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Near-IR observations of Vega-like stars with the VLTI: β Pic, α PsA, ϵ Eri and τ Cet

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Abstract. We have conducted K band interferometric observations of four nearby main-sequence Vega-like stars at the VLTI with very long baselines. The very high resolution allowed us to probe the innermost region of the disks, where planets are supposed to be formed. The diameters of three bright and nearby prototypes β Pictoris, Fomalhaut (α PsA) and ϵ Eridani as well as τ Ceti have been measured with VINCI, the VLTI commissioning instrument, with a high accuracy. The derived diameters were used to constrain their age with help of the evolution code CESAM. The precision achieved with VINCI allowed us to discuss the shape of their photosphere and the possible detection of warm circumstellar material within the narrow interferometric field of view.

1. Introduction

Following their discovery with the IRAS satellite (Aumann et al. 1984), Vega-like stars and their debris-disks have been mainly explored with sub-millimeter interferometers or visible and IR coronagraphs (with adaptive optics). These techniques revealed the presence of cold dust in extended structures from ~20 AU out to hundreds of AU from the stars. Interferometry offers a unique tool to probe the dust distribution, complementary to the AO and coronagraphic observations with both very narrow FOV, very high spatial resolution and a strong dynamics. With the current measurement accuracy ($\sim 1\%$ or less), interferometry at the VLTI enables constraining the fundamental parameters of theses stars and thus their evolution status. Besides the direct estimation of their size, we can already start searching for tiny visibility fluctuations due to the shape of the stellar photospheres or to the presence of small amount of warm circum-stellar material. The four closest main-sequence Vega-like stars were selected as prime targets on brightness criteria.

2. VLTI/VINCI observations

Our observations were conducted with the two-beam combiner VINCI instrument (Kervella et al. 2000) operating in the K band ($\lambda = 2.2\ \mu$m) at the VLTI (Glindemann et al. 2000) between November 2001 and November 2002. The interferometer could be used in three different configurations either with 8m UT1-UT3 telescopes on a 102.5m long baseline or with two 35cm test-siderostats on the E0-G1 66m long baseline or on the B3-M0 140m long one. The last two baselines have perpendicular orientations and thus enable detecting eventual asymmetries of the source brightness distribution. We measured fringe visibility amplitude squared (V^2), which is calibrated by interleaved observations of unresolved (point-like) sources or sources of known diameter (see the spectroscopic catalogue by Cohen et al. 1999). Each V^2 measure for a given projected baseline is linked to the source brightness distribution by the van Cittert-Zernike theorem.

Assuming in a first step that the intensity profile originates only from a centro-symmetric photosphere, we have fit a uniform disk (UD) diameter to the calibrated data. It was then translated into a more realistic limb-darkening (LD) model using the theoretical linear LD coefficients computed by Claret A. (2000) as a function of the stellar atmosphere's properties. The final linear radii were obtained using the *Hipparcos* parallaxes (Perryman et al. 1997). The results are summarized in Table 1 and the visibility curves are shown in Fig. 1 and 2. We have processed separately the statistical error due to the dispersion of the individual measures and the systematic error linked to the uncertainty on the calibrators' diameter.

Table 1. Best fit uniform disk diameters and linear radii

Star	Baseline	$\theta_{UD} \pm \sigma_{stat} \pm \sigma_{syst}$ [mas]	$R_\star \pm \sigma_{tot}$ [$R_\odot$]
β Pic	UT1-UT3	$0.825 \pm 0.060 \pm 0.060$	1.74 ± 0.17
α PsA	UT1-UT3, B3-M0	$2.191 \pm 0.010 \pm 0.015$	1.83 ± 0.02
	E0-G1	$2.308 \pm 0.035 \pm 0.020$	1.93 ± 0.04
ϵ Eri	UT1-UT3, B3-M0	$2.087 \pm 0.008 \pm 0.025$	0.74 ± 0.01
τ Cet	B3-M0	$2.005 \pm 0.009 \pm 0.025$	0.80 ± 0.01

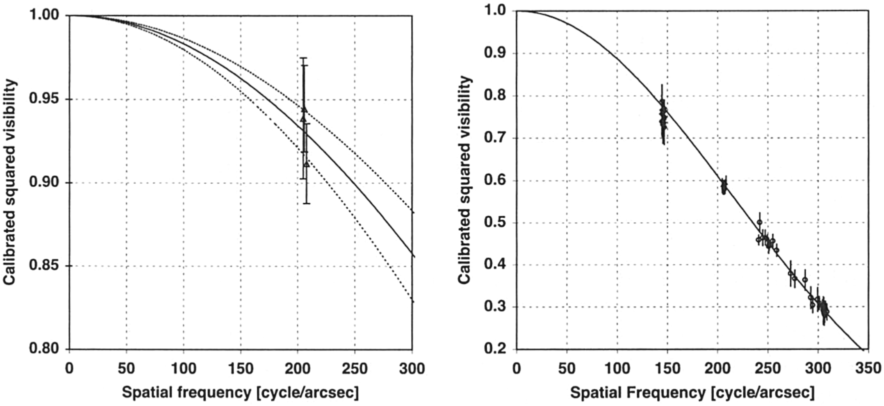

Figure 1. Squared visibilities of β Pic (left) and α PsA (right) measured with VINCI, and the best fit UD model. The V^2 measurements on the short baseline for α PsA do not fit the UD model obtained at high spatial frequencies. These former points were not taken into account in the diameter estimation, they correspond to a perpendicular baseline orientation and are discussed independently in section 4.

