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High-resolution spectroscopy for Cepheids distance determination

V. Impact of the cross-correlation method on the p-factor and the γ-velocities[⋆, ⋆⋆]

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ABSTRACT

Context. The cross correlation method (hereafter *CC*) is widely used to derive the radial velocity curve of Cepheids when the signal to noise ratio of the spectra is low. However, if it is used with an inaccurate projection factor, it might introduce some biases in the Baade-Wesselink (BW) methods of determining the distance of Cepheids. In addition, it might affect the average value of the radial velocity curve (or γ-velocity) important for Galactic structure studies.
Aims. We aim to derive a period-projection factor relation (hereafter *Pp*) appropriate to be used together with the CC method. Moreover, we investigate whether the CC method can explain the previous estimates of the "K-term" of Cepheids.
Methods. We observed eight galactic Cepheids with the HARPS[⋆⋆⋆] spectrograph. For each star, we derive an interpolated CC radial velocity curve using the HARPS pipeline. The amplitudes of these curves are used to determine the correction to be applied to the semi-theoretical projection factor. Their average value (or γ-velocity) are also compared to the center-of-mass velocities derived in previous works.
Results. The correction in amplitudes allows us to derive a new *Pp* relation: $p = [-0.08 \pm 0.05] \log P + [1.31 \pm 0.06]$. We also find a negligible wavelength dependence (over the optical range) of the *Pp* relation. We finally show that the γ-velocity derived from the CC method is systematically blue-shifted by about 1.0 ± 0.2 km s^{-1} compared to the center-of-mass velocity of the star. An additional blue-shift of 1.0 km s^{-1} is thus needed to totally explain the previous calculation of the "K-term" of Cepheids (around 2 km s^{-1}).
Conclusions. The new *Pp* relation we derived is a reliable tool for distance scale calibration, and especially to derive the distance of LMC Cepheids with the infrared surface brightness technique. Further studies should be devoted to determining the impact of the signal to noise ratio, the spectral resolution, and the metallicity on the *Pp* relation.

Key words. techniques: spectroscopic – stars: atmospheres – stars: oscillations – stars: variables: Cepheids – stars: distances

1. Introduction

The Baade-Wesselink (hereafter *BW*) method of determining the distance of Cepheids was recently used to calibrate the period-luminosity (*PL*) of Galactic Cepheids (Fouqué et al. 2007). The basic principle of this method is to compare the linear and angular size variation of a pulsating star in order to derive its distance through a simple division. The angular diameter is either derived by interferometry (for e.g. Kervella et al. 2004; Davis et al. 2008) or using the infrared surface brightness (hereafter IRSB) relation (Gieren et al. 1998, 2005a). However, when determining the linear radius variation of the Cepheid by spectroscopy, one has to use a conversion projection factor from radial to pulsation velocity. This quantity has been studied using hydrodynamic calculations by Sabbey et al. (1996), and more recently Nardetto et al. (2004, 2007).

Following the work of Burki et al. (1982), we showed in Nardetto et al. (2006, hereafter Paper I) that the first moment of the spectral line is the only method which is independent of the spectral line width (average value and variation) and the rotation velocity of the star. The centroid radial velocity (RV_c), or the first moment of the spectral line profile, is defined as

$$RV_c = \frac{\int_{\rm line} \lambda S(\lambda) {\rm d}\lambda}{\int_{\rm line} S(\lambda) {\rm d}\lambda}. \quad (1)$$

We thus used this definition of the radial velocity in paper two of this series (Nardetto et al. 2007, hereafter Paper II), to derive a semi-theoretical period-projection factor (hereafter *Pp*) relation

⋆ Based on observations made with ESO telescopes at the Silla Paranal Observatory under programme IDs 072.D-0419 and 073.D-0136.
⋆⋆ Tables 4 and 5 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/502/951
⋆⋆⋆ High Accuracy Radial velocity Planetary Search project developed by the European Southern Observatory.

based on spectroscopic measurements with the HARPS high resolution spectrograph. This relation was derived from the specific Fe I 4896.439 Å spectral line which has a relatively low depth for all stars at all pulsation phase (around 8% of the continuum). It was shown that such a low depth value is suitable to reduce the uncertainty on the projection factor due to the velocity gradient between the photosphere (corresponding to angular diameter measurements) and the line-forming region (corresponding to the radius estimation from spectroscopic measurements).

In the cross-correlation method (hereafter CC method), a mask (composed of hundreds or thousands) of spectral lines is convolved to the observed spectrum. The resulting average profile is then fitted by a Gaussian. In such a method, there is first a mix of different spectral lines forming at different levels (more or less sensitive to a velocity gradient). Second, the resulting velocity can be dependent on the abundances or effective temperature (through the line width), or the rotation of the stars. Third, in Paper III of this series (Nardetto et al. 2008), we derived calibrated center-of-mass velocities of the stars of our HARPS sample. By comparing these so-called γ-velocities with the ones found in the literature (generally based on the CC method) and in particular in the Galactic Cepheid Database (Fernie et al. 1995), we obtained an average correction of 1.8 ± 0.2 km s^{-1}. This result shows that the "K-term" of Cepheids stems from an intrinsic property of Cepheids. But, it shows also that the cross-correlation might introduce a bias (up to a few kilometers per second) on the average value of the radial velocity curve.

