The Leavitt law of Milky Way Cepheids from Gaia DR2 static companion parallaxes

Louise Breuval¹, Pierre Kervella¹, Frédéric Arenou², Giuseppe Bono³,⁴, Alexandre Gallenne⁵,⁶, Boris Trahin¹, Antoine Mérand⁷, Jesper Storm⁸, Laura Inno⁹, Grzegorz Pietrzyński¹⁰,¹¹, Wolfgang Gieren¹², Nicolas Nardetto⁶, Dariusz Graczyk¹⁰,¹¹,²², Simon Borgniet¹, Behnam Javanmardi¹, Vincent Hoebe⁶

LESIA (UMR 8109), Observatoire de Paris, PSL Research University, CNRS, UPMC, Univ. Paris-Diderot, 5 place Jules Janssen, 92195 Meudon, France, e-mail: louise.breuval@obspm.fr

1 GEPI, Observatoire de Paris, Université PSL, CNRS, 5 Place Jules Janssen, 92190 Meudon, France
2 Department of Astronomy, University of Concepción, Casilla 160-C, Concepción, Chile
3 Dipartimento di Scienze e Tecnologie, Parthenope University of Naples, Via Giovanni Porzio, 4, 80143 Napoli NA, Italy
4 European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
5 Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
6 Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, France
7 European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
8 Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
9 Dipartimento di Scienze e Tecnologie, Parthenope University of Naples, Via Giovanni Porzio, 4, 80143 Napoli NA, Italy
10 Universidad de Concepción, Departamento de Astronomía, Casilla 160-C, Concepción, Chile
11 Centrum Astronomiczne im. Mikolaja Kopernika (CAMK), PAN, Bartycka 18, 00-716 Warsaw, Poland
12 Millenium Institute of Astrophysics, Av. Vicuna Mackenna 4860, Santiago, Chile

Received ... ; accepted ...

ABSTRACT

Context. Classical Cepheids (CCs) are at the heart of the empirical extragalactic distance ladder. Milky Way CCs are the only stars of this class accessible to trigonometric parallax measurements. Until recently, the most accurate trigonometric parallaxes of Milky Way CCs were the HST/FGS measurements collected by Benedict et al. (2002, 2007). Unfortunately, the second Gaia data release (GDR2) has not yet delivered reliable parallaxes for Galactic CCs, failing to replace the HST/FGS sample as the foundation of all Galactic calibrations of the Leavitt law (the Period-Luminosity relation).

Aims. We aim at calibrating independently the Leavitt law of Milky Way CCs based on the GDR2 catalog of trigonometric parallaxes.

Methods. As a proxy for the parallaxes of a sample of 23 Galactic CCs, we adopt the GDR2 parallaxes of their spatially resolved companions. As the latter are unsaturated, photometrically stable stars, this novel approach allows us to bypass the GDR2 bias on the parallax of the CCs that is induced by saturation and variability.

Results. We present new Galactic calibrations of the Leavitt law in the J, H, Kₚ, V, Wesenheit Wᵥ, and Wesenheit Wᵥₓ bands based on the GDR2 parallaxes of the CC companions. A similar calibration using the GDR2 parallaxes of the CCs themselves results in a significantly larger scatter. We show that the adopted value of the zero point of the GDR2 parallaxes, within a reasonable range, has a limited impact on our Leavitt law calibration. However, we find a significant difference with respect to the calibration based on the HST/FGS parallaxes, that corresponds to an FGS parallax zero point of $\Delta \approx 200 \mu$as.

Conclusions. The discrepancy that we observe between the GDR2 and HST/FGS parallaxes has important consequences on the existing Galactic calibrations of the Leavitt law. We note that our results translate into a Hubble constant of $68.43 \pm 2.08$ km s⁻¹ Mpc⁻¹ and $69.30 \pm 2.08$ km s⁻¹ Mpc⁻¹ for a GDR2 parallax offset of 0.029 mas and 0.046 mas, respectively.

Key words. Stars; variables: Cepheids; Astrometry; Distance Scale; Period-Luminosity Relation.

1. Introduction

Classical Cepheids have historically a major importance among variable stars because of the simple correlation between their pulsation periods, which are easily measured observationally, and their intrinsic luminosity. The discovery of the Leavitt law, also called the period-luminosity (hereafter PL) relation by Leavitt (1908) (see also Leavitt & Pickering 1912) was the cornerstone of the discovery of the expansion of the universe by Hubble and Lemaitre. However, after more than a century of active research, the absolute calibration of the Leavitt law is still unsatisfactory. The main cause of this situation is the rarity of CCs in the Galaxy, and consequently their large distances from the Sun. This makes the measurement of their trigonometric parallaxes particularly difficult, and even the Hipparcos satellite (Feast & Catchpole 1997; Pont 1999; Groenewegen & Oudmaijer 2000; Di Benedetto 2002; van Leeuwen et al. 2007) was unable to determine sufficiently accurate parallaxes of CCs. Focused efforts, e.g., by Benedict et al. (2002, 2007), Riess et al. (2014) and Casertano et al. (2016) resulted in the measurement of the parallaxes of a limited sample of CCs, with individual precisions in the order of 5 to 15%. As a result, the absolute calibration of the Leavitt law from geometrical distances is uncertain at a $\approx 5\%$ level. It is therefore one of the main contributors to the uncertainty on the Hubble constant $H₀$ (Riess et al. 2016). A careful calibration of this relation and especially of its zero-point is fundamental, as it is used to anchor extragalactic distances and to derive cosmological parameters. Moreover, the current tension
between the determinations of $H_0$ from the Cosmic Microwave Background (CMB) modeling and the empirical distance ladder (see, e.g., Riess et al. 2019; Lemos et al. 2019) may have important implications on, for instance, the equation of state of dark energy.

The calibration of the zero-point of the Leavitt law requires the independent and accurate measurement of the distances of a sample of CCs. Unfortunately, most of Gaia’s second data release (GDR2; Gaia Collaboration et al. 2018) parallaxes of CCs are still affected by systematics. As a consequence, calibrating the PL relation using directly the GDR2 parallaxes of Cepheids leads to ambiguous results (Groenewegen 2018; Riess et al. 2018b; Gaia Collaboration et al. 2017; Clementini et al. 2019).

Kervella et al. (2019b) recently presented a sample of 28 Galactic CCs that are members of spatially resolved stellar systems. These companions are photometrically stable stars (or only very variable at a low level), and their GDR2 parallaxes are therefore not affected by such a strong chromatic PSF effect in the GDR2 as CCs. As the CC and its companion share the same parallax (their relative distance is negligible compared to the distance to the Sun), the GDR2 parallaxes of the CC companions provide a natural proxy for those of the CCs themselves.

Until the beginning of the Gaia era, most (if not all) PL relations for Galactic Cepheids relied on HST measurements (Benedict et al. 2007, 2002; Fouqué et al. 2007). Moreover, the Baade-Wesselink methods are calibrated using the projection factor ($p$-factor) from Cepheids with HST parallaxes (Breitfelder et al. 2016). As a consequence, the corresponding values of $H_0$ derived from these PL relations were also related to the HST (Freedman et al. 2001; Sandage et al. 2006; Riess et al. 2016, 2018a). Our approach is therefore the first solid alternative to Cepheid parallaxes based on HST measurements.

In this paper, we derive calibrations of the Leavitt law in the $J$, $H$, $K_s$, $V$, Wesenheit $W_{VH}$, and Wesenheit $W_{V}$ bands based on this sample of companion parallaxes. We also consider two additional stars with non-GDR2 parallaxes, V1334 Cyg and RS Pup. In Sect. 2.1, we introduce our sample of stars and their associated data. In Sect. 2.2, we determine the absolute magnitudes of the CCs from their parallaxes and averaged apparent luminosities in order to establish the PL relations. Then, we discuss the accuracy of the companion parallaxes from the GDR2 compared to CC parallaxes and we analyze the influence of the zero-point of the GDR2 parallaxes. In Sect. 2.3, we compare our PL relations with those obtained with HST/FGS parallaxes (Benedict et al. 2007) and other previous works. Finally, we discuss the effect of using our Leavitt law calibration as an anchor for the Hubble constant $H_0$.

