Astron. Astrophys. 317, 789–792 (1997)

ASTRONOMY
AND
ASTROPHYSICS

The mean angular diameter of δ Cephei measured by optical long-baseline interferometry

D. Mourard[1], **D. Bonneau**[1], **L. Koechlin**[2], **A. Labeyrie**[3], **F. Morand**[4], **Ph. Stee**[1], **I. Tallon-Bosc**[5], **and F. Vakili**[1]

[1] Observatoire de la Côte d'Azur, URA CNRS 1361, F-06460 St. Vallier de Thiey, France
[2] Laboratoire Astrophysique de Toulouse, 14 avenue E.Belin, F-31400 Toulouse, France
[3] Collège de France & Observatoire de Haute Provence, F-04870 Saint Michel l'Observatoire, France
[4] Collège de France & Observatoire de la Côte d'Azur, F-06460 St. Vallier de Thiey, France
[5] Centre de Recherche Astronomique de Lyon, UMR CNRS 5574, 9 avenue Charles Andre, F-69561 St Genis Laval Cedex, France

Abstract. Long baseline interferometric observations of δ Cep at the "Grand Interféromètre à deux Télescopes" give the first measurement of its mean angular diameter. Combined with the mean linear radius deduced from spectroscopic data, the mean angular diameter gives an improved distance determination for δ Cep. Size pulsations are marginally detected and the measured amplitude is consistent with the theoretical predictions.

Key words: stars: Cepheids – stars: individual: δ Cep – techniques: interferometric – stars: fundamental parameters

1. Introduction

The star δ Cep has long been known for its periodic fading, at 5.36627 days intervals. The Doppler shift of spectral lines supports the hypothesis of stellar surface motion, but the contracting and expanding stellar disc of Cepheids could not be resolved by existing instruments. The only angular diameter previouly obtained was derived from the lunar occultation of ζ Gem (Ridgway et al. 1982). Among existing interferometers, the "Grand Interféromètre à deux Télescopes" (GI2T) (Mourard et al. 1994a) has a unique combination of high angular resolution (1 mas), large collecting area (2x1.5m) and spectral resolution (0.1nm) allowing multiwavelength interferometric measurements at visible wavelengths. For each baseline setting, the instrument measures the visibility of the interference fringes, thus providing the modulus of a Fourier component describing the object at the corresponding spatial frequency. We compare the observed Fourier parameters with those derived from physical models of the stellar object in order to validate and improve them. The images derived from stellar atmosphere models at different wavelengths and their corresponding Fourier components are checked against and fitted to the spectral and spatial information provided by the data. This technique, routinely used at the GI2T, has already given information on the disc-shaped envelope of Be stars such as γ Cas (Stee et al. 1995) or on a possible jet-like structure in the close binary β Lyrae (Harmanec et al. 1996). The interferometric resolution of a Cepheid, a challenging goal often mentioned by different groups (Davis 1979; Sasselov and Karovska 1994) had been awaited by the GI2T observers. This has become possible, thanks to refinements in the observing and reduction procedures (Mourard et al. 1994b), which allow a precise calibration of the fringe visibility. In the following the term fringe visibility refers to the modulus of the complex visibility.

2. Observation of δ Cep with the GI2T

To derive the angular diameter of δ Cep and detect its variations, we have compared the fringe visibility on δ Cep with the fringe visibility on a reference star observed the same nights with the same baseline. To ensure a good calibration of the atmospheric and instrumental effects, the reference star must be taken as close as possible to the object. The best choice is an unresolved star, which gives the highest intrinsic fringe visibility. However, a star with a reliably known angular diameter can also be used. The choice of the reference star was also constrained by the limiting magnitude of the GI2T: about 4 in the visible at the time of the observations. We have finally adopted α Cep (BS8162 A7V V=2.44) as the reference star for δ Cep (BS8571 F5Ib-G2Ib V=3.48-4.34). The angular diameter adopted for α Cep is the value proposed by Malagnani and Morossi (1990). These authors have derived the angular diameter, the temperature, and the surface gravity (Φ_{ld} = 1.48$\pm$0.08 mas, T_{eff} = 7740 $\pm$ 170 K, $log\ g$ = 3.99) from the fit of the spectrophotometric data in the visible with the spectral energy distribution predicted by stellar atmosphere models. From this limb-darkened angular diameter we deduce the equivalent uniform disc diameter $\Phi_{ud} = 1.43 \pm 0.08$ mas, by the following relation (Hanbury Brown et al. 1974):

