

Interferometric Studies of Hot Star Disks

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Abstract. Interferometry in the visible and in the IR now provides milliarc-second spatial resolution and thus can be used for studying the circumstellar environment of hot star disks. After a brief introduction on the interferometric technique we will illustrate how the modulus and the phase of the visibility can be used to constrain the physics of hot star disks (Be, B[e]) and stellar surfaces studies through recent results from the GI2T, Keck, MkIII, NPOI, VLA and VLTI interferometers.

1. Interferometry: an introduction

The Image-Object relation of an astronomical instrument can be described by a convolution product:

$$I(\rho) = O(\rho) \otimes T(\rho) \quad (1)$$

where $O(\rho)$ is the brightness distribution of the object across the sky and $T(\rho)$ is the point spread function of the instrument. Since interferometric data reduction techniques are usually done through the analysis of the spectral density ($W(f)$) in the Fourier space (see Mourard et al. 1994 and Berio et al. 1999a), we can use the Fourier transform of eq. (1):

$$\tilde{I}(\vec{f}) = \tilde{O}(\vec{f}) \cdot \tilde{T}(\vec{f}) \quad (2)$$

where the convolution product of eq.(1) is now a simple product between $\tilde{O}(\vec{f})$ and $\tilde{T}(\vec{f})$ which are the Fourier transform of O and T , respectively. $\tilde{T}(\vec{f})$ is called the optical transfer function.

The spectral density function $W(f)$, which is related to the interferometric of the fringe contrast, is given by:

$$W(\vec{f}) = |\tilde{I}(\vec{f})|^2 = |\tilde{O}(\vec{f})|^2 |\tilde{T}(\vec{f})|^2 \quad (3)$$

Thus, it is equivalent to describe the object through its brightness distribution or through its Fourier transform. The vector $\vec{f}$ in eqs. (2) and (3) is the spatial frequency and is given by:

$$\vec{f} = \frac{\vec{B}}{\lambda} \quad (4)$$

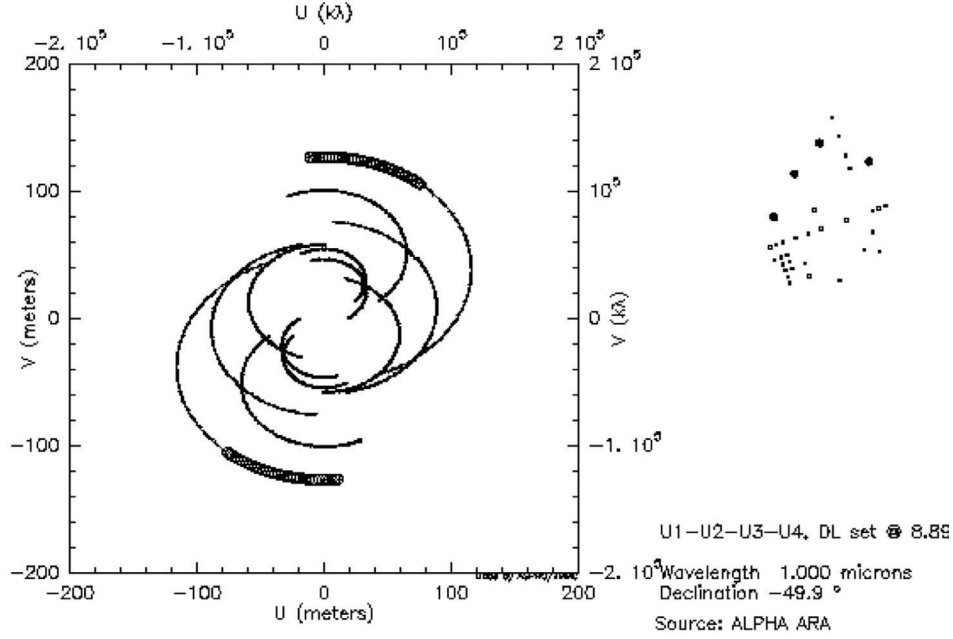


Figure 1. An example of the VLTI (u, v) plane coverage with 4 telescopes.

where λ is the observing wavelength and $\vec{B}$ is the interferometer baseline projected onto the plane of the sky. In order to obtain information on the object brightness distribution in more than one dimension, we have to vary the modulus of the projected baseline $\vec{B}$ and also its orientation. This goal, called the (u, v) plane coverage, can be accomplished (thanks to Earth's rotation) by observing a few hours before and after the transit of the star (the “super-synthesis effect”) and/or by changing the baseline orientation between two or more telescopes. From eq. (4) it is also possible to increase the (u, v) plane coverage by changing the wavelength λ , provided the object brightness distribution is constant within the considered wavelength range. An example of (u, v) plane coverage is shown in Fig. 1 for a VLTI configuration.