2. Cepheid sample and observational data

The data described in this section are listed with their uncertainties and references in Tab. 1 and 2.

2.1. Parallaxes

In the determination of Gaia DR2 parallaxes, the astrometric solution depends on magnitude and color-dependent terms. The parallaxes are determined assuming a constant mean color for each star (Lindgren et al. 2018; Gaia Collaboration et al. 2019). However, variable stars, and in particular Cepheids, RR Lyrae and Miras, show large color variations during a cycle, so this assumption is incorrect (Mowlavi et al. 2018). To derive unbiased parallaxes, chromaticity corrections must be applied to every single measurement, but this approach was not adopted in the GDR2 data reduction (see the ESA DR2 web page\footnote{https://www.cosmos.esa.int/web/gaia/dr2}). Moreover, as CCs are intrinsically very bright and distant supergiants, their flux is high, even saturated for all nearby CCs, while their parallax is small. This combination results in an amplification of the relative bias on their parallax due to their variability, and it is likely the cause of the particular behavior of this class of stars in the GDR2.

The Gaia DR2 astrometry is generally of poor quality for very bright stars ($G < 6$ mag), due to calibration issues and saturation (Drimmel et al. 2019; Lindegren 2019; Riess et al. 2018b). This problem occurs independently of the chromaticity issue raised previously, whether the star is variable or not. Although only one of our Cepheids is brighter than 6 mag in the G band (AX Cir), several of them are either very close to this limit (ER Car, V0659 Cen, RS Pup, U Sgr), with a magnitude brighter than 7 or reaching this limiting magnitude along the pulsation cycle. On the other hand, companions are in average 7 mag fainter than their Cepheids, with mean magnitudes between 8 and 15 mag in the G band (except for Delta Cep companion with $G = 6.31$ mag). The companions are therefore not as affected as CCs by the saturation issue and they are far off from the sensitivity limit. They consequently belong to the best dynamical range for Gaia DR2 capability, which shows again that they are a reliable proxy for the CCs parallaxes.

Although the presence of the companion may in principle affect the proper motion of the two components of the system, their parallax would only be affected if the period of the system was close to one year, which is the timeline of Gaia DR2. However, given the separation between the CCs and their companions, the periods of the systems considered in our study are on the order of 10 ka, which means that the parallaxes of the CCs and of the companions are not sensitive to the binarity of the system.

We use the 28 resolved companions of CCs from Kervella et al. (2019b). These authors distinguished gravitationally bound candidate companions from unrelated field stars by using a progressive selection algorithm based on their parallax and relative velocity. After a selection (Sect. 2.2 and 2.5), we use the GDR2 parallaxes of 23 of the companions listed in Kervella et al. (2019b) and we assume that their parallax is identical to that of their parent star. This assumption is justified by the fact that their projected linear separation from the CCs represent typically 0.01% of their distance to the Sun. This sample covers a broad range of periods from 2 to 41 days. The mean relative uncertainty on the Cepheids parallaxes is 9%, but because of their variability, systematic biases are likely to be present on a larger scale. For the companions, the mean relative uncertainty on the parallaxes is 12%. The companions are not variable stars (except CE Cas B, whose companion CE Cas A is also a CC), so their GDR2 parallaxes are expected to be more reliable than those of the CCs. For a given parallax $\varpi_{\text{Gaia}}$ given by GDR2, we use corrected parallaxes $\varpi = \varpi_{\text{Gaia}} - \Delta P_{\text{Gaia}}$, where $\Delta P_{\text{Gaia}}$ is the zero-point of Gaia parallaxes, a value which must be subtracted from all GDR2 parallaxes. We can also define the offset $\Delta_{\text{Gaia}}$ applied on parallaxes as: $\Delta_{\text{Gaia}} = -ZP_{\text{Gaia}}$. The parallaxes given in Tab. 1 are GDR2 parallaxes corrected from an offset $\Delta_{\text{Gaia}} = +0.029$ mas, derived by Lindegren et al. (2018). For a given Cepheid, when more than one companion was found by Kervella et al. (2019b) as CV Mon and SY Nor, we selected the companion with the smallest uncertainty on its parallax.
We also included two additional stars with independently determined parallaxes. The first is the long-period Cepheid RS Puppis, whose distance of $1910 \pm 80$ pc ($\varpi = 0.524 \pm 0.022$ mas) was determined by Kervella et al. (2014) using polarimetric HST images of the light echoes propagating in its circumstellar nebula (see also Kervella et al. 2017). We refer to this particular parallax determination as RS Pupp by Kervella et al. (2014). The second additional star is the binary Cepheid V1334 Cyg, for which Gallenne et al. (2018) obtained a distance of $720.4 \pm 7.8$ pc ($\varpi = 1.388 \pm 0.015$ mas) through the observation of its orbit by spectroscopy and optical interferometry. With an uncertainty of 1\%, this is the most accurate distance measurement of a Cepheid.

### 2.2. Quality indicators

To achieve a better precision on PL relations, we recall that we use the GDR2 parallaxes of the companions given in Kervella et al. (2019b) instead of those of the Cepheids, assuming that they are at the same distance. Since quality are not variable stars, the companions are supposed to have more precise parallaxes than their Cepheid. Various quality indicators are introduced in the second release of Gaia data, such as the astrometric excess noise or the goodness-of-fit (GOF). Another interesting quality indicator is the re-normalised unit weight error (RUWE, noted $\varrho$ in the following; see also Kervella et al. 2019a), it is particularly useful to test because it evaluates the quality of the parallax of a star compared to other stars of the same type. This parameter is defined as follows (Lindgren 2018b)

$$\varrho = \frac{\text{UWE}}{u_0(G, C)}$$

where UWE = $\sqrt{\chi^2/(N - 5)}$ is the unit weight error and $u_0$ is an empirical normalisation factor which is not directly available in the Gaia release but which can be computed from the lookup table on the ESA DR2 Known issues web page. Following Lindgren (2018b), we estimate that a parallax is reliable if $\varrho < 1.4$. The Table 1 gives the RUWE of the stars of Kervella et al. (2019b) and of their companions. We can suggest that the RUWE parameter can be an indicator of a close-in companion of a Cepheid. An example is the star AX Cir, for which a close-in component has been detected by Gallenne et al. (2014).

We note that $\delta$ Cep, R Cru and $\alpha$ UMi (Polaris) have no valid parallax value in the GDR2 catalog. Five CCs have $\varrho > 1.4$, but for all of them, the RUWE of their companion is lower, so we can use its parallax. Among the companions, all of them have a GDR2 parallax and only two have a RUWE over the limit: R Cru and V1046 Cyg, with $\varrho = 2.80$ and 1.51 respectively. We exclude them from the sample in order to keep accurate parallaxes only. The star CE Cas B is a particular case because its companion, CE Cas A, is also a Cepheid. The two components of CE Cas are present in the GDR2, but with statistically different parallaxes ($\varpi_A = 0.317 \pm 0.031$ mas; $\varpi_B = 0.262 \pm 0.030$ mas). The GDR2 parallax of component B is likely biased, possibly due to light
contamination from the nearby component A. We exclude both stars from our sample as a precaution.

The angular separation between the CCs and their companions in most cases larger than 10 arcsec, which is large enough to prevent flux contamination, given the brightness of the CCs. If, by any chance, a companion was contaminated by the brightness of its Cepheid, this contamination would be seen in its RUWE parameter. As we rejected any star with a RUWE larger than 1.4, the flux contamination should not introduce any bias to our results.

2.3. Photometry

To determine the phase-averaged magnitude of the CCs of our sample, we first searched them in the catalogue of 452 CCs assembled by Kervella et al. (2019b) and V1334 Cyg (Gallenne et al. 2018).

