Radial and Pulsation Velocities of Cepheids from High-Resolution Spectra

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The calibration of the Period-Luminosity ($P-L$) relation of Cepheids through the Baade-Wesselink (BW) technique is affected by systematic errors due to uncertainties on the projection (p-) factor. The p-factor is the conversion parameter between the observed radial velocities and the actual pulsational velocities of Cepheids and depends on the limb-darkening and the stellar atmosphere dynamics. Thus, it is the main obstacle to an accurate enough distance determination with the BW method.

We have recently developed the Spectro-Photo-Interferometry of Pulsating Stars (SPIPS) tool, that models the pulsation of Cepheids and estimates their physical parameters (including the p-factor) based on the combination of atmosphere models and all observables. The next step in this approach is to estimate directly the pulsational velocities ($v_{\rm puls}$) of Cepheids by comparing observed high-resolution (HR) spectra with synthetic Cepheid spectra built at different $v_{\rm puls}$ and temperatures. This HR-SPIPS approach will allow us to compute and characterize the p-factor in a new, spectroscopic way.

1 Introduction

Cepheids are primary extragalactic distance indicators as their pulsation period correlates directly with their luminosity – the Leavitt law, or so-called Period-Luminosity ($P-L$) relation (Leavitt & Pickering, 1912). Their contribution to precision cosmology is therefore tremendous. However, the precision of the Cepheid distance scale is still unsatisfactory, and the $P-L$ relation requires accurate calibration.

The parallax-of-pulsation (PoP) method – or Baade-Wesselink technique – is a powerful way to estimate distances of Cepheids and other pulsators. It allows us to derive the distance through the ratio of the star's pulsation amplitude (measured by integrating the radial velocity curve) over the angular diameter variation during the pulsation (directly measured through interferometry or estimated from color-brightness relations). The major weakness of the PoP technique, and the main source of systematic uncertainty on the estimated distance, is the conversion factor (the so-called *projection* or *p-factor*) used to transform the spectroscopic radial velocities

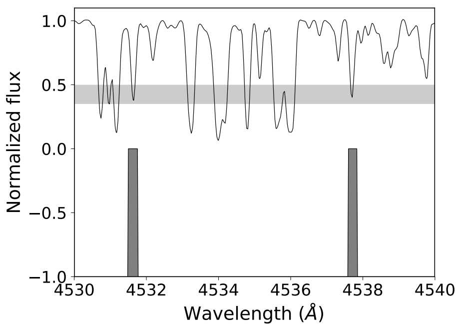

Fig. 1: Building a custom binary mask. The input spectrum (top) is synthetic (Sect. 3). The grey shadow shows the line depth selected to pick the spectral lines used to build the mask (bottom, dark grey).

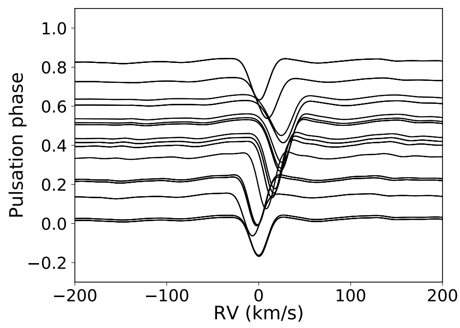

Fig. 2: β Dor observed CCF against pulsation phase. The CCF are built from *HARPS* input spectra cross-correlated to a binary mask built from a synthetic spectrum on a broad wavelength range ($4500 - 6700$ Å).

(RV) into photospheric velocities. The p-factor depends on three components: the geometrical projection factor ($= 1.5$), the limb-darkening, and the stellar atmosphere dynamics, which are not easily modeled (Nardetto et al., 2007; Anderson, 2016). The PoP technique thus provides the d/p ratio, as the distance and the p-factor are degenerate.

We have developed an innovative modeling tool to extend and improve the PoP: the *Spectro-Photo-Interferometry of Pulsating Stars* (SPIPS) code (Mérand et al., 2017). A SPIPS analysis integrates all available observables in a global model of the Cepheid pulsation, and allows us to derive the d/p ratio, the color excess, and other stellar parameters. We have calibrated the SPIPS algorithm using nearby Cepheids with both enough interferometric measurements and relatively accurate distances (Breitfelder et al., 2016), and shown its robustness and reliability (see e.g. Kervella et al., 2017).

