Gaia, Stellar Populations and the Distance Scale

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Abstract. We discuss the impact that Gaia, a European Space Agency (ESA) cornerstone mission that has been in scientific operations since July 2014, is expected to have on the definition of the cosmic distance ladder and the study of resolved stellar populations in and beyond the Milky Way, specifically focusing on results based on Cepheids and RR Lyrae stars.

Gaia is observing about 1.7 billion sources, measuring their position, trigonometric parallax, proper motions and time-series photometry in 3 pass-bands down to a faint magnitude limit of \( G \approx 21 \) mag. Among them are thousands of Cepheids and hundreds of thousands of RR Lyrae stars. After a five years of mission operations the parallax errors are expected to be of about 10 microarcsec for sources brighter than \( V \approx 12, 13 \) mag. This will allow an accurate re-calibration of the fundamental relations that make RR Lyrae stars and Cepheids primary standard candles of the cosmic distance ladder and will provide a fresh view of the systems and structures that host these classical pulsators. Results for Cepheids and RR Lyrae stars published in Gaia Data Release 1 (DR1) are reviewed along with some perspectives on Gaia DR2, scheduled for 25 April 2018, which will contain parallaxes based only on Gaia measurements and a first mapping of full-sky RR Lyrae stars and Cepheids.

1. Introduction

The Gaia mission has been surveying the whole sky since July 2014, measuring astrometric parameters (positions, parallaxes and proper motions) and collecting multi-epoch photometry in three different pass-bands (Gaia G, \( G_{BP} \) and \( G_{RP} \)) of sources within a limiting magnitude of \( G = 21 \) mag and a bright limit of \( G \approx 3 \) mag that transit across its field of view. The spacecraft also simultaneously collects spectroscopy with the Radial Velocity Spectrometer (RVS) of the sources brighter than \( V \approx 16 \) mag. At the end of a five year nominal duration of the mission each source will have on average 70 photometric measurements (over 200 observations for sources at \( |\text{DEC}|=45 \pm 10 \) deg) and about 40 spectroscopic measurements with the RVS. This makes Gaia a most powerful tool to discover and characterise variable sources. About 1.7 billion sources
are being measured by Gaia, among which are thousands of Cepheids and hundred of thousands RR Lyrae stars in the Milky Way (MW) and its nearest neighbours.

Astrometric, photometric and spectroscopic performances of Gaia vary depending on the source magnitude and spectral type. Estimated end-of mission (e.o.m.) values are summarised on the ESA Gaia web page (https://www.cosmos.esa.int/web/gaia/science-performance). In particular, for the typical spectral types of RR Lyrae stars and Cepheids e.o.m. standard errors of the integrated photometry are expected to be of 0.2 millimag in G and 1 millimag in $G_{BP}$ and $G_{RP}$ at $G \sim 15$ mag, and 3.7, 56, and 48 millimag, respectively, at $G \sim 20$ mag. Astrometric standard errors are of 24 $\mu$as at $V \sim 15$ mag and 540 $\mu$as at $V \sim 20$ mag and radial velocity errors are below 1 km s$^{-1}$ for $V < 12$ mag and below 15 km s$^{-1}$ for $V < 15$ mag.

A major asset of Gaia observations is that there are no proprietary data rights. Gaia data become public as soon as they have been fully processed and properly validated. Release of the Gaia final catalogue of data collected over the 5 year nominal duration of the mission is scheduled for 2022. However, publication of preliminary data products is also anticipated through a number of intermediate data releases, the first of which (Gaia Data Release 1 - DR1) took place on 14 September 2016, a second release (Gaia DR2) will occur on 25 April 2018 and a third one (Gaia DR3) is currently foreseen in the second half of 2020.

2. Cepheids and RR Lyrae stars with Gaia

The potential of Gaia in the field of variable stars such as Cepheids and RR Lyrae stars is enormous, encompassing the complete census of such variables in and beyond the MW and the direct measure through parallax of their distances, hence absolute magnitude, locally and farther than the Magellanic Clouds, although with relatively larger individual errors in the latter case. According to current estimates, Gaia is expected to increase up to a factor of ten the number of known Classical Cepheids in the MW and to enlarge the number of known Galactic RR Lyrae stars well beyond the current value of more than a hundred thousands.

