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VINCI/VLTI interferometric observations of Cepheids

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Abstract. We report the angular diameter measurements of seven classical Cepheids, X Sgr, η Aql, W Sgr, ζ Gem, β Dor, Y Oph, and ℓ Car, that we have obtained with the VLT Interferometer Commissioning Instrument, installed at ESO's VLT Interferometer. For four of these stars, η Aql, W Sgr, β Dor, and ℓ Car, we detect the pulsational variation of their angular diameter. This enables us to compute directly their distances using a modified version of the Baade-Wesselink method. For X Sgr, ζ Gem, and Y Oph, we apply a hybrid method that makes use of published estimates of their linear diameters to derive their distances.

1. Introduction

For almost a century, Cepheids have occupied a central role in distance determinations thanks to the existence of the Period–Luminosity (P–L) relation, $M = a \log P + b$. These stars became even more important since the Hubble Space Telescope (HST) Key Project on the extragalactic distance scale (Freedman et al. 2001) has totally relied on Cepheids for the calibration of distance indicators allowing to reach cosmologically significant distances.

There are various ways to calibrate the P–L relation. The way chosen by the HST Key Project was to *assume* a distance to the LMC, thereby adopting a zero point of the distance scale. Freedman et al. (2001) present an extensive discussion of all available LMC distances, and note that the LMC distance is currently the weak link in the extragalactic distance scale. Another possibility is to determine the zero point of the P–L relation with Galactic Cepheids using, for instance, parallax measurements, Cepheids in clusters, or through the Baade-Wesselink (BW) method.

2. Observations and data processing

The interferometric observations employed in this study were obtained with VINCI (VLT INterferometer Commissioning Instrument) at Paranal observatory. Three VLT Interferometer (VLTI) baselines were used for this program: E0-G1, B3-M0 and UT1-UT3 respectively 66, 140 and 102.5 m in ground length. All stars, except ζ Gem, were observed with siderostats (E0-G1 and/or B3-M0), ζ Gem and β Dor were observed with Unit Telescopes. We also used reprocessed archive data obtained with the FLUOR/IOTA interferometer on ζ Gem, in order to improve the phase coverage of our observations. We observed in K band ($\lambda = 2.0 - 2.4\,\mu$m).

The periods of the stars cover a wide range, from 7 to 36 days: X Sgr (7 d), η Aql (7.2 d), W Sgr (7.6 d), β Dor (9.8 d), ζ Gem (10.2 d), Y Oph (17.1 d) and ℓ Car (35.6 d). This coverage is important to properly constrain the P–R (Period–Radius) and P–L relations.

The goal here is to determine the angular diameters of the Cepheids as a function of the pulsation phase. So, we use a model of the stellar disk limb darkening (LD) to deduce the photospheric angular size of the star ($\theta_{\rm LD}$) from the calibrated visibility values (V^2). The intensity profiles that we chose were computed by Claret (Claret 2000) and limb darkening is supposed to be constant with pulsation phase. Concerning interferometric data processing, we used a modified version of the standard VINCI data reduction pipeline (Kervella et al. 2003) and the calibration of the Cepheid visibilities was achieved using well-known calibrator stars that have been selected in the Cohen et al. (1999) catalogue. The *bandwidth smearing* effect is also taken into account in our visibility model (for more details, see Kervella et al. 2003).

The $V^2(\theta_{\rm LD}, B)$ model obtained in this way is adjusted numerically to the observed (B, V^2) data using a classical χ^2 minimization process to derive $\theta_{\rm LD}$. A single angular diameter is derived per observation session, the fit being done directly on the set of V^2 values obtained during the session.

Finally, each observation session was generally executed in less than three hours, a reasonably short time compared to the pulsation periods of the Cepheids of our sample. Therefore, we do not expect any phase smearing.

3. Angular diameter model fitting and distance measurement

From our angular diameter measurements, we derive both the average linear diameter and the distance applying a classical χ^2 minimization algorithm between our angular diameter measurements and a pulsating model. The minimized

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quantity with respect to the chosen model is

$$\chi^2 = \sum_i \frac{(\theta_{\rm LD\,observ}(\phi_i) - \theta_{\rm LD\,model}(\phi_i))^2}{\sigma_{\rm observ}(\phi_i)^2} \quad (1)$$

where ϕ_i is the phase of measurement i. The expression of $\theta_{\rm LD\,model}(\phi_i)$ is defined using the following parameters: the average limb-darkened angular diameter $\overline{\theta_{\rm LD}}$ (in mas); the linear diameter variation $\Delta D(\phi_i)$ (in $D_\odot$); and the distance d to the star (in pc). The resulting expression is therefore:

$$\theta_{\rm LD\,model}(\phi_i) = \overline{\theta_{\rm LD}} + 9.305 \left(\frac{\Delta D(\phi_i)}{d}\right) [\rm mas] \quad (2)$$

$\Delta D(\phi_i)$ is known from the integration of the radial velocity curve obtained by CORAVEL and we used a constant projection factor $p = 1.36$ in order to transform the radial velocities into pulsation velocities. The only parameters are the average LD angular diameter $\overline{\theta_{\rm LD}}$ and the distance d.