After a careful definition of the projection factor (Sect. 2), we apply the cross-correlation method to the Cepheids of our HARPS sample (Sect. 3), in order to derive a period-projection factor relation appropriate for the CC method (Sect. 4). As the HARPS pipeline also provides cross-correlated radial velocities for each spectral order, we take the opportunity to study the wavelength dependence of the projection factor law (Sect. 5). Finally, we quantify the impact of the CC method on the γ-velocities (Sect. 6).

2. Definition of the "CC projection factor"

In this section, we recall some results obtained in Paper II and we define the projection factor suitable for the cross-correlation method. In Paper II, we defined the projection factor as:

$$p = \frac{\Delta V_{\rm p}^{\rm o}}{\Delta RV_{\rm c}} \tag{2}$$

where $\Delta V_{\rm p}^{\rm o}$ is the amplitude of the pulsation velocity curve associated with the photosphere of the star. $\Delta RV_{\rm c}$ is the amplitude of the radial velocity curve obtained from the first moment of the spectral line. Because of the atmospheric velocity gradient, $\Delta RV_{\rm c}$ depends on the spectral line considered. Using a selection of 17 spectral lines, we thus derived an interpolated relation between $\Delta RV_{\rm c}$ and D, where D is the line depth corresponding to the minimum radius of the star:

$$\Delta RV_{\rm c} = a_0 D + b_0. \tag{3}$$

This relation was then used to quantify the correction ($f_{\rm grad}$) to be applied to the projection factor due to the velocity gradient (see Eq. (3) of Paper II). The Fe I 4896.439 Å spectral line (which forms close to the photosphere) was found to provide the lowest correction. The amplitude of the radial velocity curve corresponding to the Fe I 4896.439 Å spectral line was finally used (see $f_{\rm grad}$ in Table 5 of Paper II) to derive the semi-theoretical Pp relation. It is defined (Eq. (3)) as $\Delta RV_{\rm c}[4896] = a_0 D_{4896} + b_0$, where a_0 and b_0 are indicated in Table 3 of Paper II. D_{4896} is derived from the interpolation of the line depth curve at the particular phase corresponding to the minimum radius of the star (i.e. when $RV_{\rm c}$ corrected from the γ-velocity ≃0). D_{4896} and $\Delta RV_{\rm c}[4896]$ are given in Table 1 of this paper.

Table 1. The Cepheids studied listed with increasing period.

Cepheid	$P^{(a)}$ [days]	D_{4896} [%]	$\Delta RV_{\rm c}[4896]$ [km s^{-1}]
R TrA	3.38925	6	$28.6_{\pm 0.5}$
S Cru	4.68976	6	$33.5_{\pm 0.5}$
Y Sgr	5.77338	5	$34.3_{\pm 0.5}$
β Dor	9.84262	10	$31.7_{\pm 0.5}$
ζ Gem	10.14960	14	$25.5_{\pm 0.5}$
RZ Vel	20.40020	4	$47.6_{\pm 0.5}$
ℓ Car	35.55134	13	$32.8_{\pm 0.5}$
RS Pup	41.51500	4	$42.4_{\pm 0.5}$

[a] The corresponding Julian dates ($T_{\rm o}$) can be found in Paper II.

The projection factor suitable to the cross-correlation method (hereafter $p_{\rm cc}$) is then simply:

$$p_{\rm cc} = p \frac{\Delta RV_{\rm c}[4896]}{\Delta RV_{\rm cc}} = p f_{\rm cc} \tag{4}$$

where $\Delta RV_{\rm cc}$ is the amplitude of the radial velocity curve obtained with the cross-correlation method, and $f_{\rm cc}$ the correction factor to be applied. Our definition of $p_{\rm cc}$ is independent of the γ-velocities.

3. The CC method applied to HARPS observations

We consider eight Cepheids which have been observed with the HARPS spectrometer (R = 120 000): R Tra, S Cru, Y Sgr, β Dor, ζ Gem, RZ Vel, ℓ Car, RS Pup. Information about observations (number of measurements, pulsation phases) can be found in Paper I.

We apply the HARPS pipeline to our data in order to calculate the cross-correlated radial velocities (Baranne et al. 1996; Pepe et al. 2002). The basic principle of the CC method is to build a mask, made of zero and non-zero value-zones, where the non-zero zones correspond to the theoretical positions and widths of thousands of metallic spectral lines at zero velocity, carefully selected from a synthetic spectrum of a G2 star. A relative weight is considered for each spectral line according to its depth (derived directly from observations of a G2 type star). An average spectral line profile is finally constructed by shifting the mask as a function of the Doppler velocity. The corresponding radial velocity is derived applying a classical χ^2 minimization algorithm between the observed line profile and a Gaussian function. The whole profile is considered in the fitting procedure, not only the line core. The average value of the fitted Gaussian corresponds to the cross-correlated radial velocity (hereafter $RV_{\rm cc}$). The HARPS instrument has 72 spectral orders. The pipeline provides $RV_{\rm cc}$ averaged over the 72 spectral orders, or independently for each order. We first use the averaged values and the corresponding uncertainties.

