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# NEW RESULTS FROM THE VLTI ON MASSIVE HOT STARS: FIRST DIRECT DETECTION OF A KEPLERIAN DISK AROUND $\alpha$ ARAE

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**Abstract.** We use the VLTI/AMBER instrument operating in the K band which combine a high angular resolution with a medium spectral resolution to study the kinematics of the inner part of $\alpha$ Arae's disk and try to infer its rotation law. We obtain for the first time the direct evidence that the disk is in keplerian rotation, answering a question that occurs since the discovery of the first Be star $\gamma$ Cas by father Secchi in 1866. We also present the global geometry of the disk showing that it is compatible with a thin disk + polar enhanced winds modeled with the SIMECA code. We found that the disk around $\alpha$ Arae is compatible with a dense equatorial matter confined in the central region whereas a polar wind is contributing along the rotational axis of the central star. Between these two regions the density must be low enough to reproduce the large visibility modulus (small extension) obtained for two of the four VLTI baselines. Moreover, we obtain that $\alpha$ Arae is rotating very close to its critical rotation.

## 1 Main results

In order to avoid duplicate papers we only summarize our main results since all the details will appear very soon in A&A and are already available under the reference astro-ph/0606404:

1. Thanks to these first spectrally resolved interferometric measurements at 2 $\mu$m (see Fig. 1 and Fig. 2) we were able to propose a possible scenario for the Be star $\alpha$ Arae's circumstellar environment which consist in a thin disk + polar enhanced winds that is successfully modeled with the SIMECA code.

2. We found that the disk around $\alpha$ Arae is compatible with a dense equatorial matter confined in the central region whereas a polar wind is contributing along the rotational axis of the central star. Between these two regions the density must be low enough to reproduce the large visibility modulus (small extension) obtained for two of the four VLTI baselines. This new scenario is also compatible with our previous MIDI measurements (see Chesneau et al. 2005) and the fact that the outer part of the disk may be truncated by a unseen companion at 32 $R_\star$.

3. We obtain for the first time the clear evidence that the disk is in Keplerian rotation, closing a debate that occurs since the discovery of the first Be star $\gamma$ Cas by father Secchi in 1866.

4. We found that that $\alpha$ Arae must be rotating very close to its critical velocity.

5. These observations were done using the medium (1500) spectral resolution of the VLTI/AMBER instrument and are very promising for the forthcoming AMBER high spectral resolution observational mode (10000) and the coupling of the Auxiliary Telescopes (ATs) on the VLTI array.

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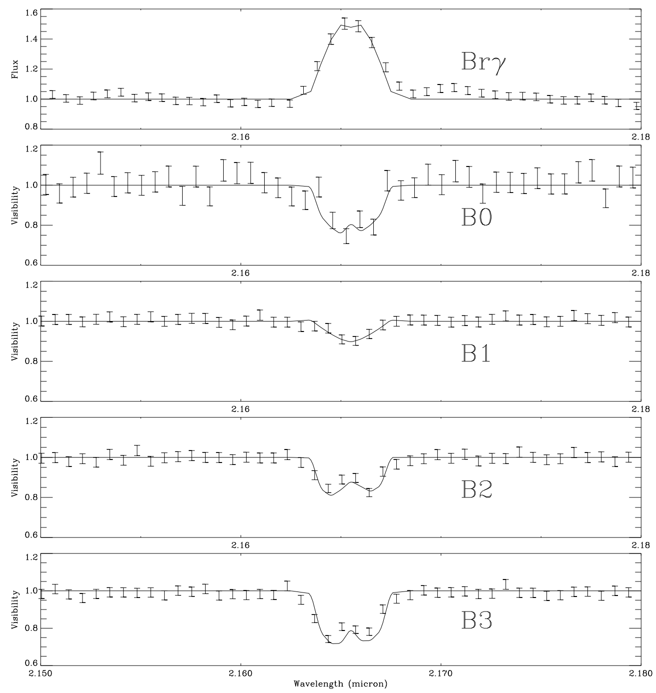


**Fig. 1.** Differential visibility across the Br$\gamma$ line profile for the $B_0$, $B_1$, $B_2$ and $B_3$ baselines. The first picture from the top is the Br$\gamma$ line profile. The plain line are the fits we obtain with SIMECA from our best model whereas the VLTI/AMBER data are the points with error bars.

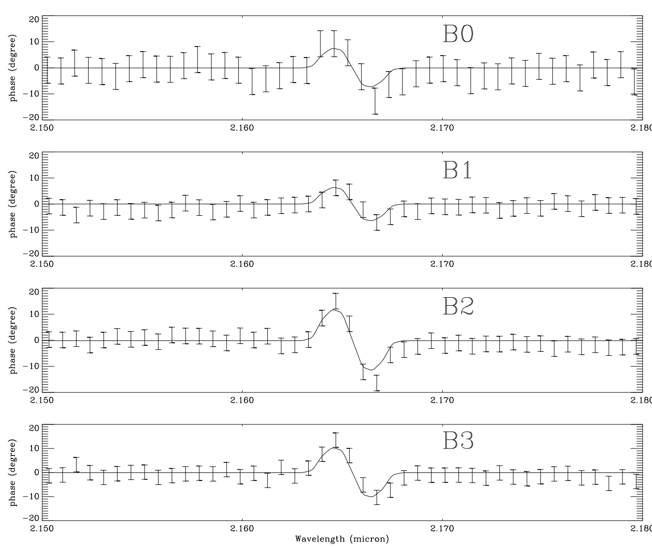


**Fig. 2.** Phase of the visibility across the Br$\gamma$ line profile for the $B_0$, $B_1$, $B_2$ and $B_3$ baselines. The plain line are the fits we obtain with SIMECA from our best model whereas the VLTI/AMBER data are the points with error bars.

