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HOT STAR WINDS AND INTERFEROMETRY: ACHERNAR AND η CARINAE

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RESUMEN

La considerable presión radiativa de estrellas calientes masivas es una máquina muy eficiente para la eyección de vientos estelares. Además, las estrellas calientes son a menudo también rotores rápidos. En este caso, su fotósfera aplanada da lugar a casquetes polares recalentados por el efecto de Von Zeipel, y a una baja gravedad eficaz en el ecuador. La pérdida de masa ocurre en los polos (viento estelar rápido) y el ecuador (un viento más lento). La geometría de las envolturas de estrellas giratorias rápidas es, por lo tanto, a menudo asumida de ser formada por un viento polar caliente y un disco alrededor del ecuador estelar. Como la mayoría de las estrellas masivas son miembros de sistemas binarios o múltiples, las interacciones estelares también desempeñan un papel fundamental. En este artículo, divulgamos resultados recientes de interferometría de gran línea de base centrada en dos estrellas calientes con vientos detectados por interferometría: Achernar y η Carinae.

ABSTRACT

The considerable radiative pressure of massive hot stars is a very efficient engine for the ejection of stellar winds. In addition, hot stars are often also fast rotators. In this case, their flattened photosphere results in overheated polar caps through the Von Zeipel effect, and a low effective gravity at the equator. Mass loss occurs from both the poles (fast stellar wind) and the equator (slower wind). The geometry of the envelopes of fast rotating stars is therefore often assumed to be formed by a hot polar wind and a disk around the stellar equator. As most massive stars are members of binary or multiple systems, stellar interactions also play an fundamental role. In this article, we report recent results from long-baseline interferometry focused on two hot stars with winds detected by interferometry: Achernar and η Carinae.

Key Words: stars: emission-line, Be — stars: individual (Achernar; $\boldsymbol{\eta}$ Carinae) — stars: mass loss — stars: rotation — stars: winds, outflows — techniques: interferometric

1. INTRODUCTION

According to Owocki's recent review (Owocki 2001), a stellar wind is "the continuous, supersonic outflow of matter from a star". Solar-like dwarf stars usually have tenuous winds, but massive stars can exhibit extremely strong winds, driven by the pressure of the radiation emitted by the star. The generation of the wind actually happens at the altitude in the star's atmosphere where the radiative pressure exceeds the effective gravity. The radiative pressure then produces an acceleration of the wind up to large distances from the star. Typical mass loss rates range from $10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$ for the Sun to $10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ for high mass stars. Massive hot stars are also generally known for being fast rotating stars. The reduced effective gravity at the equator of fast rotating stars and the corresponding gravity darkening effect (von Zeipel 1924) appear as important keys to explaining the wind structure of hot stars. These phenomena have several observable consequences. For instance, fast rotating Be stars show evidence of mass loss and circumstellar envelopes from UV resonance lines, near-IR excesses, and the presence of episodic hydrogen emission lines. Depending on its density, a stellar wind can be optically thin or thick at certain wavelengths, and can form excretion disks (outwards moving material confined into a disk) and polar plumes. In this article, we briefly review recent interferometric observations of two hot stars with winds: Achernar (HD 10144) and η Carinae (HD 93308). Although these two stars are both fast rotators and members of binary systems, their vastly different masses and effective temperatures result in very different wind properties: optically thin for Achernar (§ 2), and a very dense, optically think for η Carinae (§ 3).