The $RV_{\rm cc}$ curves are then carefully interpolated using a periodic cubic spline function. This function is calculated either directly on the observational points or using arbitrary pivot points. In the latter case, a classical minimization process between observations and the interpolated curve is used to optimize the position of the pivot points (Mérand et al. 2005). For Y Sgr and

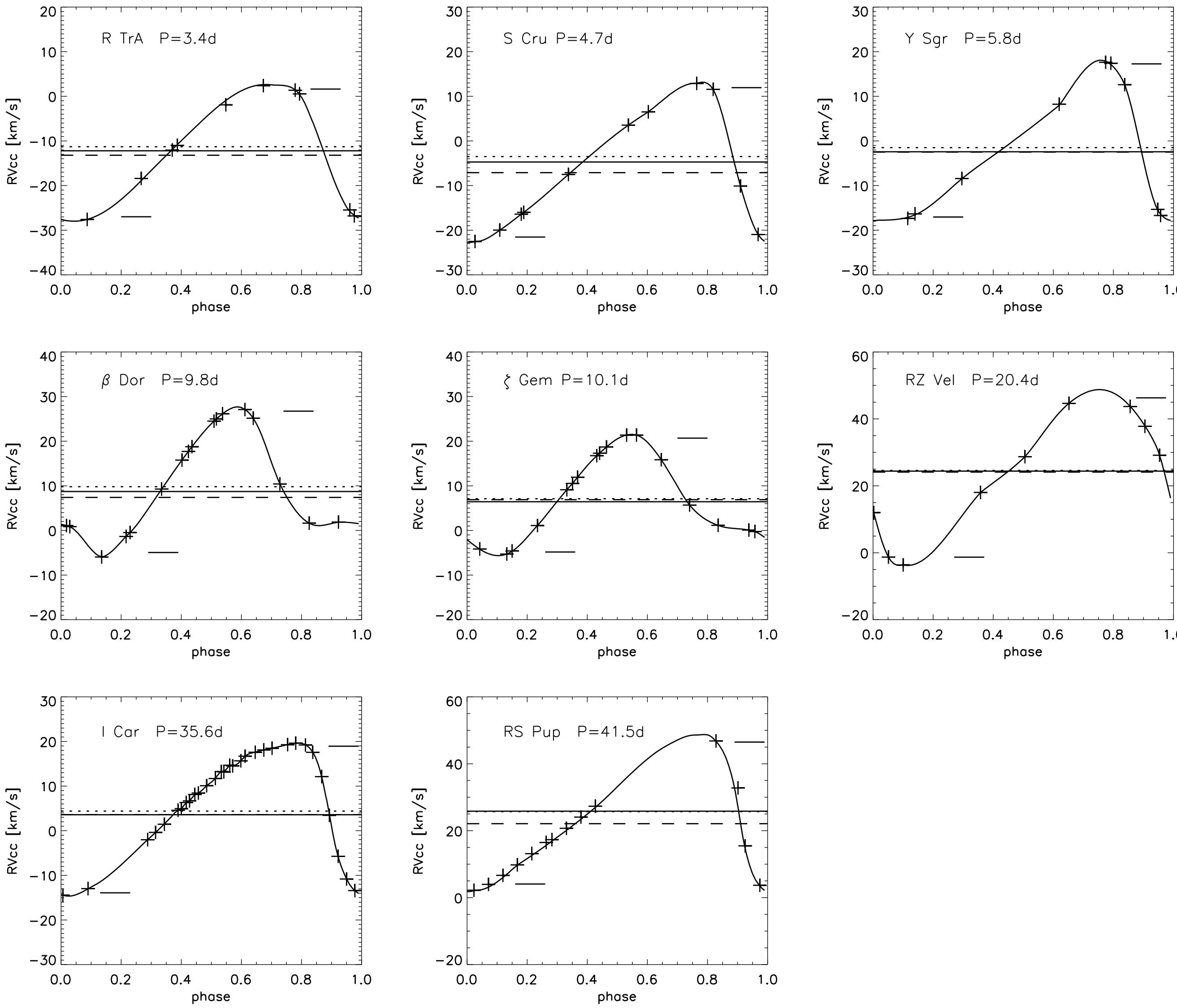

Fig. 1. Interpolated radial velocity curves based on the cross-correlation method are presented for each Cepheid in our sample. Uncertainties are too small to be seen (around 0.5 km s^{-1}). The horizontal lines near *extrema* give an indication of $\Delta RV_c[4896]$. The short horizontal lines are the γ-velocities (see Sect. 6) corresponding to the CC method (solid line), the center-of-mass velocity of Paper III (dotted line) and from Fernie et al. (1995, dashed line).