Table 2. Averaged apparent magnitudes in V, J, I, H, Ks bands, in Wesenheit Wv,k and Wh bands, and color excess E(B-V) for the Cepheids from Kervella et al. (2019b) and V1334 Cyg (Gallenne et al. 2018)

| Star     | E(B-V) | <V >  | <I >  | ref | <J >  | <H >  | <Ks>  | e_MHK | ref |
|----------|--------|-------|-------|-----|-------|-------|-------|-------|-----|
| TV CMa   | 0.611  | 10.59 | 9.180 | a   | 8.022 | 7.582 | 7.364 | 0.008 | e   |
| ER Car   | 0.118  | 6.82  | 5.932 | a   | 5.310 | 5.034 | 4.896 | 0.008 | f   |
| DF Cas   | 0.600  | 10.88 | 9.800 | b   | 8.848 | 8.036 | 7.879 | 0.025 | g   |
| V0659 Cen| 0.101  | 6.62  | 5.735 | a   | 5.177 | 4.907 | 4.651 | 0.025 | g   |
| δ Cep    | 0.080  | 3.95  | 3.260 | b   | 2.683 | 2.396 | 2.294 | 0.010 | h   |
| AX Cir   | 0.282  | 5.88  | 5.090 | b   | 4.299 | 3.879 | 3.780 | 0.025 | g   |
| BP Cir   | 0.274  | 7.55  | 6.639 | a   | 5.870 | 5.626 | 5.483 | 0.008 | f   |
| X Cru    | 0.313  | 8.40  | 7.292 | a   | 6.521 | 6.125 | 6.001 | 0.025 | i,g |
| VW Cru   | 0.681  | 9.60  | 7.978 | a   | 6.805 | 6.261 | 6.051 | 0.025 | g   |
| V0532 Cyg| 0.552  | 9.09  | 7.845 | a   | 6.863 | 6.393 | 6.250 | 0.025 | j   |
| V1334 Cyg| 0.025  | 5.86  | 5.310 | b   | 4.817 | 4.536 | 4.510 | 0.020 | k   |
| CV Mon   | 0.750  | 10.31 | 8.650 | a   | 7.314 | 6.781 | 6.529 | 0.008 | e   |
| RS Nor   | 0.614  | 10.00 | 8.523 | a   | 7.412 | 6.794 | 6.683 | 0.020 | k   |
| SY Nor   | 0.650  | 9.50  | 7.904 | a   | 6.574 | 6.105 | 5.865 | 0.008 | f   |
| QZ Nor   | 0.307  | 8.87  | 7.865 | a   | 7.085 | 6.748 | 6.614 | 0.008 | l   |
| AW Per   | 0.510  | 7.48  | 6.173 | a   | 5.213 | 4.832 | 4.657 | 0.008 | e   |
| RS Pup   | 0.480  | 7.01  | 5.479 | a   | 4.365 | 3.828 | 3.619 | 0.008 | l   |
| U Sgr    | 0.434  | 6.69  | 5.436 | a   | 4.506 | 4.109 | 3.912 | 0.008 | e   |
| V0350 Sgr| 0.328  | 7.47  | 6.413 | a   | 5.625 | 5.245 | 5.121 | 0.010 | i   |
| V0950 Sco| 0.267  | 7.31  | 6.404 | a   | 5.681 | 5.439 | 5.295 | 0.008 | f   |
| CM Sct   | 0.824  | 10.11 | 9.532 | c   | 8.300 | 7.818 | 7.558 | 0.025 | g   |
| EV Sct   | 0.663  | 10.13 | 8.668 | a   | 7.608 | 7.184 | 7.018 | 0.008 | l   |
| α UMi    | 0.017  | 1.98  | 1.270 | b   | 0.941 | 0.460 | 0.652 | 0.025 | m   |
| SX Vel   | 0.252  | 8.29  | 7.261 | a   | 6.500 | 6.133 | 5.991 | 0.008 | l   |
| CS Vel   | 0.762  | 11.7  | 10.078| c   | 8.771 | 8.246 | 8.011 | 0.008 | l   |
| DK Vel   | 0.301  | 10.69 | 9.920 | b   | 8.820 | 8.496 | 8.386 | 0.025 | g   |

References. (a) Gaia Collaboration et al. (2017); (b) ESA (1997); (c) Droege et al. (2006); (d) Ngeow & Kanbur (2006); (e) Monson & Pierce (2011); (f) Laney (private communication); (g) Genovali et al. (2014); (h) Barnes et al. (1997); (i) Welch et al. (1984); (j) 2MASS (Skrutskie et al. 2006); (k) SPIPS algorithm (Mérand et al. 2015); (l) Laney & Stobie (1992); (m) Groenewegen (2018)
The average apparent magnitudes in J, H and V bands are those from Table 2 and apparent magnitudes in the I band are taken from Gaia Collaboration et al. (2017); ESA (1997); Droge et al. (2006); Ngeow & Kanbur (2006) with an uncertainty set to 0.02 mag.

### 2.4. Color Excess

In order to determine absolute magnitudes, we need to correct the apparent magnitudes from the interstellar absorption. The values of \( E(B-V) \) are taken from the DDO database \(^{[1]}\) Fernie et al. 1995 which is a compilation of various \( E(B-V) \) from the literature determined in the same system. For the star V1334 Cyg, the color excess given in the DDO database is negative, so we took it from Kovtyukh et al. (2008).

### 2.5. Pulsation modes

The identification of first overtone Cepheids is essential for the calibration of the Leavitt law. Here we review the different pulsation modes found in the literature for the stars of our sample.

Gaia DR2 classifies the Cepheids BP Cir, EV Sct, V0532 Cyg, V0950 Sco, QZ Nor and DK Vel as first overtones. Bono et al. (2001) agrees with this classification for EV Sct and QZ Nor.

The star α UMi has no pulsation mode given by GDR2 but Bono et al. (2001), Spreckley & Stevens (2007) and Fouqué et al. (2007) classified it as a first overtone.

V1334 Cyg, which is one of our two additional stars, is classified as a fundamental pulsator according to GDR2 but Galленne et al. (2018) [Luck (2018) and Kovtyukh et al. (2012)] conclude that it is a first overtone. We thus consider this star as a first overtone. Its period was converted by Galленne et al. (2018) from the first overtone into its equivalent fundamental mode.

For the two stars BP Cir and DK Vel, GDR2 found a first overtone pulsation mode. This classification is confirmed by Zabolotskikh et al. (2004) for both Cepheids, and also by Evans et al. (1992) and Usenko et al. (2014) for BP Cir, but the recent paper from Luck (2018) classifies them as fundamentals. Given the disagreement between the sources about the pulsation mode of BP Cir and DK Vel, we decide to exclude them from the sample.

The Cepheid V0659 Cen is pulsating on its fundamental mode according to Gaia, but Zabolotskikh et al. (2004) found that it is a first overtone. As the star is consistent with a fundamental mode in our diagram, we consider here that V0659 Cen is a fundamental pulsator.

For all the CCs of our sample except V1334 Cyg, the pulsation modes given by Gaia DR2 are confirmed by the recent reclassification of Ripepi et al. (2019). The pulsation modes of the stars of our CC sample taken from different sources are given in Table 3. The second column of this table (GDR2) shows the pulsation mode provided by the GDR2 catalog, the third column gives it according to the literature, and the last column gives the pulsation mode that we adopted.

In order to establish accurate PL and PW relations without excluding the first overtones, we converted their observed periods \( P_{FO} \) into the fundamental mode equivalent period \( P_{F} \) using the equation by Feast & Catchpole (1997)

\[
P_{FO}/P_{F} = 0.716 - 0.027 \log P_{FO}
\]

The period modification of these six first overtone CCs is listed in Table 4 and shown in Fig. 4 using horizontal gray dashed lines. The result obtained after the period transformation is consistent with the distribution of the fundamental pulsators in the PL plane.

