1. Fomalhaut

A new high precision measurement of Fomalhaut (α PsA), one of the four original MS stars with a debris disk (Davis et al. 2003), yielded a surprising result. This star was observed over a range in hour angle of 21:50 – 05:24 hrs on the night of 20 October 2002. The projected baseline varied between 139.7 m and 49.8 m during the observations. No significant variation in the transfer function was found for the zenith angle range 5–70°. A new accurate limb-darkened angular diameter for Fomalhaut of 2.112 ± 0.011 mas was established by fitting the points with a uniform disk model.

This result has several important implications. First, since the instrument transfer function (V^2_{obs}/V^2_{exp}) remains rock solid during the course of a typical night and over a large range of zenith angles, the hugely critical instrument calibration now becomes much easier, safer and, therefore, accurate. Second, the precision on the angular diameter ($\pm 0.5\%$) obtained by the VLTI already in its first year of commissioning and without the benefit of the ultimate sensitivity available soon with AMBER, MACAO and FINITO is $12\times$ that obtained previously on this object with the Narrabri stellar intensity interferometer! The precision obtained rivals that obtained at NPOI on giant stars (10 yrs after first fringes).

From the combination of the new angular diameter, the Hipparcos parallax and the known integrated flux, the deduced values of the star's fundamental parameters are:

luminosity $L/L_\odot = 16.5 \pm 0.6$
radius $R/R_\odot = 1.746 \pm 0.016$
effective temperature $T_e = 8813 \pm 66$K.

The accuracy on Te ($\pm 0.7\%$) is now $5\times$ better than previous determinations and is now limited only by the error on the integrated flux. This will allow one to obtain very stringent constraints on theoretical stellar models and, ultimately, a precise age which is the crucial parameter in determining the time scales for proto-planetary disk formation and destruction.

2.2. Alpha Cen A and B

The first direct determination of the angular sizes of the disks of the solar-type stars Alpha Centauri A and Alpha Centauri B (Kervella et al. 2003a) was another interesting product of the early operations of the VLTI. As the two largest members of this triple stellar system that also includes the much smaller Proxima Centauri, they are the Sun's nearest neighbours in space at a distance of just over 4 light-years. Together with photometric and asteroseismic observations, this fundamental measurement with the VLTI has led to a complete characterization of Alpha Centauri A and Alpha Centauri B.

This has also allowed a unique and very detailed comparison between observations and current stellar theory for solar-type stars. There is clearly very good agreement, indicating that the structure and evolution of stars like our Sun are well understood. The limb darkened angular diameters for Alpha Cen A and B are found to be respectively 8.524 ± 0.020 mas and 6.035 ± 0.047 mas. The resulting linear diameters confirm the published masses $M_A = 1.100 \pm 0.006 M_\odot$ and $M_B = 0.907 \pm 0.006 M_\odot$ for both stars.

2.3. Low mass stars

The first radius measurements of very low mass stars (Segransan et al. 2003) were also obtained in this program. The angular diameters of 4 very low mass stars were measured in the range 0.7–1.5 mas with accuracies of 0.04–0.11 mas, and for spectral types ranging from M0V to M5.5V. An empirical mass-radius relation for M dwarfs based on all available radius measurements was derived and compared with theoretical models. The observed relation agrees well with theory at the present accuracy level, with possible discrepancy around 0.5–0.8 $M_\odot$ that needs to be confirmed. In the near future, dozens of M dwarfs radii will be measured with 0.1–1% accuracy, with the VLTI, thanks to the improvements expected from the near infrared instrument AMBER. This will bring strong observational constraints on both atmosphere and interior physics.

2.4. Sirius A

The VLTI also measured the direct angular diameter of the bright star Sirius A. A uniform disk angular diameter of 5.936 ± 0.016 mas and a limb darkened value of 6.039 ± 0.019 mas was derived. In combination with the Hipparcos parallax of 379.22 ± 1.58 mas, this translates into a linear diameter in solar units of 1.711 ± 0.013. The chief object of the study was to model the internal structure of Sirius A in order to reproduce its macroscopic characteristics. In conjunction with constraints from previous spectro-photometric observations, an evolutionary model for Sirius A was derived in which the apparently high surface metallic content of Sirius is not characteristic of the whole average value of Z for the star, and is caused by the levitation of the heavy elements on the thin upper convective layer of Sirius A.

By means of a theoretical model, an age of 200 ± 12 Myr is derived consistent with the evolutionary time of Sirius B. The accuracy on this age is greatly strengthened by the VLTI/VINCI radius, thus encouraging further studies to improve our knowledge of the diameter of nearby stars. Based on the same model, the asteroseismic large frequency spacing of Sirius A should be 82.4 μHz if it exhibits radial oscillations.

2.5. Eta Carinae

An important result was obtained on the enigmatic star η Carinae. Located in TR16 in the Carina nebula at a distance of 2.5 ± 0.3 kpc it is one of the most luminous stars known in our galaxy with 5×10^6 $L_\odot$ and an initial mass between 150 and 200 $M_\odot$. It loses mass at a prodigious rate (between 0.3–3 $\times 10^{-3}$ $M_\odot$) in a 500 km/s wind. In an enormous eruption in the middle of the 19th century that created the homunculus, several $M_\odot$ were ejected and it reached a luminosity of 30×10^6 $L_\odot$ becoming the second brightest object in the sky. Its present temperature is in the 15–40 $\times 10^3$ K range.