RS Pup, pivot points are used due to an inadequate phase coverage. When the phase coverage is good (which is the case for all other stars), the two methods are equivalent (Fig. 1). From these curves we are finally able to calculate ΔRV_{cc} (Table 2). The statistical uncertainty on ΔRV_{cc} is set as the average value of the uncertainty obtained for all measurements over a pulsation cycle of the star.

4. A *Pp* relation dedicated to the CC method

From $\Delta RV_c[4896]$ and ΔRV_{cc} obtained for all stars we derive the correction factor f_{cc} using Eq. (2). The result is plotted as a function of the period in Fig. 2a. No particular trend is found. However, the f_{cc} correction factors are clearly statistically dispersed around a mean value of 0.93 ± 0.02.

Following our definition ($p_{cc} = pf_{cc}$), the corrected projection factors suitable for the CC method are given in Table 2. The relation between the period and p_{cc} remains clear according to the statistical uncertainties:

$$p_{cc} = pf_{cc} = [-0.08 \pm 0.05] \log P + [1.31 \pm 0.06]. \quad (5)$$

The corresponding reduced χ^2 is 1.2. We refer to this relation in the following using Pp_{cc}. We recall that the Pp relation we found in Paper II dedicated to the FeI *4896* spectral line was: $p = [-0.064 \pm 0.020] \log P + [1.376 \pm 0.023]$. These two relations are shown in Fig. 2b. The impact of the cross-correlation method on the zero-point of the Pp is thus significant, while the slope increases only slightly (in absolute value) from −0.064 to −0.08.

We have several possible explanations for these results. The cross-correlation induces two biases:

1. The cross-correlated radial velocities are derived using a Gaussian fit, making the result sensitive both to the spectral line width (i.e. the effective temperature and abundances) and the rotation velocity projected on the line of sight. These two quantities, independently, and even more the combination of both, are not expected to vary linearly with the logarithm of the period. This might explain why no clear linear relation is found between f_{cc} and the period of the star. However, the mean values of the correction factors (around 0.93 ± 0.02) have a non negligible impact on the zero-point of the Pp relation, which decreases from 1.376 to 1.31 (5%).

Table 2. The projection factor (p_{cc}) and the γ-velocities (V_γ[CC]) derived from the CC radial velocity curves.

Name	$p(a)$	ΔRV_{cc} [km s^{-1}]	f_{cc}	p_{cc}	V_γ[GCD](b) [km s^{-1}]	V_γ[N08](c) [km s^{-1}]	V_γ [CC] [km s^{-1}]
R TrA	$1.35_{\pm 0.03}$	$30.6_{\pm 0.6}$	$0.93_{\pm 0.03}$	$1.25_{\pm 0.07}$	$-13.2_{\pm 2.0}$	$-11.3_{\pm 0.3}$	$-12.2_{\pm 0.6}$
S Cru	$1.34_{\pm 0.03}$	$35.9_{\pm 0.6}$	$0.93_{\pm 0.03}$	$1.25_{\pm 0.07}$	$-7.1_{\pm 2.0}$	$-3.5_{\pm 0.4}$	$-4.7_{\pm 0.6}$
Y Sgr	$1.33_{\pm 0.03}$	$36.0_{\pm 0.5}$	$0.95_{\pm 0.03}$	$1.26_{\pm 0.05}$	$-2.5_{\pm 2.0}$	$-1.5_{\pm 0.2}$	$-2.4_{\pm 0.5}$
β Dor	$1.32_{\pm 0.02}$	$33.5_{\pm 0.2}$	$0.94_{\pm 0.02}$	$1.24_{\pm 0.05}$	$7.4_{\pm 2.0}$	$9.8_{\pm 0.1}$	$8.7_{\pm 0.2}$
ζ Gem	$1.31_{\pm 0.02}$	$27.2_{\pm 0.2}$	$0.94_{\pm 0.03}$	$1.23_{\pm 0.05}$	$6.9_{\pm 2.0}$	$7.1_{\pm 0.1}$	$6.4_{\pm 0.2}$
RZ Vel	$1.30_{\pm 0.02}$	$52.5_{\pm 0.7}$	$0.91_{\pm 0.02}$	$1.18_{\pm 0.05}$	$24.1_{\pm 2.0}$	$24.6_{\pm 0.4}$	$24.4_{\pm 0.7}$
ℓ Car	$1.28_{\pm 0.02}$	$34.3_{\pm 0.2}$	$0.96_{\pm 0.02}$	$1.22_{\pm 0.04}$	$3.6_{\pm 2.0}$	$4.4_{\pm 0.1}$	$3.6_{\pm 0.2}$
RS Pup	$1.27_{\pm 0.02}$	$46.9_{\pm 0.5}$	$0.90_{\pm 0.02}$	$1.16_{\pm 0.04}$	$22.1_{\pm 2.0}$	$25.7_{\pm 0.2}$	$25.8_{\pm 0.5}$

[a] The projection factor as derived in Paper II. [b] The γ-velocities derived from the Galactic Cepheid Database (Fernie et al. 1995). [c] The γ-velocities or calibrated center-of-mass velocities of the stars from Paper III.

