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## Gaia Data Release 1: Testing parallaxes with local Cepheids and RR Lyrae stars

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# Gaia Data Release 1

## Testing the parallaxes with local Cepheids and RR Lyrae stars

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## ABSTRACT

**Context.** Parallaxes for 331 classical Cepheids, 31 Type II Cepheids and 364 RR Lyrae stars in common between *Gaia* and the Hipparcos and Tycho-2 catalogues are published in *Gaia* Data Release 1 (DR1) as part of the Tycho-*Gaia* Astrometric Solution (TGAS, Lindegren et al. 2016).

**Aims.** In order to test these first parallax measurements of the primary standard candles of the cosmological distance ladder, that involve astrometry collected by *Gaia* during the initial 14 months of science operation, we compared them with literature estimates and derived new period-luminosity ( $PL$ ), period-Wesenheit ( $PW$ ) relations for classical and Type II Cepheids and infrared  $PL$ ,  $PL$ -metallicity ( $PLZ$ ) and optical luminosity-metallicity ( $M_V$ -[Fe/H]) relations for the RR Lyrae stars, with zero points based on TGAS.

**Methods.** Classical Cepheids were carefully selected in order to discard known or suspected binary systems. The final sample comprises 102 fundamental mode pulsators, with periods ranging from 1.68 to 51.66 days (of which 33 with  $\sigma_\pi/\pi < 0.5$ ). The Type II

Cepheids include a total of 26 W Virginis and BL Herculis stars spanning the period range from 1.16 to 30.00 days (of which only 7 with  $\sigma_{\pi}/\pi < 0.5$ ). The RR Lyrae stars include 200 sources with pulsation period ranging from 0.27 to 0.80 days (of which 112 with  $\sigma_{\pi}/\pi < 0.5$ ). The new relations were computed using multi-band ( $V, I, J, K_s, W_1$ ) photometry and spectroscopic metal abundances available in the literature, and applying three alternative approaches: (i) by linear least squares fitting the absolute magnitudes inferred from direct transformation of the TGAS parallaxes; (ii) by adopting astrometric-based luminosities, and (iii) using a Bayesian fitting approach. The latter two methods work in parallax space where parallaxes are used directly, thus maintaining symmetrical errors and allowing negative parallaxes to be used. The TGAS-based  $PL$ ,  $PW$ ,  $PLZ$  and  $M_V - [\text{Fe}/\text{H}]$  relations are confronted by comparing the distance to the Large Magellanic Cloud provided by different types of pulsating stars and alternative fitting methods.

**Results.** Good agreement is found from direct comparison of the parallaxes of RR Lyrae stars for which both TGAS and HST measurements (Benedict et al. 2011) are available. Similarly, very good agreement is found between the TGAS values and the parallaxes inferred from the absolute magnitudes of Cepheids and RR Lyrae stars analysed with the Baade-Wesselink method. TGAS values also compare favourably with the parallaxes inferred by theoretical model fitting of the multi-band light curves for two (out of three) classical Cepheids and one RR Lyrae star in our samples. The  $K$ -band  $PL$  relations show the significant improvement of the TGAS parallaxes for Cepheids and RR Lyrae stars with respect to the Hipparcos measurements. This is particularly true for the RR Lyrae stars for which improvement in quality and statistics is impressive.

**Conclusions.** TGAS parallaxes bring a significant added value to the previous Hipparcos estimates. The relations presented in this paper represent first *Gaia*-calibrated relations and form a “work-in-progress” milestone report in the wait for *Gaia*-only parallaxes of which a first solution will become available with *Gaia*’s Data Release 2 (DR2) in 2018.

**Key words.** Astrometry – Parallaxes – Stars: distances – Stars: variables: Cepheids – Stars: variables: RR Lyrae – Methods: data analysis

## 1. Introduction

On 14 September 2016, photometry and astrometry data collected by the *Gaia* mission during the first 14 months of science operation have been released to the public with *Gaia* first data release (hereinafter *Gaia* DR1; *Gaia* Collaboration et al. 2016b,a). In particular, *Gaia* DR1 catalogue includes positions, proper motions and parallaxes for about 2 million stars in common between *Gaia* and the Hipparcos and Tycho-2 catalogues, computed as part of the Tycho-*Gaia* Astrometric Solution (TGAS), of which the principles are discussed in Michalik et al. (2015) and results published in *Gaia* DR1 are described in detail in Lindgren et al. (2016). Among the TGAS sources is a sample of Galactic pulsating stars that includes 331 classical Cepheids, 31 Type II Cepheids and 364 RR Lyrae stars. As part of a number of checks performed within the *Gaia* Data Processing and Analysis Consortium (DPAC) we have tested TGAS parallaxes for Cepheids and RR Lyrae stars by building canonical relations followed by these variable stars, such as the period-luminosity ( $PL$ ) and period-Wesenheit ( $PW$ ) relations for classical and Type II Cepheids and the infrared  $PL$ ,  $PL$ -metallicity ( $PLZ$ ) and optical luminosity-metallicity ( $M_V - [\text{Fe}/\text{H}]$ ) relations for RR Lyrae stars, with zero points based on TGAS parallaxes. Results of these tests are presented in this paper.

Thanks to the characteristic  $PL$  relation discovered at the beginning of the last century by Mrs Henrietta Swan Leavitt (1868 - 1921), classical Cepheids have become the basis of an absolute calibration of the extragalactic distance scale (see e.g. Freedman et al. 2001; Saha et al. 2006; Fiorentino et al. 2013; Riess et al. 2011, 2016, and references therein). The  $PL$  is a statistical relation with an intrinsic dispersion caused by the finite width of the instability strip for pulsating stars. This dispersion is particularly significant in the optical bands (e.g.  $B, V$ ), where it is of the order of  $\pm 0.25$  mag, but decreases moving towards longer wavelengths becoming less than  $\sim \pm 0.1$  mag in the near and mid-infrared (NIR and MIR) filters (see e.g. Madore & Freedman 1991; Caputo et al. 2000a; Marconi et al. 2005; Ngeow et al. 2012; Ripepi et al. 2012; Inno et al. 2013; Gieren et al. 2013, and references therein). Main open issues concerning the use of the Cepheid  $PL$  for extragalactic distance determinations are: (i) the dependence of the  $PL$  relation on chemical composition, on which no general consensus has been reached yet in the literature and, (ii) the possible nonlinearity of the Cepheid  $PL$  relations

at the longest periods, for which some authors find evidence in the form of a break around 10 days, with a clear corresponding change of the  $PL$  slope in  $B, V, R$  and  $I$  (see e.g. Ngeow & Kanbur 2006; Tammann et al. 2003). Both metallicity (and helium) dependence and nonlinearity effect, besides the effect of the finite intrinsic width of the instability strip mentioned above, decrease when moving from optical to NIR and MIR passbands (see e.g. Madore & Freedman 1991; Caputo et al. 2000a; Marconi et al. 2005; Ripepi et al. 2012, 2016; Inno et al. 2013; Gieren et al. 2013, and references therein).

When optical bands are used great advantages are obtained by adopting reddening-free formulations of the  $PL$  relation, called Wesenheit functions ( $PWs$ ) (see Madore 1982; Caputo et al. 2000a; Ripepi et al. 2012). These relations include a colour term, thus partially correcting for the intrinsic width of the instability strip, whose coefficient is given by the ratio of total to selective extinction. The Wesenheit relation in the  $V, I$  bands,  $PW(V, I)$ , is often adopted to derive accurate extragalactic distances as it is widely recognized to be little dependent on metallicity (see e.g. Bono et al. 2010, and references therein). Other filter combinations, extending to the NIR, are also commonly used in the literature (see e.g. Riess et al. 2011, 2016; Fiorentino et al. 2013; Ripepi et al. 2012, 2016). However, all these relations need an accurate calibration of their zero points and a quantitative assessment of the dependence of slope and zero point on the chemical composition, as any systematic effects on the coefficients of both  $PL$  and  $PW$  relations directly propagates in the calibration of the secondary distance indicators and the estimate of the Hubble constant,  $H_0$ . *Gaia* will play a crucial role to definitely address all these issues of the Cepheid-based distance ladder.