$$\frac{\Phi_{ld}}{\Phi_{ud}} = \left[\frac{(1 - \frac{u_\lambda}{3})}{(1 - \frac{u_\lambda}{15})}\right]^{\frac{1}{2}}, \qquad (1)$$

where u_λ is the limb-darkening coefficient. We have adopted u_{650}=0.43 for α Cep, following the atmosphere models by Kurucz et al. (1969). For an equivalent uniform disc of diameter Φ_{ud}, a projected baselength Bp and a wavelength λ, the visibility is:

$$V = \frac{2|J_1(z)|}{z} \qquad with\ \ z = 15.23\frac{B_p(m).\Phi_{ud}(mas)}{\lambda(nm)}. \qquad (2)$$

To calibrate the GI2T interferometric data and avoid any instrumental bias variable with the hour angle, the object and the reference star are observed near transit without moving the telescopes on the baseline. The large difference in declination between α and δ Cep as well as the limited stroke and speed of the optical delay line currently limit the ground baseline to B_g=29.0 m. for maximal observing time on both stars. At the time of transit, the baseline projected onto the sky was B_p=28.1 m for δ Cep and B_p=27.5 m for α Cep. The expected visibility is 0.90 for α Cep. The angular diameter of δ Cep is expected to be in the range of 1.4 to 1.6 mas, according to the Surface-Brightness - Colour (F_V-(V-R)) relation proposed by Barnes et al. (1977). The visibility for δ Cep should vary thus between 0.87 and 0.90.

Adverse weather did not allow observing on a large number of consecutive nights, but the phase coverage appears sufficient to undertake a first analysis of the interferometric data. The phases (maximum brightness) are deduced from an ephemeris given by Szabados (1980) using P=5.366270 and T_0=2442756.49.

3. Data reduction and visibility calibration

Pending more extensive data, special attention has been paid to the calibrations and the errors of estimation. The spectral bandpass selected for this work is in the continuum, from 669 to 675 nm, near the HeI line. The 30 minutes of observation on each star are divided in sequences of 3 minutes. We first remove the "bad" images, i.e. 1 or 2% of the exposures containing fewer than half the average number of photons per frame, owing to guiding errors. For each sequence, the visibility is derived from the Fourier transform of the sum of the autocorrelations of the 20 ms frames. These short exposures recorded by the CP40 camera (Blazit 1986) contain on average 80 photons for δ Cep and 120 for α Cep. The reference star is observed with a neutral density of 0.3 in order to obtain approximately the same photon statistics. The individual visibility measurements thus obtained are corrected for the effects of differential field rotation, differences in the optical trains transmission, and average guiding errors. The last two quantities are measured on-line from the ICCD guide camera during the data acquisition. The uncertainty on each visibility measurement is calculated following Eq. 11 of Mourard et al. (1994b), but with a new expression for the signal to noise ratio ($S/N = \frac{E_{hf}}{\sigma(B)}$ where E_{hf} is the high-frequency energy and $\sigma(B)$ is the standard deviation of the noise in the frequency plane).

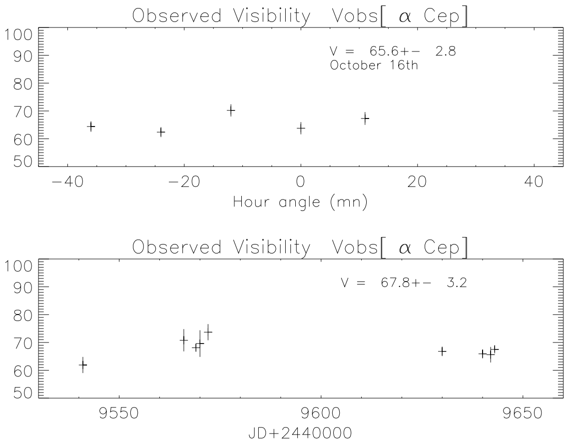

Fig. 1. *top*: Short-sequence visibility measurements for α Cep on one night. The error bars represent estimates of the noise levels or measurement uncertainties, *bottom*: Nightly-averaged visibilities for α Cep during the summer 1994. The error bars indicate the standard deviation of the set of the short-sequence visibilities for each night.