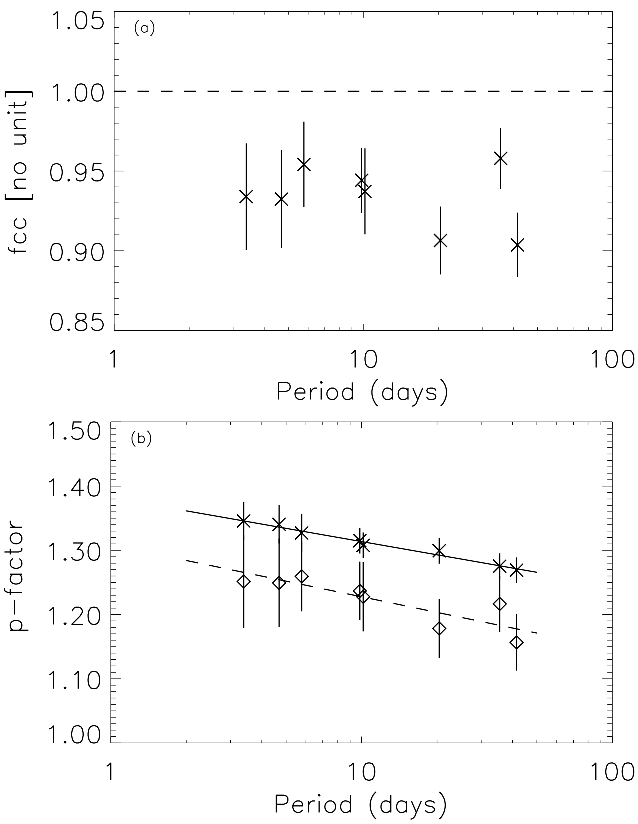

Fig. 2. a) The correction factor f_{cc} induced on the projection factor by the cross-correlation method is shown as a function of the logarithm of the period of the star. **b)** The period-projection factor (p) relation from Paper II (crosses and solid line) and the corrected relation suitable for the cross-correlation method $p_{cc} = pf_{cc}$ (diamonds and dashed line).

2. The cross-correlation method implies a mix of different spectral lines forming at different levels. In the Pp relation, the only quantity sensitive to the line depth is f_{grad} (as defined in Paper II) which compares the amplitude of the pulsation velocity corresponding to the line-forming region, and the photosphere. It is thus an estimate of the velocity gradient within the pulsating atmosphere of the star. The Pp relation was derived in Paper II for the *4896* spectral line which forms very close to the photosphere ($D = 8\%$), while the cross-correlated radial velocity is a mix of thousands of spectral lines forming at different levels, with an average depth of around $D \simeq 25\%$. The cross-correlation method is thus more sensitive to the velocity gradient (because the average line depth is large), which may explain the increase (in absolute value) of the slope from -0.064 to -0.08. Moreover, in Paper II we provided a very rough estimate of the Pp relation associated with the cross-correlation method, considering *only* the impact of the velocity gradient (which means discarding the bias related to the Gaussian fit). We found $p = [-0.075 \pm 0.031] \log P + [1.366 \pm 0.036]$ (see Sect. 7 of Paper II). The slope we find here (-0.08) is consistent with this previous rough estimate of -0.075.

These results are important to take into account when deriving the distance of Galactic or LMC/SMC Cepheids using the cross-correlation method. We emphasize that our Pp_{cc} is consistent with the result by Mérand et al. (2005), who found $p = 1.27$ for δ Cep ($P = 5.36$).

5. Wavelength dependence of the projection factor

With the data at hand, we check for a possible dependence of the projection factor on the wavelength range used for the cross-correlation radial velocity measurement. For each order, we derive the cross-correlated interpolated radial velocity curves, and then the corresponding amplitudes $\Delta RV_{cc}(\lambda)$. Orders 59, 68 and 72 are not considered due to instrumental characteristics and/or unrealistic results. For all stars, $\Delta RV_{cc}(\lambda)$ is plotted as a function of the wavelength, defined as the orders' average values (Fig. 3a). We find linear relations between these two quantities:

$$\Delta RV_{cc}(\lambda) = a_\lambda \lambda + b_\lambda, \tag{6}$$

where a_λ and b_λ are listed in Table 3. For consistency with the previous section the $\Delta RV_{cc}(\lambda)$ quantities have been slightly shifted in velocity in such a way that:

$$\Delta RV_{cc} = a_\lambda 502.2 \text{ nm} + b_\lambda, \tag{7}$$

where ΔRV_{cc} is derived from Table 2 and 502.2 nm is the wavelength averaged over all orders.