The information that is needed for astrophysical studies is the fringe visibility (V), which is a complex quantity, i.e., $V = |V| \exp^{i\phi}$. In the quasi-monochromatic case, the modulus of the complex degree of coherence of the source is equal to the modulus of the normalized spatial Fourier transform of the source's brightness. Thus the visibility modulus can be written as:

$$|V| = \frac{|\tilde{O}(\vec{f})|}{|\tilde{O}(0)|} \quad (5)$$

In the $(X - \lambda)$ mode, used specially on the VLTI, the fringes are dispersed by a grating spectrograph in the horizontal direction, and it is thus possible to combine high angular resolution (~ 2 mas) and high spectral resolution (~ 10000).

For an unresolved source the visibility is constant and equal to one, whereas it drops to zero when you start to resolve the star. For an idealized apparent uniform disk the visibility curve follows a $|2\frac{J_1(z)}{z}|$ function with a first zero for the resolving baseline B_r (in meters) given by:

$$B_r \sim 250 \frac{\lambda}{\phi_{ud}} \quad (6)$$

where ϕ_{ud} is the stellar diameter (in mas) that you want to measure and λ the wavelength in microns.

1.1. How do we obtain interference fringes?

For a given wavelength and a given baseline there are two ways to obtain interference fringes:

1. Temporal coding

The fringes are obtained by a coaxial combination of the beams coming from the two telescopes. We obtain a “flat-tint” that is modulated through a variation of the optical path length and the corresponding interference fringes are recorded as a function of time.

2. Spatial coding

In the Stephan-Fizeau design the beams are focused and modulated fringes are observed within the common Airy disk of the subapertures. With the Michelson design the spatial modulation of the fringes is independent of the distance between the two telescopes. It is the separation of the re-imaged pupils that gives the fringes separation.

For both coding methods the most important and problematical effect is atmospheric turbulence: with large aperture telescopes with $\frac{D}{r_0} > 1$, where D is the telescope’s diameter and r_0 the Fried parameter, fringes are spread over numerous speckles and we have to take short exposures (~ 20 ms) to “freeze-out” the turbulence. Nevertheless if you sum different speckles contributions you can increase drastically the SNR and take full advantage of the large apertures (e.g. VLTI), but of course the best approach will be to use adaptive optics. For $\frac{D}{r_0} < 1$ you are in the idealized case with a Airy pattern that is modulated by interference fringes but without adaptive optics you are limited to very bright stars (e.g. MkIII).

Although stellar interferometers are capable of measuring the angular diameters of stars, with longer baselines they may also be used to measure brightness variations across a star’s surface and to provide constraints on models of stellar

envelopes. In this paper we will look at the interpretation of visibility data and some of the more exciting prospects for current interferometers.

2. Disk size, shape and position measurements

Since the first measurements by Thom et al. (1986) of γ Cas in the continuum and in the H α emission line with the CERGA small interferometer I2T (measuring a 3.25 mas diameter for the envelope that was found to be entered on the star), a lot of progress and results have been obtained by a few interferometers. Mourard et al. (1989) used the capability of the Grand Interféromètre à 2 Télescopes (GI2T) interferometer to combine high spatial resolution and medium spectral resolution interferometer to show that the envelope around γ Cas was in rotation and was approximately fitted a disk model.

One of the first “images” of a Be disk was made using the VLA by Dougherty & Taylor (1992) for ψ Per. The high projected rotational velocity of ψ Per (300 km s^{-1}) indicates that the rotation axis of the star lies close to the plane of the sky. The detection of centimeter wavelength radio emission due to free-free emission demonstrates that the gas extends to very large radii. The major axis found at 15 GHz is more than 34 times the diameter observed at visible wavelengths. By assuming that their data correspond to the diameter of the optically thick emitting region, they found a linear size for the radio emission of $3700 R_{\odot}$ for a distance of 155 pc. The results are summarized in Table 1.