From the set of individual visibility measurements, we calculate a nightly average and a standard deviation for each star. This method takes into account the photon noise as well as the residual bias. It gives a good estimate for the global error on the visibility. Our visibility estimator is not completely insensitive to the seeing conditions. The raw visibility measurements on the reference star α Cep for a three months observing period have a 5% rms fluctuation. The variable lifetime of the atmospheric disturbances ($t_0 \approx 10ms$) and the fixed exposure time of the detector (20 ms) may account for the variations, as large changes in the atmospheric turbulence may cause fluctuations in the interferometer response. However, Fig. 1 indicates that the stability of the interferometer response is adequate if we switch from the target star to the reference star every 30 minutes.

Using the ratio of the observed and theoretical visibilities for α Cep as the system visibility (i.e., the interferometer response to a point source) for the night, we derive the calibrated visibility $V_{cal}(\delta)$ of δ Cep:

$$V_{cal}(\delta) = \frac{V_{th}(\alpha)}{V_{obs}(\alpha)} V_{obs}(\delta) \qquad (3)$$

4. Analysis and discussion

Being given the short baseline used for these observations, the variation of the visibility for δ Cep as a function of the pulsating phase is not expected to exceed the uncertainty of visibility measurements and has been neglected in a first analysis. Then, from the mean calibrated visibility obtained from Table 1, $< V_{cal}(\delta) >$=88.1±2.5, we can derive the mean value for the equivalent uniform disc angular diameter Φ_{ud} =

Table 1. Journal of observations and visibility measurements. First column is the Julian date, second one gives the corresponding phase of δ Cep. Columns 3 and 4 give the nightly averaged visibility of α and δ Cep and column 5 gives the calibrated visibility of δ Cep.

JD	Phase	$V_{obs}(\alpha)$	$V_{obs}(\delta)$	$V_{cal}(\delta)$
2449541.6	0.405	61.9±2.9	59.5±2.2	86.2±7.2
2449566.6	0.050	70.8±4.0	72.2±1.2	91.5±6.7
2449569.5	0.608	68.1±1.3	66.7±3.8	87.9±6.7
2449570.5	0.794	69.6±4.8	71.5±3.4	92.1±10.7
2449571.5	0.980	66.8±1.7	65.3±2.7	87.7±5.9
2449572.5	0.166	73.7±2.9	73.5±4.4	89.5±8.9
2449640.3	0.803	65.9±1.6	63.1±3.4	85.9±6.7
2449642.3	0.174	65.6±2.8	66.4±1.9	90.8±6.5
2449643.3	0.360	67.5±1.0	61.3±4.4	81.5±7.1

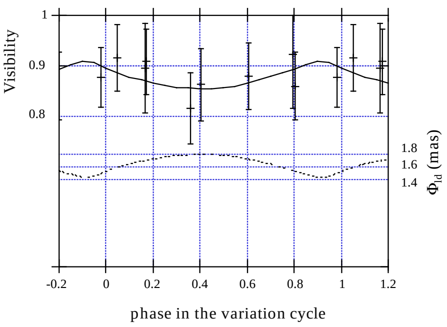

Fig. 2. Diameter variations for δ Cep (dotted line) fitted to long baseline interferometry observations in a 6 nm bandpass around λ 672nm. The corresponding visibility curve (solid line) is superposed on the measures. The mean diameter is 1.60mas and the amplitude of the diameter variation is 0.36mas. The shape of the diameter variation curve (dotted line) is from figure 16 in Breitfellner and Gillet (1993).

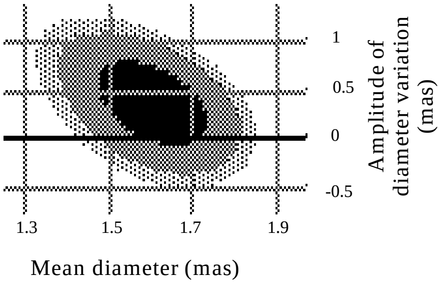

Fig. 3. 2-D error domain for the measured mean diameter and diameter variation of δ Cep. The black, dark and light grey zones respectively correspond to a 68%, 96%, 99% probability of the extracted parameters to be within the enclosed area.

1.56 ± 0.18 mas. Adopting a mean limb-darkening coefficient u_{670}=0.54 taken from Kurucz et al. (1969) for T=6000K and log g=2, we obtain a mean limb-darkened angular diameter Φ_{ld} = 1.63 ± 0.19 mas.

