At the crossroads of astrophysics and cosmology: Period–luminosity relations in the 2020s
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Impact of the *Gaia* ESA mission on the primary Period–Luminosity Calibrators in the Milky Way: Cepheids and RR Lyrae

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Abstract. We discuss the impact of *Gaia*, the cornerstone mission of the European Space Agency (ESA), on the calibration of the period–luminosity and luminosity–metallicity relations of Cepheids and RR Lyrae stars, with specific reference to data published as part of the most recent *Gaia* releases: Early Data Release 3 (EDR3), on 19 December 2020, and Data Release 3 (DR3) on 13 June 2022. We provide future perspectives for the *Gaia* mission, including extensions approved by ESA and a tentative schedule of the data releases that will take place in the next few years. We briefly present plans for cross-Coordination Unit processing of *Gaia* data of Cepheids and RR Lyrae stars for DR4 and conclude by outlining the expected improvement in astrometry at the end of the extended *Gaia* mission, which will help to further strengthen the calibration of the first rung of the cosmic distance ladder.

Keywords. Stars: oscillations – Stars: variables: RR Lyrae – Stars: variables: Cepheids – Methods: data analysis

1. Introduction

Cepheids and RR Lyrae stars are the most important stellar standard candles at the basis of the cosmological distance ladder through their period–luminosity(–metallicity) and luminosity–metallicity relations. They are also excellent tracers of the Milky Way's (MW) structure and of its formation via accretion and mergers.

The *Gaia* mission is producing the largest, most homogeneous and parameter-rich catalogues of Cepheids and RR Lyrae stars ever published, hence causing a step change in many astrophysical contexts. This is thanks to *Gaia*'s capability to scan the whole sky (at an average of 14 times per year) and collect astrometry nearly simultaneously to multiband photometry of all sources brighter than $G \sim 21$ mag and spectroscopy of sources brighter than $G \sim 16.5$ mag.

The *Gaia* focal plane, with physical dimensions of 1.0×0.4 m^2, is the largest ever developed for a space mission. It hosts an array of 106 CCDs (Gaia Collaboration et al. 2016; their Figure 4), featuring almost 1,000 million pixels in total, which are devoted to the following main scientific functions: (i) astrometry measurements and white-light photometry in the G band (330–1050 nm) on the CCDs of the astrometric field; (ii) blue (330–680 nm) and red (640–1050 nm) spectro-photometry employing low-resolution ($R \sim$ 20–90) prism spectra obtained by the blue and red photometers; and (iii) intermediate-resolution ($R = 11,500$) slitless spectroscopy in the calcium triplet region (847–874 nm) with the radial-velocity spectrometer (RVS; Cropper et al. 2018).

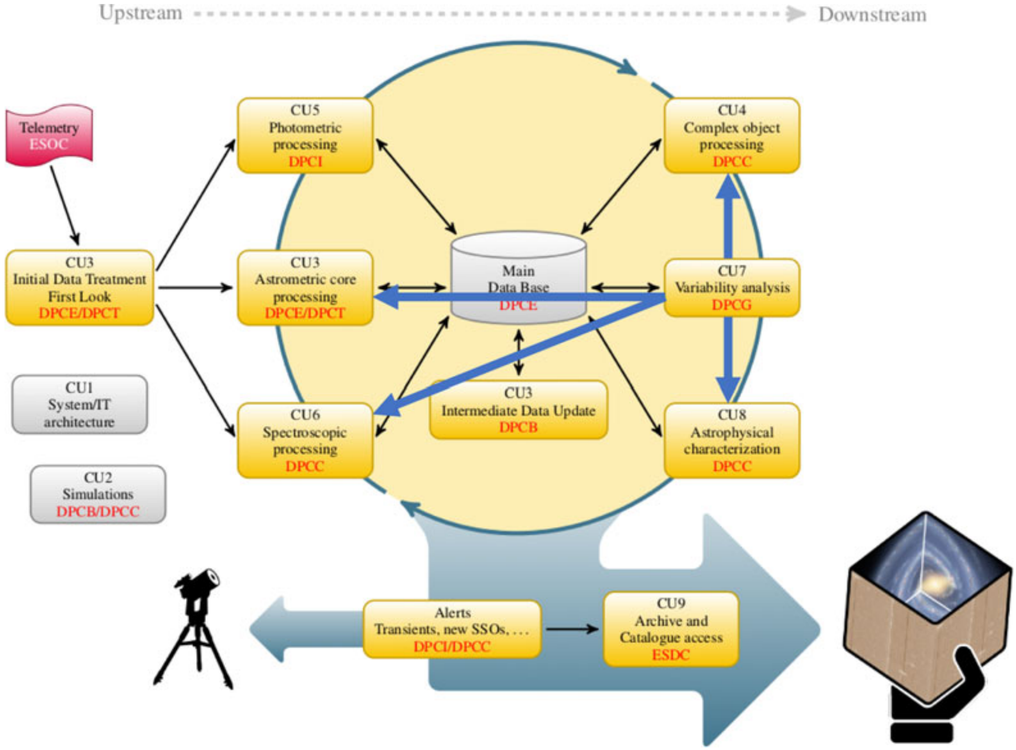


Figure 1. Schematic overview of the *Gaia* Data Processing and Analysis Consortium (DPAC) showing its organisation into different Coordination Units (CUs). Blue arrows show the inter-CUs exchange (cross-CUs processing) planned for DR4 to improve the processing of the *Gaia* data for Cepheids and RR Lyrae stars (see Section 4.1). (Adapted from `https://www.cosmos.esa.int/web/gaia/dpac`).