The nature of this eruption is still not understood. The resultant debris now forms the homunculus, a large prolate nebulosity surrounding the star, with an elongation along a position angle of 135°, which is the orientation of the polar axis of the rapidly spinning star. Clumps are found at all spatial scales; the strong inhomo-

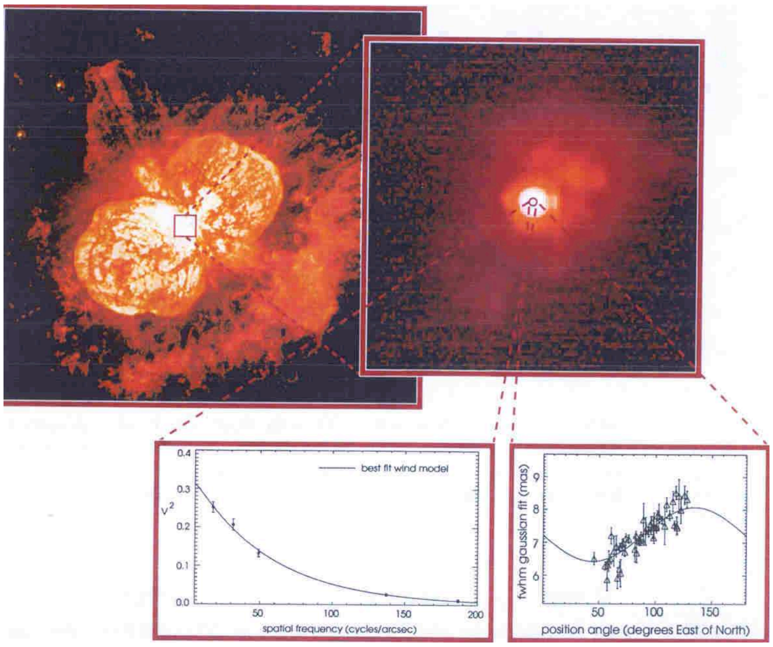

Fig. 1. Zoom into the η Carinae nebula. Top left: WFPC2 image. Top right: NACO observations at $2\,\mu$m. Bottom left: Vinci data reveal an object with size 5 mas. This is not the photosphere of the star, but the radius at which the stellar wind becomes opaque. Bottom right: VINCI data, converted to an effective diameter, plotted against the position angle of the baseline. The diameter change with p.a. implies that the object is elongated; the orientation is the same as that of the large-scale nebula shown in the top left panel. From Van Boekel et al. (2003).

geneities make it impossible to determine the mass loss rate from spectroscopy alone. The central object is not viewed directly because of several magnitudes at least of dust obscuration at IR wavelengths.

The main questions about this object that need a precise answer are:

- What was it? Yellow Super Giant? Red Super Giant? Wolf-Rayet?
- What is it now? Single? Binary? Cluster? What is its current mass loss rate exactly? What is its or their mass?
- What will it become? A normal star after more eruptions? Will it collapse into a SN or hypernova?
- Is it rotating? What is the origin of the 5.5 yr periodicity in some lines and x-rays? Is there a massive equatorial torus?
- What is the physical mechanism responsible for the violent instability (outburst(s)), the homunculus bipolar geometry, the double ring structure seen in the mid IR in the inner homunculus and the x-ray emission?
- What is going to happen this summer at x-ray peak?

It is important to answer these questions because we need to know more about the formation and evolution of extremely massive stars (most likely the first stars were this big): is it accretion onto a single object or due to mergers? We also need to know more about the dynamical and chemical interactions with their environment, the role of stellar instabilities in the outer envelopes of single stars and/or of periodic tidal forcing by a companion and the for-

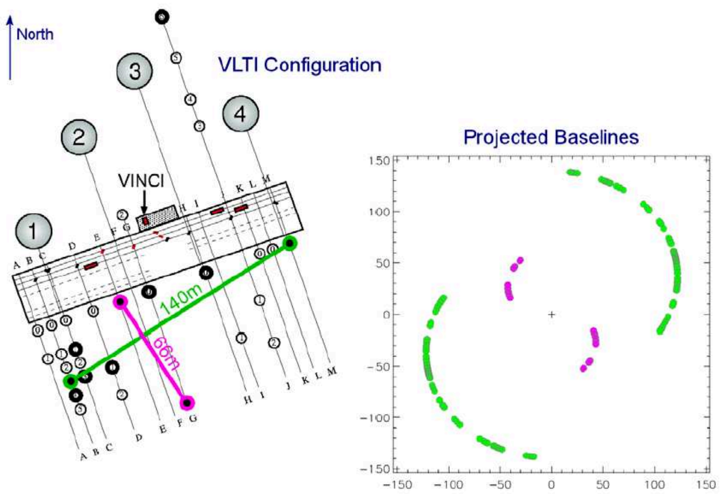

Fig. 2. The orientations of the 66m and 140m baselines are shown in the left panel. The right panel shows the corresponding baseline projections onto the sky as seen from the star. The inner points come from the 66m baseline while the outer ones come from the 140m baseline. Note the very efficient super-synthesis (different projections due to Earth rotation) resulting in a nearly complete coverage in azimuth angles.

mation of asymmetric nebulosity and the relation of extremely massive stars to peculiar supernovae and hypernovae.

