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VLTI-AMBER observations of Eta Carinae with high spatial resolution and spectral resolutions of 1,500 and 10,000 *

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ABSTRACT

We present the first interferometric NIR observations of the LBV η Carinae with high spectral resolution. The observations were carried out with three 8.2 m VLTI Unit Telescopes in the K -band. The raw data are spectrally dispersed interferograms obtained with spectral resolutions of 1,500 (MR-K mode) and 12,000 (HR-K mode). The observations were performed in the wavelength range around both the He I 2.059 μm and the Br γ 2.166 μm emission lines. The spectrally dispersed AMBER interferograms allow the investigation of the *wavelength dependence* of the visibility, differential phase, and closure phase of η Car. In the K -band continuum, a diameter of 4.0 ± 0.2 mas (Gaussian FWHM) was measured for η Car's optically thick wind region, whereas the Br γ and He I emission line regions are larger. If we fit Hillier et al.¹ model visibilities to the observed AMBER visibilities, we obtain 50% encircled-energy diameters of 4.3, 6.5 and 9.6 mas in the 2.17 μm continuum, the He I, and the Br γ emission lines, respectively. In the continuum near the Br γ line, an elongation along a position angle of $128^\circ \pm 15^\circ$ was found, consistent with previous VLTI/VINCI measurements.² We find good agreement between the measured visibilities and the predictions of the radiative transfer model of Hillier et al.¹ For the interpretation of the non-zero differential and closure phases measured within the Br γ line, we present a simple geometric model of an inclined, latitude-dependent wind zone. Our observations support theoretical models of anisotropic winds from fast-rotating, luminous hot stars with enhanced high-velocity mass loss near the polar regions.

Keywords: Stars: individual: η Carinae – Stars: mass-loss, emission-line, circumstellar matter, winds, outflows – Infrared: stars – Techniques: interferometric, high angular resolution, spectroscopic

* Based on observations obtained with the VLTI interferometer of the European Southern Observatory (ESO), Chile
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1. INTRODUCTION

η Car is one of the most luminous ($L \sim 4 \times 10^6 L_\odot$) and most massive ($M \sim 100 M_\odot$) unstable Luminous Blue Variables suffering from an extremely high mass loss at a rate of $\sim 10^{-3} M_\odot \text{yr}^{-1}$.³ It is surrounded by the expanding bipolar Homunculus nebula ejected during the Great Eruption in 1843. The inclination of the polar axis of the Homunculus nebula with the line-of-sight is $\sim 41^\circ$ with the southern pole pointing towards us.⁴ The first measurements of structures in the innermost sub-arcsecond region of the Homunculus were obtained by speckle-interferometric observations.^{5,6} These observations revealed a central object (component A) plus three compact and unusually bright objects (components B, C, and D) at distances ranging from approximately $0.1''$ to $0.2''$. Recent observations of η Car by Chesneau et al.⁷ using NACO and VLTI/MIDI revealed a butterfly-shaped dust environment at 3.74 and $4.05 \mu\text{m}$ and resolved the dusty emission from the individual speckle objects with unprecedented angular resolution in the NIR.

Spectroscopic studies of the Homunculus nebula^{8,9} showed that the wind of η Car is latitude-dependent. Van Boeckel et al.² resolved the optically thick, aspheric wind region with NIR interferometry using the VLTI/VINCI instrument. They measured a size of 5 mas (50% encircled energy diameter), an axis ratio of 1.25 ± 0.05 , and a position angle (PA) of the major axis of $134^\circ \pm 7^\circ$, and derived a mass-loss rate of $1.6 \times 10^{-3} M_\odot/\text{yr}^{-1}$. This aspheric wind can be explained by models for line-driven winds from luminous hot stars rotating near their critical speed.^{10,11} The models predict a higher wind speed and density along the polar axis than in the equatorial plane. Van Boeckel et al.² showed that the K broad-band observations obtained with VINCI are in agreement with the predictions from the detailed spectroscopic model by Hillier et al.¹ The Hillier et al. model was developed to explain STIS HST spectra.

A variety of observations suggest that the central source of η Car is a binary. Daminelli et al.¹² first noticed the 5.5-year periodicity in the spectroscopic changes of this object, which has been confirmed by several other studies since then.^{13–17} On the other hand, to date, the binary nature of the central object in η Car is still a matter of debate.^{18–21} HST STIS observations show that the He I lines are strongly variable and blue-shifted throughout most of the 5.54 year variability period. These observations cannot be explained in the context of a spherical wind model. It now appears likely that the He I emission lines originate in the bow shock and ionization zone, associated with the wind-wind interaction zone in a binary system.^{22,23} Very recent FUSE observations of η Car seem to have revealed a hot star component.²⁴

2. AMBER OBSERVATIONS AND DATA PROCESSING

AMBER^{26–28} is the near-infrared (J , H , K band) beam-combiner instrument of ESO's *Very Large Telescope Interferometer*. AMBER allows the measurement of visibilities, differential visibilities, differential phases, and closure phases.²⁹ AMBER offers three spectroscopic modes: low (LR mode; $R=\lambda/\Delta\lambda=75$), medium (MR mode; $R=1,500$), and high (HR mode; $R=12,000$) spectral resolutions. The fibers in AMBER limit the field-of-view to the diameter of the fibers on the sky ($\sim 60 \text{ mas}$). In AMBER the light is spectrally dispersed using a prism or grating. The AMBER detector is a Hawaii array detector with 512×512 pixels.