Yet, the SPIPS approach is still imperfect: first, it relies on RV available in the literature, i.e. that are not homogeneously computed and thus can lead to different p-factors, and for which the computation details (such as the binary mask used to cross-correlate the spectra) are not usually known. Second, the p-factor itself is still present in the analysis. Thus, the next step to the SPIPS approach aims to estimate *directly* the pulsational velocities $v_{\rm puls}$ by modeling high-resolution (HR) Cepheid spectra (hence HR-SPIPS) for various $v_{\rm puls}$ and effective temperatures $T_{\rm eff}$.

Here, we briefly present in Sect. 2 the main proxy we use in HR-SPIPS to describe the Cepheid spectra – the cross-correlation function or CCF. Then, we show in Sect. 3 how we build a grid of synthetic Cepheid spectra and CCF for different $v_{\rm puls}$ and $T_{\rm eff}$, and how the comparison of the observed and synthetic CCF allow us to derive the pulsation velocities (Sect. 4). We use the case of β Dor as a prototype for our HR-SPIPS approach to show its potential, and finally discuss the perspectives and future improvements of HR-SPIPS in Sect. 5.

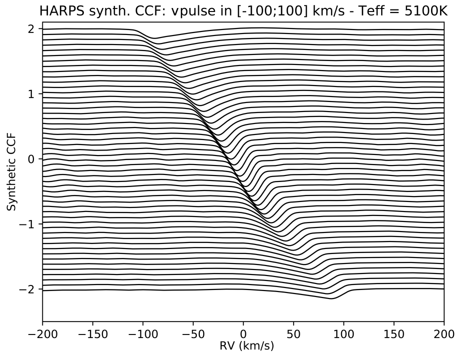

Fig. 3: CCF built from synthetic spectra based on PHOENIX models, at *HARPS* spectral resolution.

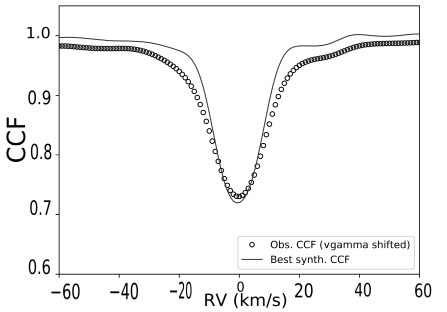

Fig. 4: Best fit of an observed CCF (*open circles*) by a synthetic CCF (*solid line*) from our ($v_{\rm puls}$, $T_{\rm eff}$) grid.

2 Computing the Cross-Correlation Function (CCF)

The main input of HR-SPIPS is observed high-resolution spectra of Cepheids and other pulsators. As they exhibit thousands of spectral lines, modeling entire spectra is time-consuming and over-constraining. An efficient way to keep the information in the line profile (Doppler shift, depth, width, asymmetry) while decreasing the computation time is to use the cross-correlation function (CCF) of the spectrum instead of the spectrum itself. The CCF is the product of the cross-correlation of the observed spectrum with (generally) a binary mask (see e.g. Baranne et al., 1979). The CCF is widely used to compute the RV of stars. The key principle of the HR-SPIPS approach is that the binary mask used to compute the CCF is custom-built, allowing to fully control the CCF computation. Here, the binary mask is built based on an input spectrum, that can be either an observed or a synthetic one (see Sect. 3). Spectral lines from the input spectrum are selected in order to build the mask in an optimal way; i.e. we can keep only unblended lines, a pre-defined set of lines, or lines of a certain depth only (Fig. 1).

Once the binary mask is built, it is cross-correlated to each of the observed spectra to obtain the CCF (Fig. 2). The CCF constitutes a "mean line profile" from which various observables can be derived: the RV, but also different line profile observables that characterize the shape of the CCF and hence the Cepheid pulsation phase (CCF depth, asymmetry, etc). The classical way to derive the RV from the CCF is to fit it by a Gaussian profile. However, this approach is not optimal for Cepheids for which the pulsation induced strong deformations of the CCF. New approaches, such as a bi-Gaussian profile, have also been proposed (Nardetto et al., 2006).

3 Building Synthetic Spectra and CCF

To build synthetic spectra, our approach relies on static PHOENIX atmosphere models of Cepheids. The model input spectra are Doppler shifted and calibrated according to the input $v_{\rm puls}$ and $T_{\rm eff}$, and then integrated over the visible stellar disk (thus taking into account limb-darkening) to obtain the final synthetic spectrum.

