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New Interferometric Constraints on the Physics of Active OB-Stars

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Abstract. In the recent years the optical interferometry proved its ability to provide important observational constraints on the physics of active OB stars by spatially resolving not only circumstellar environments but also central stars. Particularly, an increasingly rich image information obtained by a modern generation of interferometers provided an evidence of extremely oblate shape of the Be star Achernar (Domiciano de Souza et al. 2003). We present this result and discuss it with respect to the most recent discovery of similar oblateness of Regulus (McAlister et al. 2005) in the context of the Circum-Stellar Envelope formation of Be stars in combination with their fundamental property of rapid rotation.

We also discuss new interferometric observational constraints from direct measures of Be star photospheres which should prove whether these objects rotate close, to a few percent, of their critical velocity or not, with a profound impact on the dynamical models of Be stars disk formation from rapid rotation combined to mechanisms like non-radial pulsation, radiation pressure of photospheric hot spots or expelled plasma by magnetic flares.

Optical interferometry is currently rapidly evolving, and stronger constraints for more stars can be expected using new interferometers that allow spectral resolution, for instance the VLTI with the AMBER instrument as well as the next generation VLTI instrumentation. In this contribution we review a selection of outstanding problems in physics of OB stars (the study of *gravity darkening*, *non-radial pulsations*, *surface brightness distribution*, *differential rotation* and *magnetic fields*) that can be resolved using new interferometric constraints. We show the potential of dedicated Interferometric-Doppler Imaging methods (Jankov et al. 2001) which provide a qualitatively new information that cannot be obtained with classical techniques as photometry and spectroscopy.

1. Introduction

The classical primary goal of interferometry has been the determination of fundamental astrophysical parameters characterizing stars through angular size measurements. The combination of the angular diameter with the bolometric flux is the most direct method to obtain the effective temperature of the star. This is an important constraint for comparisons of model atmospheres with stellar

spectra. With the advent of accurate parallaxes from the Hipparcos astrometry satellite *linear radii* can be determined precisely as well. Additionally, interferometry can provide a very precise determination of stellar *masses* from binary star orbital motion studies as well as other fundamental stellar parameters (e.g. Hummel et al. 1995)

The primary observables of an interferometer are the amplitude and phase of the complex visibility function, which is the Fourier transform of the object intensity distribution (Zernike-Van Cittert theorem). In presence of atmospheric turbulence, usually only the squared visibility amplitudes and the triple products are accessible by optical and near-infrared interferometers. A triple product is the product of three complex visibilities corresponding to baselines that form a triangle. The phase of the triple product, the closure phase, is free of atmospheric phase noise. Thus, the measurement of triple products is a method to obtain phase information of the object intensity distribution, i.e. allows us to detect deviations from point symmetry.

However, stellar interferometry is not limited only to these classical applications. For example the exact behavior of photospheric limb darkening leads to better insight into *stellar atmospheres theory* through wavelength dependence of the uniform disk diameter (e.g. Quirrenbach et al. 1996, Wittkowski et al. 2001). In addition to visibility amplitudes and triple products, the phase of the complex visibility is an interferometric observable as well, if atmospheric and instrumental noise can be controlled or compensated. This can be achieved for example by phase referencing using the same source at another wavelength or a reference star, when the relative position of the object on the sky can be derived with an accuracy which is much higher than the diffraction. If the position of the photocenter of the object depends on the wavelength, such differential phase measurements can be used to derive information on the brightness distribution on the stellar surface. Other applications, as well as interferometric techniques, have been reviewed by Quirrenbach (2001), and here we give a non-exhaustive list updated with some more recent developments in the field.

