Optical interferometry and Gaia parallaxes for a robust calibration of the Cepheid distance scale

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Image: S. Brunier / ESO
Parallax of pulsation & SPIPS

• The accuracy of the calibration of the Leavitt law is insufficiently competitive due to systematic uncertainties.

• Our project is to employ the *Gaia* parallaxes of Galactic Cepheids to:
  1. Calibrate the *parallax-of-pulsation* (PoP) technique (a.k.a. *Baade-Wesselink*).
  2. Improve the calibration of the *Leavitt law*.
  3. Apply the PoP technique to individual stars in distant galaxies using ELT, JWST,…

• We developed a robust modeling approach through the *Spectro-Photo-Interferometry of Pulsating Stars* (SPIPS) code to simultaneously fit the Cepheid photometry, radial velocities and interferometry.
PARALLAX OF PULSATION

Radial velocity

Expansion
Max radius
Contraction
Min radius

Angular diameter

$\theta_{\text{min}}$
$\theta_{\text{max}}$

DU (mas)

0 0.2 0.4 0.6 0.8 1

Phase
0 1.50 1.55 1.60 1.65 1.70 1.75

Heliocentric wavelength (Å)
The distance $d$ is given by the relation:

$$
\frac{d}{R_{\odot}} = \frac{2\delta R(T)}{\delta \theta(T)} = \frac{-2kp}{\theta_{UD}(T) - \theta_{UD}(0)} \int_0^T \nu_{rad}(t) \, dt
$$

$p$ = projection factor

$k$ = limb darkening correction
THE P-FACTOR

- Pure geometry = 1.5
- Limb darkening component < 1
- Atmosphere dynamics = ?


Main limitation for PoP Cepheid distances
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photometry from
tensively, in particular by optical interferometer. We took the
as FITS tables at the CDS.

Note that the observational data, and best fit model are available
3. Prototypical stars
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ions are shown on the right side of the plot, below the reduced

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3.1.

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Cep data fit. Various panels show pulsation and radial velocities with spline model and residuals (panel

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To properly interpolate the photospheric models, we adopted a

Andrievsky et al. (2002)
Mérand et al. (2005)
van Leeuwen et al. (1997)
Bersier et al. (1994)


engle et al. (2014)

For the
averaging, we used four groups of observables:

brightness values and is undetectable with our data set.


3. Andrievsky et al. (2002)
Mérand et al. (2006)
Storm et al. (2004)


k)

The angular diameters are the ones published
angles and


Radial velocity

Effective temperature

SPIPS model parameters
p-factor / distance
E(B-V)
Envelope infrared excess

Radial velocity
Photometry
Angular diameters

Multiparameter fit
to observations

Kurucz’s ATLAS9
Reddening law
Envelope
Fig. 3. Cep data fit. Various panels show pulsation and radial velocities with spline model and residuals (panel a); angular diameters and residuals, with the baseline color-coded for the data and CSE-biased model – as a dash line, based on the model shown in Fig. 2 – (panel b); effective temperatures (panel c)); photometric measurements and models (panels d to k) for different photometric bands or colors. Typical error bars are shown on the right side of the plot, below the reduced $\chi^2$ values.

For example, the slow (compared to the pulsation time) evolution of the star's interior leads to a first-order period change. The amount of linear change is an indicator of the evolutionary stage of the Cepheids and can be computed theoretically (see, for example, Fadeyev 2014). We allowed the period to change linearly in our model.

3. Prototypical stars

Note that the observational data, and best fit model are available as FITS tables at the CDS.

3.1. Cep Cep is the prototypical Cepheid and has been observed extensively, in particular by optical interferometer. We took the photometry from Moiett & Barnes (1984), Barnes et al. (1997), Kiss (1998), Berdnikov (2008) and Engle et al. (2014). We also added photometric observations from Tycho and Hipparcos from van Leeuwen et al. (1997) and ESA (1997). We took the cross-correlation radial velocities from Bersier et al. (1994) and Storm et al. (2004). The angular diameters are the ones published in Mérand et al. (2005) and Mérand et al. (2006). In addition, to properly interpolate the photospheric models, we adopted a metallically of $[\text{Fe/H}] = 0.06$, based on Andrievsky et al. (2002). We note that the metallicity has a very weak effect on surface brightness values and is undetectable with our data set.

For the $\chi^2$ averaging, we used four groups of observables: radial velocities (91 measurements) angular diameters (67 measurements), photometric magnitudes (483 measurements), and colors (421 measurements). Error bars for each of these groups were multiplied by $\sim 0.59$, $\sim 0.50$, $\sim 1.26$, and $\sim 1.35$, respectively.

We show the fit in Fig. 3, and the most important parameters are listed in Table 3.

It is interesting to compare the result we obtain here with that of our previous study, which did not include photometry.

**beta Dor** $p=1.356 \pm 0.08$, $d=318.5 \pm 0.5$ pc, $E(B-V)=-0.018$, $K_s=0.021$ mag, $H_s=0.006$ mag

*Radial velocity*  
Fig. A.7: SPIPS model of Dor.  
Fig. A.8: SPIPS model of Gem.

*Photometry*  

Angular size

Radial velocity
RS Puppis

- Long-period Cepheid
  \( P = 41.5 \) days

- \( \pi = 0.524 \pm 0.022 \) mas
  (4.2\%) from its light echoes

RS Pup (P~41.4d) \( p = 1.25 \pm 0.06 \) d = 1910.0 pc E(B-V) = 0.496 \( K_{\alpha} = 0.027 \) mag \( H_{\alpha} = 0.016 \) mag
p = 1.29 ± 0.04
\( \chi^2_{\text{red}} = 0.9 \)

Binarity

+ see poster by Alexandre Gallenne

Circumstellar envelopes


Included in SPIIPS modeling