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INTERFEROMETRIC VIEWS ON THE CEPHEIDS

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RESUMEN

El método de paralaje de pulsación, o método de Baade-Wesselink (BW), es una poderosa manera de medir distancias a Cefeidas en una manera pseudo-geométrica. En la búsqueda para obtener la más precisa distancia usando interferometría de gran línea de base (alcanzamos 1.5%), nosotros obtuvimos dos resultados quizás no tan insospechados. En primer lugar, nuestros estudios demuestran que alcanzamos un punto donde la suposición que la fotósfera que pulsa se puede aproximar usando modelos estáticos no es válida en el contexto del método BW. En segundo lugar, revelamos la presencia sistemática de envolturas circunestelares (CSE) en escala de algunos diámetros estelares, como un leve exceso del infrarrojo cercano, que podría ser una indicación de que está ocurriendo una pérdida de masa. No sólo estos dos resultados representan un sesgo al método BW, y merece ser estudiado observacionalmente, sino también vierten nuevas luces a nuestro conocimiento de las cefeidas y requieren un extenso modelamiento.

ABSTRACT

The pulsation parallax method, or Baade-Wesselink method (BW), is a powerful way to measure distances to Cepheids in a pseudo-geometric way. In the quest for obtaining the most precise distance using long baseline interferometry (we reached 1.5%), we obtained two maybe not so unsuspected results. First of all, our studies show that we reached a point where the assumption that the pulsating photosphere can be approximated using static models is not valid in the context of the BW method. Secondly, we unveiled the systematic presence of Circum Stellar Envelopes (CSE) at a few stellar diameters scale, as a slight near-infrared excess, which could be an indication that mass loss is currently taking place. Not only these two results represent biases to the BW method, and deserve to be observationally studied, they also shed new lights on our knowledge of the Cepheids themselves and call for extensive modeling.

Key Words: Cepheids — stars: circumstellar matter — stars: mass oss

1. INTRODUCTION

Cepheids pulsating stars play a crucial role in the determination of distances, using the Period-Luminosity relation, also known as the Leavitt's law (1908). Not only this is one of the oldest technics used to determine directly distances, but Cepheids also allow to access a range of distance right between geometric parallax astrometric distances (up to about kilo-parsecs) and extragalactic cosmological distance (from a few mega-parsecs and above). Hence measuring accurate distances to Cepheids is a powerful tool to calibrate technics use to measure cosmological distances, which play a critical role in the determination of the Hubble constant for instance (e.g. Sandage et al. 2006).

Stellar interferometry allows to directly measure distances to pulsating stars by the way of the parallax pulsation technic. This technic, also known as the Baade-Wesselink method (Baade 1926; Wesselink 1946), compares the actual change in angular diameter (θ) and the change in pulsation velocity (v_p) in order to measure the distances. By definition:

$$\theta(T) - \theta(0) = -\frac{2}{d}\int_0^T v_p(t)dt\,. \qquad (1)$$

It is to be noted that even though Baade and Wesselink are quoted as at the origin at the method, Lindeman (1918) presented the method in a short paper. We will refer in the rest of this paper to the method as IBWM (interferometric Baade-Wesselink Method).

In the course of observations of Cepheids, we present the results we obtained regarding different aspects of the Cepheids: precision, accuracy and biases to the IBWM.

2. CURRENT STATE OF THE ART: PRECISION ON DISTANCES

The amplitude of pulsation of a typical Cepheids if of the order of 10 to 20% in term of diameter, and

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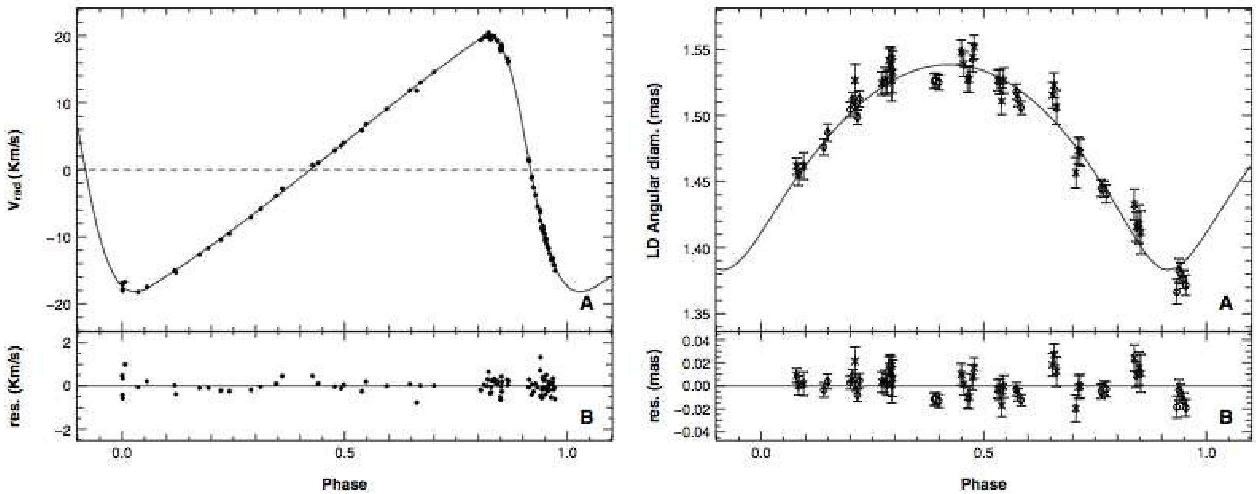