### Table 3. Pulsation mode of the Cepheids of our sample.

| Cepheid     | GDR2 | Literature | Adopted |
|-------------|------|------------|---------|
| TV CMa      | F    | -          | F       |
| ER Car      | F    | -          | F       |
| DF Cas      | F    | -          | F       |
| V0659 Cen   | FO   | \( a_i,j \) | F       |
| \( \delta \) Cep | -    | -          | -       |
| AX Cir      | F    | -          | F       |
| BP Cir      | FO   | \( a_i,j \) | F       |
| X Cru       | F    | -          | F       |
| VW Cru      | F    | -          | F       |
| V0532 Cyg   | FO   | \( j \)    | FO      |
| V1334 Cyg   | F    | \( j \)    | FO      |
| CV Mon      | -    | -          | F       |
| RS Nor      | -    | -          | -       |
| SY Nor      | -    | -          | F       |
| QZ Nor      | FO   | \( k,j \)  | FO      |
| AW Per      | F    | -          | F       |
| RS Pup      | F    | -          | F       |
| U Sgr       | F    | -          | F       |
| V0350 Sgr   | -    | -          | F       |
| V0950 Sco   | FO   | \( j \)    | FO      |
| CM Set      | F    | -          | F       |
| EV Set      | FO   | \( k,j \)  | FO      |
| \( \alpha \) UMi | -  | \( a_i,j \) | FO      |
| SX Vel      | F    | -          | F       |
| CS Vel      | F    | -          | F       |
| DK Vel      | FO   | \( a_i,j \) | F       |

Notes. \( F \) = Fundamental; ‘FO’ = First Overtone; \(*\) = excluded because of uncertain pulsation mode.

### Table 4. Transformation of first overtones into fundamental pulsators.

| Cepheid     | \( P_{FO} \) (days) | \( P_{F} \) (days) |
|-------------|----------------------|---------------------|
| EV Sct      | 3.0910               | 4.3983              |
| V0532 Cyg   | 3.2836               | 4.6771              |
| V1334 Cyg   | 3.3330               | 4.7900              |
| V0950 Sco   | 3.3804               | 4.8174              |
| QZ Nor      | 3.7860               | 5.4056              |
| \( \alpha \) UMi | 3.9696          | 5.6722              |

### 3. Calibration of the Leavitt law of MW Cepheids

#### 3.1. Astrometry Based Luminosities

In order to calibrate near-infrared (NIR) and optical PL relations, as well as Period-Wesenheit (PW) relations, we used the approach introduced by Feast & Catchpole (1997) and Arenou & Luri (1999) and we computed the Astrometric Based Luminosity (ABL), defined as:

\[
ABL = 10^{0.2M} = \sigma 10^{0.2m-2}
\]

---

*Breuval et al.: The Leavitt law of Milky Way Cepheids from Gaia DR2*
where $M$ is the absolute magnitude, $m$ is the dereddened apparent magnitude and $\varpi$ is the parallax in milliarcseconds.

Calibrating the Leavitt Law following this approach is equivalent to determine the coefficients $a$ and $b$ in the equation:

$$ ABL = 10^{0.2[a \cdot \log(P - \log(P_0)] + b)} $$

One advantage of using ABL instead of absolute magnitudes is that the results are not subject to the Lutz-Kelker bias (Lutz & Kelker 1973) as modified by Hanson (1979) (hereafter LKH bias). Moreover, the ABL have symmetrical error bars.

The LKH correction only occurs when a truncation is performed on the observed parallaxes. In the search of companions by Kervella et al. (2019b), no selection was carried on GDR2 parallaxes of CCs, and they range in a particularly large interval ([0.2 - 7.3] mas), which justifies why the LKH correction is unnecessary for this sample. We still note the presence of a natural bias which is beyond our control: the more distant is a Cepheid, the harder it is to detect a companion around it. However, if Cepheids with small parallaxes were available and hosted companions, their parallaxes would be too small to be reliable for our study.

The extinction $A_\lambda = R_\lambda E(B-V)$ is computed using the multiplicative total-to-selective absorption ratios from Fouqué et al. (2007) that is based on the Laney & Caldwell (2007) system: $R_V = 3.23$ (Sandage et al. 2004) $R_J = 0.94$, $R_H = 0.58$, and $R_K = 0.38$. The uncertainties on the absolute magnitudes are dominated by the uncertainties of the parallaxes.
According to, e.g., Benedict et al. (2007) and Riess et al. (2018b) a small correction on the derived absolute magnitudes should be made for the Lutz-Kelker bias (Lutz & Kelker 1973) as modified by Hanson (1979, hereafter LKH bias) This bias depends on the sample of stars and on the parallaxes distribution (Oudmaijer et al. 1998) Koen & Laney (1998) showed that the LKH bias can only arise when the sample of stars is selected on the basis of parallax. For our sample, the stars are not selected according to their parallax, so following the criterion of Koen & Laney (1998) we therefore do not apply any LKH correction on our absolute magnitudes.

3.2. Fit of the PL relation

We performed a weighted fitting of the ABL function by using the curve_fit function from the python Scipy library to fit the PL relation in the different bands. The robustness of the fit and of the uncertainties is ensured by a bootstrapping method, applied with 50000 iterations. The distributions of the slope and zero-point of our $K_p$ Leavitt law inferred from companion GDR2 parallaxes and obtained by this technique are represented on Fig. [A.1] in Appendix.

The PL diagrams represented in Fig. 1 were obtained with the Gaia DR2 parallaxes of the companions (top panel) and of the CCs themselves (bottom panel). We chose to represent the PL diagram in the $K_p$ band because it exhibits a low intrinsic dispersion. The stars that contribute the most to the linear fit, for which $S/N > 7$, are represented in dark blue, while the other stars are shown in grey. In the lower panel of each diagram are shown the residuals in terms of parallax, computed as the difference between the input GDR2 parallax and the parallax given by the best fit. The empty circles represent first overtone pulsators and the two red points are the two additional stars with independent distance measurement, V1334 Cyg and RS Pupecho.

We used the formalism detailed in Gallenne et al. (2017), i.e. we adopted the following linear parametrization:

$$M_i = b_1 + a_1 \log P - \log P_0$$

where $a_1$ and $b_1$ are respectively the slope and the zero-point of the PL relation. Such a parametrization removes the correlation between $a_1$ and $b_1$ and minimizes their respective uncertainties. The optimum value of $P_0$ depends on the dataset (see Gallenne et al. 2017 for further details):

$$\log P_0 = \frac{\langle \log P_i / \epsilon_i^2 \rangle}{\langle 1/\epsilon_i^2 \rangle}$$

where $\log P_i$ are the periods of the stars, and $\epsilon_i$ are the uncertainties on their mean magnitude measurements; $\langle \rangle$ denotes the averaging operator. We find our sample centered around $\log P_0 = 0.77$. We use this value in the following, except in Sect. 4.2 where we set $\log P_0 = 1$ in order to compare our results with other PL from the literature more easily.

Even if converting first overtones into fundamentals may introduce a small uncertainty on the period, we decide not to exclude them from our sample. Fundamentalizing those six stars instead of rejecting them induces only a very small change on the intercept of the PL relation and allows to improve the precision of the fit.

For example, if we fundamentalize the overtones, the sample includes 25 Cepheids and we obtain $K_p = -5.125 \pm 0.031 - 3.341 \pm 0.161 \log P - 0.77$, which gives $K_p = -4.223 \pm 0.053$ mag at $\log P = 0.5$ and $K_p = -5.893 \pm 0.048$ mag at $\log P = 1$. If we excluded those six Cepheids, the sample would be reduced to 19 stars and we would get $K_p = -5.139 \pm 0.060 - 3.346 \pm 0.261 \log P - 0.77$, which gives $K_p = -4.236 \pm 0.092$ mag and $K_p = -5.909 \pm 0.085$ mag respectively for $\log P = 0.5$ and $\log P = 1$. The current findings agree, within the errors, either neglecting or including first overtones. However, the precision of the fit is significantly better when the first overtones are fundamentalized. In the following, the observed period of first overtone CCs is not represented anymore, but only the fundamentalized period.

