

A new interferometric study of four exoplanet host stars: θ Cygni, 14 Andromedae, ν Andromedae and 42 Draconis^{★,★★}

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ABSTRACT

Context. Since the discovery of the first exoplanet in 1995 around a solar-type star, the interest in exoplanetary systems has kept increasing. Studying exoplanet host stars is of the utmost importance to establish the link between the presence of exoplanets around various types of stars and to understand the respective evolution of stars and exoplanets.

Aims. Using the limb-darkened diameter (LDD) obtained from interferometric data, we determine the fundamental parameters of four exoplanet host stars. We are particularly interested in the F4 main-sequence star, θ Cyg, for which Kepler has recently revealed solar-like oscillations that are unexpected for this type of star. Furthermore, recent photometric and spectroscopic measurements with SOPHIE and ELODIE (OHP) show evidence of a quasi-periodic radial velocity of ~ 150 days. Models of this periodic change in radial velocity predict either a complex planetary system orbiting the star, or a new and unidentified stellar pulsation mode.

Methods. We performed interferometric observations of θ Cyg, 14 Andromedae, ν Andromedae and 42 Draconis for two years with VEGA/CHARA (Mount Wilson, California) in several three-telescope configurations. We measured accurate limb darkened diameters and derived their radius, mass and temperature using empirical laws.

Results. We obtain new accurate fundamental parameters for stars 14 And, ν And and 42 Dra. We also obtained limb darkened diameters with a minimum precision of $\sim 1.3\%$, leading to minimum planet masses of $M \sin i = 5.33 \pm 0.57$, 0.62 ± 0.09 and $3.79 \pm 0.29 M_{\text{Jup}}$ for 14 And b, ν And b and 42 Dra b, respectively. The interferometric measurements of θ Cyg show a significant diameter variability that remains unexplained up to now. We propose that the presence of these discrepancies in the interferometric data is caused either by an intrinsic variation of the star or an unknown close companion orbiting around it.

Key words. stars: fundamental parameters – methods: data analysis – techniques: high angular resolution – instrumentation: interferometers

1. Introduction

Many techniques have been developed during the past decade to enable the discovery of exoplanets. The radial velocity method, based on the reflex motion of the host star, is one of the most successful of these and has to date enabled the discovery of 535 planetary systems¹. Most of these planets were found orbiting slowly rotating stars, late-type stars, or A giants. While A and F main sequence stars were usually avoided because of their high $v \sin i$, a survey of A and F main sequence stars was nonetheless recently undertaken using a specialized analysis method to look for planets around these stars, and planets

were indeed found around a few F stars (Lagrange et al. 2009). Unfortunately, the possible planet configurations fitting the radial velocity (RV) data were found to be dynamically unstable. To resolve this problem it is important to better understand the link between the presence and mass of exoplanets, the host star parameters, and the separation of the planet and host star.

Interferometric data are now able to bring additional information to bear on stellar variability and its contribution to noise in the radial velocity measurements, and can help to directly determine many of the fundamental parameters of the host stars with an accuracy of about 5% (see for example Baines et al. 2009; von Braun et al. 2011). This is not only very important for deriving accurate radii for transiting planets, but also for RV planets. Understanding the link between the presence and nature of exoplanets and the fundamental parameters of the star requires sampling a large number of targets. We have started a survey with VEGA (Visible spEctroGraph and polArimeter) (Mourard et al. 2009), a visible spectro-interferometer located on the CHARA (Center for High Angular Resolution Astronomy)

[★] Based on interferometric observations with the VEGA/CHARA instrument.

^{★★} Appendix A is available in electronic form at <http://www.aanda.org>

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¹ As of December 23, 2011 (Schneider et al. 2011).

array at Mount Wilson, California (ten Brummelaar et al. 2005), to measure all currently accessible exoplanets stars, i.e. almost 40 targets. To build this sample, we first selected the exoplanet host stars listed in Schneider’s catalog (Schneider et al. 2011). Those stars have to be observable by VEGA, therefore we sorted out those that had a magnitude smaller than 6.5 in the V - and in the K band, and a declination higher than -30° . Knowing the error on the squared visibility allowed by VEGA at medium resolution ($\approx 2\%$), we can estimate the maximum and the minimum diameters for which we can obtain an accuracy of $\approx 2\%$ taking into account the maximum and minimum baselines. We consider this accuracy as the minimum allowed to obtain sufficiently good informations on fundamental parameters of the stars and planets. Diameters included between 0.3 and 3 ms of arc (mas) are sufficiently resolved to achieve this accuracy. We finally found 40 stars whose planets were discovered with the transit or RV techniques.

Interferometry is complementary to the transit method or RV measurements in determining exoplanet parameters. For instance, the transit method allows determining the exoplanet radius, while the RV method is used to detect the minimum mass. The main goal of these observations is to directly constrain these parameters, and to study the impact of stellar noise sources (e.g., spots, limb darkening) applied to these observing methods. In the long term, the results will be compared to a catalog of limb darkening laws from 3D hydro-dynamical modeling and radiative transfer. Thus, we will be able to create a catalog of measured angular diameters, and derive revised surface brightness relationships.

From October to December 2011, we obtained data on three stars of our sample: 14 And, ν And and 42 Dra, while a fourth star θ Cyg was observed over a longer period, from June 2010 to November 2011. We found that while the first three stars yield stable and repeatable results, there are discrepancies in the results of θ Cyg, forcing us to study this system more carefully. New and unexplained RV variations recorded with SOPHIE and ELODIE at the Observatoire de Haute-Provence (Desort et al. 2009) provided a first clue that this star hosts either a complex planetary system, undergoes hitherto unknown variations, or has a hidden companion.

After a short introduction to the basics of interferometry, we describe in Sect. 3 the observations made of 14 And, ν And and 42 Dra during the year 2011 and derive the star and planet fundamental parameters. We then compare these values to those found in the literature. In Sect. 4, we present the observations of θ Cyg made during the last two years. We discuss the fundamental parameters we derived for this target in Sect. 5, and compare them with the previously known parameters for this star (see Table 7). We then discuss the variation of the angular diameter of θ Cyg in Sect. 6 and some possible explanations of this variability.

2. Observations with VEGA/CHARA

2.1. VEGA/CHARA and visibility determination

The CHARA array hosts six one-meter telescopes arranged in a Y shape that are oriented to the east (E1 and E2), south (S1 and S2) and west (W1 and W2). The baselines range between 34 and 331 m and permit a wide range of orientations. VEGA is a spectro-interferometer working in the visible wavelengths at different spectral resolutions: 6000 and 30000. Thus, it permits the recombination of two, three or four telescopes, and a maximum angular resolution of ≈ 0.3 mas. Interferometry is a

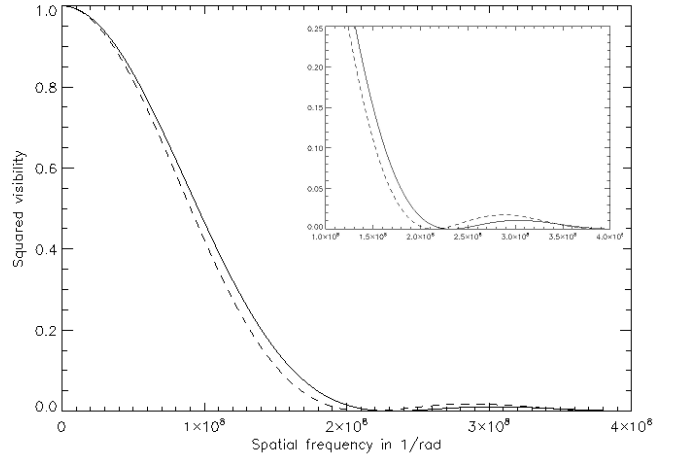


Fig. 1. Squared visibility of a uniform disk (solid line) and of a limb-darkened disk (dashed line) for a star of 1.17 mas of diameter, a wavelength of 720 nm and a baseline ranging from 0 to 330 m. The LDD is sensitive close to the zero and in the second lobe of visibility, where it is higher than for a UD.

high angular resolution technique allowing one to study the spatial brightness distribution of celestial objects through measuring their spatial frequencies. By measuring the fringe contrast, also called visibility, one is able to determine the size of stars, thanks to the van Cittert-Zernike theorem (Born et al. 1980). The simplest representation of a star is a uniform disk (UD) of angular diameter θ_{UD} . The corresponding visibility function is given by

$$V^2 = \left| \frac{2J_1(x)}{x} \right|^2, \quad (1)$$

where $J_1(x)$ is the first-order Bessel function and $x = \pi B \theta_{UD} \lambda^{-1}$. B represents the length of the projected baseline, λ the wavelength of the observation. However, stars are not uniformly bright: a better representation of the surface brightness is the limb-darkened disk (LDD). The main differences between the two profiles arise close to the zero of visibility and in the second lobe, as shown in Fig. 1.