The *Gaia* Data Processing and Analysis Consortium (DPAC), an international team composed of 400–450 European scientists and software developers, is in charge of developing the data processing algorithms and software to turn the raw telemetry from *Gaia* into the final scientific data products to be released to the scientific community. DPAC activities involve cyclic, iteratively improved processing of all data collected by *Gaia* which is carried out within dedicated Coordination Units (CUs). Figure 1, shows a schematic view of the *Gaia* DPAC and its organisation into CUs. Three upstream 'core' CUs perform the astrometric (CU3), photometric (CU5) and spectroscopic (CU6) processing. An additional three downstream CUs process complex sources such as binaries or galaxies (CU4), perform variability analysis (CU7) and carry out astrophysical characterisation (CU8) of the sources.

Three releases of *Gaia* data products have occurred since the start of the mission in 2013. *Gaia* data for Cepheids and RR Lyrae stars were published already as part of the first data release (DR1) in 2016 (Clementini et al. 2016), showcasing the extraordinary quality of *Gaia*'s light curves and the astrometric quality already achieved by employing the Tycho–*Gaia* astrometric solution (TGAS; Lindegren et al. 2016) for an unprecedented number of these standard candles defining the astronomical distance ladder (Gaia Collaboration et al. 2017). The third and most recent *Gaia* release was split into two separate instalments, both covering 34 months of *Gaia* observations obtained from 25 July 2014 to 28 May 2017. *Gaia* Early Data Release 3 (EDR3; Gaia Collaboration et al. 2021) on 3 December 2020 published positions on the sky, parallaxes and proper motions for about 1.468 billion sources with G magnitudes in the range from ∼3 to ∼21 mag, G photometry for about 1.806 billion sources and integrated $G_{\rm BP}$ and $G_{\rm RP}$ magnitudes for about 1.5 billion. Data Release 3 (DR3; Gaia Collaboration et al. 2023), on 13 June 2022, complemented EDR3 with new products (for a full list, see `https://www.cosmos.esa.int/web/gaia/dr3`), among which in particular were included results from the variability analysis, together with the underlying epoch photometry, for a total sample of 10.5 million sources, including around 15,000 Cepheids and 271,000 RR Lyrae stars.

2. Variability processing

Identification and characterisation of the variable sources observed by *Gaia* is performed within DPAC Coordination Unit 7 (CU7) based on analysis of the time-series data of all sources observed by the satellite. For DR3 the integrated G, $G_{\rm BP}$ and $G_{\rm RP}$ time-series photometry (Riello et al. 2021) of more than 1.8 billion sources was fed into the CU7 pipelines, along with their EDR3 astrometry (positions on the sky, parallaxes and proper motions). For a small sample of Cepheids and RR Lyrae stars comprising 799 Cepheids and 1196 RR Lyrae stars, the CU7 pipelines also analysed the epoch radial velocities obtained with the RVS (Sartoretti et al. 2022).

Statistical and Machine Learning methods are used to identify, characterise and classify the candidate variable sources into different types (Eyer et al. 2017, 2023; Rimoldini et al. 2023). Candidate variables of the different types are then ingested into the Specific Object Study (SOS) pipelines, which are specialised to validate the classification into types and derive specific attributes for the variable sources, which are confirmed to actually belong to the classes they have been assigned to. A summary of the variability processing steps and the variability content of *Gaia* DR3 is presented by Eyer et al. (2023) to which the interested reader is referred for details.

2.1. *Cepheids and RR Lyrae stars in Gaia DR3*

Variable stars classified as Cepheid and RR Lyrae candidates are processed by the SOS Cep&RRL pipeline (Clementini et al. 2016, 2019, 2023; Ripepi et al. 2023), which was specifically devised to test the classification into types and derive characteristic parameters of variable sources confirmed as Cepheids and RR Lyrae stars. Attributes computed by the SOS Cep&RRL pipeline include: pulsation period and secondary periodicities in case of multimode pulsation modes; identification of RR Lyrae/Cepheid types and pulsation modes; G, $G_{\rm BP}$, $G_{\rm RP}$ and RV amplitudes of the light and radial velocity (RV) curves computed as peak-to-peak amplitudes of the non-linear Fourier modelling of the light and RV variations, respectively; G, $G_{\rm BP}$ and $G_{\rm RP}$ intensity-averaged mean magnitudes; mean RV; parameters of the Fourier decomposition of the light and RV curves; metal abundance of fundamental-mode classical Cepheids (DCEP_Fs) with periods shorter than 6.3 days inferred from the R_{21} and R_{31} Fourier parameters of the G-band light curves and the calibration of Klagyivik et al. (2013); metal abundance of RR Lyrae stars inferred from the ϕ_{31} Fourier parameter of the G-band light curves and the calibration of Nemec et al. (2013); and G absorption of fundamental-mode RR Lyrae stars (RRab) inferred from the pulsation period, the amplitude of the G-band light curve and the $(G - G_{\rm RP})$ colour, based on the relation of Piersimoni et al. (2002) and the procedure described by Clementini et al. (2019).

We refer the reader to Clementini et al. (2023) and Ripepi et al. (2023) for detailed descriptions of the SOS Cep&RRL processing of RR Lyrae stars and Cepheids released as part of DR3. Attributes computed by the SOS Cep&RRL pipeline for *bona fide* Cepheids and RR Lyrae can be retrieved from the `vari_rrlyrae` and `vari_cepheid` tables of the

Table 1. Number of SOS Cepheids released in DR3 divided by type, pulsation mode and sky region[1].

Cepheids (type/mode)	LMC	SMC	M31	M33	All-Sky	Total
DCEP_F	2357	2487	309	173	2008	7334
DCEP_FO	1931	1803	10	12	1101	4857
DCEP_MULTI	58	110	-	-	195	363
DCEP (Total)	4346	4400	319	185	3304	**12,554**
ACEP_F	69	87	-	-	150	306
ACEP_FO	32	80	-	-	132	244
ACEP (Total)	101	167	-	-	282	**550**
T2CEP BL Her	66	16	-	-	579	661
T2CEP W Vir	120	20	-	-	795	935
T2CEP RV Tau	30	13	2	-	261	306
T2CEP (Total)	216	49	2	-	1635	**1902**
Cepheids (Grand total)	**4663**	**4616**	**321**	**185**	**5221**	**15,006**

Notes: [1] All numbers in this table refer to the clean DR3 SOS Cepheid sample (see Ripepi et al. 2023).

