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Prospects for direct distance determination of LMC Cepheids by differential interferometry

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Abstract. We investigate the feasibility of extending the application of the *Interferometric Baade Wesselink* method from galactic cepheids to LMC cepheids. After a rapid description of this technique, we will discuss the nice and recent results obtained on the VLTI on seven galactic cepheids. Then, on the basis of a selected sample of LMC cepheids, we estimate the typical range of their angular diameters and estimate the possibility of using differential interferometry measurements.

Key words. Interferometry, Cepheids, LMC

1. Scientific rationale

The Period-Luminosity (P-L) relationship of Cepheids is a fundamental link between interstellar and intergalactic distances. Galactic Cepheids have already been measured by different interferometers such as GI2T, PTI, NPOI, VLTI and CHARA. The basic principle of the Interferometric Baade Wesselink method is to compare the linear and angular size variation of a pulsating star, in order to derive its distance through a simple division. This method is a well-established way to determine the luminosity and radius of a pulsating star. On one hand, the linear size variation can be obtained relatively easily by high resolution spectroscopy, through the integration of the radial velocity curve obtained by monitoring the Doppler shift of the spectral lines present in the spectrum. On the other hand, the angular size is more difficult to estimate. Until recently, the only method to estimate the angular size was through the surface brightness of the star, but it is now possible to measure it directly by interferometry.

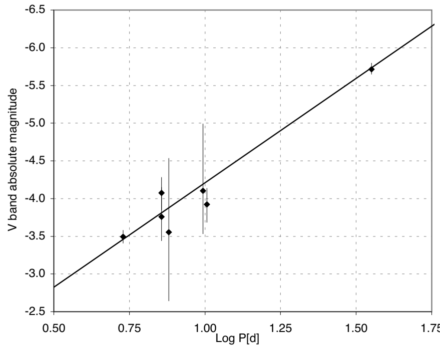

Fig. 1. Period-Luminosity diagram in the V band deduced from seven galactic cepheids measured by the VLTI/VINCI Kervella et al. (2004a,b).

A recent work Kervella et al. (2004b) shows first attempts to the absolute calibration of the 0 point of the P-L relationship (see

Fig. 1). Direct access to Cepheids in the LMC will allow a direct calibration of secondary distance indicators, which are the most useful for the distance scales in the Universe.

2. Main characteristics of LMC Cepheids

We have used a sample of LMC Cepheids extracted from a recent work done by Persson and collaborators Persson et al. (2004). This sample gives access to J, H and K magnitudes of about 90 cepheids with periods ranging from 3 to 48 days. In order to estimate angular diameter for each star of this sample, we have used empirical relations based on the (J,J-K) parameters. These empirical calculations have been derived initially to find calibration stars for optical long baseline interferometry Bonneau et al. (2005); Delfosse et al. (2005). They are based on a polynomial adjustment of a compilation of measured angular diameters (interferometric measurements, lunar occultation and eclipsing binaries) and on $BVRIJHK$ photometry for a large sample of stars of spectral type O to M and for all the luminosity classes.

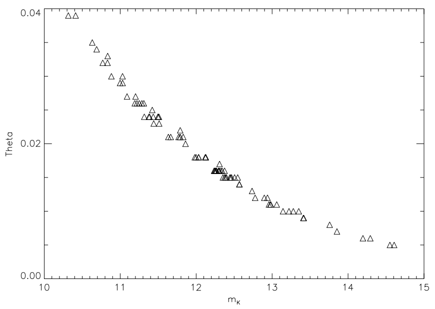

Fig. 2. Angular diameters (in mas) of our LMC cepheids sample as a function of the K magnitude.

The results for the LMC cepheids sample are presented in Fig. 2. Half of the sample have a K magnitude between 10 and 12 and an angular diameter between 20 and 40μas.

3. Observing strategy and estimation of performances

These very small angular diameters are very far of being resolved by a 200 meters baseline in the near infrared. However, such small diameters could be measured by the Differential Interferometry technique Petrov et al. (1986).

A classical stellar interferometer gives a measure of the complex degree of mutual coherence of the collected wavefronts, which is directly related to the complex fourier transform of the brightness spatial distribution $O(x, y, \lambda)$ of the source (Van Cittert and Zernike theorem). An interferometer with spectral capabilities is usually able to measure differential spectral quantities. The differential phase of such an interferometer could be written as:

$$\psi(\lambda_1, \lambda_2) = Arg(\tilde{I}(\lambda_1).\tilde{I}^*(\lambda_2)) \qquad (1)$$

where $I(\lambda)$ is the interferogram at the wavelength λ. By using, the Van-Cittert and Zernike theorem, it comes:

$$\psi(\lambda_1, \lambda_2) = Arg(\tilde{O}(\frac{\overrightarrow{B}}{\lambda_1})) - Arg(\tilde{O}(\frac{\overrightarrow{B}}{\lambda_2})) \qquad (2)$$