Our AMBER η Car observations were carried out on 2004 December 26, 2005 February 25, and 2005 February 26 with the three 8.2 m *Unit Telescopes* UT2, UT3, and UT4.²⁵ Figure 2 (left) shows two AMBER raw interferograms taken in the wavelength range around the $\text{Br}\gamma$ line in HR (top) and MR (bottom) mode. In the MR data sets, the Doppler-broadened $\text{Br}\gamma$ line covers ~ 8 spectral channels, whereas in HR mode, the line is resolved by ~ 50 spectral channels. With projected baseline lengths up to 89 m , an angular resolution of $\sim 5 \text{ mas}$ was achieved in the K band. The MR- K observations were performed in the wavelength range around both the He I $2.059 \mu\text{m}$ and the $\text{Br}\gamma$ $2.166 \mu\text{m}$ emission lines. The HR- K observations were only performed in a wavelength range around the $\text{Br}\gamma$ line. The widths of the wavelength windows of the obtained MR- K and HR- K observations are approximately $0.05 \mu\text{m}$ and $0.02 \mu\text{m}$, respectively.

For the reduction of the AMBER data, we used version 2.4 of the *amdlib*[†] software package. This software uses the P2VM (*pixel-to-visibilities matrix*) algorithm³⁰ in order to extract complex visibilities for each baseline

[†]This software package is available from
<http://amber.obs.ujf-grenoble.fr>

and each spectral channel of an AMBER interferogram. From these three complex visibilities, the amplitude and the closure phase are derived.

3. RESULTS

Our AMBER observations of η Car were performed with the spectral resolutions of $R = 1,500$ and $R = 12,000$ in Dec. 2004 ($\phi = 0.268$) and Feb. 2005 ($\phi = 0.299$) in spectral windows around the He I and Br γ emission lines at $\lambda = 2.059$ and $2.166 \mu\text{m}$, respectively. From the measurements, we obtained spectra, visibilities, differential visibilities, differential phases, and closure phases. From the analysis of the data, we derived the following results:²⁵

In the K -band continuum, we resolved η Car’s optically thick wind. From a Gaussian fit of the K -band continuum visibilities in the projected baseline range from 28–89 m, we obtained a FWHM diameter of 4.0 ± 0.2 mas.

When comparing the AMBER *continuum* visibilities with the NLTE radiative transfer model from Hillier et al.,¹ we find very good agreement between the model and observations. The best fit was obtained with a slightly rescaled version of the original Hillier et al.¹ model, corresponding to an observed FWHM diameter of 2.4 mas and a 50% encircled-energy diameter of 4.3 mas at $\lambda = 2.17 \mu\text{m}$. Taking the different FOVs into account, we found good agreement between the AMBER measurements and previous VLTI/VINCI observations of η Car presented by van Boeckel et al.²

If we fit Hillier et al.¹ model visibilities to the observed AMBER emission line visibilities, we obtain 50% encircled-energy diameters of 6.5 and 9.6 mas in He I and the Br γ emission lines, respectively.

In the continuum around the Br γ line, we found an elongation towards position angle $128^\circ \pm 15^\circ$ with a projected axis ratio of 1.21 ± 0.08 . This result confirms the earlier finding of van Boeckel et al.² using VLTI/VINCI and supports theoretical studies which predict an enhanced mass loss in polar direction for massive stars rotating close to their critical rotation rate.¹¹

For both the Br γ and the He I emission lines, we measured non-zero differential phases and non-zero closure phases within the emission lines, indicating a complex, asymmetric object structure. We developed a physically motivated model,²⁵ which shows that the asymmetries (DPs and CPs) measured within the wings of the Br γ line are consistent with the geometry expected for an aspherical, latitude-dependent stellar wind. Additional VLTI/AMBER measurements and radiative transfer modeling will be required to determine the precise parameters of such an inclined aspherical wind.

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The data reduction software `amdlib` is freely available on the AMBER site <http://amber.obs.ujf-grenoble.fr>. It has been linked with the free software Yorick[‡] to provide the user-friendly interface `ammyorick`.

The NSO/Kitt Peak FTS data used here to identify the telluric lines in the AMBER data were produced by NSF/NOAO.