Gaia DR3 archive. The epoch photometry and the RV time-series data can be downloaded by querying the *Gaia* data release archive (`http://archives.esac.esa.int/gaia/`).

2.1.1. *Gaia DR3 catalogue of SOS Cepheids*

The *Gaia* DR3 catalogue of Cepheids validated and characterised by the SOS Cep&RRL pipeline lists 15,006 *bona fide* Cepheids (hereafter SOS Cepheids). Among these, 474 are new Cepheids discovered by *Gaia* and an additional 327 are variable stars with a different classification in the literature, which have been re-classified as Cepheids based on our analysis of the *Gaia* data (Ripepi et al. 2023). They are subdivided into classical Cepheids (DCEPs), anomalous Cepheids (ACEPs) and Type 2 Cepheids (T2CEPs). According to their pulsation modes, DCEPs and ACEPs are further subdivided into fundamental-mode (DCEP_F, ACEP_F), first-overtone (DCEP_FO, ACEP_FO) and multi-mode (only for DCEPs, DCEP_ MULTI) when more than one mode is excited, whilst T2CEPs are subdivided into three distinct types: BL Herculis (BL Her), W Virginis (W Vir) and RV Tauri (RV Tau) based on the Cepheid pulsation period and their evolutionary status.

Table 1 summarises the number of SOS Cepheids, divided by type, pulsation mode and position on the sky, according to the following five regions defined by Ripepi et al. (2023): Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), Andromeda galaxy (M31), Triangulum galaxy (M33) and All-Sky, which mainly contains MW Cepheids.

General statistics and information pertaining to the number of SOS Cepheids with astrophysical parameters computed by the SOS Cep&RRL pipeline or by other CUs are provided in Table 2.

2.1.2. *Gaia DR3 catalogue of SOS RR Lyrae stars*

The *Gaia* DR3 catalogue of RR Lyrae stars validated and characterised by the SOS Cep&RRL pipeline contains 270,905 entries (hereafter SOS RR Lyrae), of which 174,947 are fundamental-mode pulsators (RRab), 93,952 are first-overtone pulsators (RRc) and 2006 are RR Lyrae stars that pulsate in both modes simultaneously. Around 70,000 of the SOS RR Lyrae were not known previously and are new discoveries by *Gaia*. Figure 30 of Clementini et al. (2023) shows the distribution on the sky of the SOS RR Lyrae released

Table 2. Information about the DR3 SOS Cepheids.

Characteristic	N1	N2
Total sample	15,006	–
Known	14,205	–
Reclassified	327	–
New discoveries	474	–
Range in mean magnitude	$3.4 < G < 20.9$ mag	–
MW DCEPs with $\sigma_\pi/\pi \leq 0.1$ and RUWE$\leq$1.4[1]	$\sim$1060	–
$[\mathrm{Fe/H}]^{[2]}_{\mathrm{SOS}}$	5123	–
Epoch RVs	>799	–
Mean RVs (CU6)	>2000	–
$E(B-V)$ from GSP_phot (CU8)	$\sim$1700	278[3]
[M/H] from GSP_spec (CU8)	$\sim$1000	400[4]

Notes: [1] RUWE is a parameter that measures the quality of the parallax estimate. Reliable parallaxes have RUWE values < 1.4 (see Section 14.1.2 of *Gaia* Data Release 2 Documentation release 1.2; `https://gea.esac.esa.int/archive/documentation/GDR2/`); [2] only for DCEP_Fs with $P < 6.3$ days and less reliable for values more metal-poor than [Fe/H] ~ 0.3 dex (for details, see Ripepi et al. 2023); [3] with $\Delta E(B-V) = \pm0.2$–0.25 mag from literature values; [4] with Δ[M/H] $= \pm0.2$-0.3 dex from literature values.

Table 3. Number of SOS RR Lyrae stars released in DR3 by sky region or host system[1].

LMC	SMC	95 GCs	7 dSphs & 16 UFDs	All-Sky	Total
31,379	4788	1676	1114	231,948	**270,905**

Note: [1] All numbers in the table refer to the clean DR3 SOS RR Lyrae sample (see Clementini et al. 2023).

in DR3. They populate all Galactic components, from the halo to the bulge to the disc of the MW. The new RR Lyrae stars are mainly located in the MW disc and bulge, where crowding is very high. Hence, their light curves may be more noisy and have their amplitudes reduced owing to blending with other sources. Concentrations of sources seen in the DR3 SOS RR Lyrae sky distribution correspond to the variables in the Magellanic Clouds, the Sagittarius dwarf spheroidal galaxy (dSph), six other dSphs (among which Sculptor, Ursa Minor and Carina), 16 ultra-faint dwarf (UFD) MW satellites and 95 globular clusters (GCs). Table 3 provides the number of SOS RR Lyrae stars released in DR3 split by sky region and/or host system. General statistics and information about the number of SOS RR Lyrae with astrophysical parameters computed by the SOS Cep&RRL pipeline or by other CUs is provided in Table 4.