However from the data (Table 1) the scattering of the visibility measurements appears slightly larger for δ Cep than for α Cep. This result encourages us to take into account the effect of the diameter variation of δ Cep in the final data reduction procedure. The shape of the variation of the photospheric radius as a function of the pulsating phase is taken from high resolution spectroscopy (Breitfellner and Gillet 1993). Assuming a mean angular diameter and an amplitude for this curve of variation, we compute the angular diameter as a function of the pulsating phase. We have processed the data globally with an optimization algorithm. This algorithm finds the best fit in a two-dimensional space by adjusting the above parameters searching for a minimum of the corresponding rms error. The effect of the limb darkening variation along the pulsating cycle has been checked and found negligible when compared to the residual errors. A constant limb darkening coefficient u_{670} = 0.54 has been applied throughout the cycle.

The best fit shown in Fig. 2, gives a mean limb-darkened angular diameter Φ_{ld} = 1.60 ± 0.12 mas and the amplitude of variation $\Delta\Phi_{ld}$ = 0.36 ± 0.36 mas. The probability density for these two parameters has been computed in a two-dimensional space assuming a Gaussian distribution for the error on the visibilities The black, dark gray and light gray shaded areas respectively correspond to a 68%, 96% and 99% probability of the diameter and diameter variation to be within the defined bounds. (Fig. 3). One can see that the averaged visibilities and the more refined data processing yield very close results for the mean diameter. This confirms the good coverage of the phase cycle by the observations. The value of the amplitude of variation is only marginally significant at the 1σ level but is not in contradiction with the predicted values of the amplitude of about 11% to 13% of the photospheric radius pulsations (Breitfellner and Gillet 1993).

The value of the mean angular diameter Φ_{ld} = 1.60 ± 0.12 mas derived from interferometric measurements may be compared with predicted values of the mean angular diameter based on the Surface-Brightness technique. T. G. Barnes et al. (1977) find 1.48 ± 0.07 mas from the photometric $(F_v, V-R)$ calibration then D. S. Evans gives 1.44 mas (1995) and using the photometric $(F_v, V-K)$ calibration (Di Benedetto 1993) and adopting the mean photometric parameters from Fernley et al. (1989) we obtain 1.41 ± 0.05 mas. The interferometric determination of the diameter appears $\sim$ 0.12-0.20 mas larger than the predicted diameters. It is interesting to note that an excess of the same order between observed and computed diameters of ζ Gem was mentioned (Ridgway et al. 1982) but it would be necessary to reduce at least by a factor 2 the error on the measured angular diameter before discussing the possible origin of this discrepancy.

5. Distance determination

A semi-empirical determination of the distance to δ Cep may be obtained by combining the observed mean angular diameter with the mean linear radius previously provided by spectroscopic observations. Applying an improved version of the Baade-Wesselink method, Turner (1988) found a mean linear radius of δ Cep equal to $42.7 \pm 1.0\ R_{\odot}$. With the assumption that there is no significant difference between the photospheric radius determined from BV photometric data and the stellar disk observed with the GI2T at $\lambda 672 \pm 3$ nm, we deduce the distance $d = 240 \pm 24$ pc, which leads to a parallax $\pi = 4.2 \pm 0.4$ mas and a distance modulus of $m - M = 7.19 \pm 0.22$ for δ Cep. This value is in good agreement with the trigonometric parallaxes adopted in the Hipparcos Input Catalogue (Turon et al. 1992): $\pi = 5.0 \pm 3.0$ mas, and the more recent statistical parallax estimated to 2.80 ± 0.96 mas (Gatewood et al. 1993). The formal accuracy of our measurements is of the order of 10%, comparable to or slightly better than the 15-20% accuracy achieved for this star with the Hipparcos satellite (Froeschle et al. 1994). However, the actual accuracy is limited to $\sim 17\%$ by the uncertainty on the linear radius estimate due to the assumptions made for this radius calculation are based as is apparent from the published values ranging from 37 to 45 $R_\odot$ (Turner 1988).