On the other hand, an alternative and independent route to  $H_0$  using the cosmic “distance ladder” method is provided by Population II pulsating stars such as the RR Lyrae stars, (see, e.g. Beaton et al. 2016, and references therein), the Type II Cepheids and the SX Phoenicis variables, old ( $t \gtrsim 10$  Gyr), sub-solar mass variables, that typically populate globular clusters and galactic halos. While Type II Cepheids and SX Phoenicis stars follow  $PL$  relations, the standard candle commonly associated with RR Lyrae stars is the relation existing between the mean absolute visual magnitude  $\langle M_V(RR) \rangle$  and the iron content  $[\text{Fe}/\text{H}]$ , usually assumed in a linear form:  $M_V(RR) = a[\text{Fe}/\text{H}] + b$ . Current determinations of the slope  $a$  and zero point  $b$  of this relation span a

wide range of values (see e.g. Clementini et al. 2003; Cacciari & Clementini 2003; Marconi 2015, and references therein) and theoretical investigations based on evolutionary and pulsation models also suggest a change in the slope at  $[\text{Fe}/\text{H}] \approx -1.5$  dex (see e.g. Caputo et al. 2000b; Cassisi et al. 1998; Lee et al. 1990). The other characteristic relation that makes RR Lyrae stars fundamental primary distance indicators for systems mainly composed by Population II stars is the  $PL$  relation they conform to at infrared wavelengths and in the  $K$  ( $2.2 \mu\text{m}$ ) band in particular, as first pointed out in the pioneering investigations of Longmore et al. (1986, 1990). Due to the strict relation between the  $V - K$  colour and the effective temperature and between the latter quantity and the pulsation period the nearly horizontal distribution of the RR Lyrae stars in the  $M_V$  versus  $\log P$  plane evolves into a strict  $PL$  relation in the  $M_K$  versus  $\log P$  plane (see e.g. fig. 2 of Catelan et al. 2004), by which longer periods correspond to brighter pulsators in the  $K$  band. It has also been demonstrated (Bono et al. 2001) that the intrinsic dispersion of the  $PL(K)$  relation drastically decreases when metallicity differences and evolutionary effects are taken into account. However, coefficients and zero point of the  $M_K - \log P - [\text{Fe}/\text{H}]$  relation (hereinafter,  $PM_KZ$ ) are still matter of debate in the literature and may differ significantly from one study to the other (see e.g. Marconi 2015). Bono et al. (2003) and Catelan et al. (2004) analysed the  $PM_KZ$  from the semi-theoretical and theoretical point of view and found a non-negligible dependence of the RR Lyrae  $K$ -band absolute magnitude,  $M_K$ , on metallicity:  $b = 0.231 \pm 0.012$  and  $b = 0.175$ , respectively. Conversely, the dependence of the  $K$ -band luminosity on metallicity derived in empirical studies is generally much shallower (Del Principe et al. 2006) or even negligible (Sollima et al. 2006, 2008, Borissova et al. 2009, Muraveva et al. 2015). As for the dependence of  $M_K$  on period, values in the literature vary from  $-2.101$  (Bono et al. 2003) to  $-2.73$  (Muraveva et al. 2015).

In this paper we use TGAS parallaxes of local Cepheids and RR Lyrae stars along with literature  $V, I, J, K_s, W_1$  photometry to compute new  $PL$ ,  $PW$  and  $M_V - [\text{Fe}/\text{H}]$  relations through a variety of methods and compare their results. This enables us to test TGAS parallaxes for these primary standard candles. Estimation of distances from trigonometric parallaxes is not straightforward and still matter of debate. The direct transformation to distance (and then absolute magnitude) by parallax inversion is not often advisable if errors are large, since it causes asymmetric errors in the magnitudes and does not allow the use of negative parallaxes. Methods that operate in parallax space such as the Astrometric Based Luminosity (ABL, Arenou & Luri 1999) and Bayesian approaches are to be preferred. In this paper we adopt the least squares fit of the absolute magnitudes obtained from direct transformation of the parallaxes, the ABL method and a Bayesian approach to fit the various relations that Cepheids and RR Lyrae stars conform to, then compare the results that different types of variables and different fitting methods provide for the distance to the Large Magellanic Cloud (LMC). Far from seeking results on the cosmic distance ladder as re-designed by these first *Gaia* measurements, the exercise presented in this paper is meant to assess limitations and potential of this first astrometry solution and to compare different methods of handling parallaxes. The present approach partially differs from the photometric parallax approach adopted in Lindegren et al. (2016) and Casertano et al. (2017), where literature Cepheid  $PL$  relations (whether in the visual or the near-infrared) are assumed to probe TGAS parallaxes of classical Cepheids, and, hopefully, it is less prone to shortcomings arising from the intrinsic width of the Cepheid instability strip and the poor knowledge about universality, linearity

and metallicity-dependence of the reference relations used in the aforementioned studies.

The paper is organized as follows: in Section 2 we present the samples of Cepheids (both classical and Type II) and RR Lyrae stars we have analysed, describe how they were selected and compare their TGAS parallaxes with parallax values (Hipparcos and/or HST) available in the literature for some of them, with the parallaxes inferred from the theoretical modelling of the light curves and from Baade-Wesselink studies. In Section 3 we analyse possible biases that affect the Cepheid and RR Lyrae samples and describe the methods we used to fit the various relations of these variable stars. In Section 4 we present the photometric dataset used for the classical Cepheids and the derivation of the corresponding  $PL$  and  $PW$  relations. Section 5 is devoted to the Type II Cepheids, and Section 6 to the RR Lyrae stars. In Section 7, we discuss the TGAS-based relations derived in the previous sections by comparing the distance to the Large Magellanic Cloud they provided and present a few concluding remarks.

## 2. Cepheid and RR Lyrae samples

### 2.1. Sample selection

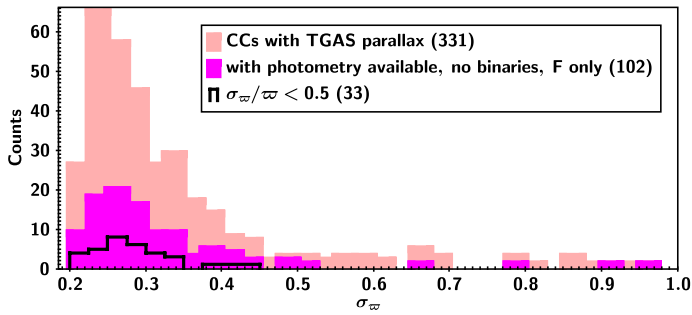
The magnitude distribution of the sources for which a parallax measurement is available in *Gaia* DR1 is shown in fig. 1 of *Gaia* Collaboration et al. (2016a) and includes sources with a mean  $G$ -band apparent magnitude between  $\sim 5$  and  $\sim 13.5$  mag (but only very few with  $G \lesssim 7$  mag). The typical uncertainty of the TGAS parallaxes is 0.3 milliarcsecond (mas), to which a systematic component of 0.3 mas should be added, arising from model assumptions and simplifications of data processing for DR1, among which, mainly, position and colour of the sources, as widely discussed in Lindegren et al. (2016) and also summarised in section 6 of *Gaia* Collaboration et al. (2016a). Since TGAS parallaxes are available for sources observed by Tycho-2 (Høg et al. 2000), of which only a fraction are also in the Hipparcos catalogue (ESA 1997; van Leeuwen 2007a), to build the largest possible samples we used the list of Cepheids and RR Lyrae stars in the Tycho-2 catalogue as reference. To create this list we cross-identified the Tycho-2 whole catalogue with the General Catalog of Variable Stars (GCVS database; Samus et al. 2007-2015) that contains a total of 1100 between classical and Type II Cepheids and with the David Dunlap Observatory Database of Galactic Classical Cepheids (DDO<sup>1</sup>; Fernie et al. 1995) that contains over 500 classical Cepheids. In particular, according to the variability types in the GCVS, in these selections we included, under the definition of *Classical Cepheids*, the following types: Cepheids and classical Cepheids or Delta Cephei-type variables (CEP and CEP(B), DCEP, DCEPS and DCEPS(B), as labelled in the GCVS) and under *Type II Cepheids*, the following types: CW, CWA, CWB, RV, RVA and RVB. Crossmatching these databases with the Tycho-2 general catalogue ( $\gtrsim 2.5$  billion sources) and following supplements ( $\gtrsim 18$  thousand sources) we found final samples of 388 classical and 33 Type II Cepheids<sup>2</sup>. We then queried the `tgas_source` table in the *Gaia* Archive Core Systems (GACS)<sup>3</sup> to retrieve TGAS parallaxes and *Gaia*

<sup>1</sup> <http://www.astro.utoronto.ca/DDO/research/cepheids/>

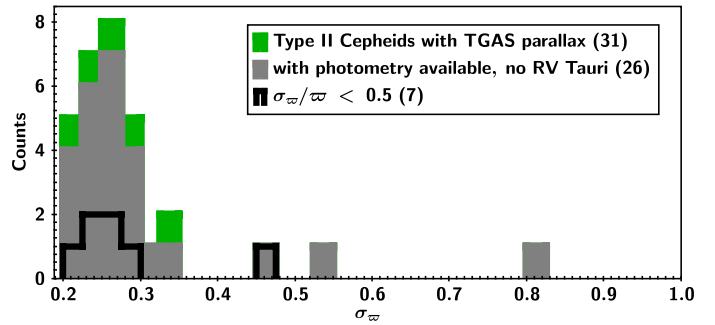
<sup>2</sup> The cross-match between Tycho-2 and GCVS sources was done using equatorial J2000 RA, DEC coordinates and assuming an astrometric error of 1 arcsec between catalogues. Conversely, we converted the DDO database equatorial B1950 coordinates to J2000 before matching the Tycho-2 and DDO catalogues and assumed 1-5 arcsec as maximum difference of the two sets of coordinates.

<sup>3</sup> <http://Gaia.esac.esa.int/archive/>





**Fig. 1.** Error distribution of TGAS parallaxes for classical Cepheids (CCs, in the label): whole sample (331 stars, pink), subsample with literature photometry after removing binaries and retaining only fundamental-mode (F) pulsators (102 stars, magenta), subsample of the previous 102 sources retaining only stars with positive parallax and parallax errors  $\sigma_\pi/\pi < 0.5$  (33 stars, black contour). The bin size is 0.025 mas.