3. *Gaia* DR3 Cepheids and RR Lyrae stars as standard candles of the cosmic distance ladder

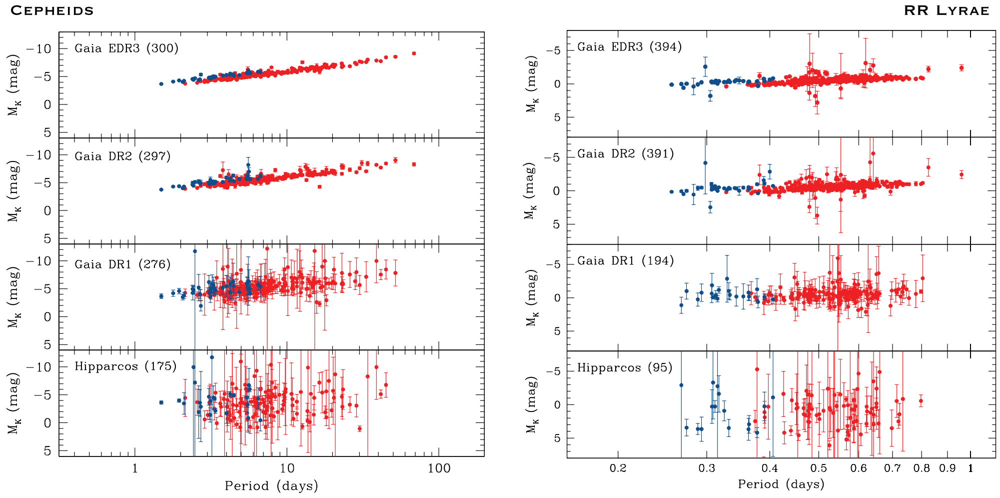
The dramatic improvements in the Cepheid and RR Lyrae astrometry as *Gaia* data releases proceed (see Figure 2) and the large number of Cepheids and RR Lyrae stars released as part of DR3 have allowed to derive an improved absolute geometric calibration using parallaxes of the fundamental relations that make Cepheids and RR Lyrae stars primary standard candles of the cosmic distance ladder.

More than one thousand of the SOS DCEPs in the MW have DR3 parallaxes better than 10% and RUWE$\leq$1.4 (see Table 2). They were used to calibrate, with unprecedented accuracy, the DCEP period–luminosity–metallicity (PLZ) and period–Wesenheit–metallicity (PWZ) relations (see, e.g., Breuval et al. 2021, 2022; Ripepi et al. 2021, 2022a). This represents a crucial step forward in constraining the first rung of the cosmic distance ladder and reduce the uncertainty in the estimate of the Hubble constant, H_0, obtained from distance ladder measurements (see, e.g., Riess et al. 2021, 2022a,b).

Table 4. Information about the DR3 SOS RR Lyrae stars.

Characteristic	**Number**
Total sample	270,905
Known	200,294
New discoveries	70,611
Fundamental mode (RRab)	174,947
First overtone (RRc)	93,952
Double mode (RRd)	2006
Range in mean magnitude	$7.64 < G < 21.14$
RR Lyrae with $\sigma_\pi/\pi \leq 0.1$ and RUWE$\leq$1.4	$\sim$300
$[\mathrm{Fe/H}]^{[1]}_{\mathrm{SOS}}$	135,559
Epoch RVs	1096
Mean RVs (CU6)	5096
$A(G)^{[2]}_{(\mathrm{SOS})}$	142,660
$A(G)$ from GSP_phot (CU8)	84,500
[M/H] from GSP_spec (CU8)	$193^{[3]}$
[M/H] from GSP_phot (CU8)	87,273

Notes: [1] Metallicity errors published in the `vari_rrlyrae` table are slightly overestimated; [2] $A(G)$ estimates are available only for RRab stars; [3] Selected using the flags_gspspec flag to filter out sources with GSP_spec abundances of poor quality.


CEPHEIDS

RR LYRAE

CREDIT: ESA/GAIA/DPAC, CREATED BY: V. RIPEPI

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Figure 2. Near-infrared period–luminosity relations showing the improvement of the astrometry for MW Cepheids (left panels) and RR Lyrae stars (right panels) from *Hipparcos* (*Gaia*'s predecessor; bottom panels) to *Gaia* DR1, DR2 and EDR3. Red and blue points correspond to fundamental-mode and first-overtone pulsators, respectively. The reduction in the K absolute magnitude error and the increasing number of sources with reliable parallaxes are impressive. (Figures produced to showcase the improvement of *Gaia*'s parallaxes on the occasion of the EDR3 release. They update the figures originally published by Gaia Collaboration et al. 2017; `https://www.cosmos.esa.int/web/gaia/edr3-vs-dr2`)

With typical ages greater than 9–10 billion years, RR Lyrae stars are standard candles for systems mainly composed of old stellar populations. RR Lyrae stars obey luminosity-metallicity (LZ) relations in optical bands such as the Johnson V and the *Gaia* G band, PLZ relations in the near-infrared (NIR) and PWZ relations in optical and NIR bands. Around 300 SOS RR Lyrae stars in the MW have parallaxes better than 10% and RUWE$\leq$1.4 (see Table 4). They were used to recalibrate the RR Lyrae optical and NIR relations (Muraveva et al. 2018; Bhardwaj et al. 2021; Garofalo et al. 2022; Li et al. 2023).

Table 5. Estimates of the parallax zero-point offset published after *Gaia* EDR3.

ZPO value (**μas**)	**Source/Method**	**Reference**
-14 ± 6	Classical Cepheids	Riess et al. (2021)
-15 ± 3[1]	Asteroseismology of red giants	Zinn (2021)
-10 ± 7	RR Lyrae stars	Gilligan et al. (2021)
-39[2]	Comparison with *HST* parallaxes	Groenewegen (2021)
$-7 \pm 3/-32 \pm 4$[3]	RR Lyrae stars	Bhardwaj et al. (2021)
-28[4]	RR Lyrae stars	Garofalo et al. (2022)
-22 ± 4[5]	Classical Cepheids	Molinaro et al. (2023)

Notes: [1] For $G \geq 10.8$ mag; [2] Mean value of individual ZPOs; [3] Without or with Lindegren et al. (2021) corrections, respectively; [4] Mean value without Lindegren et al. (2021) corrections; [5] With Lindegren et al. (2021) corrections.