2. Rotation

Achernar's pronounced apparent asymmetry (Fig. 1) as revealed by Domiciano de Souza et al. (2003), together with the fact that it is a Be star, raised the question of whether they observed the stellar photosphere with or without an additional contribution from a Circum-Stellar Envelope (CSE). Arguing that the observed asymmetry of Achernar reflects its true photospheric distortion with a negligible CSE contribution, they concluded that the usual Roche approximation does not apply to Achernar, where deviations from gravitational potential and differential rotation must be closely regarded with respect to the internal momentum distribution. One possible scenario is that of the shellular rotation law (Zahn 1992), in which the angular velocity increases toward the stellar center, implying the oblateness larger than that of a uniformly rotating star (Maeder 1999). In this context their result on Achernar's surface distortion should also impact other internal mechanisms like meridional circulation, turbulence, transport and diffusion of the chemical elements and angular momentum,

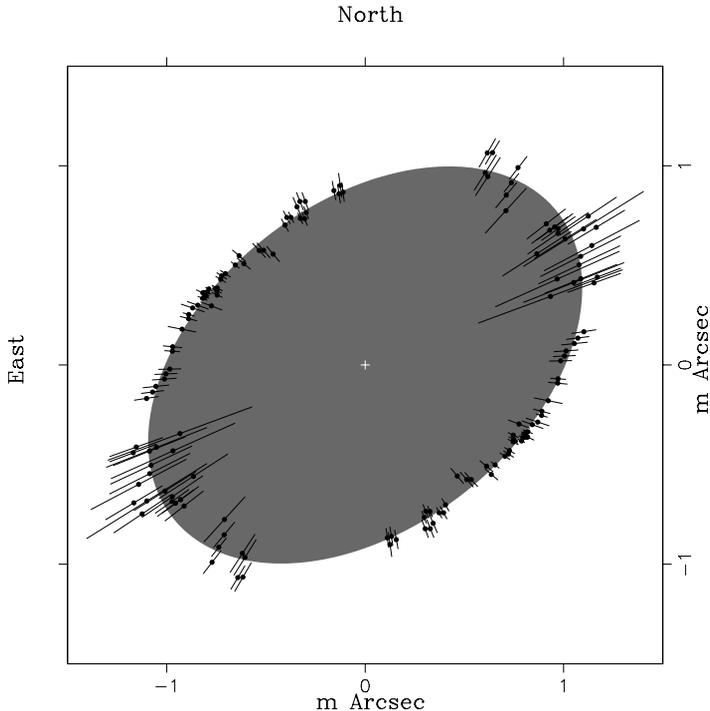


Figure 1. *Fit of an ellipse over the observed squared visibilities V^2 translated to equivalent uniform disk angular diameters. Each V^2 is plotted together with its symmetrical value in azimuth. Large error bars correspond to the 66 m baseline while the small ones correspond to the 140 m baseline. The fitted ellipse results in major axis $2a = 2.53 \pm 0.06$ milliarcsec, minor axis $2b = 1.62 \pm 0.01$ milliarcsec. The distribution of measurements reveals an extremely oblate shape of Achernar, with a ratio $2a/2b = 1.56 \pm 0.05$.*

increase of mass loss with rotation as well as anisotropies in the mass ejection and wind density from rotating stars.

The rotation is the biggest unknown in our current understanding of stellar evolution and especially of hot stars (Maeder & Meynet 2000). However, the new era of long baseline interferometry allows to test models of interior structure and evolution for massive rotating stars (Endal & Sofia 1979, Meynet & Maeder 2000). Reporting a similar very high oblateness of Regulus (α Leonis A), and taking into account the effects of rapid rotation, McAlister et al. (2005) showed that the position of Regulus in this diagram indicate that the star is over-luminous for its mass when compared with the theory (Heger & Langer 2000, Meynet & Maeder 2000) since fresh hydrogen is mixed into the convective cores of rapidly rotating stars. If Regulus is placed on an isochrone without consideration of this excess luminosity, the age of the star is overestimated.