3.3. The Leavitt law from Cepheid and companion parallaxes

In this section, we assess the GDR2 parallaxes of the resolved companions compared to the parallaxes of their Cepheid parent stars. Figure 2 shows the difference between GDR2 parallaxes of CCs and of their associated companion, against the parallaxes predicted by Berdnikov et al. (2000). We notice that in some cases the parallaxes of CCs and of their companions show significant differences with the predicted values. As a general trend, the CC parallaxes appear slightly smaller than the companion parallaxes.

Figure 2 shows a comparison of the PL relations obtained in the $K_p$ band using the GDR2 parallaxes of: 1) the companions (left panel), and 2) the CCs (right panel). When we adopt the CC parallaxes, the error bars are smaller than when we use the companion parallaxes, because CCs are brighter than their companions. But as we mentioned in Sect. 2.1 the variability of CCs is problematic for the present astrometric processing, resulting in a possible bias. As a result, the CC parallax values in the GDR2 catalog are unreliable and the formal associated uncertainties are underestimated. We note that the $\chi^2$ is smaller when we use the companion parallaxes: we obtain a reduced $\chi^2$ = 0.85 with companion parallaxes compared to $\chi^2$ = 2.01 with the CCs parallaxes. This is also the case in the $V$, $J$ and $W_K$ bands (see Table B.1 in Appendix).

We can infer from this comparison that the idea of using the parallaxes of the companions is reliable and that the PL relations derived are more precise when the companion parallaxes are used instead of the CC parallaxes. Moreover, the two closest
Table 5. Zero-point offset for GDR2 parallaxes found in the literature.

| ZP$_{\text{Gaia}}$ (mas) | Reference                                      | Type of sources     |
|--------------------------|------------------------------------------------|---------------------|
| −0.029                   | Lindegren et al. (2018)                        | Quasars             |
| −0.031 ±0.011            | Graczyk et al. (2019)                          | Eclipsing binaries  |
| −0.0319 ±0.0008          | Arenou et al. (2018)                           | MW Cepheids         |
| −0.035 ±0.016            | Sahlihoft & Silva Aguirre (2018)               | Dwarf stars         |
| −0.041 ±0.010            | Hall et al. (2019)                             | Red giants          |
| −0.046 ±0.013            | Riess et al. (2018b)                           | MW Cepheids         |
| −0.049 ±0.018            | Groenewegen (2018)                             | MW Cepheids         |
| −0.053 ±0.003            | Zinn et al. (2019)                             | Red giants          |
| −0.054 ±0.006            | Schönrich et al. (2019)                        | GDR2 RV             |
| −0.057 ±0.003            | Muraveva et al. (2018)                         | RR Lyrae            |
| −0.070 ±0.010            | Ripepi et al. (2019)                           | LMC Cepheids        |
| −0.082 ±0.033            | Stassim & Torres (2018)                        | Eclipsing binaries  |

Table 6. PL and PW relations obtained with the Gaia DR2 parallaxes of Cepheid companions, for a fixed parallax zero-point of −0.029 mas. The equations are of the form $M = a(log P − 0.77) + b$.

| band       | $a$          | $b$          | $\chi^2$ | $\sigma$ |
|------------|--------------|--------------|----------|----------|
| $V$        | $−2.521^{±0.181}$ | $−3.744^{±0.030}$ | 0.80     | 0.32     |
| $J$        | $−3.142^{±0.130}$ | $−4.807^{±0.018}$ | 0.64     | 0.33     |
| $H$        | $−3.304^{±0.423}$ | $−5.142^{±0.070}$ | 2.33     | 0.35     |
| $K_S$      | $−3.341^{±0.161}$ | $−5.125^{±0.031}$ | 0.85     | 0.32     |
| $W_{VK}$   | $−3.442^{±0.180}$ | $−5.307^{±0.036}$ | 0.96     | 0.33     |
| $W_H$      | $−3.481^{±0.553}$ | $−5.364^{±0.082}$ | 3.03     | 0.36     |

We can also evaluate the influence of the two additional stars, RS Pup, RS Pup, and V1334 Cyg, on the quality of the fit. These two stars have a parallax accuracy better than most stars of the sample, so they have an important weight in the fit. Without these two additional stars, the linear fit of the data gives in the $K_S$ band:

$$K_S = −5.130^{±0.038} − 3.227^{±0.029}(\log P − 0.77)$$

with $\chi^2 = 0.88$. When they are taken into account, $\chi^2 = 0.85$ and the PL relation becomes:

$$K_S = −5.125^{±0.031} − 3.341^{±0.016}(\log P − 0.77)$$

The uncertainty on the slope is divided by two when the additional stars are included, and the two equations are consistent within their error bars. We also observe in the upper panel of Fig. 1 that the two corresponding points, represented in red, are in agreement with the other stars of the sample. We therefore include these two stars in our fit of the PL and PW relations.

3.4. Gaia DR2 parallax offset

After the second Gaia data release, many authors found different possible offset values for the parallaxes. Lindegren et al. (2018) used quasars to derive that Gaia parallaxes are underestimated by 0.029 mas. Based on Milky Way Cepheids, Arenou et al. (2018) finds ZP$_{\text{Gaia}} = −0.0319$ mas, while Riess et al. (2018b) derive ZP$_{\text{Gaia}} = −0.046$ mas. From detached eclipsing binaries and surface brightness-color relations, Graczyk et al. (2019) derived a zero-point shift of −0.031 mas. The recent work of Ripepi et al. (2019) suggested that the GDR2 parallaxes may be underestimated by 0.070 mas. Here we study the influence of the parallax zero-point on the calibration of the CC PL relations. The recent determinations of ZP$_{\text{Gaia}}$ are listed in Table 5.

In Table B.2 in Appendix, we list the PL and PW relations obtained for different values of ZP$_{\text{Gaia}}$. In Fig. 3 we represent in blue the intercept as a function of slope of our PL relation in the $K_S$ band, for different values of $\log P$. The different shades of blue represent the different parallax zero-point values: [0; −0.029; −0.046; −0.070] mas, from the lightest to the darkest blue. This diagram shows the influence of ZP$_{\text{Gaia}}$ on the calibration of the PL relation slope and intercept. The comparison of our PL relation with other results from the literature will be discussed in Sect. 4.2. Changing the value of ZP$_{\text{Gaia}}$ has a relatively small effect on the slope and intercept of the PL relation. For example, most of the recent determinations of ZP$_{\text{Gaia}}$ range between 0.029 and 0.070 mas, which corresponds to a change of 0.038 mag for the intercept and 0.051 mag for the slope. This shift is of the order of the error bars of the PL relation. In all bands, rising the value of the offset (that is equivalent to making the zero-point more negative) decreases the intercept of PL and PW relations. This results in less luminous CCs, as expected from their increased parallaxes.

In the following sections, we chose to set the GDR2 parallax zero-point to −0.029 mas, as Kervella et al. (2019b) did for their resolved CC companion search.

4. Discussion

4.1. Comparison with the HST/FGS parallax sample

In order to test the quality of the companions GDR2 parallaxes, we compared our calibration of the Leavitt Law in the $K_S$ band with another PL relation based on HST/FGS parallaxes. In this section, we extend the initial sample by including 9 additional stars with HST parallaxes. Those parallaxes are taken from Benedict et al. (2002, 2007) and were measured using the Fine Guidance Sensor (FGS) on board the Hubble Space Telescope (HST).

In this sample, only FF Aql is classified as a first overtone by GDR2. We found various results about this CC: while some authors classified it as a fundamental pulsator (Gallenne et al. 2012; Groenewegen 2018; Ripepi et al. 2007 and Marang et al. 2010), others claimed it is a first overtone (Feast & Catchpole 1997; Groenewegen 2018; Ripepi et al. 2019). We tried both pulsation modes: considering FF Aql as a
fundamental pulsator is in perfect agreement with the fit of the 9 other CCs of Benedict et al. (2007), while assuming it is a first overtone moves the CC away from the PL sequence at more than 3σ. We finally decided to discard FF Aql from the sample for safety.

