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GALACTIC CEPHEIDS WITH GAIA DR2 : PERIOD-LUMINOSITY RELATIONS AND IMPLICATIONS ON H_0

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Abstract.
Cepheids represent a fundamental tool for measuring the distances in the Universe, thanks to the simple correlation between their pulsation periods and their instrinsic luminosity: the period-luminosity (PL) relation. In order to calibrate this relation accurately, precise distance measurements are required. However, the recent data releases of the Gaia satellite show that Cepheids parallaxes are subject to biases due to saturation and to the large amplitude of their color variation, which makes the improvement of the PL calibration impossible. In order to bypass this bias, we use the parallaxes of Cepheids detached companions as a proxy for the Cepheids parallaxes themselves, since they are stable and classical stars, to calibrate the Leavitt law. This new method also allowed us to estimate a value of 69 ± 2 km/s/Mpc for the Hubble constant, in agreement with the determination from the Planck satellite.

Keywords: Stars: variables: cepheids, Astrometry, Distance scale, Period-Luminosity relation.

1 Introduction

Through the relation between their pulsation period and absolute magnitude (Leavitt 1908), Cepheids gives us a direct access to distances and to the local value of the Hubble constant H_0. This cosmological parameter exhibits a 4.4σ tension between its two recent measurements (Planck Collaboration et al. 2018; Riess et al. 2019). However, the calibration of this law is still unsatisfactory because of the lack of precise Cepheid distances measurements. In order to determine precisely its coefficients, accurate Cepheid distance measurements are required.

The second Gaia data release (GDR2) was expected to provide the first alternative to Hubble Space Telescope distances, by publishing parallaxes of hundreds of Milky Way Cepheids of unprecedented precision. Unfortunately, several biases affect the GDR2 parallaxes of Cepheids. First, the astrometric solution is determined assuming a constant color for each star (Lindegren et al. 2018; Mowlavi et al. 2018). This ignores the color variations of pulsating stars, particularly significant in the case of Cepheids and Mira stars, which show the largest variations. Secondly, it has been shown (Riess et al. 2018b; Drimmel et al. 2019) that saturation problems affect the GDR2 astrometry of very bright stars ($G < 6$ mag). These issues make GDR2 Cepheid parallaxes unreliable for the calibration of the Leavitt law.

2 Method

Kervella et al. (2019) recently detected 28 bound resolved companion stars of Cepheids in the Milky Way. As they are photometrically stable stars, these companions are not subject to the chromaticity problem raised previously. Moreover, being a few magnitudes fainter than the Cepheids, they are not affected by saturation and belong to the best dynamical range for Gaia DR2 astrometry. For these reasons, the 28 companions from Kervella et al. (2019) represent an excellent proxy for GDR2 Cepheid parallaxes. In this work, we calibrate the Leavitt law assuming that the Cepheids and their bound companions share the same parallax.

In addition to the companions, we include in our sample two more stars with independently determined parallaxes: RS Pup, whose distance was accurately measured using the propagation of the light echoes in its

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circumstelllar nebula (Kervella et al. 2017), and the binary Cepheid V1334 Cyg, whose distance was estimated by Gallenne et al. (2018) based on a spectroscopic and interferometric study of its orbit.

After removing the few stars with bad quality indicators, we investigated the pulsation mode of our Cepheids. We found 6 Cepheids pulsating in the first overtone mode, for which we fundamentalized the period through the relation given by Feast & Catchpole (1997), and two stars with uncertain pulsation mode that we decided to discard for safety. The final sample contains 23 companions and the two additional stars.

We adopted Astrometric Based Luminosities (ABL) as described by Arenou & Luri (1999), therefore no selection on positive parallaxes is required and the results are not subject to Lutz-Kelker bias (Lutz & Kelker 1973). We performed a weighted fit of the ABL function to determine the zero-point and the slope of the PL relation. A bootstrap technique iterated 50000 times ensures the robustness of the results and of the uncertainties.

The Gaia DR2 parallaxes are subject to a zero-point offset, a value that should be added to parallaxes and whose exact value is still under debate. Recent works estimate its value between 0.029 mas (Lindegren et al. 2018) and 0.082 mas (Stassun & Torres 2018). In our investigation, we vary this parameter and analyse its effect on the PL relation and on its dispersion.