Further, the highly distorted photospheres of Achernar and Regulus poses the question of Be stars rotation rate and the formation of out-flowing disks from Be stars which remains their central puzzle. Under the Roche approximation the observed oblateness indicates that Achernar should rotate close to its critical velocity since the model solution which implies 96% of the critical

velocity is more consistent with the data. Original vision of a critically rotating Roche star, ejecting material from its equator, has been discarded in the past by observing that Be stars rotate at most at 70% to 80% of their critical velocity. However, this statistically observed limit may be biased by the fact that close to or beyond such velocities the diagnosis of Doppler-broadened spectral lines fails to determine the rotation value due to gravity darkening. The direct measures of Be star photospheres by interferometry can overcome the challenge to prove whether these objects rotate close, to a few percent, of their critical velocity or not. This will have a profound impact on the dynamical models of Be stars disks formation from rapid rotation combined to mechanisms like pulsation, radiation pressure of photospheric hot spots or expelled plasma by magnetic flares.

The new interferometric methods very significantly extended the analysis initiated by Slettebak (1949) for rapidly rotating O and B stars which includes the effects of limb darkening, gravity darkening based on Roche models incorporating the von Zeipel Effect (von Zeipel 1924), and differential rotation. Domiciano de Souza et al. (2002) showed that the interferometric signal from an asymmetric star depends on the sky orientation of the baseline ξ and gravity darkening coefficient β and stellar inclination i (Fig. 2). This method has been applied successfully by Domiciano de Souza et al. (2005) to the determination of gravity darkening of Altair, while McAlister et al. (2005) deduced the same value $\beta = 0.25$ for Regulus.

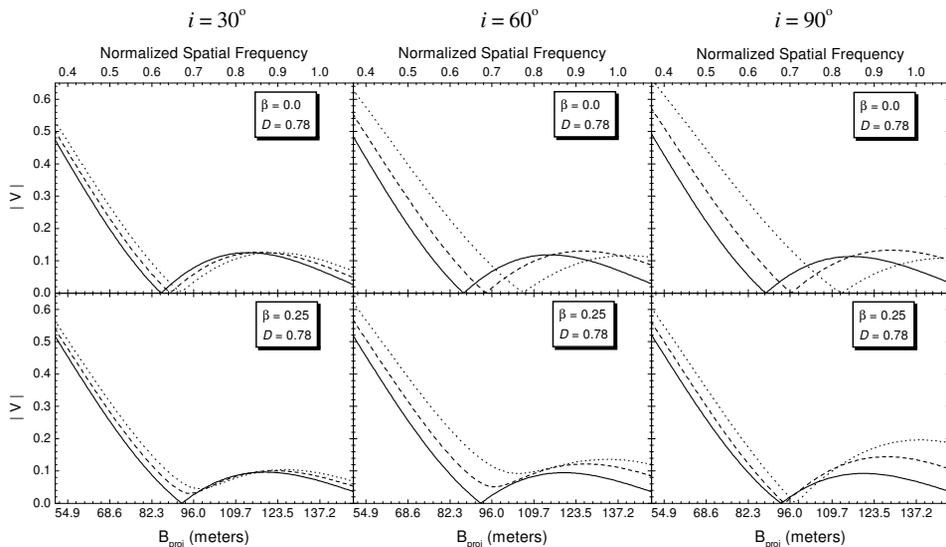


Figure 2. *Complex visibility amplitudes $|V|$ as a function of projected baseline (in meters) at selected values of orientation of the baseline with respect to the rotation axis of the star (ξ), inclination (i) and gravity darkening coefficient (β). Part of the first and the second $|V|$ lobes are shown. The curves cover part of the first and the second $|V|$ lobes for three different projected baseline orientations corresponding to $\xi = 0$ deg (solid), 45 deg (dashes) and 90 deg (dots).*

Using spectrally resolved interferometry with VLTI/AMBER (Petrov et al. 2003) the differential rotation can be studied as well (Domiciano de Souza et al.