These nine stars are listed with their data in Table 7. We stress here that only parallaxes were retrieved from Benedict et al. (2002, 2007). The magnitudes are from the Groenewegen (2018) catalog and the color excesses are from the DDO database Fernie et al. (1995) to be consistent with our GDR2 sample.

In order to compare our results with the FGS sample of Benedict et al. (2007), we plot them together on the same PL diagram, in the Ks band (see Fig. 4). The fit of GDR2 data is represented by a blue line and the fit of FGS data is in green. The lower panel shows the residuals in terms of parallax (in mas), which is defined as the difference between the observed parallaxes and the best fit based on the GDR2 parallaxes. The green line in the lower panel represents a parallax excess of 0.25 mas.

We can notice that the PL relation based on FGS parallaxes is shifted towards the bottom of the diagram compared to the relation based on GDR2 parallaxes. This discrepancy may be explained by the presence of an uncorrected ΔFGS zero-point offset of the HST/FGS parallaxes, or a bad choice of the GDR2 parallaxes zero point.

As a first hypothesis, we assume a fixed offset of ZPGaia = −0.029 mas for GDR2 parallaxes and we try to determine a possible ZP for FGS parallaxes. We fix the slope of the FGS sample to the value found for the GDR2 sample. In order to match the FGS points with the GDR2 relation (i.e. to decrease their absolute magnitude), we need to reduce their parallax values. Therefore, we apply a positive zero-point on the FGS parallaxes. The best agreement is found by applying ZPFGS = 0.23 ± 0.02 mas to the HST/FGS parallaxes. Moreover, we notice that the dispersion of FGS points in the PL diagram is substantially improved by this offset correction (χ² = 0.47 and χ² = 0.32, respectively before and after applying the offset).

Alternatively, we here assume that FGS parallaxes do not need any offset correction and we look for a value of ZP Gaia that would minimize the discrepancy between the two samples. We find that raising the GDR2 offset higher than 0.029 mas increases considerably the dispersion of the GDR2 points (χ² = 0.85 and χ² = 2.16, respectively with offsets of 0.029 and 0.100 mas). An offset of at least 0.2 mas is needed to match GDR2 points with the FGS fit. Such a high GDR2 zero point seems very unlikely, according to the recent various determinations of ZPGaia listed in Table 5.

We note that the FGS sample includes the brightest and closest Cepheids, which all have very large parallaxes (1.9 mas < σ < 3.66 mas). Contrary to our GDR2 Cepheids, this sample presents an obvious selection on the observed parallaxes, which means that the LKH bias, mentioned in Sect. 3.1, should be corrected, as done by Benedict et al. (2007). As a test, we applied the LKH correction on the FGS sample, with the values from Benedict et al. (2007). This correction yields an offset of 0.19 ± 0.02 mas between the two samples, instead of 0.23 ± 0.02 found without LKH correction. The effect of the LKH correction is not significant, and does not allow us to solve the discrepancy. It is represented as a dashed green line in Fig. 4. We also found in Smith (2003) and Francis (2014) that the LKH correction should not be applied in the case of individual stars.

The prototype δ Cep is particularly interesting for this study because it is available in both GDR2 and FGS samples: it hosts a resolved companion, and its parallax has also been measured by the HST/FGS. In addition, it is one of the closest CCs, and has a precise parallax from both techniques: the parallax of its companion from GDR2 is 3.393 ± 0.049 mas and its parallax from HST/FGS is 3.66 ± 0.15 mas. These two points are not in agreement within their error bars. To match the FGS parallax of δ Cep with the GDR2 companion value within 1σ without applying any LKH correction, an offset of −0.27 mas (−7% in relative terms) is necessary on the FGS parallax.

We conclude that FGS parallaxes, whether they take into account the LKH correction or not, are in disagreement with the GDR2 companion parallaxes. This could suggest that FGS parallaxes are likely biased due to an uncorrected zero point offset,
or it could be explained by a combination of biases on both FGS and Gaia DR2 parallaxes.

### 4.2. Comparison with other Leavitt law calibrations

We here compare different PL relations from the literature to our results (listed in Table 8). Groenewegen (2018) provides relations in the $V$, $K_S$ and $W_{14}$ bands. His work is based on a large sample of CCs whose parallaxes are taken from the GDR2 catalog. This author adopted several different values for GDR2 parallaxes zero point offset. We chose to retrieve his PL relations in the case where he assumes an offset of 0.029 mas, as it is the value that we decided to apply to our sample. Fouqué et al. (2007) derived PL relations in the $V$, $J$, $H$ and $K_S$ bands from HST/FGS parallaxes and revised Hipparcos distance measurements. Gieren et al. (2018) used an infrared surface brightness (IRSB) Baade-Wesselink method to determine individual distances to CC sample and build PL relations in the $V$, $J$ and $K$ bands. His PL relation in the $K$ band is expressed in the UKIRT system. According to Carpenter (2001), the difference between $K$ magnitudes in the UKIRT system and in the 2MASS system is of the order of 0.003 mag. We decide to ignore this correction and to compare directly this PL relation with others PL relations in the 2MASS system. Benedict et al. (2007) derived PL relations in $V$ and $K$ bands from the same HST/FGS parallaxes that we used in the previous section, taking into account the LKH correction. Their $K$ magnitudes are in the CIT system, which, contrary to the UKIRT magnitudes, show a small but significant difference with 2MASS magnitudes. In order to compare this PL relation with our results, we converted their $K$ magnitudes from the CIT to the 2MASS system, using the equation from Carpenter (2001). Finally, Riess et al. (2016) used $J$, $H$, $V$ and $I$ magnitudes and spatial scanning parallaxes from the HST-WFC3 instrument to derive a PW relation in the Wesenheit $W_H$ band.

---

**Fig. 4.** Period-luminosity relation in the $K_S$ band for the Cepheid companion sample (GDR2 parallaxes) and the Cepheid sample from Benedict et al. (2007) (HST/FGS parallaxes).

**Table 7.** Data for the Cepheids with HST/FGS parallaxes. The parallaxes and LKH values are from Benedict et al. (2007) $E(B-V)$ from the DDO database (Fernie et al. 1995) $V$ apparent magnitudes from Mel’nik et al. (2015) and $J$, $H$, $K_S$ apparent magnitudes from the Groenewegen (2018) catalog, a compilation of apparent magnitudes in different systems from the literature and converted here in the 2MASS system.

| Star  | Period | $\sigma$ (mas) | $<J>$ | $<H>$ | $<K_S>$ | $\epsilon_{JHK}$ | ref | $<V>$ | $E(B-V)$ | LKH |
|-------|--------|----------------|-------|-------|---------|------------------|-----|-------|----------|-----|
| FF Aql | 4.471  | 2.81±0.18     | 3.854 | 3.592 | 3.468   | 0.010           | i   | 5.37  | 0.211±0.008 | -0.03 |
| RT Aur | 3.728  | 2.40±0.19     | 4.284 | 4.050 | 3.943   | 0.008           | a   | 5.45  | 0.063±0.025 | -0.05 |
| l Car  | 35.551 | 2.01±0.20     | 1.706 | 1.225 | 1.073   | 0.008           | b   | 3.70  | 0.163±0.017 | -0.08 |
| δ Cep  | 5.366  | 3.66±0.15     | 2.688 | 2.401 | 2.299   | 0.010           | c   | 3.95  | 0.080±0.019 | -0.01 |
| ζ Gem  | 10.151 | 2.78±0.18     | 2.564 | 2.217 | 2.116   | 0.008           | d   | 3.92  | 0.044±0.020 | -0.03 |
| β Dor  | 9.842  | 3.14±0.16     | 2.387 | 2.043 | 1.943   | 0.008           | b   | 3.76  | 0.080±0.015 | -0.02 |
| W Sgr  | 7.595  | 2.28±0.20     | 3.323 | 2.965 | 2.801   | 0.025           | e   | 4.67  | 0.116±0.011 | -0.06 |
| X Sgr  | 7.013  | 3.00±0.18     | 2.970 | 2.634 | 2.511   | 0.008           | d   | 4.56  | 0.201±0.021 | -0.03 |
| Y Sgr  | 5.773  | 2.13±0.29     | 4.071 | 3.713 | 3.589   | 0.010           | f   | 5.75  | 0.216±0.014 | -0.15 |
| T Vul  | 4.435  | 1.90±0.23     | 4.545 | 4.281 | 4.179   | 0.010           | c   | 5.75  | 0.098±0.018 | -0.12 |