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2. THE OPTICALLY THIN POLAR WIND OF ACHERNAR

The southern Be star Achernar (α Eri, HD 10144) is the brightest member of its class, and has received

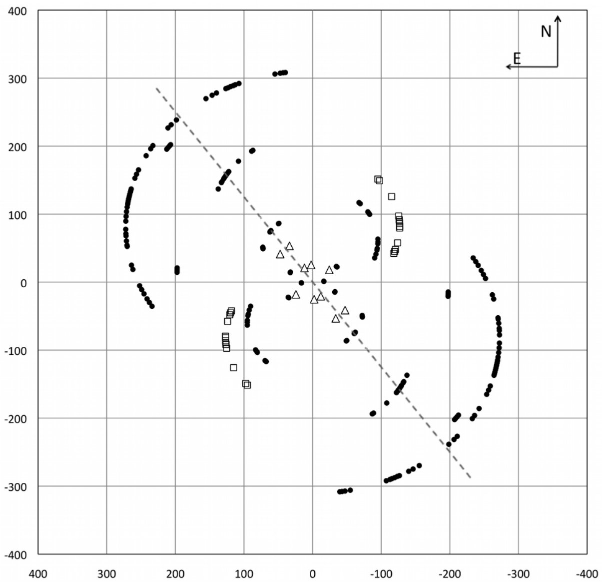

Fig. 1. Coverage of the (u,v) plane for the VINCI K (black dots) VINCI H (open squares) and MIDI N (open triangles) observations of Achernar. The units of both axes are cycles/arcsec. The dashed line indicates the orientation of the polar axis of Achernar.

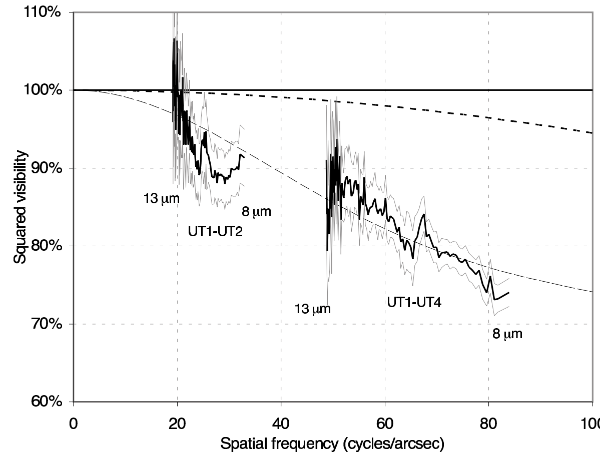

Fig. 2. Squared visibility of Achernar measured with MIDI along the polar direction and adjusted photosphere+Gaussian envelope model (dashed curve), as a function of spatial frequency. The polar photospheric V^2 is shown as a dotted curve. The difference between the dotted and dashed curves is caused by the presence of the polar wind.

a lot of interest since its oblate photosphere was resolved by long-baseline interferometry (Domiciano et al. 2003), with major and minor axes of respectively $\theta = 2.13 \pm 0.05$ and 1.51 ± 0.02 milliarcseconds (Kervella & Domiciano de Souza 2006). Due to its extremely fast rotation ($v \sin i \approx 250$ km s^{-1}) and consequent flattening, the von Zeipel effect (von Zeipel 1924) causes the polar caps to be overheated (Jackson et al. 2004; Kanaan et al. 2008). Achernar was extensively studied using the VLT Interferometer since its first observations. Its very southern declination prevents its observation by interferometers located in the northern hemisphere. A total of nine baselines were used for these observations with the VINCI and MIDI instruments. Thanks to an efficient supersynthesis effect, the coverage in azimuth of the projected baselines is relatively good, as shown in Figure 1, but with a strong emphasis on the polar direction of Achernar.

As shown by Kervella & Domiciano de Souza (2006), the K band ($\lambda \approx 2.2\,\mu$m) visibility curve of Achernar along the polar direction shows a deficit at low spatial frequencies (i.e. at large spatial scales), that indicates the presence of a spatially extended flux contributor in addition to the star. This can be interpreted using the simple model of a uniformly bright photosphere surrounded by a Gaussian envelope, with a full width at half maximum ρ and a flux contribution relatively to the photosphere $\alpha = f_{\rm CSE}/f_{\star}$. The adjustment of this model gives a flux contribution of the polar plume in the K band of $\alpha = 4.7 \pm 0.3$ % and an extension $\rho = 17.6 \pm 4.9$ mas.