3 Results and discussion

3.1 Cepheid versus companion parallaxes

The calibration of the Leavitt law using companion parallaxes is represented in the K_S band in Fig. 1. The same calibration obtained with Cepheid parallaxes gives a higher χ^2 value compared with companions parallaxes, even though the error bars are smaller. Moreover, GDR2 parallaxes and the two additional stars are in better agreement when the parallaxes are those of the companions. As stated previously, Cepheid parallaxes are subject to a bias due to the absence of chromaticity correction. The uncertainties on Cepheid parallaxes are therefore underestimated compared with the error bars given by GDR2. We infer that using companions as a proxy for Cepheid parallaxes is reliable.

3.2 Influence of the GDR2 parallax offset

We then vary the value of the parallax zero-point offset between 0.029 mas and 0.100 mas and we find that the dispersion of the points increases with the offset. The zero-point and the slope of the PL relation are both sensitive to the offset value. For example, for offset values of 0.029 mas and 0.070 mas, we obtain respectively $K_S = -5.893_{\pm 0.048} - 3.341_{\pm 0.161} (\log P - 1)$ and $K_S = -5.844_{\pm 0.057} - 3.290_{\pm 0.196} (\log P - 1)$. For reasonable offset values, the derived magnitudes agree within their error bars.

In the following, we fix the GDR2 zero-point offset to 0.029 mas, which gives the smallest dispersion and which is also the offset adopted by Kervella et al. (2019) in the search for the companions.

3.3 Comparison with other Leavitt law calibrations

We compare our Leavitt law calibration with different results from the literature. We considered the result of Groenewegen (2018) who uses a large sample of GDR2 Cepheid parallaxes (in the case where the parallax offset is set to 0.029 mas), and also the calibrations by Benedict et al. (2007) and Fouqué et al. (2007), based on HST/FGS parallaxes of bright Cepheids. The corresponding PL relations are represented in Fig. 1, in green, dark red and orange, respectively.

In the present range of periods, our calibration agrees well with Groenewegen (2018), even though this author finds a slightly different slope. However, the two calibrations based on HST/FGS parallaxes differ by $\sim$0.2 mag from our Leavitt law. This discrepancy may be explained by a HST/FGS zero-point offset on the order of 0.2 mas that has not yet been considered, or alternatively by a GDR2 parallax offset significantly larger than the current estimation, of at least $\sim$0.15 mas.