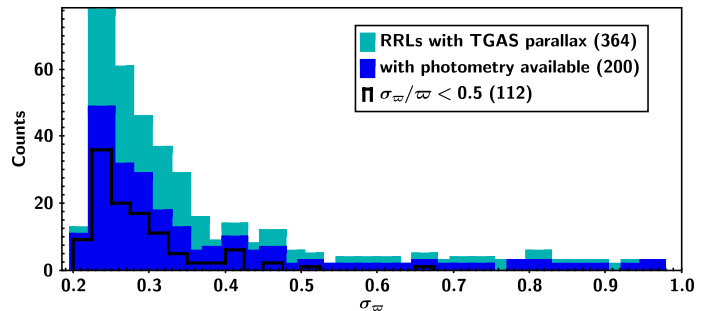


**Fig. 2.** Error distribution of TGAS parallaxes for Type II Cepheids: whole sample (31 stars, green), subsample with literature photometry and removing variables of RV Tauri type (26 stars, gray), subsample of the previous 26 sources retaining only stars with positive parallax and parallax errors  $\sigma_\pi/\pi < 0.5$  (7 stars, black contour). The bin size is 0.025 mas.

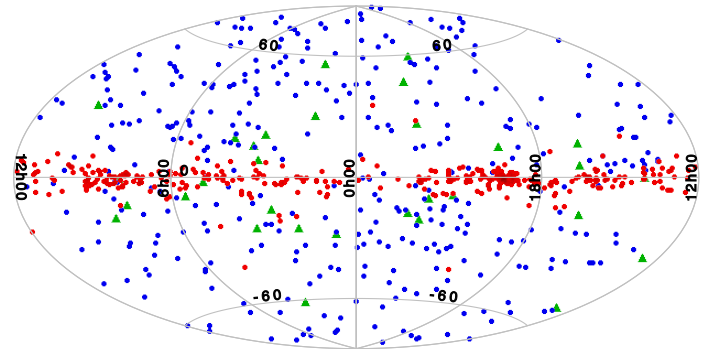
*G*-band apparent magnitudes for the samples of 388 classical and 33 Type II Cepheids. Only for 331 of the classical Cepheids in our list TGAS parallaxes and *Gaia* *G* magnitudes are actually available in GACS. They span *G*-band apparent magnitudes in the range  $4.68 \leq G \leq 12.54$  mag. Their parallaxes span the range from  $-1.610$  to  $6.214$  mas, with parallax errors in the range from 0.215 and 0.958 mas, and with 29 sources having TGAS negative parallax. The error distribution of TGAS parallaxes for the 331 classical Cepheids is shown by the pink histogram in Fig. 1. Of the 33 Type II Cepheids only 31 have *G* magnitude and TGAS parallax available. They span *G*-band apparent magnitudes in the range  $6.89 \leq G \leq 12.10$  mag. Their parallaxes span the range from  $-0.234$  to  $3.847$  mas, with parallax errors from 0.219 mas to 0.808 mas, and with negative parallax for 5 of them. The error distribution of the TGAS parallax for the 31 Type II Cepheids is shown by the green histogram in Fig. 2.

Concerning the RR Lyrae stars, the GCVS (Samus et al. 2007-2015) contains information on 7954 such variables which are labelled as RR, RR(B), RR:, RRA, RRAB, RRAB:, RRC, RRC:, where ":" means uncertain classification. We cross-matched the GCVS RR Lyrae star sample against the Tycho-2 general catalogue and its supplements, and found 421 sources in common. Three sources, (namely, S Eri, V2121 Cyg and NZ Peg) have uncertain classification according to "The SIMBAD astronomical database" (Wenger et al. 2000) and were removed. We then crossmatched the remaining 418 sources against the *tgas\_source* table in GACS and found a TGAS parallax for 364 of them. Values of the *G*-band apparent magnitude for these 364 RR Lyrae stars are in the range  $7.03 \leq G \leq 13.56$  mag. Their parallaxes are in the range from  $-0.837$  to  $13.131$  mas with parallax errors spanning the range from 0.209 to 0.967 mas and six stars having negative parallaxes. The error distribution of TGAS parallax for the 364 RR Lyrae stars is shown by the cyan histogram in Fig. 3.

Finally, the distribution on sky of the 331 classical Cepheids, 31 Type II Cepheids and 364 RR Lyrae stars considered in this paper is shown in Fig. 4, where red filled circles mark the classical Cepheids that, as expected, mainly concentrate in the Milky Way (MW) disk. Type II Cepheids and RR Lyrae stars are shown by green filled triangles and blue filled circles, respectively, and nicely outline the MW halo. We note that by combining results from these three different standard candles and the improved census of such variables that *Gaia* is expected to provide, it will be possible to further probe the MW 3D structure and the all



**Fig. 3.** Error distribution of the TGAS parallaxes for RR Lyrae stars (RRLs in the label): whole sample (364 stars, cyan), subsample with literature photometry (200 stars, blue), subsample of the previous 200 sources retaining only stars with positive parallax and parallax errors  $\sigma_\pi/\pi < 0.5$  (112 stars, black contour). The bin size is 0.025 mas.



**Fig. 4.** Sky distribution, in Galactic coordinates, of the 331 classical Cepheids (red filled circles), 31 Type II Cepheids (green filled triangles) and 364 RR Lyrae stars (blue filled circles) discussed in this paper.

sky extension of the Galactic halo, a topic in which *Gaia* already demonstrated its potential through discovery of over 300 new RR Lyrae stars in the far, still unexplored outskirts of one of our closest neighbours, the LMC (Clementini et al. 2016).

## 2.2. Comparison with other parallax measurements

Parallaxes obtained with the TGAS for classical and Type II Cepheids and for the RR Lyrae stars published in *Gaia* DR1 are listed in Tables 7, 8 and 9, where we also provide *G*-band magnitudes and other relevant photometric and spectroscopic information for these stars. In order to assess qualitatively the

goodness of the TGAS parallaxes for Cepheids and RR Lyrae stars we compared the parallax values for variables having both TGAS and Hipparcos measurements (248 classical Cepheids, 31 Type II Cepheids and 188 RR Lyrae stars). The comparison TGAS *versus* Hipparcos for the classical Cepheids is shown in Fig. 5, using black filled circles to mark the whole sample. We have labelled in the figure two stars, RW Cam and SY Nor, for which a significant discrepancy exists between Hipparcos and TGAS parallax values. Both stars are known to have very bright close-by companions (Evans 1994; Fernie 2000). We also do not plot the three sources with largest differences, namely, V1477 Aql, UX Per and AQ Pup. The TGAS-Hipparcos comparison for classical Cepheids shows comforting results, the number of negative parallaxes has reduced from 32% in Hipparcos to only 4% in TGAS: of the 248 classical Cepheids 79 have a negative Hipparcos parallax to compare with only 5 of them still having negative parallax and an additional 6 stars for a total of 11 sources in TGAS. This is not surprising, since the fraction of negative parallaxes is expected to decrease when uncertainties get smaller. We have created different sub-samples based on absolute and relative errors of the Hipparcos parallaxes, in order to highlight the samples with most reliable parallaxes. Classical Cepheids with  $(\sigma_{\varpi}/\varpi)_{\text{Hipparcos}} < 0.20$  are marked in Fig. 5 by cyan filled circles, they are V2081 Cyg and PR Peg<sup>4</sup>. Red and magenta filled circles highlight stars with  $(\sigma_{\varpi})_{\text{Hipparcos}} < 0.50$  and  $0.30$  mas, respectively. Increasing agreement between the TGAS and Hipparcos results is found if we consider only sources with precise Hipparcos values, suggesting that more precise Hipparcos measures correspond to more precise TGAS measures. Figures 6 and 7 show the same test but for Type II Cepheids and RR Lyrae stars, respectively. Red filled circles in Fig. 6 indicate Type II Cepheids with  $(\sigma_{\varpi})_{\text{Hipparcos}} < 0.50$ . Of the 31 Type II Cepheids with both Hipparcos and TGAS parallaxes, 13 had a negative Hipparcos parallax (42% of the sample), to compare with only 4 of them still having negative parallax and an additional 1 for a total of 5 sources (16%) in TGAS. MZ Cyg is the source with largest discrepancy between Hipparcos and TGAS among the Type II Cepheids with a positive parallax value. Red filled circles in Fig. 7 are RR Lyrae stars with  $(\sigma_{\varpi})_{\text{Hipparcos}} < 0.70$  while cyan filled circles are a few RR Lyrae stars with  $(\sigma_{\varpi}/\varpi)_{\text{Hipparcos}} < 0.20$ . Of the 188 RR Lyrae stars with both Hipparcos and TGAS parallax, 59 had a negative Hipparcos parallax (31% of the sample) to compare with only 2 of them still having a negative parallax (1%) in TGAS. CH Aql is the source with largest discrepancy between Hipparcos and TGAS among the RR Lyrae stars with positive parallax values. From these first global comparisons the improvement of *Gaia* with respect to Hipparcos is straightforward and is even more so for the Population II standard candles, that is for RR Lyrae stars and Type II Cepheids.