In spite of the impressive improvement in quality of *Gaia*'s parallaxes and the increasing number of Cepheids and RR Lyrae stars with reliable parallax values, a number of issues still affect the calibration of the fundamental relations followed by these standard candles. Some of these issues are discussed in the following sections.

3.1. *Gaia parallax zero point offset*

Gaia's parallaxes are known to be underestimated due to unexpectedly large variations of the 'basic angle' between the viewing directions of the two *Gaia* telescopes (Lindegren et al. 2021). The exact value of the *Gaia* parallax zero-point offset (ZPO) has been found to depend on the magnitude, colour and position on the sky of the sources.

Lindegren et al. (2018) estimated a median ZPO of the *Gaia* DR2 parallaxes of about -29 μas with respect to a sample of bright quasars. The DR2 average ZPO was found to be ~ -33 μas for Cepheids and ~ -56 μas for RR Lyrae stars (Arenou et al. 2018; 2018). However, a larger ZPO of -46 ± 13 μas was estimated for Cepheids by Riess et al. (2018), and a smaller value of -42 ± 13 μas was determined by Layden et al. (2019) for RR Lyrae stars. In *Gaia* EDR3, the parallax ZPO was reduced to ~ -17 μas, with systematic variations on the order of $\sim$10 μas (Lindegren et al. 2021). These latter authors also developed a code to compute individual parallax zero-point offsets for sources with five and six-parameter solutions, separately. The code is availabe as a Jupyter notebook, at `https://gitlab.com/icc-ub/public/gaiadr3$_$zeropoint`.

Different estimates of the ZPO value have also been published after the release of the *Gaia* EDR3 parallaxes. Some of these estimates are summarised in Table 5, including in particular the ZPO values inferred from Cepheids and RR Lyrae stars. Suggestions have also been made that the Lindegren et al. (2021) corrections might overestimate the ZPO of the EDR3 parallaxes (see, e.g., Riess et al. 2021; Molinaro et al. 2023).

The ZPO remains one of the most important issues affecting the *Gaia* parallaxes that limits our precision in measuring the Hubble constant with the distance ladder method. While the existence of the ZPO limits *Gaia*'s ability to determine absolute parallaxes, improving the characterisation and modelling of the ZPO so as to mitigate systematic effects such as the dependence on magnitude, colour and position on sky should be possible.

3.2. *Metallicity dependence of the Cepheid PL/PW relations*

A significant source of uncertainty that limits the use of Cepheids as standard candles of the astronomical distance ladder is our poor knowledge of the dependence on metal abundance of their PL/PW relations. Rather discordant estimates are found in the literature, with recent values ranging from -0.221 ± 0.051 mag dex^{-1} (Breuval et al. 2021) up to -0.456 ± 0.099 mag dex^{-1} (Ripepi et al. 2021) for the Cepheid PL relation in the K_s band. The contribution to the H_0 error budget of the uncertainty in the behaviour of the Cepheid PL/PW relations as a function of chemical composition is estimated between 0.5% (out of 1.2%; Riess et al. 2022) for the LMC and 0.15% for other anchors of the cosmic distance ladder, such as NGC 4258 or M31.

Observing programmes are in progress (see, e.g., Ripepi et al. 2021) to directly measure the metallicity dependence of the DCEP PL/PW relations using only Cepheids in the MW with accurate metallicities from abundance analysis of high-resolution spectra and spanning a large metallicity range. The metallicities derived from abundance analysis of the *Gaia* RVS spectra of Cepheids may also contribute to study the metallicity dependence of the DCEP PL/PW relations (see Section 3.3).

3.3. *Astrophysical parameters of Cepheids and RR Lyrae stars in Gaia DR3*

Astrophysical parameters such as metal abundance and reddening are needed, in addition to the parallax, to compute the period–luminosity and luminosity–metallicity relations. The astrophysical parameters of Cepheids and RR Lyrae stars published in the *Gaia* DR3 archive were derived independently by CU7 as part of the variability processing, and by CU8 as part of the astrophysical characterisation of the sources, using different pipelines and input data from *Gaia*. Specifically, photometric metallicities and G absorption values of the Cepheids and RR Lyrae stars in the `vari_cepheid` and `vari_rrlyrae` tables of the *Gaia* DR3 archive were determined by the CU7 SOS Cep&RRL from the characteristic parameters of the light variation along the source pulsation cycle (pulsation period, amplitude, colour and parameters of the Fourier decomposition of the light curve). Astrophysical parameters of Cepheids and RR Lyrae stars published in the `astrophysical_parameters` tables were determined instead by the GSP_spec and GSP_phot modules of the CU8 Apsis pipeline (Creevey et al. 2023, and references therein) from analysis of the stacked RVS and BP/RP prism spectra of the sources, in practice 'absorbing' the variation owing to the pulsation as an increased measurement uncertainty.

The DR3 `vari_cepheid` table contains photometric [Fe/H] abundances for 5123 fundamental-mode DCEPs with periods shorter than 6.3 days. They were inferred by the SOS Cep&RRL pipeline from the R_{21} and R_{31} Fourier parameters of the G-band light curves based on the Klagyivik et al. (2013) calibration. The comparison with metal abundances from high-resolution spectra that are available in the literature for 185 DCEPs with photometric metallicities from CU7 shows the latter to be about 0.08 dex higher than the literature values, but still reliable, at least in the metallicity range $-0.3 <$ [Fe/H] $< +0.4$ dex (Ripepi et al. 2023). Spectroscopic [M/H] abundances estimated with the GSP_spec pipeline are available for about 1000 DR3 Cepheids. A comparison with the abundances from high-resolution spectra in the literature shows that for around 400, the two estimates agree within ±0.20–0.35 dex. While the agreement among Cepheids abundances from high-resolution spectroscopy and metallicities from the either the SOS Cep&RRL or the GSP_spec pipelines are already quite good, further improvement of the latter may result, in particular, from analysis based on the RVS per-transit spectra.