The LDD is conventionally described by the function $I_\lambda[\mu]$, where μ is the cosine between the normal to the surface at that point and the line of sight from the star to the observer and u_λ the limb darkening coefficient (Hanbury Brown et al. 1974):

$$I_\lambda[\mu] = I_\lambda[1][1 - u_\lambda(1 - \mu)]. \quad (2)$$

A good approximation of θ_{LD} is given by

$$\theta_{LD}[\lambda] = \theta_{UD}[\lambda] \times \left[\frac{1 - u_\lambda/3}{1 - 7u_\lambda/15} \right]^{1/2}, \quad (3)$$

(Hanbury Brown et al. 1974).

The Claret & Bloemen (2011) coefficients are listed in tables and depend on the effective temperature and the $\log(g)$. We calculated that in our observing conditions, a difference of 10% on the coefficients leads to a difference of 0.65% on the LDD and of 0.33% on the T_{eff} . Using approximated coefficients is then of negligible consequence on the final parameters’ values.

Because we performed 3T observations, we obtained three calibrated squared visibility points for each observation in the observed spectral band. The systematic and statistical errors were calculated for each data point. The systematic error accounts for the influence of the estimated error on the angular diameter of the calibrators. In almost all cases, the systematic

error is negligible compared to the statistical one by a factor 10, because our diameters are small (Mourard et al. 2009). The statistical error takes into account the instrumental variations, the variations of atmospheric conditions (seeing), and vibrations of the telescopes or the delay lines. It is measured when we estimate the noise and the error on the noise.

2.2. Determination of the fundamental parameters

We used empirical relations to derive the fundamental parameters of the stellar and planet components. From the LDD (θ_{LD}) expressed in mas and the parallax (π) given in second of arc, we calculated the star's linear radius (R) and mass in the following manner. Using a simple Monte Carlo simulation, we obtain a correct estimate of the radius and its error:

$$R \pm \delta R(R_{\odot}) = \frac{\theta_{LD} \pm \delta\theta_{LD}}{9.305 \times (\pi \pm \delta\pi)}. \quad (4)$$

We then use the gravitational acceleration relation to estimate the mass:

$$\|\vec{g}\| = GM/R^2, \quad (5)$$

where G is the gravitational constant. The modulus of g is given in Table 1. The error of the mass estimate is dominated by the uncertainty in parallax. We also estimated the effective temperature using the black body law and the luminosities (L) shown in Table 1:

$$L = 4\pi R^2 \sigma T_{\text{eff}}^4. \quad (6)$$

Starting from the stellar masses, we use the mass function to determine the exoplanet masses and estimate its error by performing a Monte Carlo test:

$$f(m) = \frac{M_{\text{pl}}^3 \sin(i)^3}{(M_* + M_{\text{pl}})^2}, \quad (7)$$

where M_{pl} and M_* are the planet and stellar masses respectively. The results of the calculated planet masses are given in Table 6.

Given that $M_{\text{pl}} \ll M_*$ and using Kepler's third law, we can write

$$M_{\text{pl}} \sin(i) = \frac{M_*^{2/3} P^{1/3} K (1 - e^2)^{1/2}}{(2\pi G)^{1/3}}, \quad (8)$$

where K is the velocity semi-amplitude and e the planet eccentricity.

3. 3T measurements of 14 And, ν And and 42 Dra

3.1. VEGA observations

In 2011, we observed two giant stars, 42 Dra (K1.5III: Döllinger et al. 2009) and 14 And (K0III: Sato et al. 2008), and one main-sequence star, ν And (F9V: Fuhrmann et al. 1998). The observations provided measurements close to the zero or up to the second lobe of squared visibility.

14 And (HD 221345, HIP 116076, HR 8930) hosts one exoplanet of minimum mass $M_2 \sin i = 4.8 M_J$ discovered in 2008, and it has also been shown that this star does not exhibit measurable chromospheric activity (Sato et al. 2008). The general properties of this star are given in Table 1.

ν And (HD 9826, HIP 7513, HR 458) is a bright F star that has undergone numerous spectroscopic investigations

Table 1. Coordinates and parameters of the three host stars 14 And, ν And and 42 Dra.

Parameter	14 And	ν And	42 Dra
RA (J2000)	23:31:17.4	01:36:47.8	18:25:59.14
Dec (J2000)	+39° 14' 10''	+41° 24' 20''	+65° 33' 49''
Stellar type	K0III ^a	F9V	K1.5III ^c
V mag	5.225	4.10	4.833 ^c
K mag	2.331	2.86	2.085
M_V	0.67 ^a	3.44 ± 0.02 ^b	-0.09 ± 0.04 ^c
$\nu \sin i$ [km s ⁻¹]	2.60 ^a	9.5 ± 0.8 ^b	
T_{eff} [K]	4813 ± 20 ^a	6107 ± 80 ^b	4200 ± 70 ^c
Parallax [mas]	12.63 ± 0.27 ^d	74.12 ± 0.19 ^d	10.36 ± 0.20 ^d
Mass [M_{\odot}]	2.2 ^{+0.1} _{-0.2} ^a	1.27 ± 0.06 ^b	0.98 ± 0.05 ^c
log g	2.63 ± 0.07 ^a	4.01 ± 0.1 ^b	1.71 ± 0.05 ^c
[Fe/H]	-0.24 ± 0.03 ^a	0.09 ± 0.006 ^b	-0.46 ± 0.05 ^c
L [L_{\odot}]	58 ^a	3 ^e	149.7 ± 15.3 ^f

References. ^(a) Sato et al. (2008); ^(b) Fuhrmann et al. (1998); ^(c) Döllinger et al. (2009); ^(d) van Leeuwen (2007); ^(e) Butler et al. (1999); ^(f) Baines et al. (2010).

Table 2. Parameters of the calibrators used for 14 And, ν And and 42 Dra.

#	Name	Spectral type	m_V	m_K	θ_{UD} [mas]
1	HD 211211	A2Vnn	5.71	5.63	0.20 ± 0.01
2	HD 1439	A0IV	5.87	5.86	0.18 ± 0.01
3	HD 14212	A1V	5.31	5.27	0.24 ± 0.02
4	HD 187340	A2III	5.90	5.71	0.21 ± 0.02

Notes. The value of the equivalent uniform disk θ_{UD} is given at 700 nm (Bonneau et al. 2006).

(Fuhrmann et al. 1998, and references therein). Four exoplanets are known to orbit around it: they were discovered between 1996 and 2010 (Schneider et al. 2011; Butler et al. 1999; Lowrance et al. 2002; Curiel et al. 2011).

42 Dra (HD 170693, HIP 90344, HR 6945) is an intermediate-mass giant star around which a $3.88 \pm 0.85 M_J$ exoplanet has recently been discovered (Döllinger et al. 2009).

Observations of these three exoplanet host stars were made in October and November 2011 with the E1E2W2 triplet. The data processing and the results analysis were presented in Sect. 2.1. We used the calibrators HD 211211 (*cal1*) and HD 1439 (*cal2*) for 14 And, HD 14212 (*cal3*) for ν And and HD 187340 (*cal4*) for 42 Dra (Table 2). They were found using the SearchCal utility² developed by the JMMC (Bonneau et al. 2006). It gives, among other parameters, the stellar magnitude in the V and K bands, the spectral type, and also an estimate of the angular diameter along with the corresponding error. Angular diameters are determined by surface-brightness versus color-index relationships. We used the $V/(V - K)$ polynomial relation given by Bonneau et al. (2006). Its accuracy of 7% is the highest concerning the color-index polynomial fits. We mainly observed with the three telescope (3T) configuration, but sometimes the conditions only allowed for 2T measurements (Table 3). VEGA data are recorded as blocks of 1000 frames each of 15 ms of exposure time. The observations of the targets were 30 min long (60 blocks), and those of the calibrators were 10 to 20 min long (20 or 40 blocks). The data were recorded at medium spectral resolution ($R = 6000$) and the data processing used 15 nm wide channels in the continuum of the

² Available at <http://www.jmmc.fr/searchcal>

Table 3. Journal of the observations of 14 And, ν And and 42 Dra. RJD is the reduced Julian day.