The MIDI observations were obtained in 2006 and 2007, using three 8.2 m telescope baselines, and were reported by Kervella et al. (2009). As for the K band measurements, they sample essentially the polar direction of Achernar. The thermal-IR contribution ($\lambda \approx 10\,\mu$m) of the polar envelope is clearly visible in Figure 2 as a visibility deficit compared to the photospheric model. Using the same model as for the VINCI data, the derived polar envelope parameters are a FWHM of $\rho = 9.9 \pm 2.3$ mas and a flux contribution of $\alpha = 13.4 \pm 2.5\%$ relatively to the photosphere, in average over the N band.

What could explain the presence of a polar plume around Achernar? From the measured flattening ratio of the photosphere, the polar temperature of Achernar could be higher than 20 000 K, thus creating a high radiative pressure at the poles and a fast polar wind. This scenario appears realistic, as shown by the SIMECA model of Achernar's environment presented by Kanaan et al. (2008) and Kervella et al. (2009). Due to the limited number of visibility measurements along the direction of the equator of Achernar, it is difficult to conclude on the presence of a circumstellar disk in addition to the polar wind. As discussed by Carciofi et al. (2008), the presence a small equatorial disk could affect the measurement of the oblateness of Achernar's disk.

In the case of of α Arae, another Be star similar to Achernar (rotation velocity, spectral type), recent AMBER observations (Meilland et al. 2007) also showed that an elongated polar wind should be included in the model together with a thin equatorial disk in order to explain the near-IR visibilities. Although the central stars are similar, one important difference is that α Arae presented hydrogen lines in strong emission during the interferometric observations, while they were very faint or absent in the spectrum of Achernar. Both stars show an elongated polar wind responsible for a free-free and free-bound near-IR continuum emission, while only one of them (α Arae) shows a dense equatorial disk where hydrogen emission lines are formed.

Kervella & Domiciano de Souza (2007) discovered a close-in companion of Achernar, of spectral type A1V-A3V (Kervella et al. 2008). Although its orbital parameters are still uncertain, its orbit appears to be excentric, and its periastron crossing may therefore trigger the excretion of an equatorial disk. Achernar thus appears similar to the B0.2IVe star δ Sco, which has a 1.5 mag fainter companion on a highly excentric 10.6 yr orbit (Bedding 1993; Miroshnichenko et al. 2001). This suggests that the presence of companions around Be stars should be examined carefully, as it may play a key role in triggering the Be phenomenon.

3. THE OPTICALLY THICK WIND OF η CARINAE

As one of the most massive stars known in our Galaxy, η Car underwent a spectacular evolution over the past 150 years, especially since its colossal 1843 eruption created the Homunculus nebula (Smith 2006). Classified as a luminous blue variable, its binary nature was established in late 2005, explaining the regular 5.54 years periodicity in its variation cycle (Daminelli et al. 2008) by regular interactions between the two components. Thanks to its brightness at infrared wavelengths, η Car has been a favorite target of the VLTI since its first observations in 2001. Van Boekel et al. (2003) observed η Car using the VINCI instrument in the K band. They detected an elongation of η Car's central source with a ratio of major to minor axis of 1.25 ± 0.05, at a position angle of 134 ± 7 degrees (east of North). This position angle is in excellent agreement with the lobes of the Homunculus nebula (132 degrees) determined by Davidson et al. (2001). The typical size of the source is estimated to 5 mas FWHM from a spherical physical model. Further observations were reported by Kervella (2007), showing that the visibility function of η Car follows closely an exponential function (Figure 3). Chesneau et al. (2005) observed η Car with the MIDI instrument, but the emission at this wavelength is essentially due to thermal emission from the dust, and the stellar wind is mostly unresolved.