Photometric metal abundances are published in the DR3 `vari_rrlyrae` table for 133,559 RR Lyrae stars. They were computed by the SOS Cep&RRL pipeline from the ϕ_{31} Fourier parameter of the G-band light curves and the stellar pulsation period (P), adopting Nemec et al. (2013)'s calibration of the [Fe/H]–P–ϕ_{31} relation. There have been claims that the Nemec et al. (2013) calibration produces significantly biased metal abundances (e.g., Li et al. 2023). However, a comparison of the $\mathrm{[Fe/H]_{SOS}}$ values with RR Lyrae abundances from high-resolution spectroscopic studies (Clementini et al. 1995; Lambert et al. 1996; Pancino et al. 2015; Crestani et al. 2021) shows reasonably good agreement within the errors, except that the $[\mathrm{Fe/H}]_{\mathrm{SOS}}$ estimates are about 0.2 dex higher around $[\mathrm{Fe/H}]\sim -1.5$ dex. Similarly, the GSP_spec [M/H] estimates obtained for 193 RR Lyrae stars from the RVS spectra (Recio-Blanco et al. 2023) are also in satisfactory agreement with the $[\mathrm{Fe/H}]_{\mathrm{SOS}}$ values, within the errors (see Clementini et al. 2023; their Figure 23). Finally, about 87,000 DR3 RR Lyrae stars have [M/H] abundances estimated from the BP/RP low-resolution spectra using the GSP_phot pipeline (Andrae et al. 2023). However, the GSP_phot metallicities of RR Lyrae stars are affected by very large uncertainties and systematic effects that prevent a meaninful comparison with the $[\mathrm{Fe/H}]_{\mathrm{SOS}}$ abundances.

$E(B-V)$ reddening estimates obtained by the GSP_phot pipeline from the BP/RP prism spectra are available for about 1700 DR3 Cepheids. The GSP_phot values are in reasonably good agreement with the literature values: for a subsample of 278 Cepheids the difference between the two estimates is on the order of 0.2–0.25 mag.

Interstellar G-band absorption values were obtained by the SOS Cep&RRL pipeline for 142,660 fundamental-mode DR3 RR Lyrae stars. They were compared with the G-band absorption values computed by the GSP_phot pipeline, which are available for about 84,500 DR3 RRab stars. This comparison showed that the GSP_Phot DR3 absorption estimates of RR Lyrae stars are often affected by the temperature–absorption degeneracy and by misidentification of RR Lyrae stars for much hotter sources (see Clementini et al. 2023; their Section 5.2.1).

4. Future perspectives

The inconsistent results obtained for Cepheids and RR Lyrae stars by different DPAC pipelines clearly showed the need for more coordinated joint processing of these most important calibrators of the cosmic distance ladder by the different CUs. In light of *Gaia* DR4, a significant joint effort of the DPAC CUs is thus being devoted to better characterise the parallax ZPO and derive consistent astrophysical parameters (temperature, metallicity, gravity and absorption values) for Cepheids and RR Lyrae stars.

4.1. *Cross-CUs processing of Cepheids and RR Lyrae stars for Gaia DR4*

Gaia's Cepheids and RR Lyrae stars are identified and characterised by CU7's processing. However, this information is not subsequently taken into account by other DPAC analysis pipelines. This is largely because of how the processing of the *Gaia* data naturally develops, with the CUs processing the astrometry, photometry and spectroscopy starting their processing and freezing their results much earlier than CU7, and CU4 and CU8 running almost in parallel to the variability processing. In addition, the rather tight schedule of the *Gaia* data releases so far has made such cross-processing practically impossible.

The lack of internal coherence introduces systematic errors and uncontrolled uncertainties in the DPAC products. The magnitude and colour variations of Cepheids and RR Lyrae stars implies variations in effective temperature of up to more than one thousand degrees and variations in gravity values that can be as large as 1 dex during a pulsation cycle. So far, the analysis of the RVS and BP/RP prism spectra performed within CU8 has neglected the per-transit variations of the atmospheric parameters of variable sources. This likely explains the inconsistent results described in the previous sections.

Cross-processing of the RVS data for Cepheids and RR Lyrae stars was already successfully implemented between CU6 and CU7 for *Gaia* DR3, leading to the first release of RVS RV curves for a small sample of these variable stars (see Section 2). This collaborative effort will continue for DR4, extending also to other CUs. A DPAC Task Force has been created, including members from CU8, CU7, CU6, CU4 and CU3, to discuss and coordinate the cross-CUs processing of a restricted, selected sample of Cepheids and RR Lyrae stars for which an optimised per-transit treatment can be performed to increase the precision and reduce systematic errors in the *Gaia* data products (astrometric measurements, chemical abundances, epoch and mean RVs, absorption values, etc.) published for these sources in future releases, starting from *Gaia* DR4. This cross-CU processing is schematically illustrated in Figure 1 by the blue arrows connecting the CUs involved.

Processing of the astrometry that will be released as part of DR4 is well advanced. A number of iteratively improved astrometric solutions have already been realised. Tests are underway using the PL(Z), PW(Z) and LZ relations to select the best solution for Cepheids and RR Lyrae stars. In parallel, astrophysical parameters derived by the SOS Cep&RRL pipeline for DR3 Cepheids and RR Lyrae stars, complemented by literature values were fed back to the pipelines processing the RVS spectra to improve the accuracy of the RV determinations. Tests of abundance analysis of the per-transit RVS spectra are also in progress.