Star	RJD	Seq	Base	PA	V^2
14 And	55 855.4	1T1	66	-123.4	0.306 ± 0.022
			222	-118.7	0.004 ± 0.032
	55 849.68*	1T1	104	109.1	0.047 ± 0.015
			153	-108.2	0.012 ± 0.016
			244	-93.2	0.008 ± 0.017
55 847.77*	1T1	65	-134.1	0.321 ± 0.016	
		154	-127.2	0.020 ± 0.008	
55 847.72*	1T2	66	-122.9	0.420 ± 0.022	
		156	-118.1	0.039 ± 0.012	
ν And	55 883.74*	3T3	66	-131.3	0.384 ± 0.020
			156	-124.46	0.007 ± 0.009
			221	-126.4	0.007 ± 0.009
	55 855.69*	3T3	92	131	0.277 ± 0.011
	55 855.72*	3T3	95.9	124.2	0.245 ± 0.009
	55 855.85*	3T	107	89.9	0.226 ± 0.012
	55 854.78*	3T3	156	-120.2	0.437 ± 0.027
42 Dra	55 883.63*	4T4	66	169.5	0.100 ± 0.015
			156	-159.0	0.000 ± 0.006
			222	-160.7	0.006 ± 0.011
			66	-164.9	0.086 ± 0.007
			66	-164.9	0.111 ± 0.009

Notes. The projected baseline is given by baseline (in meters) and PA in degree. V^2 is the calibrated squared visibility, the error of the squared visibility includes the statistical and systematic errors. All measurements use a band of 15 nm around 707.5 nm, except for the last observation of 42 Dra, which was centered around 732.5 nm. In most cases (*), CLIMB data in K band are also available.

red spectrum. We alternated the calibrators and target using the standard sequence *Cal-Target-Cal*, which provides a better estimate of the transfer function during the observations of the target. We know (Mourard et al. 2009) that, under correct seeing conditions, the transfer function of VEGA/CHARA is stable at the level of 2% for more than one hour. This has been checked in all our data set, and bad sequences were removed. We used the CLIMB beam combiner operating in the near-infrared as a 3T fringe tracker (Sturmann et al. 2010) to stabilize the optical path differences during the long integrations.

3.2. Fundamental parameters of stars and planets

Because our data sets are covering many frequencies in the second lobe of the visibility function, we decided to fix the LDD coefficient and to adjust the diameter only. We used Claret & Bloemen (2011) tables.

- 14 And. This star is well-fitted by a limb-darkened diameter model that provides a χ^2_{reduced} of 2.8 (see Fig. 2). It is obtained with the Claret coefficient $u_\lambda = 0.700$, defined by the effective temperature and the $\log(g)$ given in Table 1. It follows a LDD of 1.51 ± 0.02 mas. Baines et al. (2009) found an LDD of 1.34 ± 0.01 mas for 14 And, which is smaller by $\sim 10\%$ than the one we found with VEGA. But we recorded the data in the V band, whereas their values were recorded in the K band. Sato et al. (2008) found that 14 And's exoplanet minimum mass is $M_{\text{pl}} \sin(i) = 4.8 M_{\text{Jup}}$, which is close to our result (see Table 6), but was derived from radial velocity data, which induces a different bias.
- ν And. The data points obtained at low spatial frequency are slightly lower than the LDD model. This explains the

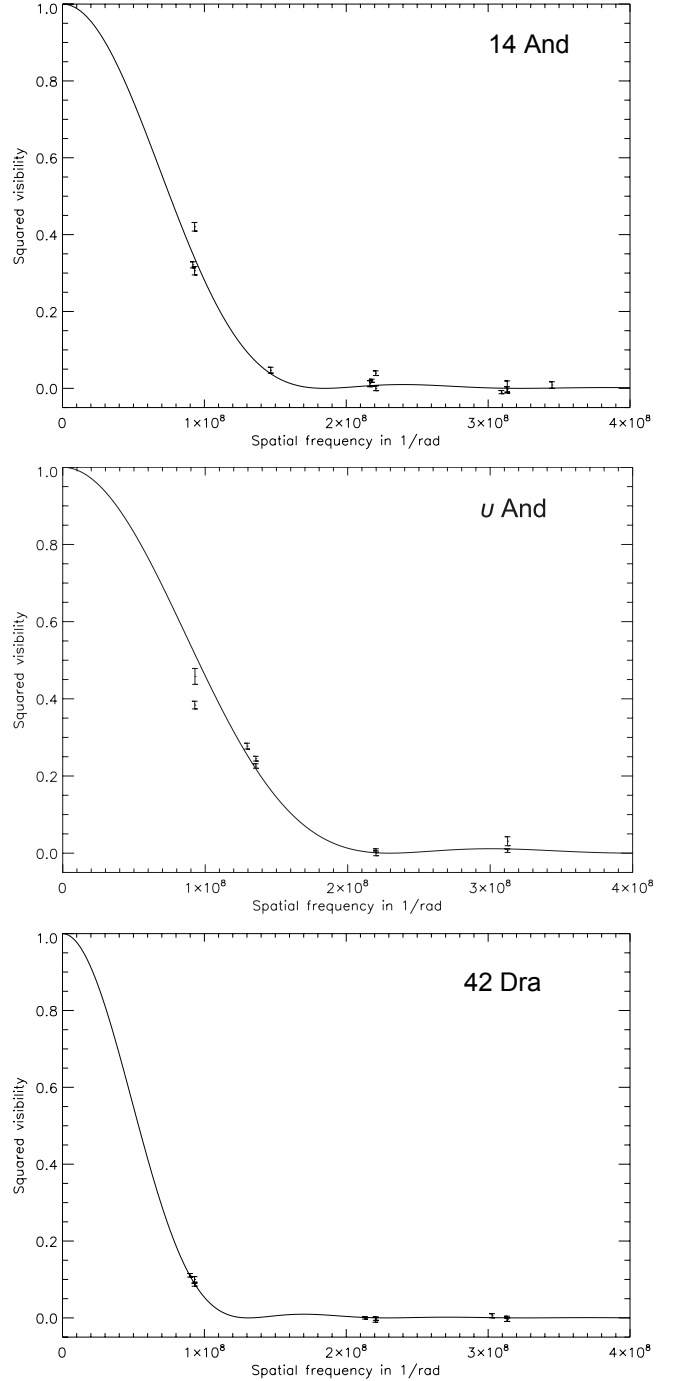


Fig. 2. Squared visibility of 14 And (top), ν And (middle) and 42 Dra (bottom) versus spatial frequency [1/rad] for VEGA data points. The solid line is the model of the limb-darkened angular diameter provided by the LITpro software.

higher χ^2_{reduced} than for the other stars, which equals 6.9 (Fig. 2). Then, we obtained $\theta_{\text{LD}} = 1.18 \pm 0.01$ mas using $u_\lambda = 0.534$. ν And was observed by van Belle & von Braun (2009) with the Palomar Testbed Interferometer (PTI), who estimated its LDD to be 1.02 ± 0.06 mas. Baines et al. (2008) found a higher diameter with CHARA/CLASSIC (McAlister et al. 2005): 1.11 ± 0.01 mas. However, it appears that, due to the dispersion in their measurements, the value of their error bars could be underestimated. In our case, the formal uncertainty is also very small but the high value of the χ^2_{reduced}

Table 4. Summary of the 14 And, ν And and 42 Dra limb-darkened diameters (mas) calculated for VEGA data, CLIMB data and both instruments.

Star	VEGA		CLIMB		VEGA+CLIMB	
	θ_{LD}	χ^2	θ_{LD}	χ^2	θ_{LD}	χ^2
14 And	1.51 ± 0.02	2.8	1.30 ± 0.13	1.5	1.50 ± 0.02	2.1
ν And	1.18 ± 0.01	6.9	0.96 ± 0.16	0.8	1.17 ± 0.01	4.6
42 Dra	2.12 ± 0.02	0.2	2.10 ± 0.27	0.4	2.12 ± 0.02	0.3

Table 5. Summary of the fundamental parameters of 14 And, ν And and 42 Dra calculated using VEGA interferometric data.

Star	Radius	Mass	T_{eff}
14 And	12.82 ± 0.32	2.60 ± 0.42	4450 ± 78
ν And	1.70 ± 0.02	1.12 ± 0.25	5819 ± 78
42 Dra	22.04 ± 0.48	0.92 ± 0.11	4301 ± 71

Notes. θ_{LD} is the limb-darkened diameter in mas. The radius and mass are given in solar units and T_{eff} is given in K.

indicates a poor adjustment by this simple model. No value is consistent with the respective other, ours being separated from Baines et al. (2008)'s by more than 5σ . More observations are definitively necessary to improve the accuracy and reliability of these measurements.