Considering now the most accurate astrometric parallaxes available in the literature, we note that 3 classical Cepheids in our sample, namely, FF Aquilae (FF Aql), SY Aurigae (SY Aur) and SS Canis Majoris (SS CMa), have their parallax measured with the Hubble Space Telescope (HST) by Benedict et al. (2007), Riess et al. (2014) and Casertano et al. (2016), respectively. The parallax of FF Aql was determined with the HST Fine Guidance Sensor, reaching a precision of  $\sigma_{\varpi}/\varpi \sim 6\%$ . The as-

tronomical measurements of SY Aur and SS CMa were obtained with the Wide Field Camera 3 (WFC3) by spatial scanning that improved the precision of the source position determination allowing to derive parallaxes with uncertainties in the range of  $\sim 0.3$ - $0.5$  mas ( $\sigma_{\varpi}/\varpi \sim 11$ - $12\%$ ). Parallax measurements available for these three stars are summarised in the upper portion of Table 1. Taking into account the rather small sample and the much larger errors, as expected for these first *Gaia* parallaxes, agreement between TGAS and HST is within  $2\sigma$  for FF Aql and SS CMa, and within  $1\sigma$  for SY Aur. We also note that FF Aql is known to be in a binary system and this may have affected the measure of its parallax (see Section 4.1). Figure 8 shows for these 3 classical Cepheids the comparison between the TGAS and HST parallax values (lower panel), between TGAS and Hipparcos (middle panel) and between Hipparcos and the HST (upper panel). Going from top to bottom the agreement between different parallax values increases, the best agreement existing between the TGAS and HST values, thus confirming that TGAS, although less precise than HST, provides more reliable parallax measurements and an improvement with respect to Hipparcos.

The parallax has been measured with the HST only for one of the Type II Cepheids in our sample, VY Pyx (Benedict et al. 2011). Results of the comparison between the TGAS, Hipparcos and HST parallaxes for this star are summarised in the middle portion of Table 1 and shown in Fig. 9. The TGAS parallax for VY Pyx differs significantly from the HST and Hipparcos values, which, on the other hand seem to be in reasonable agreement to each other. However, as discussed in Benedict et al. (2011) the *K*-band absolute magnitude of VY Pyx inferred from the HST parallax places the star 1.19 mag below the  $PM_K$  relation defined by five RR Lyrae stars with parallax also measured by the HST (see fig. 6 in Benedict et al. 2011 and the discussion below), in contrast with the Type II Cepheids being expected to lay on the extrapolation to longer periods of the RR Lyrae star  $PM_K$  relation (see e.g. Ripepi et al. 2015 and references therein). Benedict et al. (2011) explain this discrepancy either as due to the wide range in absolute magnitude spanned by the short-period Type II Cepheids or as caused by some anomaly in VY Pyx itself. We have reproduced Benedict et al. (2011)'s fig. 6 in our Fig. 10 using for the 5 RR Lyrae stars in Benedict et al.'s sample the  $M_K$  magnitudes calculated on the basis of their TGAS parallaxes (blue filled circles) and plotting with red lines the  $PM_K$  relations obtained using instead Benedict et al.'s HST parallaxes for the five RR Lyrae stars with (solid red line) and without (dashed red line) Lutz-Kelker corrections (Lutz & Kelker 1973). Green circles represent star VY Pyx with the  $M_K$  magnitude calculated on the basis of Benedict et al. HST parallax (open circle) and TGAS parallax (filled circles), respectively. The TGAS parallax makes VY Pyx nicely follow the  $PM_K$  relation defined by the 5 RR Lyrae stars, both in the formulation based on their TGAS parallaxes (black solid line) and that based on the Benedict et al.'s parallaxes (red solid lines).

As anticipated in the discussion of VY Pyx, HST parallaxes have been measured by Benedict et al. (2011) for five RR Lyrae stars. The comparison between Hipparcos, TGAS and Benedict et al. (2011) for these five variables is summarised in the lower portion of Table 1 and graphically shown in Fig. 11 for Hipparcos *versus* HST (upper panel), TGAS *versus* Hipparcos (middle panel) and TGAS *versus* HST (lower panel), respectively. Errors of the Hipparcos parallaxes are much larger than those of the HST and TGAS measures and, except for RR Lyrae itself, the Hipparcos parallaxes differ significantly from the HST values, whereas the TGAS and HST parallaxes agree within  $1\sigma$  for RR Lyr, SU Dra, UV Oct, and XZ Cyg. On the other hand, the  $1\sigma$

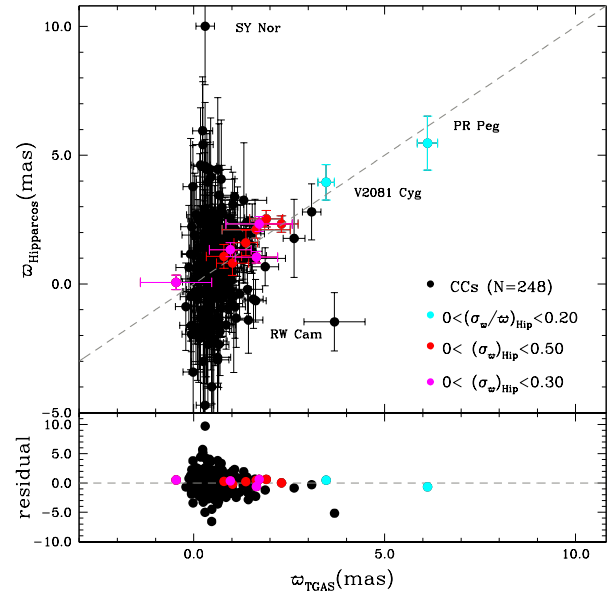
<sup>4</sup> Following the referee's comment that considering their periods and absolute magnitudes these two stars are maybe not classical Cepheids, we double-checked the literature and found that both stars are still classified as Cepheids in the latest version of the General catalogue of variable stars: Version GCVS 5.1 (Samus et al. 2017).

agreement of Hipparcos, TGAS and HST parallax values for RR Lyrae itself is particularly satisfactory, also in light of the much reduced error bar in the TGAS value: 0.23 mas, to compare with 0.64 mas in Hipparcos. For the remaining star, RZ Cep, Benedict et al. (2011) provide two different parallax values, 2.12 and 2.54 mas (Neeley et al. 2015). We show both values in Fig. 11. Although Benedict et al. (2011) preferred value for this star is 2.12 mas (corresponding to the grey filled circle in Fig. 11) the alternative value of 2.54 mas is in much better agreement with the TGAS parallax of RZ Cep and nicely places the star on the bisector of the HST and TGAS parallaxes. To conclude, as already noted for the classical Cepheids (see Fig. 8), best agreement is found between the TGAS and the HST parallaxes confirming once again the higher reliability of the TGAS parallaxes and the improvement with respect to Hipparcos.

Fig. 10 deserves further comments. There is a systematic zero-point offset of about 0.14 mag between the  $PM_K$  relation inferred from the HST parallaxes of Benedict et al. (2011) for the 5 RR Lyrae stars without applying any Lutz-Kelker correction (red dashed line) and the relation (black solid line) obtained with the  $M_K$  magnitudes inferred from the TGAS parallaxes (blue filled circles). The latter was obtained by linear least squares fit of the  $M_K$  magnitudes based on the TGAS parallaxes, adopting the same slope as in Benedict et al. (2011), that is  $-2.38$  from Sollima et al. (2008) and without applying Lutz-Kelker corrections. Since there is good agreement between the TGAS and HST parallaxes of these 5 RR Lyrae stars, the observed zero point offset between  $PM_K$  relations might hint to some systematic effect in the method used to compute these relations. Indeed, as discussed in detail in Section 3.2, direct transformation of parallaxes to absolute magnitudes and linear least squares fit is not advisable in presence of large errors as those affecting the parallaxes of these stars and this might have induced systematic effects.

We remind the reader that although globally the possible systematic errors in the TGAS parallaxes are well below their formal errors<sup>5</sup>, there could still be some systematic effects at a typical level of  $\pm 0.3$  mas depending on the sky position and the colour of the source (Lindgren et al. 2016). However, the question of these additional systematic errors is still under very much debate within DPAC and its value has often been recognized as an overestimate, which is why uncertainties smaller than 0.3 mas can be found in the TGAS catalog. In principle, the nominal uncertainties quoted in the TGAS catalog already contemplate all sources of variance including the systematic uncertainties and a safety margin. Therefore, there should be no need to add the 0.3 mas extra-variance. Furthermore, the zero point error in the parallaxes is of the order of  $-0.04$  mas (Arenou et al. 2017), hence, does not seem to support the need for the extra-variance. Additionally, while the analysis of regional/zonal effects (for example in quasars) shows differences across various regions of the sky, these systematic effects are spatially correlated and not totally random over the celestial sphere. Hence, they become an important issue only if analysing a particular region of the sky, like star clusters. However, in all-sky studies like those presented in this paper, and particularly for the RR Lyrae stars, which are not concentrated in any specific part of the sky (see Fig. 4) this systematic effect does not influence the global zero-point of the derived  $PL$ ,  $PLZ$  and  $M_V - [Fe/H]$  relations.