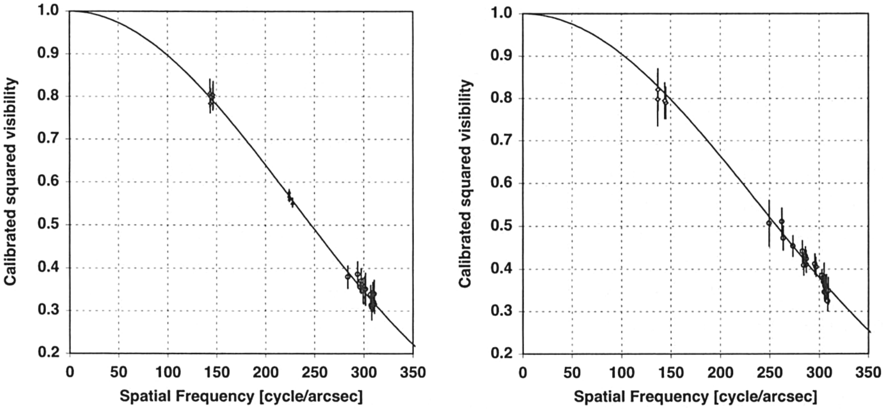

Figure 2. Squared visibilities of ϵ Eri (left) and τ Ceti (right) measured with VINCI, and the best fit UD models. Several calibrators were used in order to decrease the final systematic uncertainty. This is especially important for the long baseline measurements for which the bright calibrators are well resolved.

The diameters derived from our observations compare generally well with previous estimates. They all agree with the adopted luminosity and effective temperature, within the error bars. The diameter of α PsA is consistent with the LD diameter from Hanbury Brown et al. (1974) (2.10 ± 0.14 mas) while the global uncertainty is drastically reduced. τ Ceti was also recently measured with the same VLTI set of observations by Pijpers et al. (2003): $R = 0.77 \pm 0.02\ R_\odot$. The 2 σ discrepancy is probably due to different calibration strategies, whereas our value is consistent with the observed spectroscopic quantities and our systematic uncertainty is smaller thanks to the use of numerous calibrators.

3. Modeling the stellar fundamental parameters with CESAM

The evolution code CESAM (Morel, P. 1997) was used together with the interferometric diameters in order to further constrain the properties of the four bright Vega-like stars. Their mass and initial abundance being not well known, the simulations were initialized with guessed values and the final state was reached when the code converged into the adopted luminosity-temperature box. We managed to built consistent models, compatible with our interferometric measurements and able to reproduce the adopted observed spectroscopic properties of the stars (luminosity, effective temperature, metallicity, surface gravity). Stellar ages were inferred from the simulation, the results are presented in Table 2.

Table 2. Stellar parameters from the modeling with CESAM.

Star	$\log(L_\star/L_\odot)$	Teff (K)	Age (Myr)	$M/M_\odot$	$R/R_\odot$	log g	$[Z/H]_s$
β Pic	0.959	8117	20	1.75	1.53	4.31	-0.02
α PsA	1.247	8750	290	2.0	1.835	4.21	-0.1
ϵ Eri	-0.481	5052	850	0.86	0.752	4.62	0.03
τ Cet	-0.309	5408	8200	0.82	0.800	4.55	-0.3

It turned out that β Pic must be very young in order for the model to reproduce the observed physical parameters. An age around 20 Myr was derived, in good agreement with the recent studies. We computed for Fomalhaut an age of 290 Myr. This work confirms also that ϵ Eri and τ Ceti (a metal deficient star of the old galactic disk) are somewhat older with respective ages around 850 Myr and 8.2 Gyr. All these values agree with previous estimations (for references and a detailed comparison, see Di Folco et al. 2003, in prep.).

4. Fomalhaut: a departure from the uniform disk model ?

The measurement carried out with the short E0-G1 baseline (perpendicular to B3-M0) evidences a small V^2 deficit (1-4 %) compared to the value extrapolated from the fit UD model (Fig.1). This variation could be linked to a photospheric effect (e.g., a weak oblateness due to the intermediate rotation velocity of the star $v \sin i = 93 \pm 9$ km/s) or to a small amount of dust grains close to the sublimation limit. We have investigated the first hypothesis and have modeled the expected oblateness in the framework of a Roche model of rigid rotation body (Domiciano de Souza et al, 2002). The V^2 difference (Pole - Equator) is estimated around 0.8 % at our spatial frequency, independently of the inclination of the rotation axis. If the almost edge-on disk lies in the stellar equatorial plane, it is likely that we measured diameters close to the poles and the equator with our VLTI configuration. However, a better UV coverage is necessary to confirm this deficit and unambiguously constrain the source profile. The residual V^2 deficit could be as a signature of a possible small amount of warm dust around α PsA (for a detailed discussion, see Di Folco et al., 2003).

5. Conclusion and perspective

We have measured at the VLTI the diameter of four bright Vega-like stars with a high accuracy and have estimated their age through a consistent modeling with the CESAM code. The current precision allowed us to detect tiny variations in the visibility curves linked to asymmetries in the brightness profiles. This work will be soon continued with an improved accuracy thanks to the implementation of the fringe tracking facility FINITO and the future near-IR instrument AMBER, which will rapidly tackle the detection of hot circum-stellar dust around these IR-excess stars as well as the shape of the rapid rotators' photosphere.

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