Table 1. ψ Per observed with the VLA radio interferometer

Wavelength	15 GHz
Major axis	$111 \pm 16 \text{ mas}$
Position angle	$158^{\circ} \pm 10^{\circ}$
Minor axis	Unresolved ($< 68 \text{ mas}$)

In 1993 Quirrenbach et al. (1993) exploited the capability of the MkIII interferometer to cover a large (u, v) plane by using the “super-synthesis” effect, and they definitively proved that Be stars envelopes are not spherical. They found that γ Cas envelope is elongated to the East from 20° with respect to the North-South direction. They also found that, if the envelope is symmetric with respect to the rotation axis, the inclination angle of this axis must be at least 42° . These results confirm the usual picture for the origin of the linear polarization by electron scattering in a flattened envelope.

In 1994 they presented a reconstructed intensity map, made using a maximum entropy algorithm, of the Be star ζ Tau (Quirrenbach et al. 1994) showing for the first time the extreme flattening of the envelope. The disk of ζ Tau is certainly seen edge-on and they were able to derive a disk inclination angle of at least 73° assuming an axially symmetric stellar rotation axis (see Fig. 2).

Stee et al. (1995) presented a radiative wind model of γ Cas based on spectroscopic and interferometric data collected with the GI2T. They found that 90% of

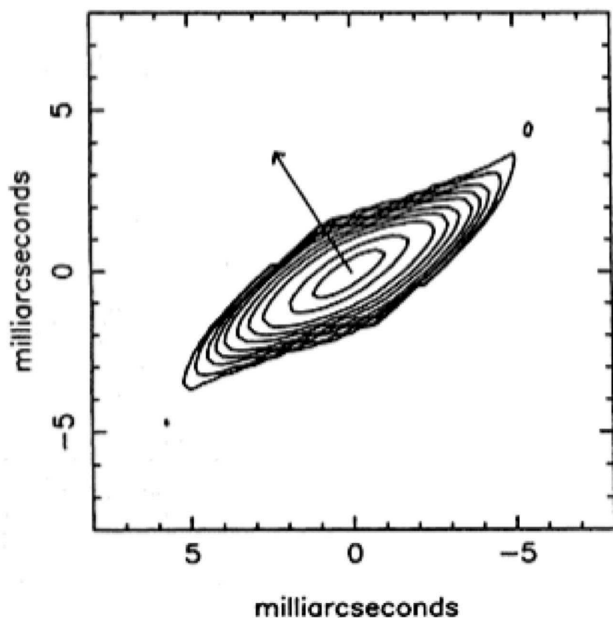


Figure 2. ζ Tau Maximum Entropy image reconstruction from the MkIII interferometer (Quirrenbach et al. 1994).

the $H\alpha$ emission originates from an ellipsoid with a ratio of minor to major axis of 0.72. This major axis is about 17 stellar radii which corresponds to ~ 4 mas assuming a stellar diameter of 0.45 mas for the stellar photosphere. This value is in the same range but larger than those of 3.25 mas found by Thom et al. (1986) and 3.2 mas by Quirrenbach et al. (1993).

Quirrenbach et al. (1997) obtained constraints on the geometry of the circumstellar envelopes of seven Be stars using optical interferometric observations in the $H\alpha$ emission line from the MkIII interferometer and polarimetric data from the PBO spectropolarimeter at the University of Wisconsin. Their results are summarized in Table 2. (Note that the photometric diameters are not interferometric measurements but are from Barnes-Evans relation.) The envelope diameters are smaller than 5 mas for the 7 Be stars. Among these 7 stars, 4 were not circularly symmetric and showed evidence of elongation. The result (3.47 mas) for γ Cas agrees well with the diameter in the N-S direction of 3.25 ± 0.4 mas measured by Thom et al. (1986) with the I2T interferometer and with the ~ 4 mas found by Stee (1996).

The position angles of the major axis of the elongation were in agreement with the disk orientation determined from polarization data and also with the result from radio observations for ψ Per. This means that there is no misalignment between the larger scale envelope from the radio observation ($\sim 100R_*$), the intermediate scale from $H\alpha$ emission ($\sim 10R_*$), and the inner regions where the polarization is produced.