Fig. 1. Best distance precision obtained using the IBWM. Left, radial velocity (Bersier et al. 1994); right, the measured angular diameters, using CHARA/FLUOR, as well as the integrated radial velocity (fine line).

of a few tens of kilometers per second, peak-to-peak. The current precision of spectroscopic radial velocity is well below one kilometer per second, whereas precision in interferometric angular diameters hardly reaches one percent. Hence it is expected that the ultimate precision on d in equation 1 is going to be limited by the precision on the interferometric angular diameters, by about an order of magnitude.

Using the CHARA Array (ten Brummelaar et al. 2005) and the FLUOR instrument (Mérand et al. 2006a), we were able to obtain a formal precision of 1.4% on the distance to the Cepheid δ Cep (Figure 1, Mérand et al. 2005).

Our further study showed that there are two biases that strongly limit the accuracy of the result: the uncertainty on the projection factor and on the morphology of the Cepheid.

2.1. *Projection factor*

The first limitation regarding determining distances using the IBWM is the projection factor. It is well known that spectroscopy does not directly measures the pulsation velocity, but the projected velocity, integrated over the surface on the star: $v_{\rm rad} = v_p/p$. Not only the geometry of the star has to be taken account, but also the actual structure of the photosphere that affects the weighting of a given absorption line other the projected star.

People have been using $p = 1.36$ for a long time, based on simple model (Burki et al. 1986) but recent attempts to model hydrodynamically Cepheids gave results ranging from $p = 1.45$ (Sabbey et al. 1995) to $p = 1.27$ (Nardetto et al. 2004). Just considering the range of values given by models, one can conservatively assume that there is a large uncertainty on the value of p, larger than the formal precision of the IBWM distance to δ Cep for example. Using the known distance to δ Cep from a direct parallactic measurement (with a precision of 4%, Benedict et al. 2002), we were able to determine p with a precision of 5%: $p = 1.27 \pm 0.04$.

2.2. *Uncertainty on the morphology of Cepheids*

Another limiting factor on the distance precision is the bias on the angular diameter interferometric measurement. The first bias one thinks about is the center-to-limb darkening (CLD). CLD is usually corrected using models computed to hydrostatic models (e.g. Kurucs', PHOENIX, MARCS etc.).

In an attempt to measure directly the CLD of a Cepheid, we discovered (Mérand et al. 2006b) that apparently the photosphere of a Cepheid has a CLD close to a non pulsating star. This was expected from pseudo-hydrodynamic models (Marengo et al. 2003). The surprise came from the fact that the Cepheid was actually found to have a morphology departing from a single star: it turned out that the interferometric measurement are compatible with a star surrounded by a large envelop, many stellar diameters in size, accounting for a few percent of the total flux in the infrared K band. The presence of such Circum Stellar Envelops (CSE) can cause a bias to the distance up to a few percent, far more again that the formal precision. We have detected such CSE around more Cepheids since then (e.g. Kervella et al. 2006)

2.3. *Biased IBWM formalism*

Equation 1 can be rewritten to take into account the p-factor and the k factor, that takes into account the morphology of the star:

$$\theta_{\mathrm{UD}}(T) - \theta_{\mathrm{UD}}(0) = -\frac{2kp}{d}\int_0^T v_{\mathrm{rad}}(t)dt\,, \quad (2)$$

where θ_{UD} is the unambiguous interferometric uniform disk diameter. Both k and p introduce a direct bias to the distance measurement.

3. CEPHEIDS' CSE

3.1. *Why are they important*

Cepheid's CSE are worth studying for two different reasons. First of all, the bring an insight to the mass loss phenomenon on Cepheids. CSE are most probably due to mass loss, since interferometry detected material very close to the star (a few stellar radii) where is is not stable. Mass loss is important for Cepheids since it affects the mass of the star: the star has a slightly different mass than its progenitor. That is why it is important to assess the mass loss rate of the Cepheids, because models have for a long time had discrepancies between internal structure evolution models and pulsation models. This problem is know as the mass discrepancy (Bono et al. 2001).