We also find a relation between a_λ and the logarithm of the period of the star:

$$a_\lambda = [-0.005 \pm 0.001] \log P - [0.002 \pm 0.001]. \tag{8}$$

From these results we can make two comments. First, the amplitude of the cross-correlated radial velocity curves decreases with wavelength. From hydrodynamical modelling, we know that the spectral lines form over a larger part of the atmosphere in the infrared compared to optical (Sasselov et al. 1990). This effect might help us to understand our result: the more extended the line forming regions are, the lower the amplitude of the radial velocity curves. Second, this effect is greater for long-period

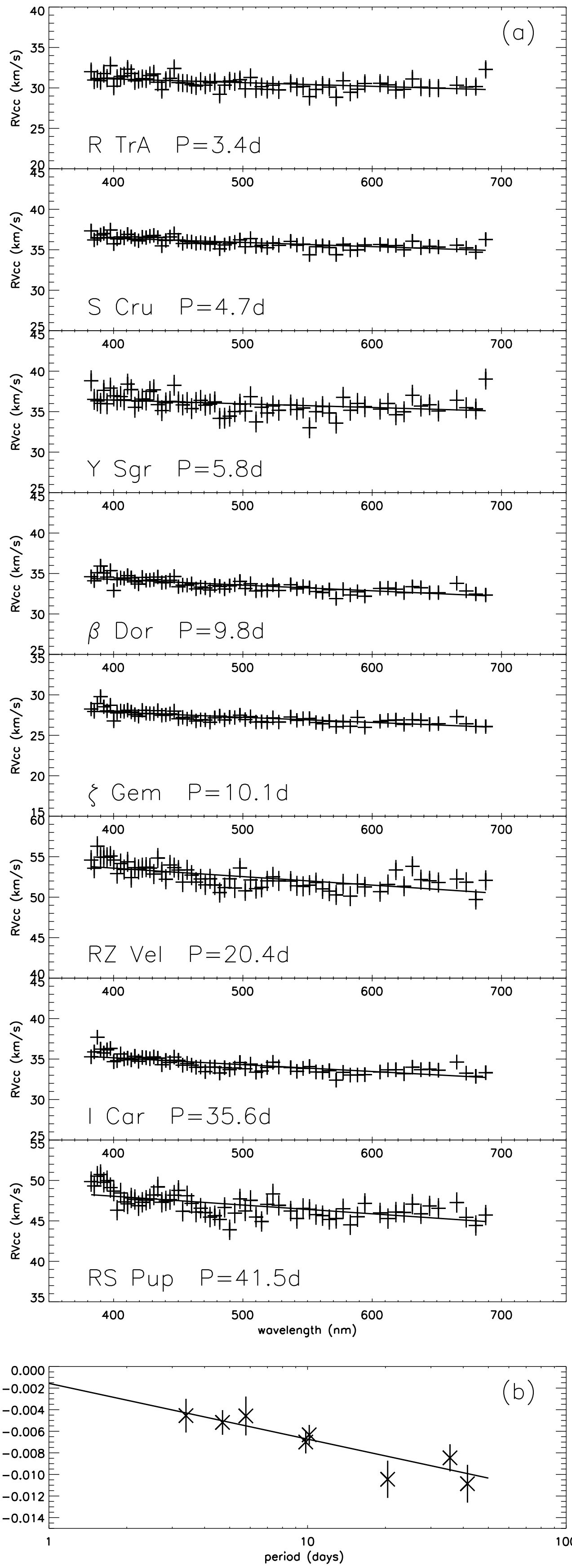

Fig. 3. a) Wavelength dependency of the amplitude of the cross-correlated radial velocity curves for each star in our sample. The corresponding linear relation are defined as: $\Delta RV_{\rm cc} = a_\lambda \lambda + b_\lambda$. **b)** The corresponding slopes (a_λ) as a function of the period.

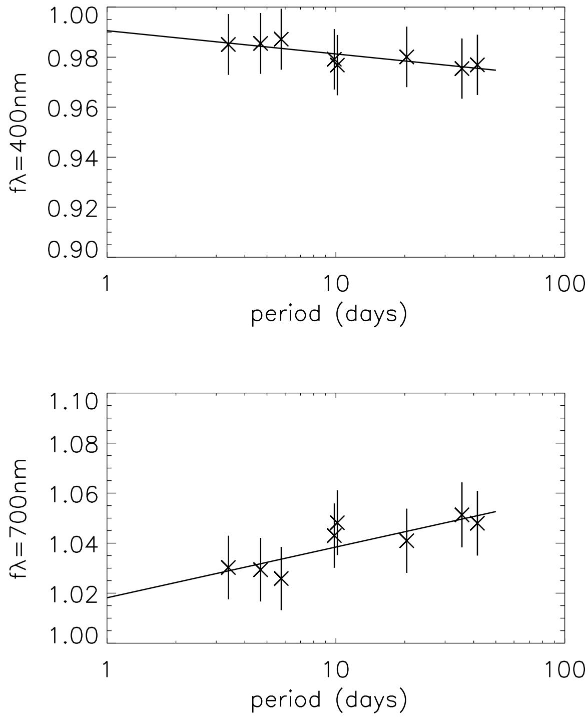

Fig. 4. Corrections to apply to the $Pp_{\rm cc}$ relation (Eq. (5)) in the blue (λ = 400 nm) and in the red (λ = 700 nm).