RR Lyrae stars and Cepheids are the most important stellar distance indicators in the Local Group (LG) and beyond (e.g. Muraveva et al. 2015, and references therein). They also are fundamental tracers of old ($t >10$ Gyr, RR Lyrae) and young ($50 < t < 500$ Myr, Classical Cepheids) stellar populations, complementing the color-magnitude diagram (CMD) in recovering the star formation histories (SFH) of the resolved stellar populations in galaxies. The complete census of Galactic Cepheids and RR Lyrae stars along with an unprecedented precision and accuracy of Gaia parallax measurements for local Cepheids and RR Lyrae will allow a breakthrough in our understanding of the MW structure, dynamics and formation, and a global re-assessment of the whole cosmic distance ladder from local to cosmological distances. Concurrently, RR Lyrae stars and Cepheids can be used to test the accuracy and precision of the parallaxes and to assess systematics, biases and correlations in the Gaia parallax data.

By observing thousands of Galactic and Magellanic Cloud pulsators, Gaia will allow us to calibrate with unprecedented precision and statistics the fundamental relations connecting the pulsation period $P$ to the mean magnitudes and colors of Cepheids and RR Lyrae stars. This specifically implies using Gaia parallaxes to calibrate the optical and near/mid infrared Period-Luminosity ($PL$), Period-Luminosity-Color ($PLC$) and Period-Wesenheit ($PW$) relations of Classical and Type II Cepheids; the opti-
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cal Luminosity-Metallicity relation \( (M_V - \text{[Fe/H]} ) \) and the near/mid-infrared \( PL \) and Period-Luminosity-Metallicity \( (PLZ) \) relations of RR Lyrae stars; to study in detail the systematics affecting these relations and, to test their universality across different stellar systems. It also opens the way to possibly extend those relations to the “ultra-long” period \( (ULP) \) Cepheids (Cepheids with periods longer than 80 days and about 2-4 mag brighter than Classical Cepheids) that could serve as stellar standard candles reaching cosmologically relevant distances \( D \geq 100 \) Mpc, in only one step. Furthermore, the parallax information combined with chemistry from the RVS and complementary spectroscopy from ongoing and future ground-based surveys will allow us to study the metallicity dependence of the \( PL/PW \) relations and at the same time determine the metallicity distribution of young (with Classical Cepheids) and old (with RR Lyrae stars) stellar populations in the host systems. \textit{Gaia} will also make it possible to directly calibrate via parallax the Tip of the Red Giant Branch (TRGB) luminosity for a number of close by stellar systems. Secondary indicators peering into the unperturbed Hubble Flow such as the Type Ia supernovae (SNe Ia) and the surface brightness fluctuations (SBF) will be re-calibrated on the \textit{Gaia}-based relations of Cepheids and RR Lyrae stars, thus setting the basis for a measurement of the Hubble constant with 1\% accuracy and at the same cementing \textit{Gaia}’s impact in the JWST, LSST and E-ELT era.

On the other hand, \textit{Gaia}’s collecting time-series photometry over the whole sky will allow the discovery and characterisation of thousands of new RR Lyrae stars and Cepheids in still unexplored regions of the MW and its satellites. By combining positions and proper motions of RR Lyrae stars and Cepheids observed by \textit{Gaia} down to \( G \sim 21 \) mag it will be possible to trace the corresponding parent stellar populations, map the 3-dimensional geometry the MW and its neighbours, specifically tracing the distribution of young and old stars, even in crowded regions, and then comparing them with existing theoretical models in order to understand their formation and evolution. For instance, this study will be particularly important to better understand the Magellanic System (Large Magellanic Cloud – LMC, Small Magellanic Cloud – SMC, and the bridge connecting them) and its interaction with the MW.

With the \textit{Gaia} DR2 release of a first mapping of full-sky RR Lyrae stars it will already be possible to use them to map the Galactic halo, the disk and the bulge, to unveil new streams, possibly discover new satellites, to study radial trends, extra-tidal stellar populations around globular clusters, and to trace tidal streams and halos around satellite galaxies within the reach of \textit{Gaia}. The study of the specific properties of these variables (period, metallicity, etc.) will help identifying the “building-blocks” that have contributed to building up the MW halo, whether “classical” satellites like Sagittarius, Carina, Sculptor, Ursa Minor and the two Magellanic Clouds, or members of the ultra-faint class of dwarfs recently discovered around the MW, ultimately providing hints about how our Galaxy has been assembled. For years, the classical CMD-reconstruction method via the \( \chi^2 \) minimization has been used to derive the space-resolved star formation histories (SFH) of nearby galaxies, setting the foundations of the so-called "near-field cosmology.” An example of how powerful and innovative the approach of combining the SF recovery based on the CMD-reconstruction and the analysis of the variable star population can be is, for instance, the study of the ultra-faint dwarf galaxy Leo T by Clementini et al. (2012). The precise photometry and distances for thousands of variables and several million constant stars provided by \textit{Gaia} will allow extending this combined approach to a large fraction of the MW, and to improve the line-of-sight resolution in the analysis of the nearest galaxies.
Finally, *Gaia*’s astrometry, spectroscopy, time-series photometry and radial velocity measurements covering the entire sky will also enable us to constrain stellar intrinsic parameters, such as the mass, luminosity and effective temperature, to test and improve the input physics of evolutionary and pulsation models, as well as to improve the physics of indirect techniques used to measure distances beyond the reach of *Gaia* parallaxes.