The second important aspect of the CSE if the bias to the IBWM. We have studied different Cepheids using the same technic and detected infrared (K Band) excesses for all of them (Mérand et al. 2007). Moreover, it seems that there is an observational correlation between the period and the observed infrared excess (Figure 2): the longer the period, the stronger the excess. Longer period Cepheids have the highest luminosity, the larger pulsation amplitude and the smaller surface gravity, all of this exacerbating the pulsation driven mass loss.

3.2. *Bias to the IBW method and other BW method*

The presence of infrared excess produces a bias to the angular diameter measurement (k factor), hence, according to equation 2, a bias to the distance. In the context of the P-L relation calibration, this effect which can be as strong as a few percent, poses a serious problem. For instance, in the case of our observations of Y Oph, the distance is biased by as much as 3.5%, comparable to our formal (*i.e.* statistical) precision.

It is to be noted that the popular infrared surface brightness (IRSB) technic is also used to determine diameters in the context of BWM, is affected by the

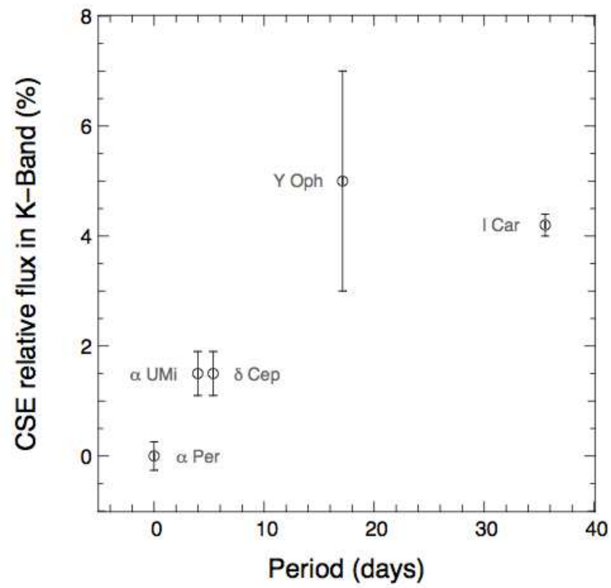

Fig. 2. K Band photometric excess, attributed to the presence of CSE, as a function of the pulsation period.

presence of a K band excess. In particular, if one uses the V, V-K method, the bias is quite strong. Using the IRSB calibration of Kervella et al. (2004b):

$$\begin{aligned}\log(\theta) &= 8.4414 - 0.2V - \\ &\quad 2(-0.1336(V-K) + 3.9530) \\ &= 0.5354 - 0.2672K + 0.0672V\,,\end{aligned}$$

where log is the base-10 logarithm function, V and K the V and K magnitudes. Based on the precedent equation, a 1% K band excess leads to a bias of

$$10^{0.2672\times 2.5\times\log(1.01)} \approx 1.0067\,,$$

in the diameter, which corresponds to -0.67% bias in the distance. We found K band excesses of the order of 3 to 5%, leading to distances biases from -2 to -3.5%. This is crucial since the bias on the distance is not much smaller than the current precision on the P-L calibration: a few percent (e.g. Kervella et al. 2004a). Note only it affects the zero point of the P-L relation, but also the slope, since a dependency on the IR excess with period translates into a bias which is function of the period, hence a biased slope when calibrating the P-L relation.

3.3. *Towards a better understanding of the CSE*

A clearer view is starting to emerge from recent observational studies of Cepheids CSE. Recently, we (Kervella et al. 2009) studied two long period Cepheids: ℓ Car and RS Pup. Thought we expect these tow stars to have similar CSEs, it did not turn out to be the case. Using thermal to mid infrared, we showed that both the spatial scale and the importance of the CSE (in term of infrared excess) are different from one star to the other. In particular, RS Pup is surrounded by an impressive dust envelop, whereas ℓ Car has a much less important CSE. In both cases, it seems that the CSE are structured and span large spatial scale, denoting that the mass loss should have taken place for a long time.

It is crucial to better characterize and understand Cepheids' CSEs, not only because it will help to better understand the mass loss phenomenon, but also because they introduce a rather large bias in the P-L relation and the method used to calibrate it. Finally, it is to be noted that the problem will be even of larger proportion when Cepheids are observed in the mid-IR. This will pose a problem when determining unbiased distances using future highly sensitive mid-IR facilities, such as the *NGST* (Next Generation Space Telescope) or the different projected *ELT* (Extremely Large Telescopes), which will perform distances measurement to remote galaxies by detecting Cepheids. Recent models (Neilson et al. 2009a,b) have already started to reproduce our infrared excesses and promise a better control of the bias to the distance estimates using the BW methods.

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