Table 2. Photospheric and disk diameters from the MkIII interferometer (Quirrenbach et al. 1997)

Star	V	photosphere (mas)	envelope (mas)	env/photo	$W(H\alpha)$ (Å)
γ Cas	2.47	0.56	3.47	6.2	20.1
ϕ Per	4.07	0.39	2.67	6.8	53.8
ψ Per	4.23	0.35	3.26	9.4	38.0
η Tau	2.87	0.71	2.65	3.8	6.0
48 Per	4.04	0.34	2.77	8.0	19.7
ζ Tau	3.00	0.39	4.53	11.6	22.0
β CMi	2.85	0.74	2.65	3.6	5.4

An important result is the agreement between the position angles of the circumstellar disks derived from the interferometric measurements and from the polarimetric data. In every case the polarization angle is perpendicular to the major axis, which rules out envelopes that are both optically and geometrically thick since they produce a polarization which is parallel to the plane of the disk.

Nevertheless, we must be cautious with the diameters of the circumstellar envelopes given in Table 2 since the MkIII interferometer observations were done using a narrow filter (10 Å) centered on the $H\alpha$ line. In fact, most of the 7 stars had an $H\alpha$ emission equivalent width larger than 10 Å (see last column in Table 2). This is an important point since line flux is lost not only in the wings of the profile but through spatial filtering. Thus, there is potential confusion due to “cross-talk” of flux produced from iso-velocity regions and from other regions which emit line flux at wavelengths outside the bandpass limits of the $H\alpha$ filter.

Stee et al. (1998) report the first spectrally resolved observations with the GI2T of γ Cas in the HeI $\lambda 6678$ and $H\beta$ emission lines. Putting all these different measurements together, we find that the envelope size in the visible increases following the sequence: HeI $\lambda 6678$ ($2.3 R_*$), $0.48 \mu m$ continuum ($2.8 R_*$), $0.65 \mu m$ continuum ($3.5 R_*$), $H\beta$ ($\lesssim 8.5 R_*$), and $H\alpha$ ($18 R_*$).

Stee & Bittar (2001) computed theoretical HI visible and near-IR line profiles, i.e., $H\alpha$ (6562 Å), $H\beta$ (4861 Å) and $Br\gamma$ (21656 Å), and intensity maps for a large set of parameters (density, temperature, envelope geometry, inclination angle), representative of early to late Be spectral types. They found that the near-IR emission both in the $Br\gamma$ line and the nearby continuum originates from a very extended region with a typical size of 40 stellar radii which is twice the size of the $H\alpha$ -emitting region. This prediction was compared to previous estimates of the disk extension at various wavelengths (Table 3).

In fact, their large near-IR extension is mainly due to the lower brightness contrast between the central star and the envelope. In the visible the star appears very bright and thus it is more difficult to “see” the circumstellar matter. In

Table 3. Estimation of the disk size from various authors as a function of wavelength (Stee & Bittar 2001)

Wavelength	Diameter (in stellar radii)	Reference
2.3 and 19.5 μm	8 R_*	Gehrz et al. (1974)
12, 25 and 60 μm	16 R_*	Waters (1986)
IRAS Far-IR	$8 \leq \phi_{disk} \leq 26 R_*$	Waters et al. (1987)
Millimeter	$52 \leq \phi_{disk} \leq 216 R_*$	Waters et al. (1991)
near-IR	$\phi_{disk} \geq 20 R_*$	Dougherty et al. (1994)
2 cm	$\phi_{disk} \geq 200 R_*$	Taylor et al. (1990)

the near-IR, the central star is very faint and the surrounding matter can be seen at very large distances. They have also predicted the relative fluxes from the central star, the envelope contribution in the $H\alpha$, $H\beta$, $\text{Br}\gamma$ lines and in the continuum as well as the total fluxes (in erg s^{-1}), for a wide range of parameters characterizing the disk models. For the same parameters, they also predicted the behavior of the lines, the energy distribution, and the visibilities in the lines and in the continuum.

γ Cas was observed again in 2003 with the Navy Prototype Optical Interferometer (NPOI) by Tycner et al. (2003) to test a technique for calibrating optical long-baseline interferometric observations. They have clearly resolved the $H\alpha$ emitting region. Their best fit of an elliptical Gaussian model has an average angular size of the major axis of 3.67 ± 0.09 mas, an average axial ratio of 0.79 ± 0.03 and an average P.A. of $32^\circ \pm 5^\circ$ all in good agreement with values reported previously in this paper.