References. (a) Monson & Pierce (2011); (b) Laney & Stobie (1992); (c) Barnes et al. (1997); (d) Feast et al. (2008); (e) 2MASS (Skrutskie et al. 2006); (f) Welch et al. (1984).
In Fig. 5 we represent the intercept against the slope of PL relations in the $K_\text{S}$ band for different values of $\log P$. In the present work, we find a slope comparable to the values of Fouqué et al. (2007), Benedict et al. (2007), and Gieren et al. (2018). However, the slope found by Groenewegen (2018) is shallower than our value, while our intercept is larger than the one found by Groenewegen (2018). Our intercept is however $\approx 0.2$ mag smaller than Gieren et al. (2018), Fouqué et al. (2007) and Benedict et al. (2007). This result confirms the difference of 0.2 mag in the PL intercept between the HST/FGS and GDR2 that we found previously. The uncertainties on slopes and intercepts, represented by ellipses, are on the same order as those found by the other authors. This confirms that the PL relations that we found with the GDR2 parallaxes of CC companions are comparable in terms of accuracy to other calibrations found in the literature. The difference between our results and the literature calibrations obtained through the Baade-Wesselink technique can be traced back to the HST/FGS parallaxes. As this is the case for Fouqué et al. (2007) the PL calibrations based on distances all rely on the HST/FGS parallaxes for the determination of the projection factor. A discussion of the importance of this parameter can be found, e.g., in Breitfelder et al. (2016). This is the case, e.g., for Gieren et al. (2018) for which the $p$-factor calibration is from Storm et al. (2011) therefore based on the HST/FGS sample. Our PL relations are represented with other results from the literature in Appendix C.

In order to compare the different PL parameters, zero-point and slope from Table 8 we had to recover for each reference the correlation between the zero-point and the slope. This is very important for a typical CC data set, since the zero-point is usually defined for $P=1$ day ($\log P = 0$), which is outside the range of the actual Cepheid periods. This results in a very high correlation between the fitted slope and zero-point. In our case, we define $\log P_0$ such as the correlation is null.

Unfortunately, the other published PL calibrations neither use an intercept reference period centered within their CC sample, nor include the correlation coefficients. For Fouqué et al. (2007) and Benedict et al. (2007), the data sets are published so we could compute the correlations. For Gieren et al. (2018), the periods are centered around $< \log P >= 1.18$, so we can assume that the correlation is not significantly different from 0 (assuming that the uncertainties on the magnitudes are all the same). For Groenewegen (2018), we made an educated guess: the data set is very similar to the one from Fouqué et al. (2007), hence we assumed the correlation to be similar (0.97). We should note that for Fouqué et al. (2007), we did not use the published uncertainty on the zero point (i.e., $\pm 0.019$ for the $K$ band) since it is not statistically correct. It corresponds to the dispersion of the residuals around the linear fit. However, if one centers the linear fit using the proper $\log P_0$, then the zero-point has indeed this uncertainty, but not at $\log P = 0$.

### 4.3. Implications for the Hubble constant

Two recent determinations of the Hubble constant $H_0$ exhibit a tension at the 4.4$\sigma$ level:

- The empirical estimation by Riess et al. (2019) who obtained $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$ based on LMC Cepheids combined with masers in NGC 4258 and Milky Way parallaxes.
- The value $H_0 = 67.4 \pm 0.5$ km s$^{-1}$ Mpc$^{-1}$ derived from the Planck CMB data by Planck Collaboration et al. (2018) assuming a $\Lambda$CDM cosmology.

Riess et al. (2019) (hereafter R19) established a PL relation in the Wesenheit $W_H$ index for LMC Cepheids, assuming the 1.2% geometric distance from Pietrzyński et al. (2019) based on LMC eclipsing binaries. They find:

$$m_{W_H} = 15.898 - 3.26 \log P$$

(1)

This PL relation includes the CNRL correction on apparent magnitudes, a systematic effect that appears while observing faint and bright sources with the WFC3 instrument (see Riess et al. 2019), and corrections for the LMC geometry.

They combined this PL calibration with two other anchors, masers in NGC 4258 and parallaxes of MW Cepheids from the HST, and they derived $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$. The
$H_0$ value based on the LMC Cepheid anchor only is 74.22 ± 1.42 km s$^{-1}$ Mpc$^{-1}$.

Following the method given in Section 4 of Riess et al. (2018a), we can translate our results into a new value of the Hubble constant $H_{0,\text{Gaia}}$ based on our PL calibration with the GDR2 parallaxes and the Gaia DR2 Cepheid companions. Here we rescale the R19 value from LMC Cepheid anchor only, through the relation $H_{0,\text{Gaia}} = a H_{0,\text{R19}}$, where $a$ is the PL slope for the R19 calibration. In terms of magnitudes, this relation gives:

$$H_{0,\text{Gaia}} = H_{0,\text{R19}} 10^{0.2(W_{\mu,\text{Gaia}} - m_{\text{Gdr2}} + \mu_{\text{LMC}})}$$

where $W_{\mu,\text{Gaia}}$ is obtained from the GDR2 companion parallaxes, $m_{\text{Gdr2}}$ is given by Eq. (1), and $\mu_{\text{LMC}} = 18.477$ mag is the LMC distance modulus from Pietrukzynski et al. (2019). We correct for the metallicity term by applying an additional term $\gamma[F_{\text{Fe}}/H]$, with $[F_{\text{Fe}}/H]_{\text{LMC}} = -0.33$ dex and $\gamma = -0.17$ mag dex$^{-1}$, as given in R19. We make the assumption that the MW metallicity correction is null, given that $[F_{\text{Fe}}/H] = +0.00 \pm 0.05$ dex (Romaniello et al., 2008). For each Cepheid of the GDR2 sample and for the two additional stars, we compute an individual $H_0$, and we derive $H_{0,\text{Gaia}}$ as the weighted mean of these values.

The results, which depend on the value of GDR2 offset, are listed in Table 9 and represented in Fig. 6. The uncertainties take into account the error on $H_{0,\text{R19}}$, on $\mu_{\text{LMC}}$ and the dispersion of both PL relations. We find that the $H_{0,\text{Gaia}}$ value follows the linear relation: $H_{0,\text{Gaia}} = 66.93 - 51.22 ZP_{\text{Gaia}}$ where $ZP_{\text{Gaia}}$ is in mas.

Table 9. Rescaling of $H_0$ based on the GDR2 parallaxes of companions, for different values of $ZP_{\text{Gaia}}$.

| $ZP_{\text{Gaia}}$ (mas) | $H_{0,\text{Gaia}}$ (km s$^{-1}$ Mpc$^{-1}$) |
|-------------------------|------------------------------------------|
| 0                       | 66.93 ± 0.07                            |
| -0.029                  | 68.43 ± 0.08                            |
| -0.046                  | 69.30 ± 0.08                            |
| -0.070                  | 70.53 ± 0.08                            |
| -0.090                  | 71.54 ± 0.09                            |

We can also adopt a similar approach by fixing the slope to the value given by R19 in Eq. (1) and by comparing the zero points of the two PW relations. Applying this method leads to a smaller value of 67 ± 2 km s$^{-1}$ Mpc$^{-1}$, for a zero point offset between 0.029 mas and 0.046 mas. This is consistent at 1σ with the results obtained with the first approach.