Arenou et al. (2017) report systematic zero-points respectively of  $-0.014 \pm 0.014$  mas and  $-0.07 \pm 0.02$  mas in the TGAS parallaxes of 207 classical Cepheids and 130 RR Lyrae stars they



**Fig. 5.** Comparison between Hipparcos and TGAS parallaxes, obtained from a sample of 248 classical Cepheids which have both measurements. Red and magenta filled circles represent stars with  $(\sigma_w/\omega)_{\text{Hip}} < 0.50$  and  $0.30$  mas, respectively, cyan filled circles are two stars with  $(\sigma_w/\omega)_{\text{Hip}} < 0.20$ , namely, V2081 Cyg and PR Peg. A dashed line shows the bisector. Residuals are: TGAS – Hipparcos parallax values.

have analysed, and an average shift of  $-0.034 \pm 0.012$  mas when combining the two samples. We have not found in the literature information about systematic effects affecting the HST parallaxes. Nevertheless, the direct star-by-star comparison of the parallaxes in Table 1 and Fig. 11 does not seem to show evidence for the presence of a systematic difference between the TGAS and HST parallaxes of the fairly small sample (3 classical Cepheids, 1 Type II Cepheid and 5 RR Lyrae stars) for which a direct comparison with the HST is possible.

### 2.3. Comparison with parallaxes inferred by theoretical model fitting of the light curves

An independent method to infer the distance (hence the parallax) of a pulsating star is the “model fitting” of the multi-wavelength star light curves through nonlinear convective pulsation models (see e.g. Marconi & Clementini 2005; Keller & Wood 2006; Marconi et al. 2013a,b, and references therein). Indeed, one of the advantages of nonlinear hydrodynamical codes that involve a detailed treatment of the coupling between pulsation and convection is that they are able to predict the variation of any relevant quantity along the pulsation cycle. The direct comparison between observed and predicted light curve as based on an extensive set of models with the period fixed to the observed value but varying the mass, the luminosity, the effective temperature and the chemical composition, allows us to obtain a best fit model and in turn to constrain not only the distance but also the intrinsic stellar properties of the pulsating star under study. This approach was first applied to a Magellanic Classical Cepheid (Wood et al. 1997) and a field RR Lyrae (Bono et al. 2000) and later extended to cluster members (Marconi & Degl’Innocenti 2007; Marconi et al. 2013b) and variables for which radial velocity curves were also available (see e.g. Di Fabrizio et al. 2002; Natale et al. 2008; Marconi et al. 2013a,b, and references therein). Further-

<sup>5</sup> We remind that Casertano et al. (2017) claim that also formal errors of TGAS parallaxes may be overestimated.

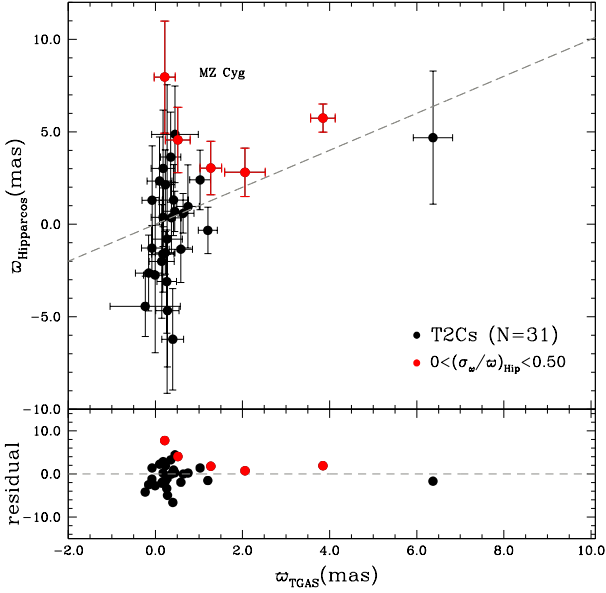
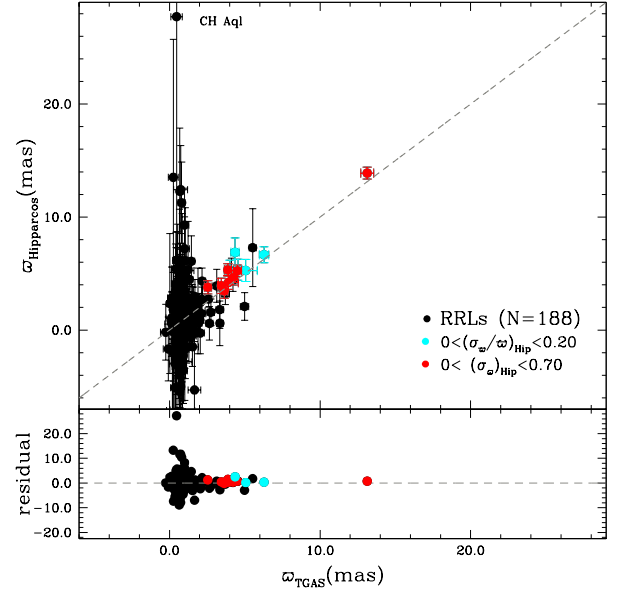
**Table 1.** Comparison between Hipparcos, TGAS and HST parallaxes

Name	ID <sub>Hipparcos</sub> *	$\varpi_{\text{Hipparcos}}$ (mas)	$\sigma\varpi_{\text{Hipparcos}}$ (mas)	$\varpi_{\text{TGAS}}$ (mas)	$\sigma\varpi_{\text{TGAS}}$ (mas)	$\varpi_{\text{HST}}$ (mas)	$\sigma\varpi_{\text{HST}}$ (mas)	HST Reference
<b>Classical Cepheids</b>								
FF Aql**	93124	2.110	$\pm 0.330$	1.640	$\pm 0.89$	2.810	$\pm 0.180$	Benedict et al. (2007)
SS CMa	36088	0.400	$\pm 1.780$	0.686	$\pm 0.234$	0.348	$\pm 0.038$	Casertano et al. (2016)
SY Aur	24281	-1.840	$\pm 1.720$	0.687	$\pm 0.255$	0.428	$\pm 0.054$	Riess et al. (2014)
<b>Type II Cepheids</b>								
VY Pyx	434736	5.00	$\pm 0.44$	3.85	$\pm 0.28$	6.44	$\pm 0.23$	Benedict et al. (2007)
<b>RR Lyrae stars</b>								
RR Lyr	95497	3.46	$\pm 0.64$	3.64	$\pm 0.23$	3.77	$\pm 0.13$	Benedict et al. (2011)
RZ Cep	111839	0.59	$\pm 1.48$	2.65	$\pm 0.24$	2.12 (2.54)***	$\pm 0.16$	Benedict et al. (2011)
SU Dra	56734	0.20	$\pm 1.13$	1.43	$\pm 0.29$	1.42	$\pm 0.16$	Benedict et al. (2011)
UV Oct	80990	2.44	$\pm 0.81$	2.02	$\pm 0.22$	1.71	$\pm 0.10$	Benedict et al. (2011)
XZ Cyg	96112	2.29	$\pm 0.84$	1.56	$\pm 0.23$	1.67	$\pm 0.17$	Benedict et al. (2011)

\* van Leeuwen (2007b)

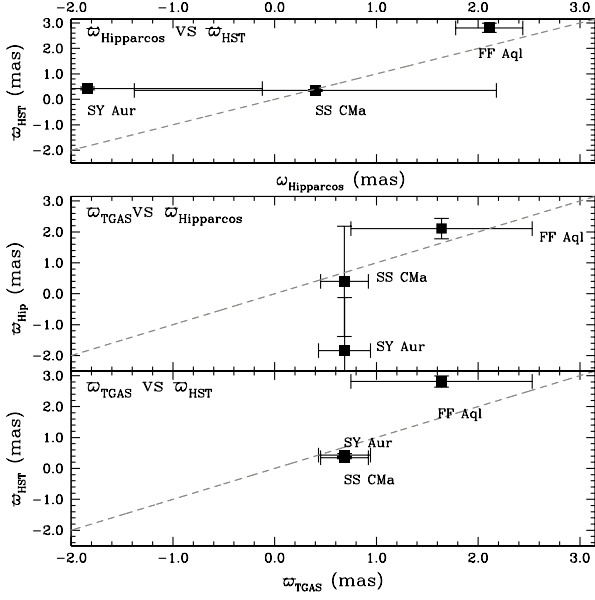
\*\*Gallenne et al. (2012) have estimated the distance to FF Aql via interferometric Baade-Wesselink technique, the corresponding parallax is  $2.755 \pm 0.554$  mas.

\*\*\* Two different parallax values are provided for this star by Benedict et al. (2011), in the table we list both values.