3. Studies of binary systems with an interferometer

Interferometers can be used to detect multiple systems. As discussed in §1, the quantity measured by an interferometer is the Fourier Transform of the brightness distribution in the plane of the sky. If you model a double star by two Dirac δ -functions, its Fourier transform will produce a sine modulation of the interferometric signal. The larger the difference of magnitude between the two stars is, the smaller the modulation will be, so that the direct detection of binary systems is probably limited to couples with a magnitude difference less than 4.

In fact, it may prove possible to detect even fainter companions by studying the phase of the fringes to follow the photocenter displacement of the binary system as a function of the orbital phase. This technique will be applied to the detection of exoplanets as well. Moreover, for very close systems we can also detect mass transfer, tidal effects, and jets as was done in a study of β Lyr by Harmanec et al. (1996). They have confirmed the spatial orientation of the projection of the vector of the orbital angular momentum on the sky ($\theta = 160^\circ$ from the North). Moreover, their interferometric, spectroscopic, photometric and polarimetric data confirm that the bulk of the $H\alpha$ and He I $\lambda 6678$ emission is produced from jets perpendicular to the orbital plane. These jets are associated

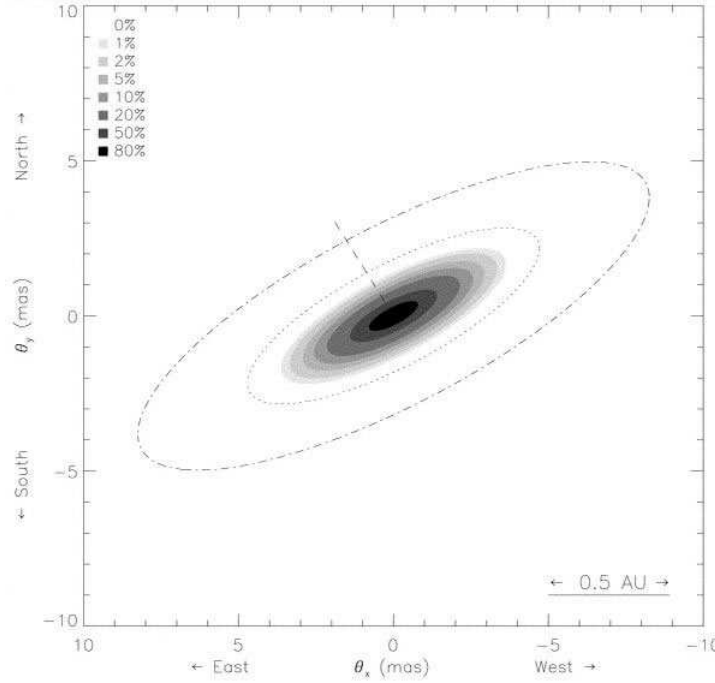


Figure 3. Schematic of the elliptical Gaussian model for ζ Tau by Tycner et al. (2004, with permission). The dashed line is the polarization vector of 32° reported by McDavid (1999), the dotted line is the Roche radius of the primary star and the dash-dotted line is the projected circular orbit of the secondary component.

with the more massive (primary) component of the binary. They may originate from a “hot-spot” in the disk where the gas stream is incident from Roche lobe overflow of the secondary component (B6-8 II). It seems that some contribution to the emission may also come from an intermediate region between the two stars. This result agrees well with the analysis of UV line polarization.

Recently Tycner et al. (2004) have observed the Be star ζ Tau using the NPOI interferometer. They obtain an angular size of the major axis of 3.14 ± 0.21 mas, a P.A. of $-62.3^\circ \pm 4.4^\circ$ and an axial ratio of 0.310 ± 0.072 . Comparing their results with those in the literature, they conclude that the envelope parameters describing the circumstellar envelope of ζ Tau are stable on time scales of years. Moreover, they conclude that ζ Tau, which is a well known single-lined spectroscopic binary with a period of about 133 days and an eccentricity of ~ 0.15 , has a disk that may be truncated by tidal interaction with its companion (see Fig. 3). This seems to be confirmed by radio measurements by Taylor et al. (1990) who did not detect any emission for the ζ Tau system, consistent with a circumstellar disk with a small spatial extension.