3. Cepheids and RR Lyrae stars in *Gaia* Data Release 1

*Gaia* Data Release 1 (DR1) published positions and $G$ magnitudes for about 1 billion stars from observations taken in 14 months from July 2014 and September 2015 (Gaia Collaboration et al. 2016a, 2016b) and five-parameter astrometry for about 2-million sources in common between the Thyco-2 and *Gaia* catalogues, obtained as a joint astrometric solution of the Thyco and *Gaia* measurements (TGAS), specific for this first release. The TGAS sample includes parallaxes for more than 700 Galactic Cepheids and RR Lyrae stars.

![Figure 1. Classical Cepheid $PL$ relation in the $Ks$-band using Hipparcos (bottom panel) and TGAS (middle panel) parallaxes (adapted from Fig. 20 in Gaia Collaboration et al. 2017). The top panel shows the Cepheid $PL$ relation based on the *Gaia*-only parallaxes released in DR2 (Ripepi et al., in prep).](image)

A taste of *Gaia*’s potential relative to Cepheid and RR Lyrae calibrations has been shown by Gaia Collaboration et al. (2017) who used the TGAS parallaxes along with literature ($V, I, J, K_s, W_1$) photometry and spectroscopy, to calibrate the zero point of the $PL$ and $PW$ relations of Classical and Type II Cepheids, and the near/mid-infrared $PL$, $PLZ$ and optical $M_V - [Fe/H]$ relations of RR Lyrae stars. Figure 1 shows a comparison of the $Ks$-band $PL$ relations defined by Galactic Classical Cepheids in DR1 when using
the Hipparcos (bottom panel) and TGAS (middle panel) parallaxes, respectively. Figure 2 shows the same comparison for RR Lyrae stars. Although this is not comparable to the final Gaia precision, it already represents a significant general improvement with respect to Hipparcos parallaxes, particularly for RR Lyrae stars. A further step forward is represented by Gaia-only astrometry released in DR2 (see upper panels of Figs. 1 and 2).

The fit the PL relations, the Gaia Collaboration et al. (2017) applied different techniques that operate either in distance/absolute magnitude or in parallax space directly. However, we note that the direct transformation to absolute magnitude by parallax inversion is not possible if parallaxes are negative, thus biasing the sample due to the selective removal of distant sources with close to zero/negative parallaxes. Additionally, due to the presence of the logarithmic term in the relation between parallax and absolute magnitude, symmetrical errors in the parallaxes become asymmetric errors in magnitude. Therefore, working in parallax space, and adopting for instance a Bayesian approach, is definitely preferred, as it allows one to maintain symmetrical the errors and use negative parallax values. The hierarchical Bayesian model used in Gaia Collaboration et al. (2017) is fully described by Delgado et al. (2018).

The publication of variability data products was originally scheduled to start much later than the Gaia first data release; however, in advance of schedule, in DR1 G-band time series photometry and characteristic parameters were released for a small sample of 3194 LMC RR Lyrae stars and Cepheids that Gaia observed at high cadence during
the first 28 days of scientific operation in Ecliptic Poles Scanning Law. A detailed description of the specific processing and main characteristics of the RR Lyrae stars and Cepheids released in DR1 can be found in Clementini et al. (2016), whereas the general approach of variability analysis and classification of the Gaia data is presented in Eyer et al. (2017). Nice examples of the Gaia photometric quality at the faint magnitudes of the RR Lyrae stars in the LMC are shown in Fig. 23 of Clementini et al. (2016), whereas Fig. 32 in that paper showcases the potential of Gaia in relation to RR Lyrae stars as tracers of galaxy halos.