## 2 Discussion

This study points out three important results touching lively debated issues:

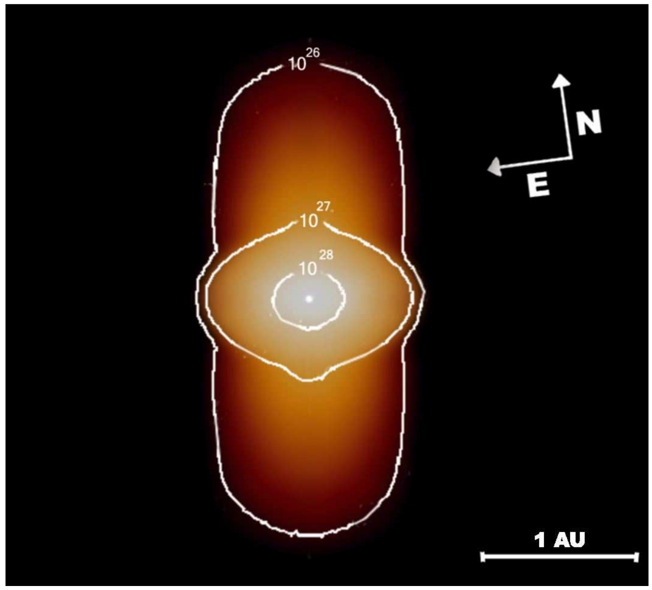


**Fig. 3.** Intensity map in the continuum at 2.15 $\mu$m obtained with SIMECA for our best model parameters. The inclination angle is $55^o$, the central bright region is the flux contribution from the thin equatorial disk whereas the smoother regions originate from the stellar wind. The brightness contrast between the disk and the wind is globally $\sim$ 30 but can reach 100 if one compares the inner region of the disk to the outer parts of the wind.

### 2.1 *Keplerian rotation*

There were already some indications that the disk may follow the Keplerian rotation by other theoretical studies, for instance the results obtained by Hanuschik (1995) regarding shell lines produced within a Keplerian disk in hydrostatic equilibrium. Hanuschik (1996; 2000) also investigate the geometrical structure of the emitting part of circumstellar envelopes around Be stars and found a good agreement with spectroscopic data using a thin disk in vertical hydrostatic and horizontal centrifuginal equilibrium, similar to a Keplerian accretion disk. These results were confirmed by Rivinius (1999) presenting high resolution echelle spectra for 6 B-type stars supposed to be seen edge-on and in good agreement with Hanuschick's models for the formation of shell lines in circumstellar disks with Keplerian rotation. In a more recent paper Rivinius (1999) propose a scenario where the disk is no more a completely stationary structure but rather a succession of outbursts which may form rings. But even within this scenario, part of the ejected matters attains sifficiently high angular momentum to form a roughly Keplerian disk, at least for the immediate times of outbursts. Finally, another indirect argument in favor of a Keplerian disk is the success of the global oscillation modeling already outlined in the paper review by Porter & Rivinius (2003). Thus, our results may be the way to put a final exclamation mark regarding the widely accepted fact that **circumstellar disk around Be stars are in Keplerian rotation**.

### 2.2 *Stellar rotation*

We found that $\alpha$ Arae must be **rotating very close to its critical velocity** since we obtain $\frac{v_{rot}}{v_{crit}} \sim 91\%$. This value is far above the conservative estimates of $\sim$ 75 % usually found in the literature for Be stars. The fact that Be stars may be rotating much closer to their critical velocities than it is generally supposed was already outlined by Townsend et al. (2004) and Owocki (1996). This nearly critical rotation has quite profound implications for dynamical models of Be disk formation and may be the clue for the Be phenomenon. It may bring sufficient energy to levitate material in a strong gravitational field or at least help other physical processes such as pulsation or gas pressure to provide sufficient energy and angular momentum to create a circumstellar disk. Moreover, observational evidences of this nearly critical rotation are growing such as the results obtained by Domiciano et al. (2003) using interferometric VLTI/VINCI data of Achernar. They measured a rotationally distorted photosphere with an apparent oblateness of 1.56 which cannot be explained using the classical Roche approximation. This scenario follows the original picture by Struve (1931) of a critically rotating star, ejecting material from its equatorial regions.

### *2.3 Polar wind enhancement*

Our interferometric measurements are evidencing **a polar wind enhancement** (see Fig. 3) which was already predicted for almost critically rotating stars. For instance, Cranmer & Owocki (1995) and Owocki & Gayley (1998) studied the effects of limb darkening, gravity darkening and oblateness on the radiation driving mechanism and found that the tendency for the higher flux from the bright poles to drive material toward the darker equatorial region is outweighed by the opposite tendency for the oblateness of the stellar surface to direct the radiative flux to higher latitudes, i.e. away from the equator. The paper review by Porter & Rivinius (2003) also outline the effect of the inclusion of nonradial line-driving force which reduces the effect of the wind compression to zero and, taking into account the gravity darkening, results in a polar wind enhancement. This physical effect goes in the opposite direction to the one proposed for the Wind Compressed Disk model from Bjorman & Cassinelli (1993). In a recent paper, Kervella & Domiciano de Souza (2006) have evidenced an enhanced polar wind for the Be star Achernar whereas this Be star presents no hydrogen lines in strong emission. Thus, it seems that a significant polar wind may be present even if the star is still in a normal B phase, i.e. this enhanced polar wind does not seem to be related to the existence of a dense equatorial envelope, as already outlined by Kervella & Domiciano de Souza (2006).

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