This first semi-empirical distance for δ Cep may be also compared with other indirect estimations combining radial velocity data with photometric determination of the angular diameter. Using the infrared flux method and published radial velocity curves, Fernley et al. (1989) give for δ Cep a linear radius $36.3 \pm 3.6 R_\odot$ and a distance of 246 ± 14 pc. More recently, an improved version of the surface brightness technique (Gieren, BarnesIII and Moffett 1993) gives for δ Cep the distance $d = 290 \pm 17$ pc. Inside the error bars, all these values are consistent with our distance estimate. Clearly, improved determinations of the distance of δ Cep will result from more accurate measurements of the angular diameter but also from an improved model of the pulsating stellar atmosphere.

6. Conclusion

The brightest Cepheid star δ Cep has been resolved for the first time with the GI2T long-baseline interferometer. The mean angular diameter deduced from the observations, combined with the linear radius given by Turner (1988), provides a direct distance determination for this star, which for the moment is the most accurate available. The attempt made to measure a variation of the angular diameter during the pulsating cycle gives a marginally significant value which is not inconsistent with the theoretical predictions but it is not yet accurate enough to confirm them. This result has to be confirmed with a more extensive data set together with the use of a refined pulsating model. The new beam-combiner of the GI2T interferometer (Mourard et al. 1994c) will be equipped with two different automatic fringe tracker devices (Koechlin et al. 1996, Gay and Rabbia et al. 1994), allowing observations of fainter stars and lower visibilities. Thus GI2T is expected to provide more accurate results required for the success of the Cepheids observing program.

Acknowledgements. GI2T is supported by the french "Programme National Haute Résolution Angulaire en Astrophysique" from CNRS/INSU.

References

Barnes T.G., Dominy J.F., D.S. Evans, P.W. Kelton, S.B. Parsons, R.J. Stover, 1977, MNRAS, 178, 661

Blazit A., 1986, Proc. Soc. Photo-Opt. Instrum. Eng. p. 259

Breitfellner M.G., Gillet, D., 1993, A&A, 277, 524

Davis J., 1979, Proc. IAU Coll. 50, Eds Davis and Tango, Sydney, 1-27

Di Benedetto G.P., 1993, A&A, 270, 315

Evans D.S., 1995, The Observatory, 115, 205

Fernley J.A., Skillen, I. and Jameson, R.F., 1989, MNRAS, 237, 947

Froeschle M., Kovalevsky J., Mignard F. et al., 1994, "Journees des systemes de reference spatio-temporels", Ed. N. Capitaine

Gatewood G., De Jonge J.K., Stephenson, B., 1993, PASP, 105, 1101

J. Gay, Y. Rabbia et al., L.A.M.P.: a concept for the ESO-VLTI fringe sensor, Proceedings SPIE Conf., Aplitude and intensity spatial interferometry II, Hawaii USA, Ed. Brekinridge, 1994, 2200, 204

W.P. Gieren, T.G. BarnesIII, T.J. Moffett, 1993, Ap. J., 418, 135

Hanbury Brown R., Davis J., Lake R., Thompson R.J., 1974, MNRAS, 167, 475

Harmanec P., Morand F., Bonneau D. et al., 1996, A&A, 312, 879

Koechlin, L., Lawson, P., Mourard, D., et al., 1996, Applied Optics, 35, 3002–3009

Kurucz R., Carbon D.F., Gingerich O., 1969, "Theory and observation of normal stellar atmospheres", ed. O. Gingerich, MIT press, Cambridge

Malagnini M.L., Morossi, C., 1990, A&AS., 85, 1015

Mourard D., Tallon-Bosc I., Blazit A. et al., 1994a, A&A 283, 705

Mourard D., Tallon-Bosc I., Rigal F. et al., 1994b, A&A 288, 675

D. Mourard, A. Blazit, D. Bonneau et al., REGAIN: a new optical beam combiner for the GI2T, Proceedings SPIE Conf, Amplitude and intensity spatial interferometry II, Hawaii USA, Ed. Breckinridge, 1994c, 2200, 593

Ridgway S.T., Jacoby G.H., Joyce R.R., Siegel J.M., Wells D.C., 1982, AJ., 87, 4, 680

Sasselov D.D. and Karovska, M., 1994, ApJ, 432, 367

Stee Ph., Araujo F., Vakili, F. et al., 1995, A&A, 300, 219

Szabados L., 1980, Mitteillungen der Sternwarte des Ungarischen Akademie der Wissenschaften, Budapest, 76,32

Turner D.G., 1988, AJ., 96, 5, 1565

Turon C. et al., 1992, ESA SP 1136

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.