4.2. *Gaia's next data releases*

The *Gaia* mission is producing unprecedented astrometry (positions, parallaxes and proper motions), multiband photometry reaching 1 mmag precision, radial velocities and astrophysical parameters for increasing numbers of Cepheids and RR Lyrae stars, with a tremendous impact on the calibration of these standard candles of the cosmic distance ladder. Precision and accuracy of the data products for Cepheids and RR Lyrae stars are expected to further improve thanks to the longer time baseline and the improved processing of the data sets that will be published in future releases.

Two releases of *Gaia* data products will take place within the next few years, a Focused Product Release (FPR) on 10 October 2023 and Data Release 4 (DR4) at the end of 2025. *Gaia* FPR will contain three data products that may be of relevance for calibrations of the distance scale:

1. Astrometry and photometry from engineering images taken in selected regions of high source density (the GC ω Cen, for this FPR);
2. RV epoch data from the RVS for a subsample of the DR3 long-period variables (LPVs);
3. Diffuse interstellar bands (DIBs) from stacked RVS spectra.

Gaia DR4, at the end of 2025, will publish data products from observations collected in the 66 months from July 2014 to January 2020. This will consist of:

1. Full astrometric, photometric and RV catalogues;
2. All available variable-star and non-single-star solutions;
3. Source classifications plus multiple astrophysical parameters (derived from BP/RP, RVS and astrometry) for stars, unresolved binaries, galaxies and quasars;
4. All epoch and transit data for all sources.

The lifetime of the *Gaia* mission is dictated by exhaustion of its cold-gas propellant, which is fundamental to maintain its precision pointing. This will occur in the second quarter of 2025. A first two-year extension of *Gaia*'s operations was already approved by ESA's Science Programme Committee (SPC), extending the collection of data from *Gaia* until the end of 2022. A further extension until mid-2025 was approved in the spring of 2023, thus turning *Gaia* a mission with continued observations over a 10 years total period. This will result in a 30% improvement in position and parallax measurements and a 70% improvement in proper motions. The ESA SPC also extended the Multilateral Agreement concerning *Gaia* data processing. *Gaia*'s post-operations phase will be completed by the end of 2030, and the fifth and last *Gaia* data release, DR5, currently scheduled not before the end of 2030, is anticipated to contain all data collected by the mission over its 10-year lifetime.

4.3. *Synergies with future surveys*

Large spectroscopic surveys of Cepheids and RR Lyrae stars are planned with the new generation spectrographs WEAVE, 4MOST and MOONS. They will use *Gaia* sources as input catalogues and will provide, within the next few years, abundances and radial velocities for *Gaia*'s Cepheids and RR Lyrae stars well beyond the magnitude limit that can be reached with the RVS. This will allow us to further improve the calibration of the PL and PW relations by better constraining their dependence on metal abundance.

A strong synergy will also exist with the Legacy Survey of Space and Time (LSST) at the Vera Rubin Observatory, which in 2024 will start collecting data reaching ∼5 mag fainter than *Gaia* in photometry and ∼3 mag in astrometry (Ivezić et al. 2014; their Figure 1).

4.4. *Gaia Near-infrared*

Gaia Near Infra-Red (GaiaNIR) is one of the proposals that have been selected as a potential future large- or medium-class mission involving international cooperation, among those received in response to the 2016 Call for New Science Ideas in ESA's Science Programme. It is a *Gaia*-type mission covering wavelengths from the optical to the NIR, with a wavelength cutoff in the K band. Proposed for launch around 2045, GaiaNIR would extend the astrometric achievements of *Gaia* to astronomical sources that are only visible in the NIR, allowing to probe deeper through the Galactic dust in the MW disc, the spiral arms and the bulge region, at the same time maintaining the accuracy of the *Gaia* optical reference frame and improving the stellar parallax and proper motion accuracy by revisiting the astronomical sources about 20 years after *Gaia*. Efforts are now underway to identify suitable detectors and to prepare for writing mission proposals.

Such a new all-sky NIR astrometric mission will expand and improve on the science cases of *Gaia*, including the calibration of the Cepheids ad RR Lyrae relations that are known to be much tighter in the NIR.

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References

Andrae, R., Fouesneau, M., Sordo, R., et al. 2023, A&A, 674, A27
Arenou, F., Luri, X., Babusiaux, C., et al. 2018, A&A, 616, A17
Bhardwaj, A., Rejkuba, M., de Grijs, R., et al. 2021, ApJ, 909, 200
Breuval, L., Kervella, P., Wielgórski, P., et al. 2021, ApJ, 913, 38
Breuval, L., Riess, A. G., Kervella, P., et al. 2022, ApJ, 939, 89
Clementini, G., Carretta, E., Gratton, R., et al. 1995, AJ, 110, 2319
Clementini, G., Ripepi, V., Garofalo, A., et al. 2023, A&A, 674, A18