Table 3. Coefficients of the linear relations between the amplitude of the radial velocity curve and the wavelength.

Name	a_λ	b_λ
R TrA	$-0.005_{\pm 0.002}$	$32.93_{\pm 0.80}$
S Cru	$-0.005_{\pm 0.001}$	$38.50_{\pm 0.58}$
Y Sgr	$-0.005_{\pm 0.002}$	$38.26_{\pm 0.92}$
β Dor	$-0.007_{\pm 0.001}$	$37.06_{\pm 0.54}$
ζ Gem	$-0.006_{\pm 0.001}$	$30.39_{\pm 0.46}$
RZ Vel	$-0.010_{\pm 0.002}$	$57.76_{\pm 0.88}$
ℓ Car	$-0.008_{\pm 0.001}$	$38.54_{\pm 0.64}$
RS Pup	$-0.011_{\pm 0.002}$	$52.39_{\pm 0.89}$

Cepheids than short-period Cepheids. A reason might be that the mean radius, the size of the line-forming regions and the velocity gradient increase with the logarithm of the period.

In order to quantify the wavelength dependency of the $Pp_{\rm cc}$ relation, we define two correction factors ($f_{\lambda=400\ \rm nm} = \frac{\Delta RV_{\rm cc}(\lambda=400\ \rm nm)}{\Delta RV_{\rm cc}}$ and $f_{\lambda=700\ \rm nm} = \frac{\Delta RV_{\rm cc}(\lambda=700\ \rm nm)}{\Delta RV_{\rm cc}}$). We find the following correcting relation as a function of the logarithm of the period:

$$f_{\lambda=400\ \rm nm} = [-0.01 \pm 0.01] \log P + [0.99 \pm 0.01], \quad (9)$$

and

$$f_{\lambda=700\ \rm nm} = [0.02 \pm 0.01] \log P + [1.02 \pm 0.01]. \quad (10)$$

The reduced χ^2 values are respectively 0.3 and 1.3. These relations are shown in Fig. 4. We find that such corrections are currently irrelevant given our statistical uncertainties on the $Pp_{\rm cc}$ relation (Eq. (5)).

6. The CC γ-velocity and the K-term of Cepheids

Interestingly, for each Cepheid in our sample, we found in Paper III a linear relation between the γ-velocities (derived using the first moment method) of the various spectral lines and

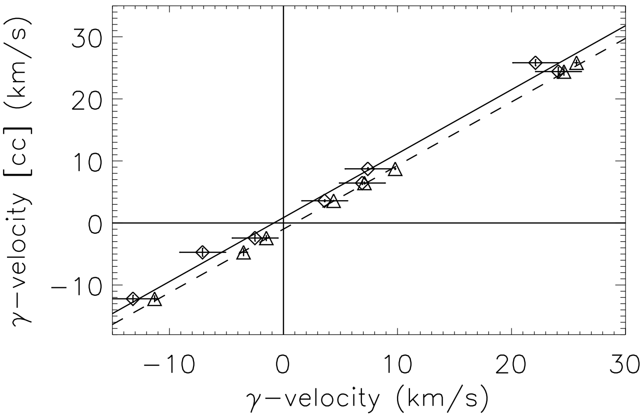

Fig. 5. V_γ [CC] as a function of V_γ[GCD] (diamond) and V_γ[N08] (triangles). The solid and dashed line are the corresponding linear interpolation.

their corresponding γ-asymmetries. Using these linear relations, we provided a physical reference to derive the center-of-mass γ-velocity of the stars (V_γ[N08]): it should be zero when the γ-asymmetry is zero. These values are consistent with an axisymmetric rotation model of the Galaxy. Conversely, previous measurements of the γ-velocities found in the literature (for e.g. Fernie et al. 1995: the Galactic Cepheid Database, hereafter V_γ[GCD]) were based on the cross-correlation method, and by using generally only a few measurements over the pulsation cycle. These results led to an apparent "fall" of Galactic Cepheids towards the Sun (compared to an axisymmetric rotation model of the Milky Way) with a mean velocity of about 2 km s^{-1}. This residual velocity shift has been dubbed the "K-term", and was first estimated by Joy (1939) to be −3.8 km s^{-1}.