However, the minimum masses of ν And's exoplanets are consistent with those calculated by Curiel et al. (2011) and Wright et al. (2009), but remain lower by $\approx 10\%$ on average, when we use the orbital periods, semi-amplitudes, and eccentricities they both give (Table 6).

- 42 Dra. The χ^2_{reduced} we obtained for 42 Dra is our lowest: 0.2. The LDD model perfectly fits the data points. This leads to a θ_{LD} of 2.12 ± 0.02 mas with a Claret coefficient of $u_\lambda = 0.725$. Baines et al. (2010) found a similar LDD to ours for 42 Dra: 2.04 ± 0.04 mas. Given the few studies of this stars, this additional measurement brings a new accurate confirmation of the diameter. Concerning the planet's fundamental parameter, we found a similar $M_{\text{pl}} \sin(i)$ to that calculated by Döllinger et al. (2009) (see Table 6).

Because CLIMB works in the K band, we used the corresponding Claret coefficients to estimate the LDD in this spectral band, resulting in $u_\lambda = 0.321$, $u_\lambda = 0.247$ and $u_\lambda = 0.353$ for 14 And, ν And and 42 Dra, respectively. In each case we used the effective temperature and the $\log(g)$ given in Table 1. Because CLIMB data are not very sensitive to limb darkening, because of the relatively low spatial frequencies and the fact that there is less limb darkening in K band, we used the visible coefficient for the global (VEGA+CLIMB) analysis. Although the χ^2_{reduced} becomes slightly lower when including CLIMB data (Table 4), the final results for the LDD are not changed, as expected because of the lower precision of the CLIMB visibilities and the lower influence on the diameter of the low spatial frequencies. The global results (VEGA+CLIMB) are thus the same as those obtained with VEGA only. The CLIMB data did not bring any improvements for this study.

4. Interferometric observations of θ Cygni with VEGA/CHARA

4.1. θ Cygni

θ Cyg (HD 185395, $d = 18.33 \pm 0.05$ pc, Table 7) is an F4V star with an M-dwarf companion of $0.35 M_\odot$ orbiting at

a projected separation of $2''$ (≈ 46 AU) and with a differential magnitude of 4.6 mag in the H band. Using the data provided by Delfosse et al. (2000), this dM translates into 7.9 mag in the V band (Desort et al. 2009). More recently, Roberts (2011) published adaptative optics (AO) data obtained with the AEOS telescopes in 2002, and reported a differential magnitude in the Bessel I -band of 5.89 ± 0.089 and a separation of $2.54''$. This is compatible with a contrast of ≈ 7 at the V band. Spectroscopic data of θ Cyg collected with ELODIE and SOPHIE at the Observatoire de Haute-Provence (OHP) revealed quasi-periodical radial velocity variations with a period of approximately 150 days. No known stellar variation modes can explain such long-term, high-amplitude RV variations. They were tentatively attributed to the presence of more than two exoplanets, possibly interacting with each other. However, this explanation was not only unsatisfactory because it is dynamically unstable, but also because it did not straightforwardly explain a peak observed in the periodogram of the bisector velocity span at ≈ 150 days. Clearly, the data at hand were not sufficient to fully understand this complex system.

Our interferometric observations in the visible wavelengths have both high spatial and spectral resolution and help us probe the same domain as these spectroscopic results. Furthermore, we obtained measurements very close to the first zero of the visibility function (see Sect. 2.1), which allows accurate angular diameter determination and the possible identification of stellar pulsations. As a Kepler target, photometric observations were obtained in 2010 and solar-like oscillations were detected (Guzik et al. 2011). These observations imply the possible presence of γ Dor gravity modes, which are generally present in early-F spectral type stars. If these oscillations are confirmed, θ Cyg would be the first star to show signs of both solar-like and γ Dor oscillations (Guzik & Mussack 2010, and references therein).

4.2. VEGA observations

We performed nine observations of θ Cyg with VEGA from June 2010 to October 2011. We used the three-telescope capabilities of the instrument (Mourard et al. 2011), using the telescope combinations E1E2W2, W1W2E2 and W1W2E1 triplets of the CHARA array.

Three stars were used as calibrators: HD 177003 (*cal1*), HD 177196 (*cal2*) and HD 203245 (*cal3*), whose parameters are summarized in Table 8.

If the target was observed only once during a night, the observing sequence was *Cal1-Target-Cal1*, each calibrator observation being 20 to 40 blocks of 1000 frames long, depending on the magnitude, that is between about 10 and 20 min, while each target observation was 60 blocks of 1000 frames long, or about 30 min. When the target was observed twice, the observing sequence was either *Cal1-Target-Cal2-Target-Cal2*, or *Cal2-Cal1-Target-Cal1-Cal2-Target-Cal3*. The data were recorded at medium spectral resolution and the data processing was performed on 15 to 30 nm wide channels in the continuum. The calibrated visibilities are presented in Table 9. To take into account the variation of the spatial frequency due to the width of the spectral band (bandwidth smearing effect), we calculated its effect on the visibility. We found it to be totally negligible (variation lower than the error bars of the measurements, Mourard et al. 2009). Moreover, the data processing was performed with the same parameters for one observing sequence and effects such as these will largely calibrate out. For most of these observations, interferometric data in the infrared wavelength (K band)

Table 6. Calculated exoplanets masses of 14 And, ν And and 42 Dra from interferometric data and comparison with previous work.

Planet	P_{orb} [days]	K [m s $^{-1}$]	e	$M_{\text{pl}} \sin(i)$ [M_{Jup}]	
				This work	Previous work
14 And b	185.84 ± 0.23	100.0 ± 1.3	0	5.33 ± 0.57	4.8^a
ν And b	4.62 ± 0.23	70.51 ± 0.45	0.022 ± 0.007	0.62 ± 0.09	0.69 ± 0.04^b
ν And c	241.26 ± 0.64	56.26 ± 0.52	0.260 ± 0.079	1.80 ± 0.26	1.98 ± 0.19^b
ν And d	1276.46 ± 0.57	68.14 ± 0.45	0.299 ± 0.072	3.75 ± 0.54	4.13 ± 0.29^b
ν And e	3848.86 ± 0.74	11.54 ± 0.31	0.0055 ± 0.0004	0.96 ± 0.14	1.06 ± 0.28^b
42 Dra b	479.1 ± 6.2	112.5	0	3.79 ± 0.29	3.88 ± 0.85^c

References. ^(a) Sato et al. (2008); ^(b) Curiel et al. (2011); ^(c) Döllinger et al. (2009).

Table 7. θ Cyg, coordinates and parameters.

Coordinates	
RA (J2000)	19:36:26.5
Dec (J2000)	+ 50° 13' 16''
Stellar parameters	
	Values
Stellar type	F4V
V mag	4.50 ± 0.09
K mag	3.5 ± 0.296
M_V	3.14
$\nu \sin i$ [km s $^{-1}$]	7
T_{eff} [K]	6745^a
Distance [pc]	18.33 ± 0.05
Parallax [mas]	54.54 ± 0.15^f
Radius [R_{\odot}]	1.70 ± 0.03^b
Mass [M_{\odot}]	1.38 ± 0.05^a
Age [Gyr]	$1.5^{+0.6a}_{-0.7}$
$\log g$	4.2^e
[Fe/H]	-0.08^a
$\log L$ [L_{\odot}]	0.63 ± 0.003^d

References. ^(a) Desort et al. (2009); ^(b) Boyajian et al. (2012); ^(c) van Belle et al. (2008); ^(d) Guzik et al. (2011); ^(e) Erspamer & North (2003); ^(f) van Leeuwen (2007).

Table 8. Calibrators used for θ Cyg observations.

#	Name	Spectral type	m_V	m_K	θ_{UD} [mas]
1	HD 177003	B2.5IV	5.37	5.89	0.13 ± 0.01
2	HD 177196	A7V	5.01	4.51	0.43 ± 0.03
3	HD 203245	B6V	5.74	6.10	0.14 ± 0.01

Notes. The value of the equivalent uniform disk θ_{UD} is given at 700 nm.

were also recorded with CLIMB, which was used as a 3T group delay fringe tracker (Sturmann et al. 2010). However, the baselines chosen for VEGA were too small for this object to be resolved in K band and the CLIMB data were not used in the final analysis.