2004). The shift of the stellar photometric barycenter (photocenter) in function of wavelength is very sensitive to the differential rotation coefficient α (Fig. 3) and stellar inclination (Fig. 4) allowing to deduce this two parameters in the approximation of solar-like latitudinal (l) angular differential rotational law $\Omega = \Omega_{\text{eq}}(1 - \alpha \sin^2 l)$.

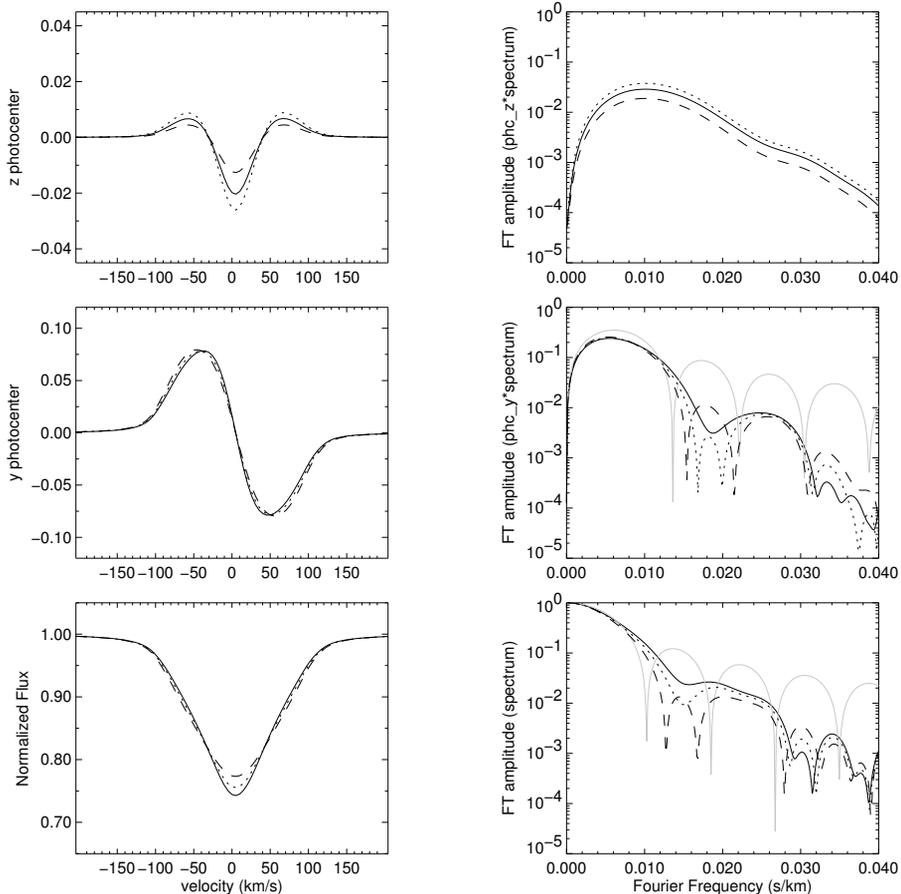


Figure 3. *Left:* The photocenter shift components, parallel (top) and orthogonal to the rotation axis of the star (middle), given in units of angular stellar radius. The flux spectrum normalized to the local continuum flux is shown at the bottom. The curves correspond to a stellar inclination $i = 45$ deg and differential rotation parameter α equal to -0.5 (solid), 0.35 (dots) and 0.6 (dashes). *Right:* The corresponding Fourier transform amplitudes. The line styles correspond to the curves at the left panel and note that they depend strongly on α . The solid gray curves are the reference analytical Fourier transforms of the rotation broadening functions for uniform rotation and a linear limb darkening parameter $\varepsilon = 0.23$. In the case of uniform rotation the photocenter shift components, parallel to stellar rotation axis is equal to zero, so that there is no gray curve in the upper right panel.