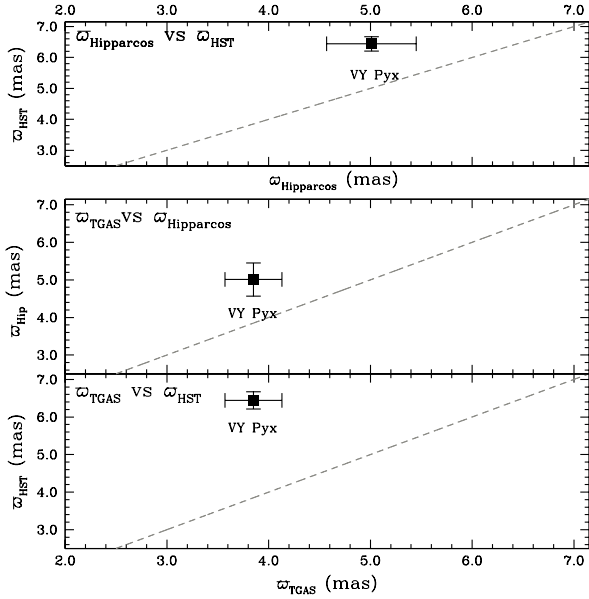
**Fig. 6.** Comparison between Hipparcos and TGAS parallaxes, obtained from the sample of 31 Type II Cepheids (T2Cs in the label) which have both measurements. Red filled circles represent stars with  $(\sigma_w/w)_{\text{Hipparcos}} < 0.50$ . A dashed line shows the bisector. Residuals are: TGAS – Hipparcos parallax values.**Fig. 7.** Comparison between Hipparcos and TGAS parallaxes, obtained from a sample of 188 RR Lyrae stars (black filled circles) which have both measurements. Cyan filled circles mark sources with  $(\sigma_w/w)_{\text{Hipparcos}} < 0.20$ . Red filled circles are RR Lyrae stars with  $(\sigma_w/w)_{\text{Hipparcos}} < 0.70$ . A dashed line shows the bisector. Residuals are: TGAS – Hipparcos parallax values.

more, the method was successfully applied to a number of different classes of pulsating stars in the LMC (see e.g. Bono et al. 2002; Marconi & Clementini 2005; McNamara et al. 2007; Marconi et al. 2013a,b, and references therein), also by different teams (see also Wood et al. 1997; Keller & Wood 2002, 2006), always obtaining consistent results. Because of the significant amount of time and computing resources required by the model fitting technique, here we applied this method only to three classical Cepheids, for which multi-band light curves are available in the literature, that we selected among the sample of classical Cepheids we use to derive the *PL* relations in

Sec. 4.2. The first case is RS Pup, pulsating in the fundamental mode with a period of 41.528 days. The photometric data for this star and for the other two analysed in this section, are taken from a number of papers (Welch et al. 1984; Laney & Stobie 1992; Berdnikov 2008; Monson & Pierce 2011) and well sample the light variations in the different filters. Fig. 12 shows the results of model fitting the star light curves in the *B, V, R, I, K* bands. RS Pup is the second longest period classical Cepheids in our sample and is known to be surrounded by a nebula reflecting the light from the central star (see e.g. Kervella et al.

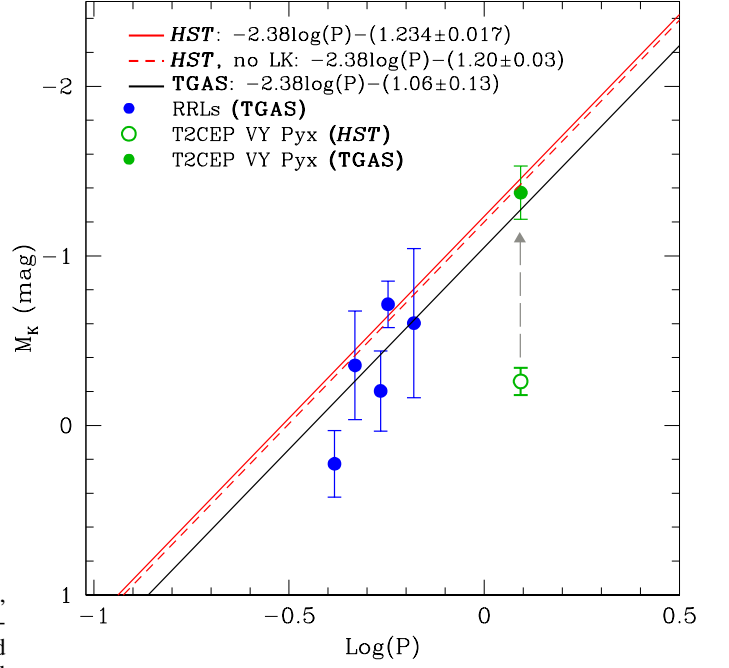


**Fig. 8.** Comparison between Hipparcos and HST parallax (upper panel), TGAS and Hipparcos parallax (middle panel) and TGAS and HST parallax (lower panel) for the classical Cepheids FF Aql, SY Aur and SS CMa. FF Aql is the brightest star in our sample of 331 classical Cepheids and is known to be component of a binary system. A dashed line shows the bisector.

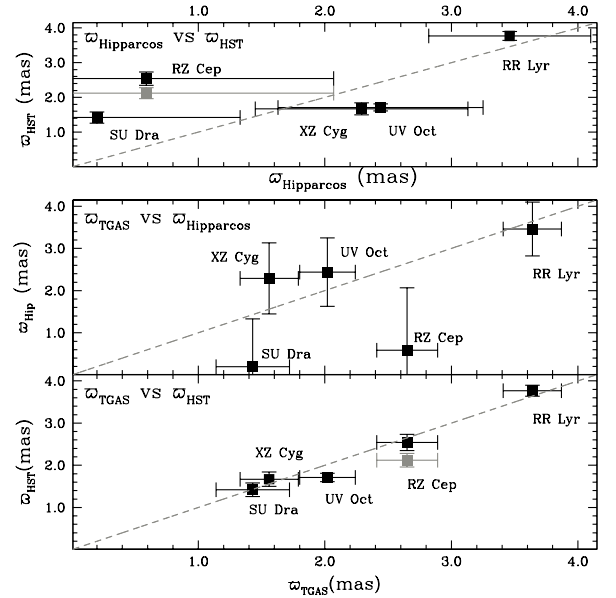


**Fig. 9.** Comparison between Hipparcos and HST parallax (upper panel), TGAS and Hipparcos parallax (middle panel) and TGAS and HST parallax (lower panel) for the Type II Cepheid VY Pyx. Dashed lines show the bisectors.

2008, 2014), thus allowing an independent geometric evaluation of the distance to be obtained from the light echoes propagating in the star circumstellar nebula, corresponding to a parallax  $\varpi_{K14} = 0.524 \pm 0.022$  mas (see Kervella et al. 2014, for details). This value is consistent within the errors with the TGAS value  $\varpi_{\text{TGAS}} = 0.63 \pm 0.26$  mas. The pulsation model best reproducing RS Pup multi-filter light curve corresponds to a  $9 M_{\odot}$  star with an intrinsic luminosity  $\log L/L_{\odot} = 4.19$ . From the apparent distance moduli obtained with the best fit in the various bands we were able to estimate the extinction correction and the intrinsic distance modulus  $\mu_0(\text{FIT}) = 11.1 \pm 0.1$  mag. This provides a



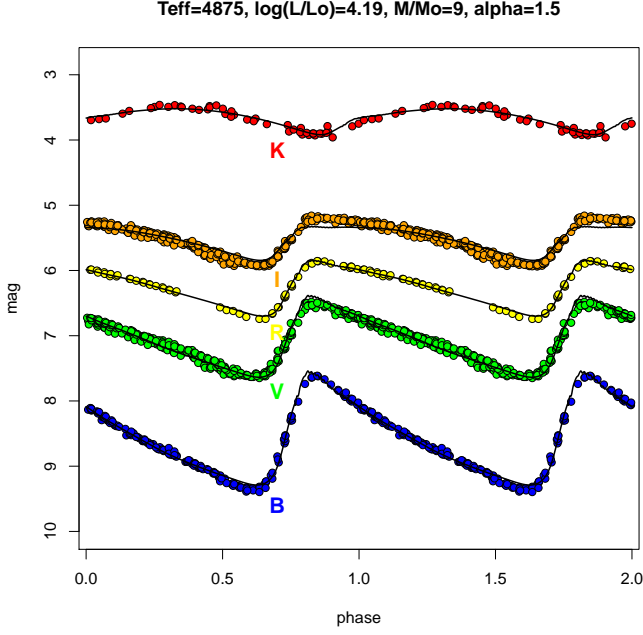
**Fig. 10.** Weighted linear least squares fit performed over the  $M_K$  magnitude of the five RR Lyrae stars in Benedict et al. (2011) using the  $M_K$  values inferred from the HST parallaxes with (red solid line) and without (red dashed line) Lutz-Kelker correction and the  $M_K$  values (blue filled circles) inferred from the TGAS parallaxes (black line). Green filled and open circles show the Type II Cepheid VY Pyx with the  $M_K$  magnitude determined from the TGAS and HST parallax, respectively. The star was not used in the fit.