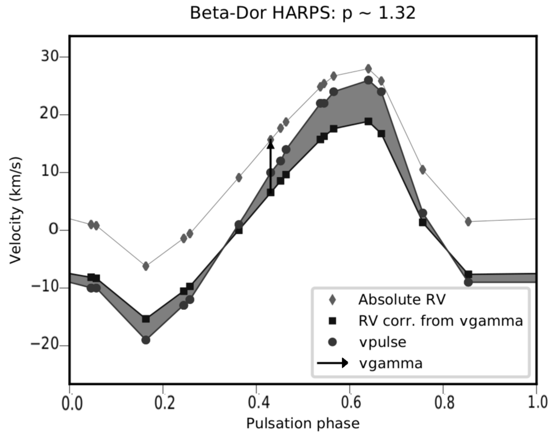

Fig. 5: Estimated β Dor v_{puls} from the comparison of observed and synthetic *HARPS* spectra.

We thus build one synthetic spectrum for a given spectral resolution R, pulsational velocity v_{puls}, and effective temperature T_{eff}.

The corresponding synthetic CCF is built in the same way as the observed CCF, i.e. by cross-correlating the synthetic spectrum with *the same binary mask*, ensuring the homogeneity of the process. Hence, we obtain a grid of synthetic CCFs for various T_{eff} and v_{puls} (Fig. 3).

4 Comparison of Observed and Synthetic CCF: Example of β Dor

The derivation of the Cepheid v_{puls} is based on the direct comparison between the observed CCF and the (v_{puls}, T_{eff}) synthetic CCF grid, i.e., bypassing the RV and p-factor. Each observed CCF is shifted from the systemic velocity v_γ (derived from the different line profile observables) and then fitted by the synthetic CCF (Fig. 4). The best fit gives the corresponding v_{puls} value (and a T_{eff} value). We tested this approach on *HARPS* spectra taken on a narrow wavelength range ($5800 - 6200$ Å) of the Cepheid β Dor. The results (measured RV, RV shifted from v_γ, and derived v_{puls}) are displayed in Fig. 5. The corresponding (spectroscopic) p-factor (~ 1.32) is compatible with previous estimations (Breitfelder et al., 2016), showing the potential of this approach.

5 Perspectives

While already giving coherent results in terms of v_{puls} and corresponding p-factors, this approach can still be refined. First, the CCF fit based on only v_{puls} and T_{eff} inputs can be improved by including a broadening factor accounting for thermal and/or rotational broadening of the observed stellar spectrum (Fig. 4). Another efficient way to improve the CCF fit is to compute an independent T_{eff} measurement based on the observed spectrum that can then be used as input in the CCF fit. A powerful T_{eff} spectroscopic estimation is the approach developed by Kovtyukh &

Gorlova (2000), that derives polynomial relations between $T_{\rm eff}$ and the depth ratio of different pairs of temperature sensitive spectral lines.

Another perspective of this approach is to investigate and to characterize the stellar atmospheric velocity gradient (and its impact on the p-factor, see e.g. Nardetto et al., 2006, 2007) by deriving different sets of RV, $v_{\rm puls}$, and p-factors for different binary masks corresponding to spectral lines of a given depth (see e.g. Anderson, 2016).

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References

Anderson, R. I., *MNRAS* **463**, 1707 (2016), arXiv: 1608.05403

Baranne, A., Mayor, M., Poncet, J. L., *Vistas in Astronomy* **23**, 279 (1979)

Breitfelder, J., et al., *A&A* **587**, A117 (2016), arXiv: 1601.04727

Kervella, P., et al., *A&A* **600**, A127 (2017), arXiv: 1701.05192

Kovtyukh, V. V., Gorlova, N. I., *A&A* **358**, 587 (2000)

Leavitt, H. S., Pickering, E. C., *Harvard College Observatory Circular* **173**, 1 (1912)

Mérand, A., et al., in European Physical Journal Web of Conferences, *European Physical Journal Web of Conferences*, volume 152, 03008 (2017)

Nardetto, N., et al., *A&A* **453**, 309 (2006), arXiv: 0804.1321

Nardetto, N., et al., *A&A* **471**, 661 (2007), arXiv: 0804.1331