4. Cepheids and RR Lyrae stars in Gaia Data Release 2

Data Release 2 (DR2) will contain astrometry, photometry, and radial velocities from the processing of all-sky sources observed over 22 months between July 2014 and May 2016. The content of the release is described in some detail in the ESA Gaia web page (https://www.cosmos.esa.int/web/gaia/dr2). Among other products, DR2 will include the five-parameter astrometric solution (positions, parallaxes and proper motions) based only on Gaia measurements for more than 1.3 billion sources with G magnitudes from about 3 to 21 mag, median radial velocities for more than 7.2 million stars with G magnitudes between about 4 and 13 mag, G magnitudes for about 1.7 billion sources and G\_BP, G\_RP photometry for about 1.4 billion sources. With specific relevance to the discussion presented in this paper, Gaia DR2 will also publish the classification (and multi-band time-series photometry) for more than half a million variable sources of which a good fraction are RR Lyrae stars spread over the whole celestial sphere. The line-of-sight extinction A\_G and the metallicity [Fe/H] inferred from the pulsation characteristics (period, amplitude and Fourier parameters of the light curve) will also be released for a significant number of these RR Lyrae stars (along with A\_G values for some Classical Cepheids). They will probe the dust and metallicity distribution of the old stellar component in the MW.

Uncertainty of the DR2 parallaxes is around 0.04 mas for sources brighter the G = 15 mag, and on the order of 0.7 mas at G = 20 mag. With these first Gaia-only

Figure 3. Sky map, in Galactic coordinates, of literature Cepheids. See Fig. 39 of Clementini et al. (2018) for an updated version of this figure showing more than 350 new Cepheids discovered by Gaia and released in DR2.
parallaxes, both the RR Lyrae and Cepheid zero points and the TRGB method will be independently calibrated with at least one order of magnitude more calibrators, each having unprecedented precision.

Figure 4. Distribution on the sky, in Galactic coordinates, of about 160,000 RR Lyrae stars known in the literature. Filled blue dots and red filled diamonds indicate globular clusters and dwarf spheroidal galaxies (classical and ultra-faint) that are known to contain RR Lyrae stars. See Fig. 45 of Clementini et al. (2018) for an updated version of this figure showing new all-sky RR Lyrae stars released in Gaia DR2 and literature variable stars, for a total of more than 223,000 sources.

Figure 5. Same as in Fig. 4 but in equatorial coordinates.

Figure 3 shows the distribution on the sky of known Cepheids. More than 13,000 Cepheids of various types (Classical, Anomalous and Type II) are shown in the figure. Over than 10,000 of these Cepheids were identified by the OGLE survey in the Magellanic Clouds. Figure 4 shows a sky map, in galactic coordinates, of known RR Lyrae stars and, Fig. 5, shows the same sample viewed in equatorial coordinates. About 160,000 fundamental-mode, first-overtone and double-mode RR Lyrae are shown, collecting data from many different surveys among which major ones are: OGLE, ASAS,
PanSTARSS, CATALINA, LINEAR, ASASSN and Gaia DR1. Filled blue dots and red filled diamonds mark globular clusters and dwarf spheroidal galaxies (classical and ultra-faint) that are known to contain RR Lyrae stars. We look forward to see the fresh view of the MW halo, disk and bulge provided by the all-sky Cepheid and RR Lyrae maps released with Gaia DR2.

5. Conclusions and Future Prospectives

*Gaia* second data release is going to deliver its promise of new and accurate astrometry (positions, parallaxes and proper motions) based only on *Gaia* measurements and of RR Lyrae stars and Cepheids identified across the whole Galaxy and its closest companions. This will already allow a breakthrough in our understanding of the MW structure, dynamics, and formation, and a re-assessment of the cosmic distance ladder. Results will further improve with Gaia DR3 in 2020 and with the release of Gaia final catalogue in 2022. Meanwhile, ESA has approved a 2-year extension of the *Gaia* mission, and further extensions of 2+1 years are likely to be approved in the future. This will leave *Gaia* still fully operational when JWST will be launched, LSST will see its first light (both events being currently foreseen for 2020) and E-ELT first light will take place (currently foreseen for 2024), thus enhancing the synergy among these outstanding projects. Looking further ahead, a new Gaia-like mission is also being conceived with all-sky absolute optical and near-infrared (NIR) astrometry (GaiaNIR). Going into the NIR, the new mission would be able to probe through the Galactic dust and most obscured regions of the MW disk, bulge and spiral arms.

In closing I would like to reflect on the great scientist to whom this meeting is dedicated. I met Jeremy more than twenty years ago, we shared the office in Bologna for about a couple of months. We started a joint project to measure the chemical composition of bright Galactic RR Lyrae stars and study their luminosity-metallicity relation. With that study we set the slope of the $M_V - [\text{Fe/H}]$ relation, now *Gaia* will pin down its zero point with unprecedented precision. Thank you Jeremy, it has been an honour and a pleasure to work with you.

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