5. Determination of θ Cygni's fundamental parameters

5.1. Determination of the limb-darkened diameter

For almost all observations including the E1E2 baseline, we obtained a χ^2_{reduced} larger than 2. The E2 telescope is known to present instabilities, like vibrations and delay line cart problems. Those points are therefore more dispersed than those at higher spatial frequencies, as shown in Fig. 3 and Table 11, and the value of χ^2_{reduced} is mostly dominated by these points.

Table 9. Journal of the observations of θ Cyg.

RJD	λ_0	$\Delta\lambda$	Seq	Base	PA	V^2
55 849.62	707.5	15	1T3	106	84.6	0.534 ± 0.022
				156	-131.9	0.237 ± 0.015
				249	-134.5	0.028 ± 0.021
55 848.62	707.5	15	1T3	106	83.9	0.502 ± 0.020
				156	-132.6	0.192 ± 0.007
				249	-135.5	0.048 ± 0.014
55 826.67	737.0	14	T1	66	-139.1	0.801 ± 0.038
				156	-132.3	0.229 ± 0.016
				221	-134.3	0.054 ± 0.028
55 826.74	737.0	14	1T	65	-157.3	0.822 ± 0.036
				152	-150.8	0.286 ± 0.014
				216	-152.7	0.017 ± 0.019
55 805.75	737.5	15	1T1	65	-143.9	0.885 ± 0.023
				155	-137.2	0.236 ± 0.011
				220	-147.7	0.039 ± 0.022
55 803.77	737.5	15	3T3	103	75.6	0.549 ± 0.011
				154	-141.3	0.195 ± 0.012
				245	-146.6	0.040 ± 0.018
55 774.73	709.5	15	1T1	106	109.9	0.481 ± 0.015
				153	-107.4	0.130 ± 0.010
				156	-121.3	0.166 ± 0.009
55 722.93	735.0	20	21T12	106	82.1	0.493 ± 0.013
				155	-134.5	0.181 ± 0.008
				150	-161.0	0.169 ± 0.009
55 486.71	670.0	20	1T1	64	-167.3	0.813 ± 0.016
				150	-161.0	0.169 ± 0.009
				214	-162.9	0.027 ± 0.019
55 486.74	670.0	20	1T1	64	179.7	0.928 ± 0.020
				148	-174.0	0.166 ± 0.010
				155 370.92	715.0	30
55 370.92	715.0	30	T2	156	-127.0	0.152 ± 0.013
				222	-129.0	0.012 ± 0.010
				55 370.96	715.0	30
55 370.96	715.0	30	2T2	154	-141.7	0.221 ± 0.019
				219	-143.7	0.039 ± 0.015

Notes. RJD is the reduced Julian day, λ_0 is the central wavelength in nm, $\Delta\lambda$ is the width in nm of the analyzed spectral band. Column 4 (entitled Seq) indicates the observing and calibration strategy, with the target (T) and the associated calibrator (1, 2 or 3). The projected baseline is given by Base (in meter) and PA (in degree). V^2 is the calibrated squared visibility with a total error including statistical and systematic errors. They all represent 3-T measurements.

In a first analysis, we have considered all data points. We used the LitPro software³ (Tallon-Bosc et al. 2008) and obtained a mean UD equivalent diameter of 0.726 ± 0.003 mas. The χ^2_{reduced} of the model fitting is equal to 8.4, which clearly indicates

³ Available at <http://www.jmmc.fr/litpro>

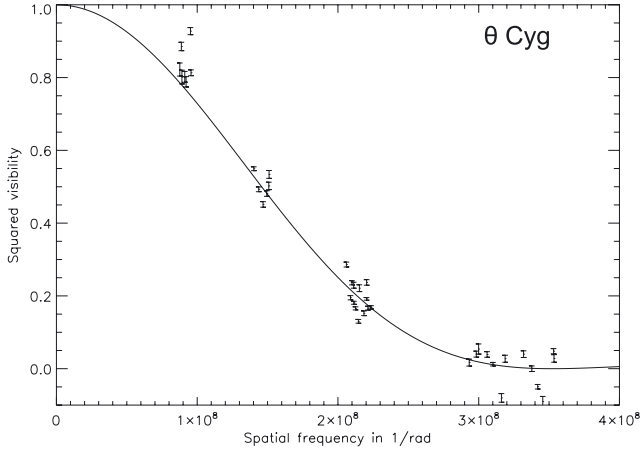


Fig. 3. Squared visibility of θ Cyg as a function of the spatial frequency [1/rad] for all data points recorded in 2010 and 2011 by VEGA (3T configuration). The solid line is the squared visibility function for a linear limb-darkened disk model with a diameter of 0.76 mas and a limb-darkening coefficient of 0.5, obtained with LITpro software.

dispersion in the measurements or possible variations of the diameter from night to night. This will be investigated in Sect. 6. We also tested a linear limb-darkened (LD) disk model with a coefficient u_λ as defined by Hanbury Brown et al. (1974). Unfortunately, the data quality at low-visibility levels is not sufficient for a correct u_λ determination. For a more detailed analysis, we decided to fix the linear LD coefficient in the LitPro software. With $T_{\text{eff}} = 6745$ K and $\log(g) = 4.2$, we used the value of the Claret coefficients (Claret & Bloemen 2011) given for the R , I and J bands, and deduced by extrapolation the value at the observing wavelengths (715 and 670 nm). We found $u_{670 \text{ nm}} = 0.510$ and $u_{715 \text{ nm}} = 0.493$, and finally took the mean value 0.5. The adjustment of the whole data set (see Fig. 3) gives the value $\theta_{\text{LD}} = 0.760 \pm 0.003$ mas, with a reduced χ^2_{reduced} equal to 8.5.

Our final value is consistent with the diameter estimated by van Belle et al. (2008) with spectral energy distribution based on photometric observations: they found $\theta_{\text{LD}} = 0.760 \pm 0.021$ mas. Boyajian et al. (2012) observed this star in 2007 and 2008 with the CHARA CLASSIC beam combiner operating in the K band, and found $\theta_{\text{LD}} = 0.845 \pm 0.015$ mas and $\theta_{\text{LD}} = 0.861 \pm 0.015$ mas, which is much larger than ours. We will return to this point in Sect. 6.

As previously stated, the CLIMB measurements have large scatter and are at much lower spatial frequencies than the VEGA data. They provide a LDD equal to $\theta_{\text{LD}} = 0.654 \pm 0.090$ mas, with a $\chi^2_{\text{reduced}} = 1.86$, obtained with a Claret coefficient of 0.22 corresponding to the K band. When combining the CLIMB and VEGA data, the diameter remains the same, except that the χ^2_{reduced} decreases to 5.3. This is because of the large error bars obtained for CLIMB data at high frequencies, which do not constrain θ Cyg's LDD at all, although they reduce the χ^2_{reduced} . For θ Cyg, the scatter affects all measurements.

5.2. Determination of fundamental parameters

The radius and the mass of θ Cyg were estimated using Eqs. (4) and (5). We took $\pi = 54.54 \pm 0.15$ mas according to van Leeuwen (2007). θ Cyg's radius is then $R = 1.503 \pm 0.007 R_\odot$. The final uncertainty is equally due to errors in the parallax and the angular diameter. This results in a mass of $1.32 \pm 0.14 M_\odot$ and locates θ Cyg between the two lines representing the evolutionary

Table 10. Table summarizing θ Cyg's fundamental parameters calculated with the interferometric data.

Stellar parameters	Value \pm error
LD diameter [mas]	0.760 ± 0.003
Radius [R_\odot]	1.503 ± 0.007
Mass [M_\odot]	1.32 ± 0.14
T_{eff} [K]	6767 ± 87

Table 11. Values of the mean θ_{LD} per night for θ Cyg and the corresponding χ^2_{reduced} .