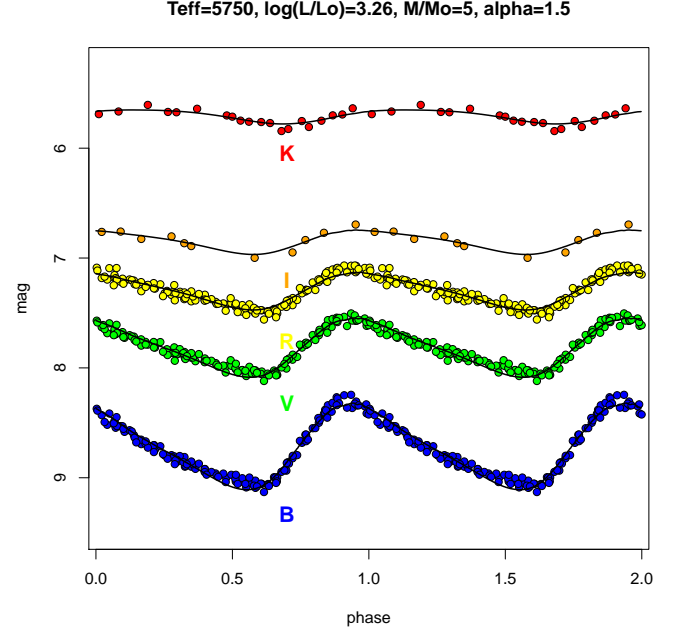
**Fig. 11.** Comparison between Hipparcos and HST parallaxes (upper panel), TGAS and Hipparcos (middle panel), TGAS and HST (lower panel) for the RR Lyrae stars: RR Lyr, RZ Cep, SU Dra, XZ Cyg and UV Oct. Two values from Benedict et al. (2011) are shown for RZ Cep: 2.12 mas (grey filled square) and 2.54 mas (black filled square). TGAS parallax for RZ Cep is in good agreement with the larger, less favourite value in Benedict et al. (2011). Dashed lines show the bisectors.

model fitting parallax  $\varpi_{\text{FIT}} = 0.58 \pm 0.03$  mas, which is in excellent agreement with the TGAS parallax for the star.





**Fig. 12.** Model fitting of the fundamental mode classical Cepheid RS Pup, the second longest period Cepheid in our sample with  $P=41.528$  days. The model fitting provides a parallax:  $\varpi_{\text{FIT}} = 0.58 \pm 0.03$  mas, in excellent agreement with the TGAS parallax for this star:  $\varpi_{\text{TGAS}} = 0.63 \pm 0.26$  mas.

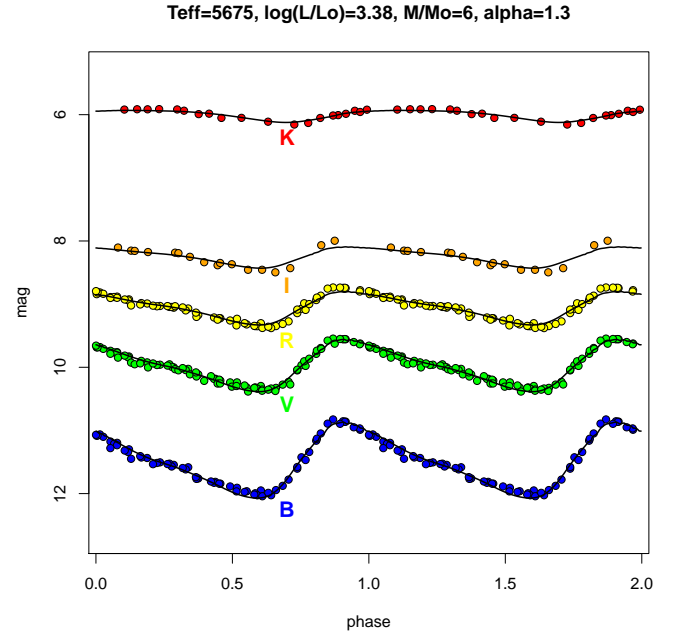


**Fig. 13.** Model fitting of the fundamental mode classical Cepheid V1162 Aql,  $P=5.376$  days. The model fitting provides a parallax:  $\varpi_{\text{FIT}} = 0.79 \pm 0.04$  mas, in agreement, within the errors, with the TGAS parallax for this star:  $\varpi_{\text{TGAS}} = 1.01 \pm 0.29$  mas.

Similarly, we performed the model fitting of V1162 Aql light curves, a Galactic fundamental mode Cepheid of much shorter period (5.376 days), as shown in Fig. 13. In this case, the pulsation model best reproducing the multi-filter light curve corresponds to a  $5 M_{\odot}$  star with an intrinsic luminosity  $\log L/L_{\odot} = 3.26$ . The inferred model fitting intrinsic distance modulus is  $\mu_0(\text{FIT})=10.5 \pm 0.1$ , corresponding to a parallax  $\varpi_{\text{FIT}} = 0.79 \pm 0.04$  mas, in agreement with the TGAS value ( $\varpi_{\text{TGAS}} = 1.01 \pm 0.29$  mas), within the errors.

The third classical Cepheid analysed with the model fitting technique is RS Cas, a Galactic fundamental mode Cepheid with a period of about 6.296 days. When applying our model fitting approach, we obtain the best fit model shown in Fig. 14, corresponding to a  $6 M_{\odot}$  star with an intrinsic luminosity  $\log L/L_{\odot} = 3.38$ . This implies an intrinsic distance modulus  $\mu_0(\text{FIT})=11.1 \pm 0.1$  and a pulsation parallax  $\varpi_{\text{FIT}} = 0.60 \pm 0.03$  mas, much smaller than the TGAS parallax  $\varpi_{\text{TGAS}} = 1.53 \pm 0.32$  mas. Consequently, the predicted distance modulus is about 2 mag longer than the TGAS-based value and the absolute magnitude is brighter by the same amount. It is interesting to note that an upward shift of approximately 1.5-2 mag would allow RS Cas to match the  $PL$  relations in Fig. 21. This seems to suggest that the TGAS parallax for RS Cas is incorrect. We wonder whether the discrepancy observed for this star may be caused by a companion such as e.g. a white dwarf, which might affect the TGAS measurement.

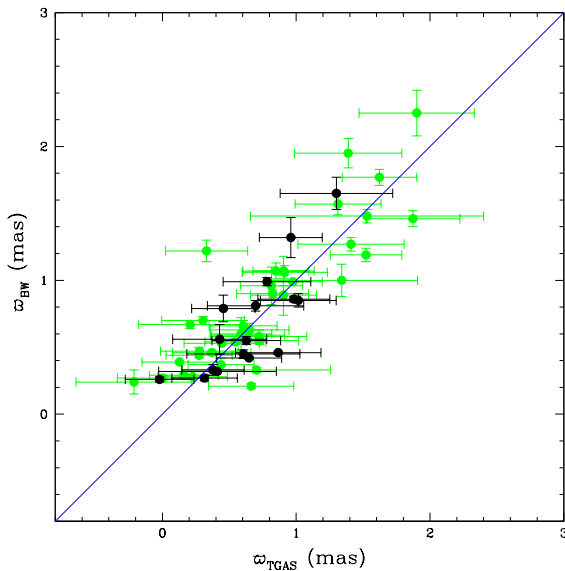
Finally, we note that the theoretical model fitting technique has been often applied also to RR Lyrae stars both in and outside the MW (e.g. Bono et al. 2000, Di Fabrizio et al. 2002, Marconi & Clementini 2005). For one of the RR Lyrae star with TGAS parallax, U Com, Bono et al. (2000) measured the parallax by fitting the star multi-band light curves with nonlinear convective pulsation models:  $\varpi_{\text{FIT}} = 0.63 \pm 0.02$  mas. This value agrees



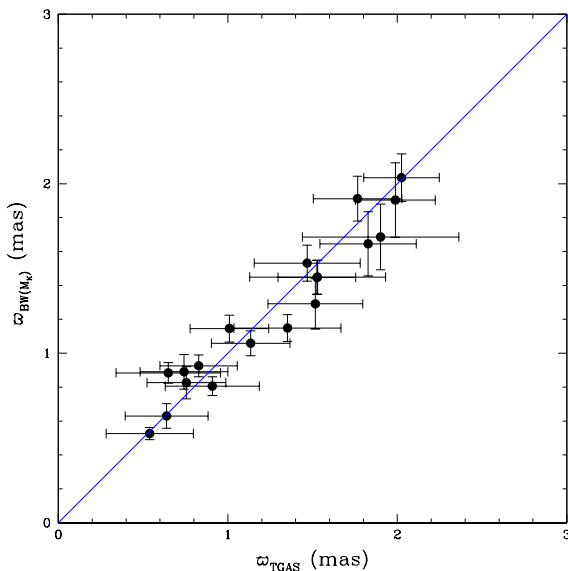
**Fig. 14.** Model fitting of the fundamental mode classical Cepheid RS Cas,  $P=6.296$  days. The model fitting provides a parallax:  $\varpi_{\text{FIT}} = 0.60 \pm 0.03$  mas in significant disagreement with the TGAS parallax for this star:  $\varpi_{\text{TGAS}} = 1.53 \pm 0.32$  mas.

within the errors with TGAS parallax for U Com:  $\varpi_{\text{TGAS}} = 0.46 \pm 0.28$  mas.

The results presented in this section confirm the predictive capability of the adopted theoretical scenario and the potential of the light curve model fitting technique to test and constrain the accuracy of empirical distance determinations.