In Fig. 5 we represent the distance modulus of the stars of our sample $\mu_{\text{Gaia}}$ computed from GDR2 companions parallaxes, against the distance modulus computed with the PW relation from R19. It appears that, as a global trend, GDR2 exhibit smaller distance modulus compared to R19. The distances of all the stars with S/N > 10 are larger with R19 than with GDR2, resulting in a lower value of $H_{0,\text{Gaia}}$.

As we saw in Sect. 3.4, the value of $ZP_{\text{Gaia}}$ has an impact on the PL relation: choosing different values of $ZP_{\text{Gaia}}$ will lead to various results for $H_0$. On Fig. 5 are represented in blue our values of $H_{0,\text{Gaia}}$ as a function of $ZP_{\text{Gaia}}$. The value of $H_{0,\text{Gaia}}$ increases linearly with Gaia parallaxes offset. Our results are in agreement with Planck Collaboration et al. (2018) within the error bars for $ZP_{\text{Gaia}}$ between 0 mas and 0.060 mas, and consistent with the value found by R19 anchored to Cepheids for a GDR2 offset larger than 0.065 mas.

Assuming a GDR2 parallax offset between 0.029 and 0.046 mas, we find $H_{0,\text{Gaia}} \sim 69 \pm 2$ km s$^{-1}$ Mpc$^{-1}$, in agreement with Planck Collaboration et al. (2018) and compatible with the recent determination by Freedman et al. (2019) based on the Tip on the Red Giant Branch. The next Gaia data releases are expected to improve the precision on parallaxes and hopefully fix the offset, allowing us to reduce the uncertainties on the Hubble constant.

5. Conclusion

We presented a new calibration of the Leavitt law of Milky Way CCs based on the GDR2 parallax measurements of resolved Cepheid companions. Thanks to the absence of large amplitude
photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves. A comparison of our photometric and color variability of these companions, this original approach allows us to bypass the uncertain reliability of the GDR2 parallaxes of the CCs themselves.
Schrödinger, R., McMillan, P., & Eyer, L. 2019, MNRAS, 487, 3568
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Smith, H. 2003, MNRAS, 338, 891
Spreckley, S., & Stevens, I. R. 2007, in Astronomical Society of the Pacific Conference Series, Vol. 366, Transiting Extrapolar Planets Workshop, ed. C. Afonso, D. Weldrake, & T. Henning, 39
Stassun, K. G. & Torres, G. 2018, ApJ, 862, 61
Storm, J., Gieren, W., Fouqué, P., et al. 2011, A&A, 534, A94
Usenko, I. A., Kniazev, A. Y., Berdnikov, L. N., & Kravtsov, V. V. 2014, Astronomy Letters, 40, 800
van Leeuwen, F., Feast, M. W., Whitelock, P. A., & Laney, C. D. 2007, MNRAS, 379, 723
Welch, D. L., Wieland, F., McAlary, C. W., et al. 1984, ApJS, 54, 547
Zabolotskikh, M. V., Rastorguev, A. S., & Egorov, I. E. 2004, in Astronomical Society of the Pacific Conference Series, Vol. 316, Order and Chaos in Stellar and Planetary Systems, ed. G. G. Byrd, K. V. Kholshevnikov, A. A. Myllri, I. I. Nikiforov, & V. V. Orlov, 209
Zinn, J. C., Pinsonneault, M. H., Huber, D., & Stello, D. 2019, ApJ, 878, 136


**Appendix A: Results of the bootstrap technique**

![Bootstrap Technique Results](image)

Fig. A.1. Results of the bootstrap technique applied on the fit of the Leavitt law in the $K_S$ band based on companions GDR2 parallaxes.

**Appendix B: Influence of the parallaxes and of the zero point on the calibration of the Leavitt Law**

**Table B.1.** PL and PW relations obtained with Gaia DR2 parallaxes of CCS companions and with Gaia DR2 parallaxes of CCs themselves. The GDR2 parallaxes offset is assumed to be 0.029 mas. The equations are of the form $M = a(\log P - 0.77) + b$.

| band | $a$ | $b$ | $\chi^2_r$ | $\sigma$ |
|------|-----|-----|------------|---------|
| V    | -2.546±0.171 | -3.775±0.022 | 2.68 | 0.32 |
| J    | -3.179±0.161  | -4.836±0.024  | 0.83 | 0.35 |
| H    | -3.351±0.439  | -5.169±0.063  | 1.96 | 0.35 |
| $K_S$| -3.381±0.205  | -5.153±0.038  | 1.01 | 0.35 |
| $W_{VK}$| -3.481±0.220 | -5.335±0.042 | 1.19 | 0.35 |
| $W_H$| -3.527±0.559  | -5.392±0.073  | 2.52 | 0.36 |

**Table B.2.** PL and PW relations obtained with Gaia DR2 parallaxes of Cepheid companions, for different parallax zero-points. The equations are of the form $M = a(\log P - 0.77) + b$.

| band | $a$ | $b$ | $\chi^2_r$ | $\sigma$ |
|------|-----|-----|------------|---------|
| ZP$_{Gaia} = 0$ mas |
| V    | -2.51±0.181 | -3.744±0.030 | 0.80 | 0.32 |
| J    | -3.14±0.130  | -4.807±0.018  | 0.64 | 0.33 |
| H    | -3.304±0.423  | -5.142±0.070  | 2.33 | 0.35 |
| $K_S$| -3.341±0.161  | -5.125±0.031  | 0.85 | 0.32 |
| $W_{VK}$| -3.442±0.180 | -5.307±0.036 | 0.96 | 0.33 |
| $W_H$| -3.481±0.535  | -5.364±0.082  | 3.03 | 0.36 |
| ZP$_{Gaia} = -0.029$ mas |
| V    | -2.500±0.218 | -3.725±0.038 | 3.28 | 0.33 |
| J    | -3.123±0.138  | -4.791±0.022  | 0.97 | 0.33 |
| H    | -3.285±0.427  | -5.126±0.076  | 2.78 | 0.36 |
| $K_S$| -3.321±0.166  | -5.109±0.031  | 0.95 | 0.32 |
| $W_{VK}$| -3.422±0.176 | -5.290±0.036 | 1.09 | 0.32 |
| $W_H$| -3.460±0.543  | -5.349±0.087  | 3.42 | 0.37 |
| ZP$_{Gaia} = -0.046$ mas |
| V    | -2.480±0.278 | -3.700±0.050 | 3.89 | 0.35 |
| J    | -3.094±0.193  | -4.765±0.030  | 1.43 | 0.34 |
| H    | -3.256±0.457  | -5.103±0.085  | 3.61 | 0.38 |
| $K_S$| -3.290±0.196  | -5.087±0.035  | 1.32 | 0.33 |
| $W_{VK}$| -3.393±0.204 | -5.265±0.039 | 1.43 | 0.33 |
| $W_H$| -3.429±0.554  | -5.328±0.095  | 4.29 | 0.39 |

**Appendix C: Leavitt law with GDR2 companions parallaxes**

![Leavitt Law with GDR2 Companions Parallaxes](image)
**Fig. C.1.** PL diagram in the $V$ band for GDR2 companions parallaxes.

**Fig. C.2.** PL diagram in the $J$ band for GDR2 companions parallaxes.
Fig. C.3. PL diagram in the $H$ band for GDR2 companions parallaxes.

Fig. C.4. PL diagram in the $K_s$ band for GDR2 companions parallaxes.
Fig. C.5. PW diagram in the $W_{VK}$ band for GDR2 companions parallaxes.

Fig. C.6. PW diagram in the $W_{H}$ band for GDR2 companions parallaxes. The PW relation found by R18 (dark red dashed line) was calibrated using the parallaxes from HST/FGS (green points) and by spatial scanning with the HST/WFC3 (orange points).