We aim to understand why such a 2 km s^{-1} error was obtained before. An hypothesis is that the cross-correlation method is biased by the dynamical structure of the atmosphere of Cepheids. To verify this hypothesis, we have the unique opportunity to compare quantitatively and in a consistent way V_γ[N08], V_γ[GCD] and the γ-velocities derived from our HARPS cross-correlated radial velocity curves (hereafter V_γ[CC]). The comparison is done by plotting V_γ[CC] as a function of V_γ[GCD] and V_γ[N08] respectively (Fig. 5). The data are presented in Table 2 and the resulting linear relations are respectively:

$$V_\gamma[\mathrm{CC}] = [1.03 \pm 0.06] V_\gamma[\mathrm{GCD}] + [0.86 \pm 0.78], \quad (11)$$

and

$$V_\gamma[\mathrm{CC}] = [1.02 \pm 0.02] V_\gamma[\mathrm{N08}] - [0.99 \pm 0.17]. \quad (12)$$

The reduce χ^2 values are respectively 3.0 and 3.8.

Several conclusions can be drawn. The slope of these relations are similar and close to one, which means that there is no particular trend of the γ-velocity with the period of the star, or at least, it remains negligible here. As in Paper III, we find a systematic difference of $0.86 + 0.99 \simeq 1.8$ km s^{-1} between V_γ[N08] and V_γ[GCD], which is consistent with the K-term of Cepheids. However, the γ-velocities we derive in this Paper using the cross-correlation method are systematically lower by (0.9 ± 0.8) km s^{-1} than the ones found in the literature (V_γ[GCD]), and they are systematically larger by 1.0 ± 0.2 km s^{-1} than the calibrated center-of-mass velocities (V_γ[N08]). As a consequence, the cross-correlation method alone cannot explain alone the K-term. The CC method is sensitive to the dynamical structure of the Cepheids' atmosphere in such a way that it is responsible for ≃50% of the K-term. An additional term is required to explain the presence of such offsets in previous determinations of the gamma-velocity. It could be related, for instance, to the quality of observations in the past (Joy et al. 1939) or to the different methods used to derive the γ-velocity (Pont et al. 1994).

7. Conclusions

By comparing the amplitude of our cross-correlated radial velocity curves with previous results based on the first moment method (Paper II), we derived a new *Pp* relation applicable to radial velocities measured by the cross-correlation method. This relation is crucial for the distance scale calibration, and in particular to derive the distances of LMC and SMC Cepheids (Gieren et al. 2005a; Gieren et al. 2009, in preparation). We also find a slight dependence of the *Pp* relation on the wavelength. Considering our current uncertainties this effect is negligible, but it might become significant in the near future. The next steps are to test the impact of the signal to noise ratio, the spectral resolution and the metallicity on the projection factor. The latter point will require a large sample of Cepheids with well-measured metallicities. These studies (including this work) are part of the international "Araucaria Project" whose purpose is to provide an improved local calibration of the extragalactic distance scale out to distances of a few Megaparsecs (Gieren et al. 2005b). Moreover, the fact that the cross-correlation method over-estimates the amplitude of the radial velocity curve and under-estimates the γ-velocity (compared to the calibrated values presented in Paper III) might have some implications for other kinds of pulsating stars, for e.g. in asteroseismology.

Moreover, we show in Paper III that the K-term of Cepheids vanishes if one considers carefully the dynamical structure of Cepheid atmosphere. From the results presented in this paper, we can state that the cross-correlation method might not be totally responsible for the K-term found in the previous studies (only 50% seems to be a consequence of the cross-correlation method). There seems to be another contribution whose nature should be investigated.

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References

Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 373
Burki, G., Mayor, M., & Benz, W. 1982, A&A, 109, 258
Davis, J., Jacob, A. P., Robertson, J. G., et al. 2009, MNRAS, tmp, 244
Fernie, J. D., Beattie, B., Evans, N.R., & Seager, S. 1995, IBVS No. 4148
Fouqué, P., Arriagada, P., Storm, J., et al. 2007, A&A, 476, 73
Gieren, W. P., Fouqué, P., & Gómez, M. 1998, ApJ, 496, 17
Gieren, W. P., Storm, J., Barnes, T. G., et al. 2005a, ApJ, 627, 224
Gieren, W., Pietrzynski, G., Bresolin, F., et al. 2005b, Msngr, 121, 23
Joy, A. H. 1939, ApJ, 89, 356
Kervella, P., Nardetto, N., Bersier, D., et al. 2004, A&A, 416, 941
Mérand, A., Kervella, P., Coude du Foresto, V., et al. 2005, A&A, 438, L9
Nardetto, N., Fokin, A., Mourard, D., et al. 2004, A&A, 428, 131
Nardetto, N., Mourard, D., Kervella, P., et al. 2006, A&A, 453, 309 (Paper I)
Nardetto, N., Mourard, D., Mathias, Ph., et al. 2007, A&A, 471, 661N (Paper II)
Nardetto, N., Stoekl, A., Bersier, D., et al. 2008, A&A, 489, 1255 (Paper III)
Pepe, F., Mayor, M., Galland, F., et al. 2002, A&A, 388, 632
Pont, F., Mayor, M., & Burki, G. 1994, A&A, 285, 415
Sabbey, C. N., Sasselov, D. D., Fieldus, M. S., et al. 1995, ApJ, 446, 250
Sasselov, D. D., Lester, J. B., & Fieldus, M. S. 1990, ApJ, 362, 333