Epoch	Baselines	θ_{LD}	$\phi \text{ mod } 150$	χ^2_{reduced}
55849.62	W2W1E2	0.700 ± 0.011	0.33	0.700
55848.62	W2W1E2	0.744 ± 0.007	0.32	5.698
55826.67	E2E1W2	0.721 ± 0.009	0.18	1.12
55805.75	E2E1W2	0.727 ± 0.010	0.04	7.749
55803.77	W2W1E2	0.759 ± 0.008	0.03	5.936
55774.73	W2W1E2	0.807 ± 0.010	0.83	13.9
55722.93	W2W1E2	0.793 ± 0.006	0.49	0.664
55486.71	E2E1W2	0.744 ± 0.007	0.91	23.2
55370.92	E2E1W2	0.764 ± 0.010	0.14	2.468

tracks of Fig. 4 in the model of Guzik et al. (2011). Finally, the effective temperature was calculated using Eq. (6) and the luminosities shown in Table 7. The errors were calculated using the Monte Carlo method. This results in $T_{\text{eff}} = 6767 \pm 87$ K, which is also consistent with the value given by Desort et al. (2009). Boyajian et al. (2012) found a lower T_{eff} of 6381 ± 65 K mostly due to a larger limb-darkened diameter (see Table 7). Table 10 summarizes the results based on our interferometric measurements.

6. Discussion

We have seen in the previous section that the scatter of measurements for θ Cyg is larger than for the three other targets. It remains then to understand these variations. Table 11 shows the night-to-night variations in the LDD of θ Cyg. The UD and LD models do not fit these results very well, as indicated by the generally high value of χ^2_{reduced} . Boyajian et al. (2012)'s CLASSIC data obtained between 2007 and 2008 also show some discrepancies in their visibility curve fitted with a UD model. This introduces the possibility of either an additional companion, or stellar variations around θ Cyg. The night-by-night observing strategy we employed so far was not optimized for the investigation of binarity but for the measurement of fundamental parameters. Thus, the UV coverage (Fig. 4), which represents the support of the spatial frequencies measured by the interferometer, does not constrain on the position of an hypothetical companion very well.

6.1. Stellar variations

Because θ Cyg's radial velocity is suspected to have a 150-day period (Desort et al. 2009), we studied a possible correlation between the variation of the diameter and this periodic behavior of the radial velocities. Figure 5 represents the individual angular diameter plotted as a function of a phase (ϕ) corresponding to the reduced Julian day modulo the spectroscopic period of 150 days. This figure highlights a possible variation with an amplitude of $\sim 13\%$ in diameter peak to peak. Solar-like oscillations lead to lower variations in amplitude than that, but Cepheid

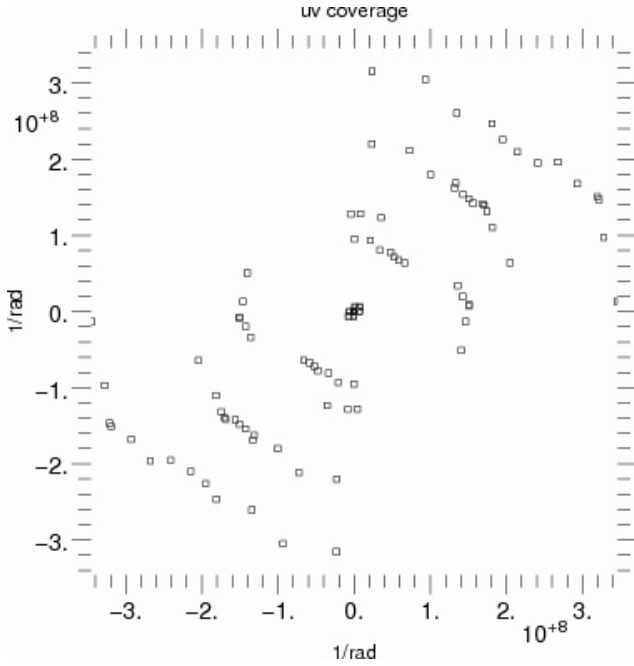


Fig. 4. UV coverage of the baselines used during θ Cyg observations from 2010 to 2011.

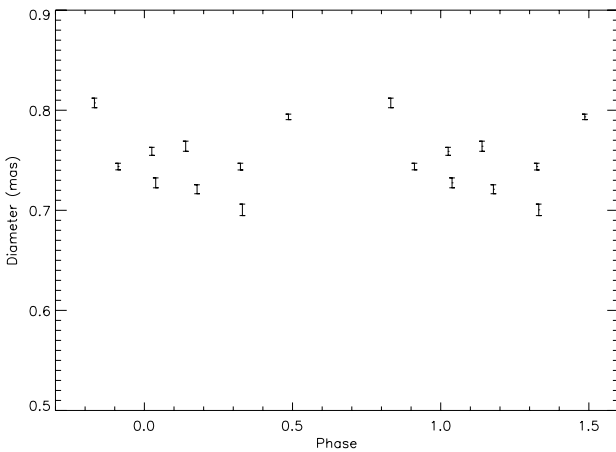


Fig. 5. Individual angular diameter measurements of θ Cyg according to the phase. The phase is proportional to the reduced Julian day $mod-ulo$ 150, as the radial-velocity period is expected to be.

stars show similar-sized pulsations. According to θ Cyg's luminosity, however, it is not bright enough to be classified as a Cepheid. Moreover, a Cepheid's light curve presents much larger amplitude variations than θ Cyg's (Fig. 1 in Guzik et al. 2011). Its luminosity and temperature would instead locate it near the instability branch of the HR diagram, identifying it as a δ Scuti or γ Dor star, which are also A- or F-type stars.

This last possibility is also mentioned by Guzik et al. (2011), who proposed two different models that could show evidence for γ Dor pulsations, but they only allowed $l = 1$ or $l = 2$ unstable g-modes. Their light curve does not reveal the typical γ Dor frequencies around $11 \mu\text{Hz}$, which are specific for these pulsations, though they do mention that these could be overshadowed by the granulation noise. Moreover, γ Dor oscillations have been found in many Kepler sources without much ambiguity because they show obvious evidence for this type of pulsation (Tkachenko et al. 2012). Also, the RV measurements published in Desort et al. (2009) do not reveal high-amplitude

and high-frequency (hours to days) RV variations typical of γ Dor stars or δ Scuti stars.

Finally, we note that if the 150-day period RV variations were due to diameter variations, these diameter variations would be unrealistically large, much larger than those observed, and very significant photometric variations should have been detected by Kepler.

We therefore conclude that stellar variations do not explain the observed features in a satisfactory manner. We therefore consider the possibility of an unseen stellar companion for θ Cyg, and see how the present interferometric data can help to test such a scenario.

6.2. An additional companion?

The known M-type companion to θ Cyg clearly does not affect our visibilities, because of the large separation in position (2 s of arc) and the large difference in magnitude (around 7). Any instrument hosted by the CHARA array and used in the same conditions as we did (e.g., medium resolution for VEGA) has an interferometric field of view much smaller than the telescopes' Airy spot, i.e. ≈ 0.1 s of arc. This means that any object located beyond this field does not interfere, but could create a photometric background that disrupts the visibility of the target if it is located in the entrance field of the instrument. In our case, the dM in the V band gives a very small contribution to this background, much lower than the error bars ($\approx 1\%$). We therefore consider the presence of a second and much closer companion. The lower limit of detection allowed by adaptive optics (AO) is at about the diffraction limit of PUEO on the CFHT, i.e. around 100 mas for low-contrast binaries. Accordingly, a companion whose position is closer in than this limit would not be seen in AO direct imaging. However, given our current accuracies in visibility measurements, it could be detected by interferometric instruments if its flux contribution is higher than 2%. Because θ Cyg is not classified as SB2, such a flux ratio would imply a pole-on bound system or a visual unbound binary.

This last possibility has been considered, but is difficult to confirm. No objects are located close to θ Cyg in the background, except for θ Cyg-B, which could have moved closer to the main star over the years. As said by Desort et al. (2009), the differential magnitude between the two bound stars in the V band is 7.9 mag and 4.6 mag in the H band. Thus, we can expect a dM of ~ 3 mag in the K band, which would make it observable with CLASSIC. A rough estimate of the orbit of θ Cyg-B based on the data published by Desort et al. (2009) shows that at the epoch of the interferometric observations, the separation is still larger than about 2 s of arc, which is well outside our interferometric field of view.

To explore the possibility of an unknown close companion around θ Cyg, we performed several tests on our data set. Because the VEGA visibilities are, at first approximation, dominated by one main resolved source, that is the primary component, we adopted a diameter of the companion of 0.2 mas, corresponding to an unresolved source. The UD diameter of the primary was fixed to $\theta_{UD} = 0.726$ mas, which is the diameter obtained when merging all nights. Then, by assuming a companion's flux in the range 2% to 15%, we obtained the position angle (PA) and angular separation (ρ) corresponding to the minimum $\chi^2_{reduced}$. We performed the same tests with Boyajian et al. (2012)'s CLASSIC data from 2007–2008 (Table 12).