The key to understanding η Car is to penetrate into the core and "see" the central object. The highest-resolution observations of η Car from a single telescope are the VLT/NACO data, shown in the top right panel of Figure 1. They resolve much of the sub-arcsecond structure, but about 60% of the flux within the inner $1.5''$ remain unresolved in a central object whose size must be smaller than 70 mas.

VLTI / VINCI observations clearly resolve this central object; its size can now be measured to be 5 mas at $2\,\mu$m. This is clearly much larger than the stellar photosphere; we are observing a surface with a temperature $T \approx 2{,}500$ K, corresponding to the radius at which the wind becomes opaque. The radiation is dominated by free-free emission and electron scattering; the radius of the surface is determined by the mass-loss rate and the wind clumping factor. The diameter measurement with the VLTI breaks the degeneracy between these two parameters in previous modeling efforts; mass loss rate and clumping factor can be derived separately from the combination of HST/STIS spectroscopy with the interferometric data.

A second important conclusion from the VLTI data is that the central object is not spherically symmetric (Figure 1, bottom right panel). In fact, its major axis is aligned with that of the large-scale structure. This alignment on all scales means that the mid 19th century outburst looks like a scaled-up version of the present-day wind, and that this wind is stronger along the poles than in the equatorial plane. This can be understood in the framework of radiation-driven winds from rapidly rotating stars: centrifugal forces favor mass-loss in the equatorial plane, but the radiation pressure is stronger in the polar regions because of the von Zeipel effect. (The stronger gravity near the poles leads to a higher temperature.)

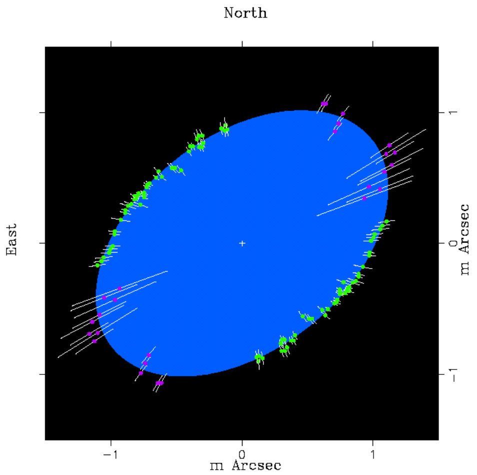

Fig. 3. Profile of the rapidly rotating star Achernar. Individual measurements are indicated as small points with an error bar. The fully drawn curve represents the best fitting ellipse.

It turns out that the von Zeipel effect is more important than the centrifugal levitation, leading to a polar wind. The VINCI observations have thus confirmed convincingly the model that interprets the morphology of η Carinae on all scales with a radiation-driven wind from a rapidly rotating star, and they have put constraints on these models that have allowed us to unambiguously determine the very high mass-loss rate from this object.

2.6. Achernar

This object was observed over a wide range of interferometric configurations that has resulted in an unprecedented view of the form of this rapidly rotating Be star (Domiciano de Souza et al. 2003). An aerial view of the VLTI ground baselines for the two pairs of siderostats used for Achernar observations are shown in Figure 2.

A fit of an ellipse over the observed V^2 points translated to equivalent uniform disc angular diameters is shown in Figure 3. The fitted ellipse results in a major axis of $2a = 2.53 \pm 0.06$ mas, minor axis $2b = 1.62 \pm 0.01$ mas, and minor-axis orientation PA $= 39 \pm 1°$ (from North to East). The points' distribution reveals an extremely oblate shape with an aspect ratio $2a/2b = 1.56 \pm 0.05$. The data was interpreted by means of a B3Vpe star model that included radiation transfer, gravity darkening (von Zeipel effect), geometrical distortion due to solid body rotation and mass concentrated at the star center and stellar parameters from the literature (225 km/s projected velocity etc). An extreme uniform Roche model with $v_{\mathrm{equatorial}} = v_{\mathrm{critical}}$ and $i = 90°$ was also used for this purpose.

The results of the comparison essentially were that:

- Normal Be star models don't work
- An extreme (equator-on, rotation at break-up speed) Roche model does but ... it is not consistent with known properties of Be stars (not uniform or rotating at critical speed)

But ... maybe we don't yet understand Be stars!

3. Conclusions and Acknowledgements

The VLTI is working well in all its aspects. This year will see the addition of adaptive optics, fringe tracking, mid IR interferometry and the 3 beam combiner at $2\,\mu$ AMBER. The future looks particularly bright for more compelling science. For this report, I thank the whole VLTI science team at ESO and participating scientists in many European institutes for making this work possible.

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