This quantity contains information on the spectrum $S(\lambda)$ as well as on the photocenter displacement $\overrightarrow{\varepsilon(\lambda)}$. The spectrum could be defined as the moment of order 0 of the brightness distribution, whereas the photocenter displacement is a measure of the moments of order 1 of the brightness distribution. The following definitions could be written:

$$S(\lambda) = \int\int O(x, y, \lambda)dxdy \qquad (3)$$

$$\varepsilon_x(\lambda) = \frac{\int\int xO(x, y, \lambda)dxdy}{\int\int O(x, y, \lambda)dxdy} \qquad (4)$$

$$\varepsilon_y(\lambda) = \frac{\int\int yO(x, y, \lambda)dxdy}{\int\int O(x, y, \lambda)dxdy} \qquad (5)$$

The photocenter displacement $\overrightarrow{\varepsilon(\lambda)}$ is related to the spectral differential phase measured with an interferometer of baseline vector $\overrightarrow{B}$, projected onto the sky as:

$$\psi(\lambda) = 2\pi \frac{\overrightarrow{B}.\overrightarrow{\varepsilon(\lambda)}}{\lambda} \tag{6}$$

Cepheid stars present interesting spectral lines including the mixing of pulsational and rotational velocity fields. The classical rotation of the star could be detected by the displacement of the photometric barycenter through the different Doppler shifted spectral channels. This effect, as well as the line profile, is symmetric with respect to the center of the line. By adding a pulsation field, it appears a dissymmetric effect since the expansion velocity will add positively to the blue shifted spectral channels and negatively for the red ones. A well-known dissymmetric line profiles also appears and this asymmetry is of course dependent of the pulsational phase. The same signature could be detected on the photocenter displacements and allows to obtain a measure of the angular diameter. Such effects are detectable by the VLTI through small phase shifts in spectral lines (see Fig. 3 and Fig. 4).

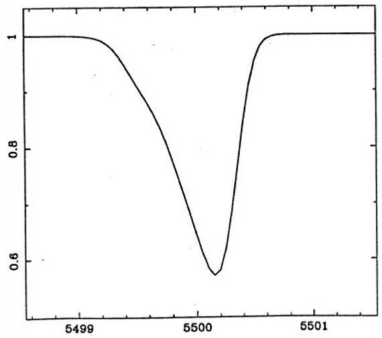

Fig. 3. Example of the spectral line profile for a star in rotation and pulsation.

Preliminary estimations Lagarde (1994) show that the photocenter displacement through a spectral line for a cepheid is typically of 15% of the angular diameter, so around 4.5μas in our case. The variation of the angular diameter during the pulsation cycle beeing estimated to 15% of the diameter, the pulsation will then lead to a typical amplitude

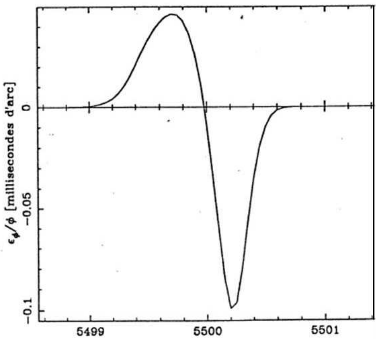

Fig. 4. Example of the photocenter displacement for a star in rotation and pulsation

of variation of the photocenter displacement of 0.7μas.

In this first estimation, we have taken into account the rotation and a pulsation but the effects of the limb darkening as well as the atmospheric dynamic are also physical effects that can contribute to the spectral line profiles or to the spectral photocenter displacements. Recent numerical simulations Nardetto et al. (2005a) for cepheids stars that will be soon observed with the VLTI/AMBER have been made and show visibility effects between 7 and 19% through spectral lines, depending of the actual spectral resolution of the spectrograph. It is clear that an optimization of the observing configuration has to be made on the case by case principle.

For a 200m baseline, a wavelength of 1μm and a precision of 10^{-3} on the phase measurements, a sensitivity of 1μas can be reached. One can estimate that such a precision could be reached within a few hours of observation. AMBER Petrov et al. (2005) on the VLTI has already achieved differential measurement at a precision of 10^{-3} for a baseline of 100 m and a wavelength of 2.2 μm.

It is clear also that the differential interferometry technique could greatly benefit from the spectral lines multiplexing. This is of course only possible for spectral lines at the same level of excitation, forming then at the same height in the atmosphere. It should be also noted that the sensitivity of this technique is proportional to the wavelength and that going down to the visible domain will greatly help for reaching the necessary performances. It has been shown recently Mourard et al. (2005) that, with the VLTI operated at visible wavelengths, the brightest cepheids of our sample ($V < 12.5$) could be measured under good seeing conditions (0.5”) in three hours of integration with the ATs.

4. Conclusions

Differential interferometry could be applied on pulsating stars like cepheids. The photocenter displacement is directly related to the angular diameter of the star. It will allow to measure very small angular diameter and then to reach the brightest of the Large Magellanic Cloud Cepheids. This opens the door to direct extragalactic distance determination.

It should be also noted that the differential interferometry technique, when successfully applied on different spectral lines, can allow to directly probe and measure the contributions functions of the spectral lines. This is of prime importance for the continuation of our work to increase the accuracy in the distance determination through their role in the projection factor and on the linear radius determination Nardetto et al. (2005b).

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