In half of the cases of the VEGA sets, we found a solution with a better $\chi^2_{reduced}$ than with a UD model. Generally, the best solution corresponds to a companion with 15% of flux, and a

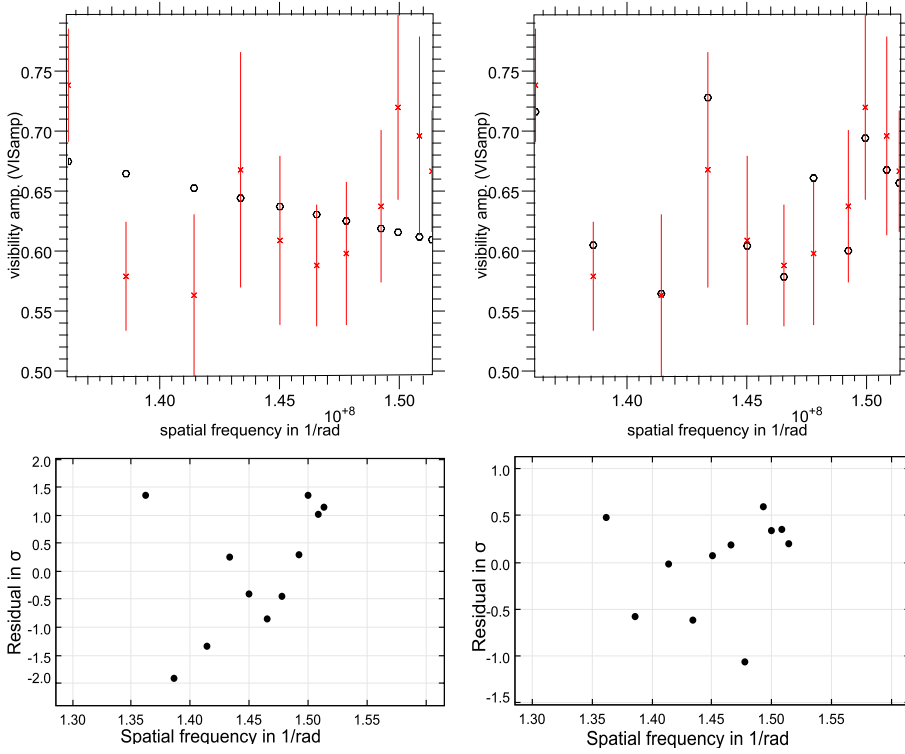


Fig. 6. *Left column:* UD model; *right column:* UD model + companion. *Top row* is for the CLASSIC data visibilities of the RJD 54301 (open circles for the models, crosses for the data), whereas the *bottom row* corresponds to the visibility residuals.

Table 12. Comparison between a UD model and a model with a companion for VEGA and CLASSIC data.

Epoch	UD model		Binary model			
	θ_{UD} [mas]	$\chi^2_{reduced}$	ρ [mas]	PA [$^\circ$]	Flux %	$\chi^2_{reduced}$
VEGA						
55849.62	0.670	0.8	7.1	72.2	15	0.9
55848.62	0.710	5.7	11.1	234.7	15	5.9
55826.67	0.689	1.1	50.5	75.2	15	1.0
55805.75	0.695	7.6	10.3	10.0	15	11.5
55803.77	0.726	5.7	66.7	182.5	15	1.3
55722.93	0.758	0.6	80.8	85.2	3	0.07
55486.71	0.710	22.7	34.4	304.8	15	20.7
55370.92	0.729	2.5	50.5	247.7	10	0.16
CLASSIC						
55794.0	0.762	0.006	72.7	115.3	8	0.02
54672.0	0.852	0.6	55.6	5.0	10	0.20
54406.0	0.928	0.03	86.9	222.6	7	0.01
54301.0	0.827	1.3	56.6	3.0	10	0.28

Notes. For each set of simulation, this table gives the orbital parameters obtained with the minimum $\chi^2_{reduced}$ and the corresponding flux.

ρ included between 17.6 and 26.9 mas. However, in the other VEGA cases, the data do fit the binary model and no better solution is found.

In the CLASSIC data, the $\chi^2_{reduced}$ is reduced by a factor 2 when we include the binarity. The better UV coverage obtained with the E1S1 baseline provides much better constraints on the model in that case. The best solution for the CLASSIC data gives a flux ratio of about 7% and a separation of about 25 mas. An example of the fit improvement for the CLASSIC measurements is presented in Fig. 6. However, this flux ratio does not permit us to tell which type of star the companion could correspond

to, because it is not necessarily bound, but could be either foreground or background.

Finally, we explored the existence of a closure phase signal generated by this close unknown companion (Le Bouquin & Absil 2012). The closure phase is the sum of the phases of the complex visibilities obtained with the three baselines of a triplet. It is independent of the atmosphere, giving direct information of the object's visibility, which results in informations about asymmetries, presence of a companion, etc. We already said that the CLIMB data were at low spatial frequencies due to the longer wavelength of operation. Simulations show that in the baseline configurations used for this paper, the companion will produce a signal lower than 5 or 10 $^\circ$, which is below the current accuracy of CLIMB phase closure measurements. However, the simulation shows that a huge closure phase signal of $\pm 40^\circ$ should be detected by VEGA with the E1E2W2 configuration. Many tests have been performed on the data sets but the signal-to-noise ratio of VEGA phase closure measurements is not sufficient for a correct determination. Unlike from the estimation published in Mourard et al. (2011), we have now a clearer understanding of the noise level in closure phase measurements with VEGA. Closure phase is a third-order moment and the multi-speckle regime of VEGA prevents us from obtaining accurate closure phase measurements for stars fainter than magnitude 1 or 2, depending on seeing conditions (Mourard et al., in prep.).

7. Conclusion

We obtained new and accurate visibility measurements of 14 And, ν And and 42 Dra using visible band interferometric observations. From these we derived accurate values of the LD diameter and of fundamental parameters that are fully consistent with those derived with other techniques and bring some improvements in precision. The error bars and $\chi^2_{reduced}$ for these three stars are in general much smaller than those obtained on our fourth target: θ Cygni. We analyzed the scatter

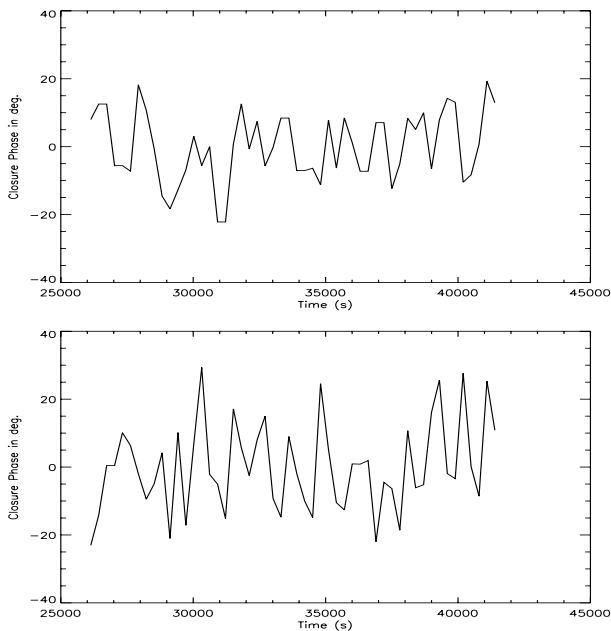


Fig. 7. Closure phase signals expected for θ Cyg with a companion located at 25 mas that contributes to 10% of the flux. *Up*: CLIMB in K band, *bottom*: MIRC in H band. We used the largest triangle of telescopes on CHARA: E1W1S1.

of measurements of θ Cyg, taking into account that instrumental or data processing bias are well understood thanks to the good results obtained on the three other stars. It appears that a solution with an unknown companion close to the star helps in reducing the residuals in the model fitting. The limited accuracy in our determination prevents us from being conclusive about the presence of a new close companion around θ Cyg, and do not allow us to tell which type of star it could be, because it is not necessarily bound. However, this result encourages organizing new observations in the visible and IR wavelengths, focused on confirming or denying this hypothesis. Closure phase signal is a good way to detect and characterize faint companions around bright stars. We performed simulations of expected closure phase signal for θ Cyg with a companion contributing 10% of the flux that is located at 25 mas. As explained before, VEGA is unfortunately not able to measure accurate closure phase signals. CLIMB in K band and MIRC (Monnier et al. 2008) in H band are well-adapted for closure phase tests with the largest CHARA triangle (E1W1S1). Expected signals are presented in Fig. 7. Therefore, a more adequate observing strategy and dedicated observations will be prepared with the combination of the different CHARA beam combiners.