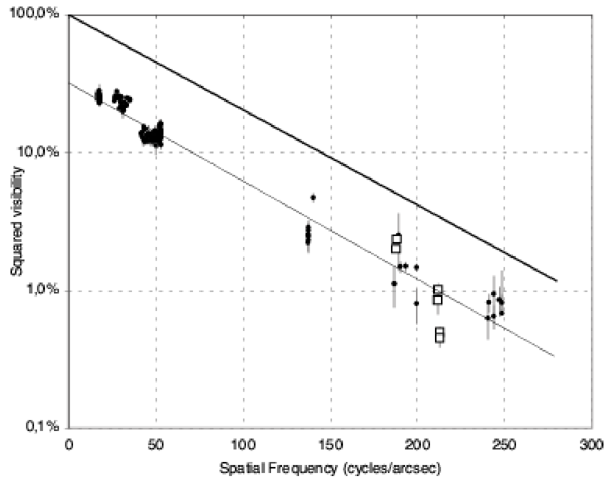

Fig. 3. Squared visibilities obtained on η Car with VINCI by Kervella (2007), compared to the model fitting result of Weigelt et al. (2007), represented as a solid curve. The UT data points are represented with open squares.

The most comprehensive interferometric work on η Car to date has been published by Weigelt et al. (2007), based on measurements obtained in December 2004 and February 2005 with the AMBER instrument of the VLTI. AMBER combines the light from three telescopes, allowing to search for object asymmetries in the closure phase, and is equipped with a spectrograph that enables spectrally dispersed observations with resolutions of up to 12 000. These authors obtained interferometric measurements in the K band continuum, and in two spectrally resolved emission lines: hydrogen Brγ and He I. In the continuum, the optically thick wind of η Car is resolved spatially, with a FWHM of 4.0 ± 0.2 mas, in agreement with VINCI's measurements and the model of η Car by Hillier et al. (2001). The asymmetry of η Car's wind is also confirmed, supporting the theoretical expectations that mass loss is enhanced above the polar caps of massive stars in fast rotation (Owocki et al. 1998).

The binary companion of η Car's main star is suspected to be an extremely hot star, less massive than η Car A, but with a strong stellar wind of its own. Its presence adds a further level of complexity to an already enigmatic object, but also offers a new "natural probe" to explore the structure of η Car's wind. New observations of η Car were obtained with AMBER by Weigelt et al. in January 2009 during the expected periastron crossing of the secondary component. During this event, the secondary star is deeply immersed in the wind of the primary, and these interferometric observations should allow to check for modifications of the stellar wind shape. For a recent publication on the binary wind interactions in η Car, the interested reader is refered to Gull et al. (2009).

4. CONCLUSION AND PROSPECTS

The wind structure of Achernar and η Car present considerable differences in terms of density and velocity, but also show interesting similarities in terms of geometry. In both cases, the von Zeipel effect plays a dominant role in shaping the mass-loss geometry, as the overheated polar caps of the two stars expel the stellar material much more efficiently than the equatorial belt.

Optically thin winds are generally difficult to observe interferometrically, as they require either a high absolute accuracy on the visibility measurements or spectral resolution to resolve emission lines and compute differential visibilities. *A contrario*, optically thick winds are realatively easier to detect as they are similar to photospheres in terms of observing constraints (resolution, visibility accuracy). The prospects for stellar wind studies by interferometry thus depend essentially on the development of instruments along three directions: high spectral resolution (to resolve spectrally the emission lines), measurement accuracy (optically thin wind signatures are faint compared to the star) and imaging capabilities (to constrain the geometry of the wind). The next generation of VLTI instrumentation, GRAVITY (Eisenhauer et al. 2009) and MATISSE (Lopez et al. 2009), will progress on the latter two aspects, while the CHARA/VEGA instrument (Mourard et al. 2008) opens a window on high spectral resolution in the visible (R=35 000, Hα line). Adaptive optics and aperture masking will complete the interferometric mapping of the environment of nearby hot stars. Massive binary star systems also offer new tests of the triggering and interaction of stellar winds (Achernar, η Car, δ Sco,...), for which interferometry will bring essential new observational data.

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