Three methods can be used to derive the distance, d, depending on the level of completeness and precision of the angular diameter measurements:

- **Constant diameter fit (order 0):** The average diameter $\overline{D}$ of the star is supposed known *a priori* from previously published P–R relations (Gieren, Fouqué & Gómez 1998). We assume here that $\Delta D(\phi) = 0$. The only remaining variable to fit is the distance d through the relation $\theta_{\rm LD\,model}(\phi_i) = \frac{\overline{D}}{d}$.

- **Variable diameter (order 1):** We still consider that the average diameter $\overline{D}$ of the star is known *a priori*, but we include in our model the radius variation derived from the integration of the radial velocity curve. The distance d is the only free parameter for the fit.

- **Complete fit (order 2):** The average LD angular diameter $\overline{\theta_{\rm LD}}$ and the distance d are both considered as variables and adjusted simultaneously to the angular diameter measurements. In the fitting process, the radius curve is matched to the observed pulsation amplitude. Apart from direct trigonometric parallax, this implementation of the BW method is the most direct way of measuring the distance and the linear diameter of a Cepheid. It requires a high precision angular diameter curve and a good phase coverage. It can be applied directly to our η Aql, W Sgr, β Dor and ℓ Car measurements (see Fig. 1).

Table 1 lists the final results of our best fit models. For each star, the highest order numerically stable fitting method was preferred.

4. Conclusion

Our best result is the distance determination of ℓ Car with a relative precision better than 5%, thanks to VINCI/VLTI observations. This value derived from "order 2" method is virtually independent of any model. We only use

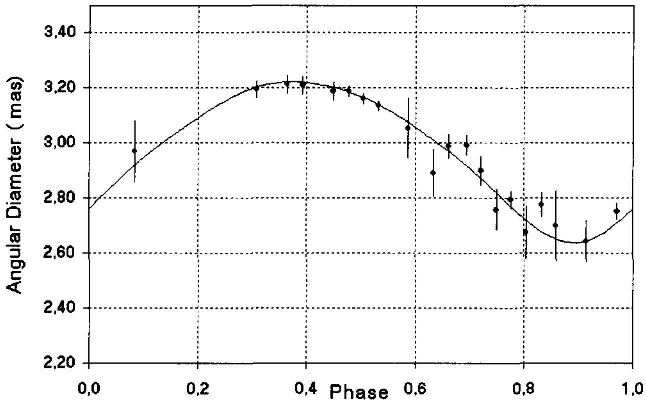

Figure 1. VINCI ℓ Car angular diameters as a function of pulsation phase. The curve corresponds to "order 2" model fit.

Table 1. Summary of the best fit LD angular diameters and distances of the seven Cepheids observed with VINCI.

Star	Order	$\overline{\theta_{\rm LD}}$ (mas)	d (pc)
X Sgr	0	1.471 ± 0.033	324 ± 18
η Aql	2	1.839 ± 0.028	276^{+55}_{-38}
W Sgr	2	1.312 ± 0.029	379^{+216}_{-130}
β Dor	2	1.891 ± 0.024	345^{+175}_{-80}
ζ Gem	0	1.747 ± 0.061	360 ± 25
Y Oph	1	1.438 ± 0.051	648 ± 52
ℓ Car	2	2.988 ± 0.012	603^{+24}_{-19}

a limb-darkened disk and a constant projection factor. Furthermore, distance determinations for all stars are in good agreement with previously published values. In this way, interferometry is a new independent and confident way for the determination of galactic Cepheid distances and *a fortiori* for the calibration of the P–L relation. Improvements in the method are foreseen, such as extending our sample of stars or more accurate determination of the projection factor. This paper summarizes the results of our paper Kervella et al. (2003).

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Discussion

Chadid: Did you try to use the new techniques from VLTi about the combination between the spectroscopy and interferometry to resolve some hydrodynamical problems in the atmosphere of the Classical Cepheids such as shock wave velocity, turbulence, Schwarzschild mechanism...?

Nardetto: Yes, we have several programmes on AMBER on these topics.

Chadid: It's very nice to hear that we can finally to see directly the variation of the Classical Cepheid's diameter with pulsation phases.

Dambis: What is the zero point of the Cepheid PL relation and hence the LMC distance modulus?

Nardetto: This paper is in preparation and it will be submitted soon, so I don't have final results at the moment.

Ireland: Comment: I was very impressed with your ℓ Car diameter measurements. I'd like to point out that in order to characterise phase-dependent limb-darkening the wavelength range of AMBER is not really wide enough at this stage. We will have measurements of ℓ Car at wavelengths as short as 580 nm within the next year that should help. CHARA is also bringing a visible instrument on line that will help with northern Cepheids.

Nardetto: I agree with you that it will be very powerful to couple visible and IR observations of the same Cepheid. We plan to do it with GI2T and AMBER and it will be very good if we can collaborate on CHARA observations. But our program with AMBER is slightly different. In a Cepheid, as the effective temperature varies with the phase (as well as the surface gravity), the limb-darkening is supposed to do the same. But in our determination of angular diameters with VINCI we have considered a limb-darkening which is constant with the phase. It was possible because this effect was under the precision on our visibility points. But as interferometric measurements are getting more and more accurate this effect will have to be taken into account in a near future. That's why we have proposed a program with AMBER to measure the limb-darkening of ℓ Car versus the phase in the spectral band where we are measuring the distance. And for this, you don't need specially a wide wavelength coverage.