New results from the MIDI/VLTI instrument reach the same conclusions for the Be star α Ara. The measurements from Chesneau et al. (2004) seem to indicate

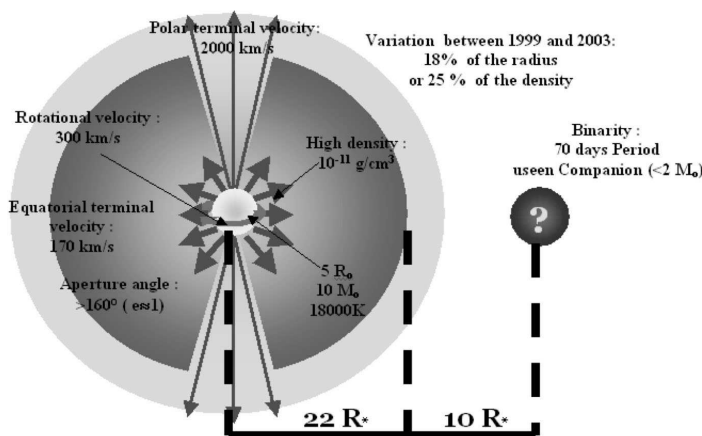


Figure 4. Schematic view of α Ara circumstellar disk from this work.

that the fact that the disk around α Ara appears unresolved might be due to an outer truncation of the disc by a close companion. Using the stellar parameters described in their paper, they obtain a radius of about $154 R_{\odot}$, assuming a circular orbit of a companion with negligible mass. With the $R_{\star} = 4.8 R_{\odot}$, this corresponds to about 32 stellar radii in agreement with the estimation based on the MIDI/VLTI data of a truncated disk at $25 R_{\star}$, i.e., smaller than the companion orbit (see Fig. 4). Thus, after ζ Tau, α Ara might be the second Be star where the presence of a nearby companion limits the extent of the circumstellar disk.

4. Details of the disk structure

Another interesting aspect is to follow the phase of the visibility as a function of wavelength or time, and thus to infer the source photocenter position on the plane of the sky. One of the first applications of this method might be to determine the rotation law in the disk of Be stars. For that purpose, Stee (1996) studied the rotational component of the wind in the envelope of γ Cas. He found that constant and solid body rotation laws can be rejected. Nevertheless, the observed variation of the photocenter displacement was insufficient to distinguish between a momentum conservation ($v \propto r^{-\beta}$ where $\beta = 1.0$), a Keplerian ($\beta = 0.5$), and a $\beta = 0.25$ circular velocity law.

Observing the Be shell star ζ Tau in 1993 October, Vakili et al. (1998) found that a high density pattern occurred around a radial velocity of $+130 \text{ km s}^{-1}$

and had a north-south projection position of 0.7 mas to the south of the continuum source (i.e., at $3.6 R_*$). By 1994 October, this density pattern had rotated prograde and occurred at a radial velocity of -70 km s^{-1} . It is now located 0.5 mas to the north of the continuum source which corresponds to $2.6 R_*$. These observations are the first detection of an axi-symmetric envelope around a Be star and they are interpreted as a direct evidence for a prograde one-armed oscillation of its equatorial disk.

After ζ Tau, γ Cas is the second Be star for which interferometric observations provide direct evidence of a prograde one-armed oscillation of its equatorial disk. This prograde precession agrees with the Okazaki's model (Okazaki 1997) of a one-armed ($m = 1$) oscillation confined by radiative effects. In their paper on γ Cas, Berio et al. (1999b) have investigated how such oscillations occur within the equatorial regions of the latitude-dependent radiative wind model developed by Stee & Araújo (1994). In this model the star is distorted due to its fast rotation. The centrifugal force makes the effective gravity and the brightness temperature decrease from pole to equator, and thus the corresponding radiative force will depend on the stellar latitude. Finally, the star has a highly ionized fast wind in the polar regions and a slow wind of low ionization, with a higher density near the equator. In the inner ($\leq 10 R_*$), cool, dense equatorial regions, the kinematics is dominated by the Keplerian rotation, while the one-armed oscillations develop in the radiative wind driven by optically thin lines.