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[‡]<ftp://ftp-icf.llnl.gov/pub/Yorick>

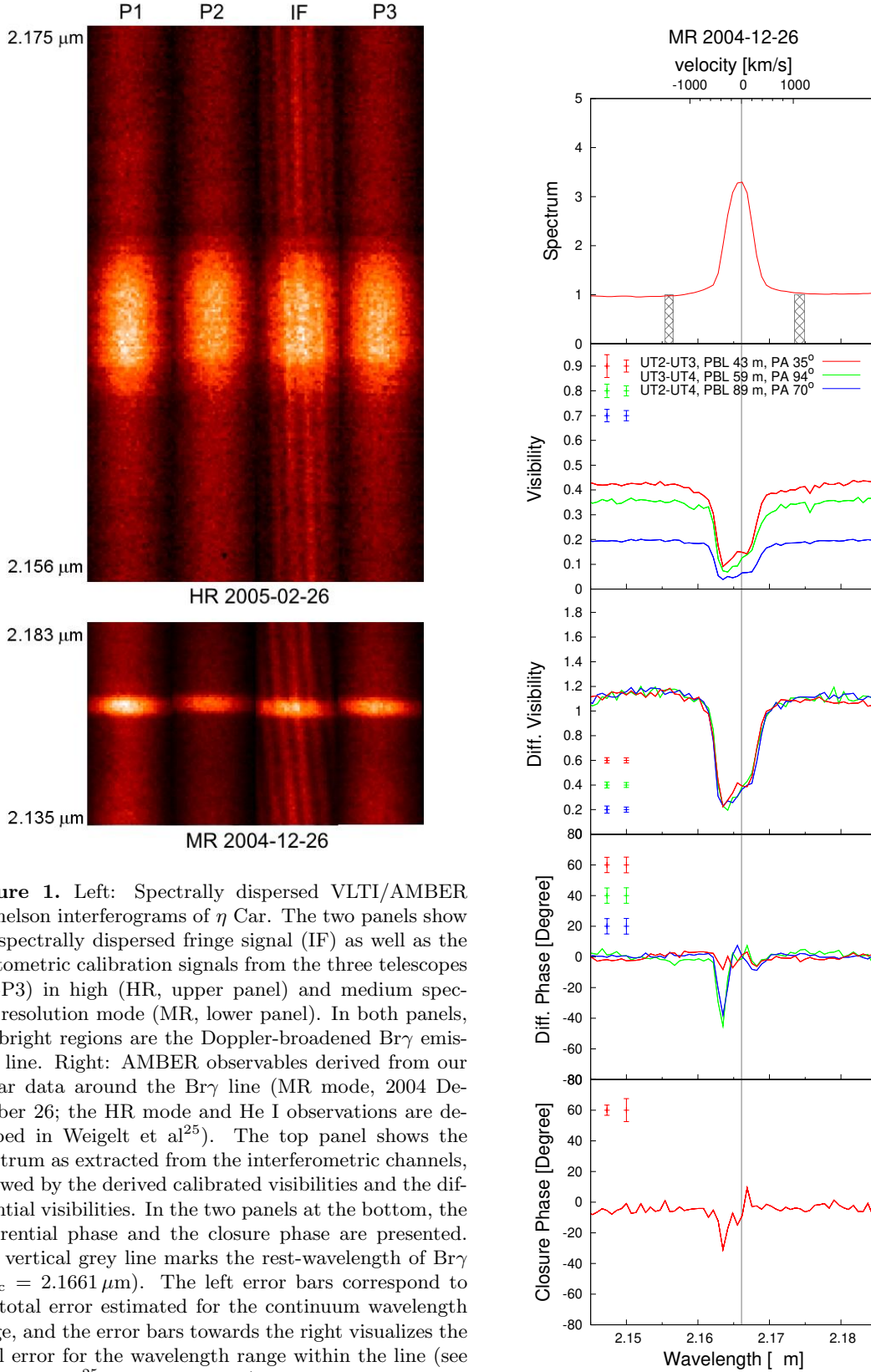


Figure 1. Left: Spectrally dispersed VLTI/AMBER Michelson interferograms of η Car. The two panels show the spectrally dispersed fringe signal (IF) as well as the photometric calibration signals from the three telescopes (P1-P3) in high (HR, upper panel) and medium spectral resolution mode (MR, lower panel). In both panels, the bright regions are the Doppler-broadened Br γ emission line. Right: AMBER observables derived from our η Car data around the Br γ line (MR mode, 2004 December 26; the HR mode and He I observations are described in Weigelt et al.²⁵). The top panel shows the spectrum as extracted from the interferometric channels, followed by the derived calibrated visibilities and the differential visibilities. In the two panels at the bottom, the differential phase and the closure phase are presented. The vertical grey line marks the rest-wavelength of Br γ ($\lambda_{\text{vac}} = 2.1661 \mu\text{m}$). The left error bars correspond to the total error estimated for the continuum wavelength range, and the error bars towards the right visualizes the total error for the wavelength range within the line (see Weigelt et al.²⁵ for more details).

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