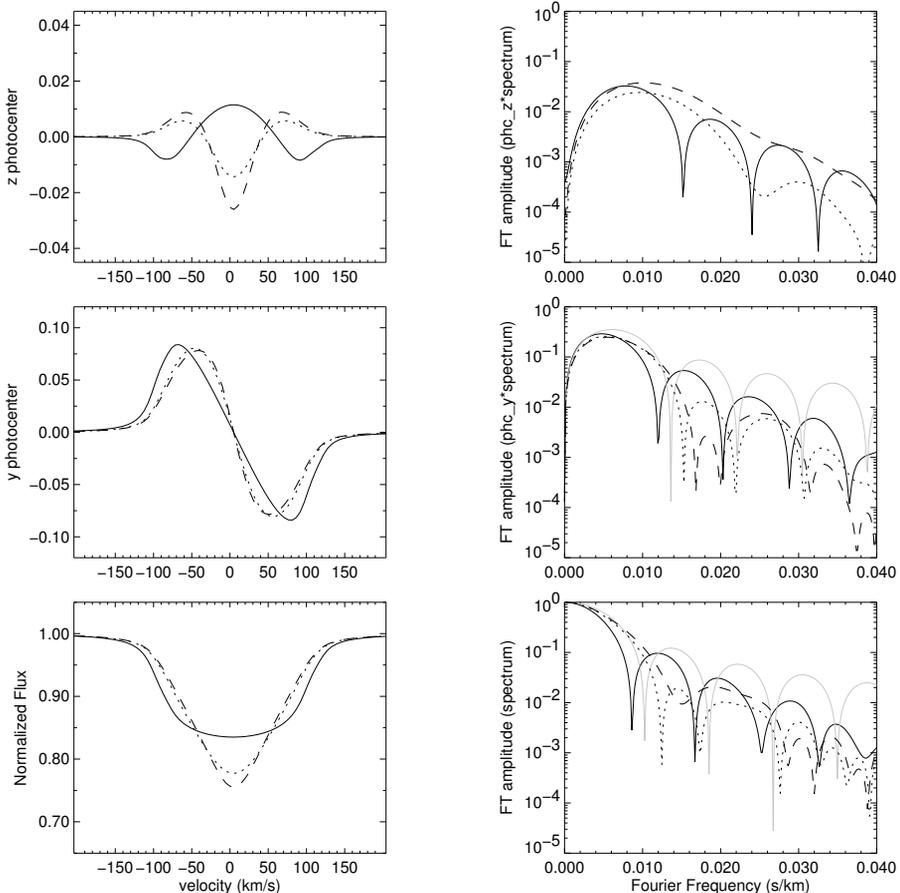


Figure 4. Same as Fig. 3, but for $\alpha = 0.60$. The curves correspond to i equal to 25 deg (solid), 45 deg (dots) and 75 deg (dashes).

3. Non-Radial Pulsations, Surface Inhomogeneities and Magnetic Fields

The significant line profile variability of O and B stars due to the non-radial pulsations (e.g. Rivinius, Baade, & Štefl, 2003), magnetic fields (Neiner et al. 2003) and associated inhomogeneities stimulated recently the development of methods in order to spatially resolve such phenomena on stellar surfaces.

In parallel to the development of interferometric techniques, the method of Doppler Imaging (Rice 1996 and references therein) allowed access to the spatial structure of non-resolved stars through observation and interpretation of temporal spectroscopic variability along the stellar rotational phase. Similarly to classical spectroscopy, the differential interferometry (Beckers 1982, Petrov 1988) makes it possible to measure the shift of the stellar photocenter of an unresolved star as a function of wavelength. The photocenter is the angular vectorial function and it provides the first order moment of the spatial brightness

distribution, in addition to the zero order moment spectroscopic information, allowing better spatial resolution of stellar atmospheres when compared to the classical Doppler Imaging (Jankov et al. 2001). Their method of Interferometric-Doppler Imaging has been applied to non-radial stellar pulsations (Jankov et al. 2001, 2002), while applications to surface inhomogeneities and magnetic fields have been studied by Jankov et al. (2003) and Rousset-Perraut et al. (2004) respectively.

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