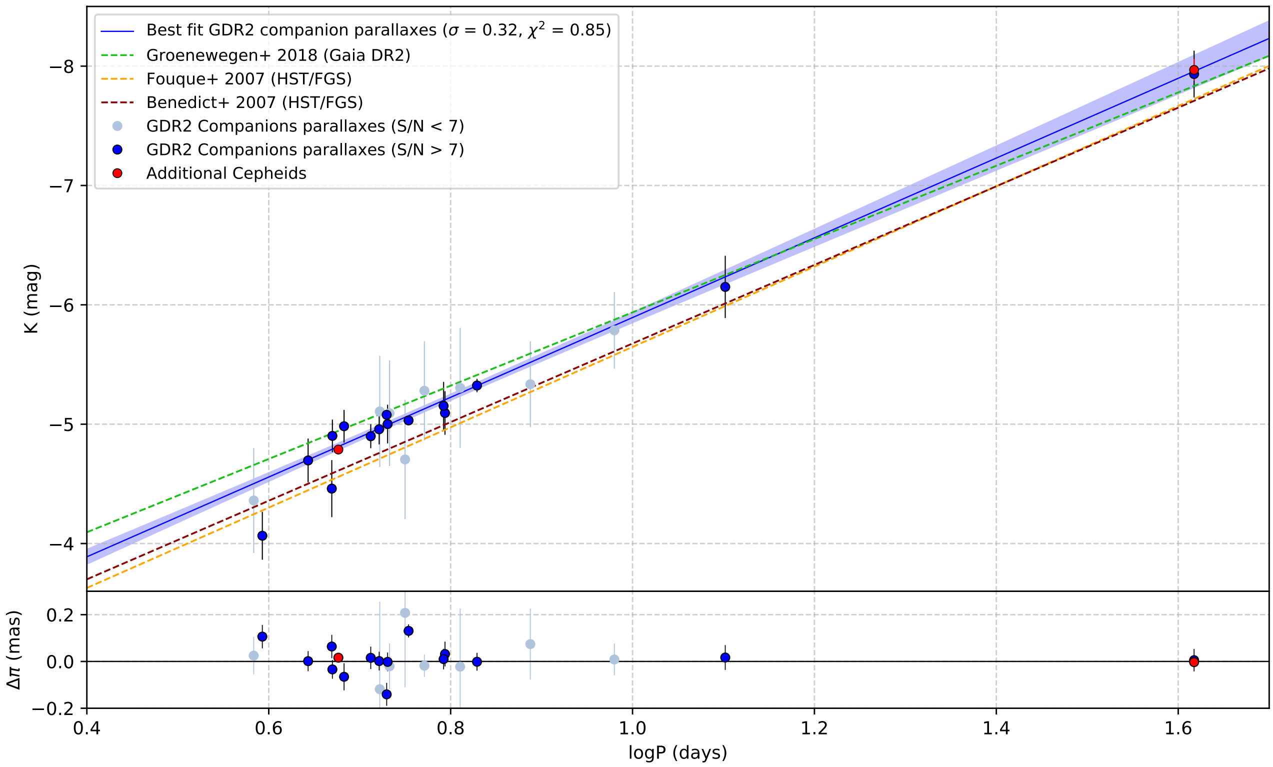

Fig. 1. PL relation in the K_S band based on GDR2 companion parallaxes, and comparison with other relations found in the literature. We adopted a GDR2 parallax offset of 0.029 mas.

4 Consequences on the local value of the Hubble constant

Following the approach presented by Riess et al. (2018a), we use our Leavitt law calibration to rescale the value of the Hubble constant from Riess et al. (2019), hereafter $H_{0,\,\mathrm{R19}}$. These authors determined $H_{0,\,\mathrm{R19}}$ based on LMC Cepheids whose distance was set to the 1% value found by Pietrzyński et al. (2019). The rescaled value $H_{0,\,\mathrm{Gaia}}$ is obtained through the relation : $H_{0,\,\mathrm{Gaia}} = \alpha\, H_{0,\,\mathrm{R19}}$ where $\alpha = \pi_{\mathrm{Gaia}}/\pi_{\mathrm{R19}}$. For each star of our sample, we estimated the parallaxes π_{Gaia} and π_{R19} respectively with our PL relation and with the corresponding Leavitt law from Riess et al. (2019), both in the Wesenheit W_H magnitude. The final estimation of $H_{0,\,\mathrm{Gaia}}$ is computed as a weighted mean of each individual value.

The result strongly depends on the GDR2 parallax offset: taking an offset of 0.029 mas leads to $H_{0,\,\mathrm{Gaia}} = 68.43 \pm 2.08\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, while an offset of 0.070 mas returns $H_{0,\,\mathrm{Gaia}} = 70.53 \pm 2.08\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. For a reasonably small offset, our Leavitt law calibration translates into a value of H_0 statistically compatible with the Planck Collaboration et al. (2018) estimate, who predicted $H_0 = 67.4 \pm 0.5\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$.

5 Conclusion

The use of GDR2 companion parallaxes as a proxy for Cepheids allows to bypass the bias due to the chromaticity problem and the saturation issues. The derived PL relation exhibits a small dispersion, confirming the interest of the method. The inconsistency between the present PL calibration and results based on HST/FGS parallaxes shows that a zero-point offset may be required on the latter, or that the offset on GDR2 parallaxes is more significant than currently estimated. This discrepancy also translates into a lower value of H_0 compared with the estimation by Riess et al. (2019), in agreement with Planck Collaboration et al. (2018).

The future Gaia Data Releases are expected to provide more precise parallaxes, and possibly a better knowledge of the parallax offset. The correction of time variable chromaticity effect in the Gaia astrometry, which is not yet considered in the Gaia data reduction, is essential for a PL calibration directly based on Cepheid parallaxes.

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