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Appendix A: Individual angular diameter determinations

We present here the different individual LD angular diameter determinations for the various epochs of observation of θ Cygni. The individual LD diameters are given in Table 11.

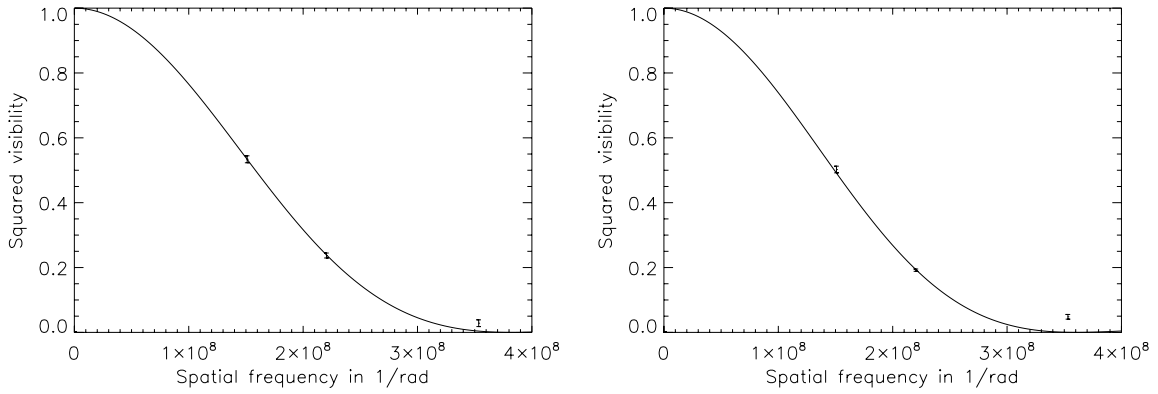


Fig. A.1. Model of squared visibility for the RJD 55 849.62 (left, $\theta_{LD} = 0.700 \pm 0.011$) and 55 848.62 (right, $\theta_{LD} = 0.744 \pm 0.007$) obtained by LITpro.

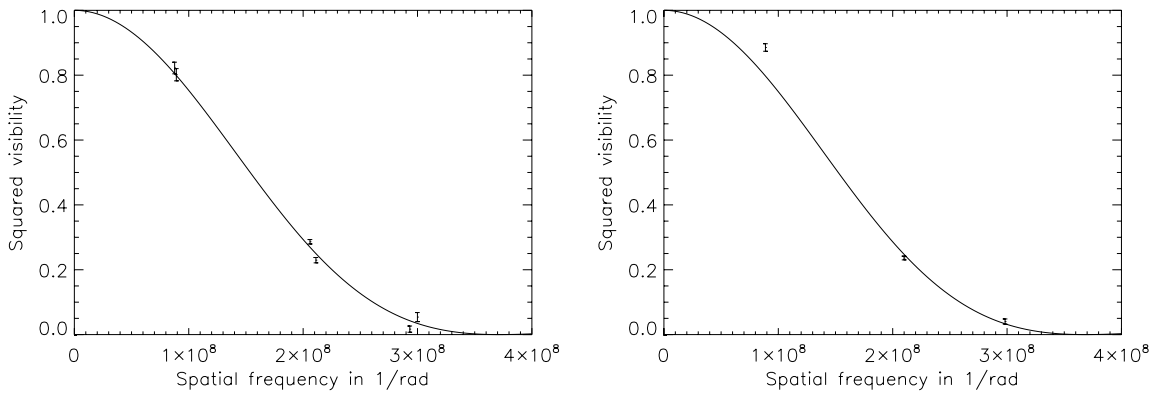


Fig. A.2. Model of squared visibility for the RJD 55 826.67 (left, $\theta_{LD} = 0.721 \pm 0.009$) and 55 805.75 (right, $\theta_{LD} = 0.727 \pm 0.010$) obtained by LITpro.

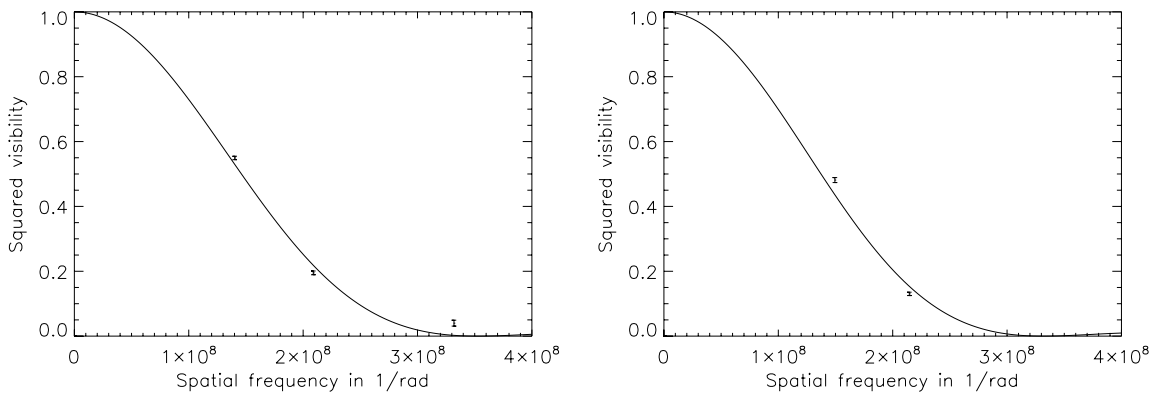


Fig. A.3. Model of squared visibility for the RJD 55 803.77 (left, $\theta_{LD} = 0.759 \pm 0.008$) and 55 774.73 (right, $\theta_{LD} = 0.807 \pm 0.010$) obtained by LITpro.

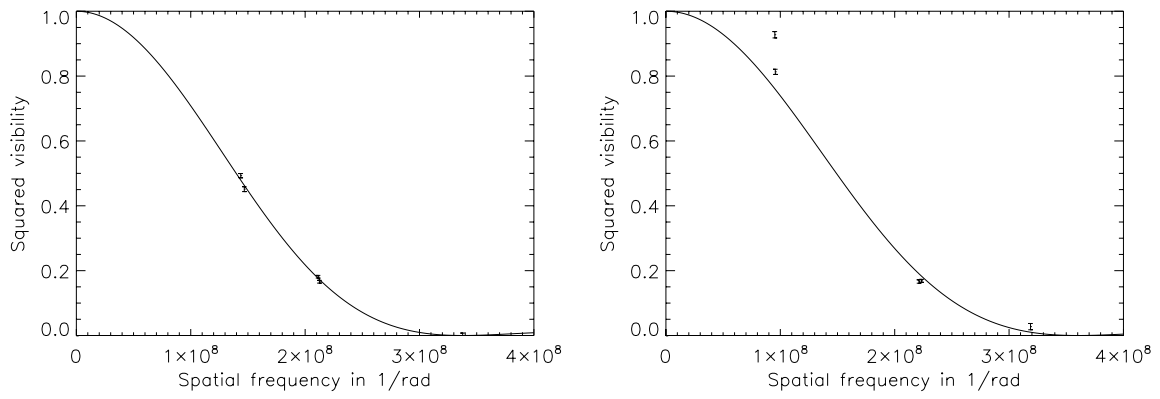


Fig. A.4. Model of squared visibility for the RJD 55 722.93 (left, $\theta_{LD} = 0.793 \pm 0.006$) and 55 486.71 (right, $\theta_{LD} = 0.744 \pm 0.007$) obtained by LITpro.

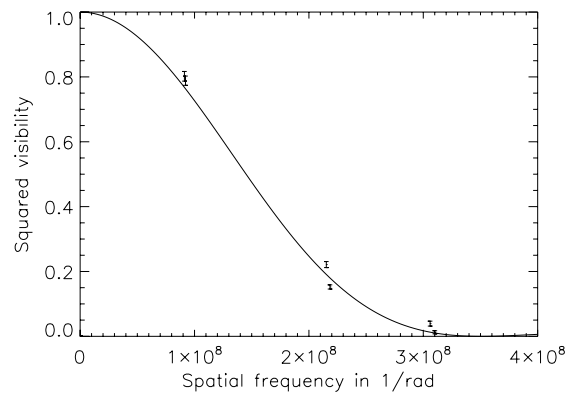


Fig. A.5. Model of squared visibility for the RJD 55 370.92 ($\theta_{LD} = 0.764 \pm 0.010$) obtained by LITpro.