Clementini, G., Ripepi, V., Leccia, S., et al. 2016, A&A, 595, A133
Clementini, G., Ripepi, V., Molinaro, R., et al. 2019, A&A, 622, A60
Creevey, O. L., Sordo, R., Pailler, F., et al. 2023, A&A, 674, A26
Crestani, J., Braga, V. F., Fabrizio, M. et al., 2021, ApJ, 914, 10
Cropper, M., Katz, D., Sartoretti, P., et al. 2018, A&A, 616, A5
Eyer, L., Mowlavi, N., Evans, D. W., et al. 2017, arXiv:1702.03295
Eyer, L., Audard, M., Holl, B., et al. 2023, A&A, 674, A13
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1
Gaia Collaboration, Clementini, G., Eyer, L., et al. 2017, A&A, 605, A79
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al. 2023, A&A, 674, A1
Garofalo, A., Delgado, H. E., Sarro, L. M., et al. 2022, MNRAS, 513, 788
Gilligan, C. K., Chaboyer, B., Marengo, M., et al. 2021, MNRAS, 503, 4719
Ivezić, Ž., Kahn, S. M., & Eliason, P. 2014, EAS Publ. Ser., 67–68, 211
Klagyivik, P., Szabados, L., Szing, A., et al. 2013, MNRAS, 434, 2418
Lambert, D. L., Heath, J. E., Lemke, M., et al. 1996, ApJS, 103, 183
Layden, A. C., Tiede, G. P., Chaboyer, B., et al. 2019, AJ, 158, 105
Groenewegen, M. A. T. 2021, A&A, 654, A2
Li, X.-Y., Huang, Y., Liu, G.-C., et al. 2023, ApJ, 944, 88
Lindegren, L., Bastian, U., Biermann, M., et al. 2021, A&A, 649, A4
Lindegren, L., Hernández, J., Bombrun, A., et al. 2018, A&A, 616, A2
Lindegren, L., Lammers, U., Bastian, U., et al. 2016, A&A, 595, A4
Molinaro, R., Ripepi, V., Marconi, M., et al. 2023, MNRAS, 520, 4154
Muraveva, T., Delgado, H. E., Clementini, G., et al. 2018, MNRAS, 481, 1195
Nemec, J. M., Cohen, J. G., Ripepi, V., et al. 2013, ApJ, 773, 181
Pancino, E., Britavskiy, N., Romano, D., et al. 2015, MNRAS, 447, 2404
Piersimoni, A. M., Bono, G., & Ripepi, V. 2002, AJ, 124, 1528
Recio-Blanco, A., de Laverny, P., Palicio, P. A., et al. 2023, A&A, 674, A29
Riello, M., De Angeli, F., Evans, D. W., et al. 2021, A&A, 649, A3
Riess, A. G., Breuval, L., Yuan, W., et al. 2022a, ApJ, 938, 36
Riess, A. G., Casertano, S., Yuan, W., et al. 2018, ApJ, 861, 126
Riess, A. G., Casertano, S., Yuan, W., et al. 2021, ApJL, 908, L6
Riess, A. G., Yuan, W., Macri, L. M., et al. 2022, ApJL, 934, L7
Rimoldini, L., Holl, B., Gavras, P., et al. 2023, A&A, 674, A14
Ripepi, V., Catanzaro, G., Clementini, G., et al. 2022, A&A, 659, A167
Ripepi, V., Catanzaro, G., Molinaro, R., et al. 2021, MNRAS, 508, 4047
Ripepi, V., Clementini, G., Molinaro, R., et al. 2023, A&A, 674, A17
Sartoretti, P., Blomme, R., David, M., et al. 2022, *Gaia* DR3 documentation, European Space Agency; *Gaia* Data Processing and Analysis Consortium.
Zinn, J. C. 2021, AJ, 161, 214

Discussion

Question (Kiss): Can we go back please to the Galactic Cepheid PL relation? Maybe this is a very naive question, but I noticed an excess of stars at periods 2 to 3 days in several talks, in other words at luminosities around −4 to −5 mag the PL relation is thicker. Why is that so? Do we understand this excess in the luminosity function of Cepheids? Is this the luminosity where the tracks turn, and is that why there are many stars there?

Answer: Im afraid we need the theoreticians to provide an answer here.

Question (Kiss): OK, then I ask the theoreticians in the audience: do we understand this feature?

Answer (Ripepi): If I understand the question well, it's simply a matter of the timescale in relation to the tracks. It is the period of time that the stars spend in the instability strip. So, you have more stars at shorter periods, simply because they are slower, and there are more [of them], also.

Answer (Clementini): Yes, because one of the improvements of *Gaia* is exactly the possibility of seeing the short-period Cepheids, so basically you are increasing this region, probably. Now, this feature shows up more clearly, but it should be an evolution effect.

Question (Riess): Very nice talk. What are the prospects for improving the parallax offset now for DR4?

Answer: Well, there have been calculations already; we are on a good track. As I said before, there will be specific work done at least for Cepheids and RR Lyrae in that context, particularly for bright Cepheids. So, we'll definitely do a more tailored processing of those sources, so there is hope. Already the first results showed that the errors are going down, but it is too early to say. There have been a number of processes already, but those are not final.

Question (Riess): But parallax offsets, are they related to this reprocessing?

Answer: Well, if you try to control the systematics, we still hope that we can improve it a little bit. The first tests show that there is still room for improvement. But how much, it is difficult to say.

Question (Skowron): As regards the forthcoming release of the time-series spectroscopy and radial velocities for long-period variables, is it going to be for all long-period variables or just for a subsample?

Answer: I don't know exactly the number. It will be for a subsample of the long-period variables (LPVs) that were already released in DR3. So, it's not something new, but it's a subsample of the LPVs for which time-series radial velocity data will be published. I don't know exactly the number. Laurent [Eyer], do you remember the number?

Answer (Eyer): Ten thousand.

Answer (Clementini): The problem is that the RVS only goes to sources brighter than about 14 mag in $G_{\rm RVS}$. So, it's the brightest subsample. This is a small sample of bright LPVs for which there is enough time-series RV data.

Question (Baruch): [I'm] very interested in the precision of the parallax measurements. Lindegren, in an earlier paper, DR3, said that for Cepheids that were close to quasars they were getting a couple of μas in precision. And so, the precision is really important, especially from my point of view, where I think there is absorption going on anyway. Do you think DR4 will produce a much better version?

Answer: Well, much better may be a big promise. Better, I'd say. I'd stay on the safe side. Because the processing is going on these days; we don't really have the final results yet.

Question (Baruch): How confident was Lindegren in saying that these were a couple of μas for Cepheids near quasars?

Answer: This is a difficult question, because there are so many effects in play. A couple of μas is really at the limit, I would say.