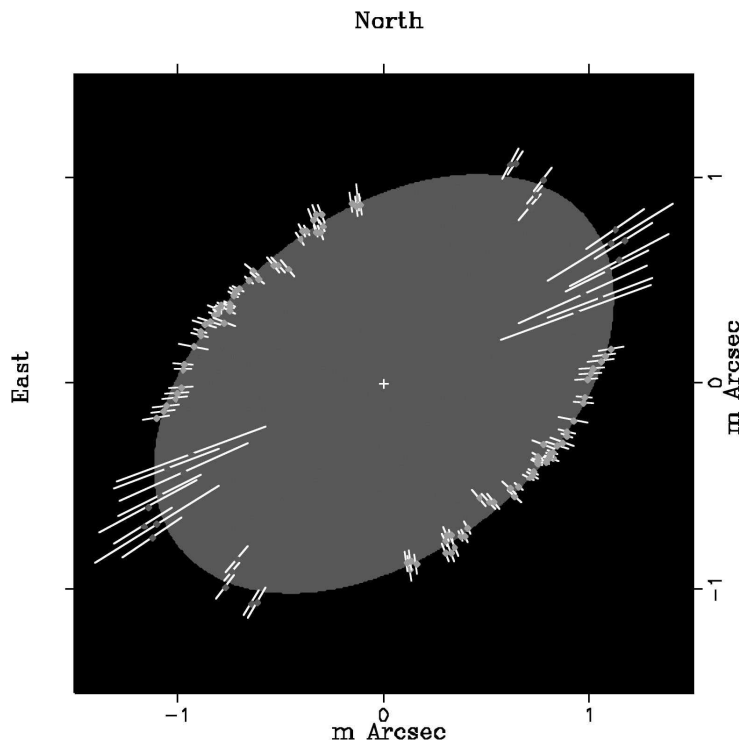


Figure 5. Fit of an ellipse over the observed VLTI data to equivalent uniform disk for α Eri (Domiciano de Souza et al. 2003 with permission).

5. Measuring the shape of fast rotators

The fast rotation of active hot stars produces a geometrical deformation of the stellar photosphere that results in a larger equatorial radius than at the poles. Another physical effect is the gravity darkening or the von Zeipel effect (von Zeipel 1924) making the surface gravity and the emitted flux decrease from the poles to the equator. This effect has been directly measured by Domiciano de Souza et al. (2003) with the VLTI for the Be star α Eri. Their measurements correspond to a major/minor axis ratio of 1.56 ± 0.05 , i.e., an extreme oblateness that rules out the commonly adopted Roche approximation in which the rotation is supposed to be uniform and the mass centrally condensed (see Fig. 5). This might also be evidence that the Be star is rotating close to the critical velocity. Townsend et al. (2004) show that the diagnosis of Doppler-broadened spectral lines may underestimate the true rotational velocity of the star due to the gravity darkening effect, and consequently the reported rotational velocities of Be stars may be systematically low.

McAlister and collaborators have used the CHARA Array at Mount Wilson Observatory to obtain K -band interferometric observations of the rapidly rotating B-star, Regulus (α Leo). This is an important test object since it is a rapid rotator that does not currently host a circumstellar disk. The long baselines available (up to 330 m) and the good coverage of the (u, v) plane have led to resolution of the rotationally distorted disk. A combined spectroscopic and interferometric analysis is underway, and preliminary results indicate that best fits are obtained using the gravity darkened von Zeipel law expected for stars with radiative envelopes.

6. Interferometric observations of the B[e] star HD 62623 with the Keck I telescope

Stee et al. (2004) have observed the B[e] star HD 62623 using aperture masking interferometry with the Keck I telescope. They found that HD 62623 is resolved at 1.24, 2.26 and $3.08 \mu\text{m}$ whereas at $1.65 \mu\text{m}$ it remains unresolved. They have shown that *both* gas and dust are needed to explain the environment of HD 62623, in contrast to the study of Rovero & Ringelet (1994) which explained the IR excess as the result of free-free and free-bound gas emission only (without dust). Stee et al. find that the dust temperature at the inner boundary ($T_{in} = 1500 \text{ K}$) is consistent with the value given by Ivezić et al. (1998) using their code DUSTY to fit the spectral energy distribution of this star and with the value of the condensation temperature for silicate grains given by Lamers & Cassinelli (1999). So, at least for the cooler B[e] supergiant stars, it seems possible to form dust even for outflows with spherical geometry.

7. Conclusion

With the commissioning of the new generation of large aperture interferometers, it is clear that the physics of active hot stars will be revisited in depth. Most of

the interferometers are now open to the community and we encourage all our colleagues to apply for open time on these new powerful instruments. For instance ESO as released the VLTI/MIDI instrument (see <http://www.eso.org/instruments/midi/>) and the ASPRO software to prepare interferometric observations is available "on-line" through the JMMC Center (<http://mariotti.ujf-grenoble.fr/>).

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