**Fig. 15.** Comparison between the photometric parallaxes estimated via B-W method and the TGAS parallaxes of classical Cepheids. Black and green circles represent single and binary Cepheids, respectively. The blue line is the bisector.



**Fig. 16.** Comparison between the photometric parallaxes inferred from the  $K$ -band absolute magnitudes ( $M_K$ ) estimated via B-W method and the TGAS parallaxes for RR Lyrae stars. The blue line represents the bisector.

#### 2.4. Comparison with Baade-Wesselink studies.

Photometric parallaxes of classical Cepheids and RR Lyrae stars have been often estimated with the Baade-Wesselink (B-W) method in various different implementations (e.g. the Infrared Surface Brightness technique or the Spectro-Photo-Interferometric modeling approach of Mérand et al. 2015 and Breitter et al. 2016).

Fouqué et al. (2007) list in their Table 6, photometric parallaxes inferred from the application of the Infrared Surface Brightness version of the B-W technique to 62 classical Cepheids, among which 54 have a TGAS parallax estimate. The comparison between the TGAS and the B-W parallaxes for these

54 Cepheids is shown in Fig. 15. The sample of 54 classical Cepheids contains a large fraction (38) of binary systems. The phenomenon of binarity/multiplicity is rather common among classical Cepheids, as it will be discussed in more detail in Sec. 4.1. The presence of a binary companion may prevent an accurate estimate of parallax. Cepheids known to be in binary systems are shown as green circles in Fig. 15, they are more scattered around the bisector line. The r.m.s scatter from the bisector line is 0.28 mag for binary classical Cepheids and reduces to 0.23 mag when the 16 non binary Cepheids are considered. A weighted least squares fit of the relation  $\varpi_{B-W} = \alpha \varpi_{TGAS}$  returns a slope value of  $(0.90 \pm 0.07)$  for the sample of 16 classical Cepheids which are not in binary systems.

A similar comparison was also done for the RR Lyrae stars. We considered 19 MW RR Lyrae variables with TGAS parallaxes and absolute visual ( $M_V$ ) and  $K$ -band ( $M_K$ ) magnitudes available in the literature from B-W studies (see Table 2 in Muraveva et al. 2015). The B-W absolute magnitudes were taken from the compilations in Table 11 of Cacciari et al. (1992) and Table 16 of Skillen et al. (1993) and revised: (i) assuming for the  $p$  factor used to transform the observed radial velocity to true pulsation velocity the value  $p = 1.38$  proposed by Fernley (1994)<sup>6</sup>, and (ii) averaging multiple determinations of individual stars. We note that the  $K$ -band magnitudes of RR Lyrae stars analyzed with the B-W method are in the Johnson photometric system, however, the difference between 2MASS  $K_s$  and Johnson  $K$  is small, of about 0.03 mag on average, for the typical colour of RR Lyrae stars (Muraveva et al. 2015) and, anyway, much smaller than individual errors in the B-W  $M_K$  magnitudes. We have transformed the B-W absolute magnitudes to photometric parallaxes. The direct transformation of parallaxes to absolute magnitudes and vice-versa should be avoided when parallax uncertainties are large because of the resulting asymmetric errors (see Sec. 3.2). However, given the small relative errors in distance moduli (less than 3%) of the 19 RR Lyrae stars analysed with the B-W technique, the uncertainties in the inferred parallaxes are symmetric and would not be affected by any reasonable prior distribution. Comparison of the photometric parallaxes inferred from the  $M_K$  absolute magnitudes of the 19 RR Lyrae stars with the corresponding TGAS parallaxes is shown in Fig. 16. The two independent parallax estimates appear to be in very good agreement within the errors. We performed also the comparison with the parallaxes inferred from the  $V$ -band absolute magnitudes. A weighted least squares fit of the relations  $\varpi_{M_V(B-W)} = \alpha \varpi_{TGAS}$  and  $\varpi_{M_K(B-W)} = \alpha \varpi_{TGAS}$  returns slopes of 0.97 and 0.98, respectively, which are both very close to the bisector slope  $\alpha = 1$ . To conclude, TGAS parallaxes are in general good agreement with the photometric parallaxes obtained in B-W studies of classical Cepheids and RR Lyrae stars. The agreement is particularly good for the RR Lyrae stars and seems to support the adoption of the larger  $p$  factor proposed by Fernley (1994).

### 3. Selection biases and methods

#### 3.1. Biases

When determining a luminosity calibration (e.g. a  $PL$ , or  $PW$ , or  $PLZ$  or  $M_V - [Fe/H]$  relation in our case) from astrometric data, we have to be very careful in taking into account possible sources of bias that can affect it, lest the results contain systematic errors.

<sup>6</sup> According to table 1 in Fernley (1994) this change in the  $p$  factor makes the B-W absolute magnitudes to become systematically brighter by 0.1 mag, on average.

A first source of such biases is the way the sample has been obtained, due to either censorship (missing data) or to truncation (some selection process done on purpose for the study). Selection criteria that directly or indirectly favour brighter or fainter stars can affect the  $PL$ ,  $PW$ ,  $PLZ$  or  $M_V - [\text{Fe}/\text{H}]$  relations derived from the sample. Specifically, the so-called Malmquist bias (Malmquist 1936) caused by the limitation in apparent magnitude of the TGAS subset has to be taken into account. In this Section we attempt to discuss qualitatively the effects of the different selection filters that result in the samples used in this work to infer the luminosity calibration. It is well known that biased samples may result in biased estimates of the (linear) model parameters. Our samples are the result of several processing stages each with a different impact on the resulting sample. As it turns out, the very limited size of our samples, and the magnitude of the uncertainties mask all of these effects.

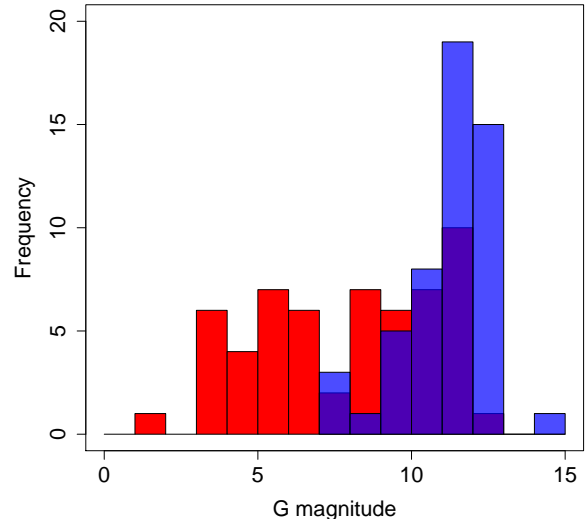
### 3.1.1. Truncations/censorships in the generation of the TGAS catalog

We first discuss the truncation of the samples at the bright end. Stars brighter than  $B_T = 2.1$  or  $V_T = 1.9$  mag were excluded from the Tycho-2 catalog. In particular, 17588 stars included in the Hipparcos catalog were not included in Tycho-2. Some of these were actually included in TGAS, but TGAS is itself affected by removal of many (but not all) sources brighter than  $G \sim 7$  mag, so the effects of the truncation are subtle and difficult to assess. We have checked the existing catalogs to identify known Tycho-2 classical Cepheids and RR Lyrae stars missing from the TGAS catalog. It turns out that 54 known RR Lyrae stars and 57 classical Cepheids in Tycho-2 are missing from the TGAS catalog. Only two Type II Cepheids are missing in the TGAS catalogue, hence in the following we focus on RR Lyrae star and classical Cepheids samples and do not discuss Type II Cepheids any further. The distributions in apparent  $G$  magnitude of the missing RR Lyrae stars and Cepheids are shown in Fig. 17. We see that the truncation at the bright end of the Tycho-2 sample does not affect the RR Lyrae sample, while it results in the loss of 24 classical Cepheids. This represents a major loss that can seriously affect the inferences of the  $PL$  and  $PW$  relations for classical Cepheids. Fortunately, 21 of these 24 sources are also in the Hipparcos catalog and we can gauge its impact in the inference. It turns out that the Hipparcos parallaxes and periods are fully consistent with the distributions from our TGAS sample both in the 2D plane and in their marginal distributions. We can therefore conclude that this loss did not bias our sample in any respect.

High proper motion ( $\mu > 3.5$  arcsec/yr) Tycho-2 stars are also missing from the TGAS catalog, although this selection has no effect on our samples, at least to the level that can be checked with Tycho-2 proper motions (that is, the Tycho-2 proper motions of the known RR Lyrae and classical Cepheids missing from TGAS are well below the limit of 3.5 arcsec/yr). So we can discard this truncation as a potential source of biases.

As discussed in Gaia Collaboration et al. (2016a), the Gaia DR1 has completeness issues in dense areas of the sky, where the limiting magnitude of the catalog can be brighter by several magnitudes. This could result in a potential loss of Cepheids in dense regions of the disk, were it not for the bright limiting magnitude of the Tycho-2 catalog. RR Lyrae stars are not concentrated in the disk (see Fig. 4) and therefore are even less likely to be affected.

Another truncation/censorship of the Tycho-2 sample comes from the rejection by the photometric processing of sources with



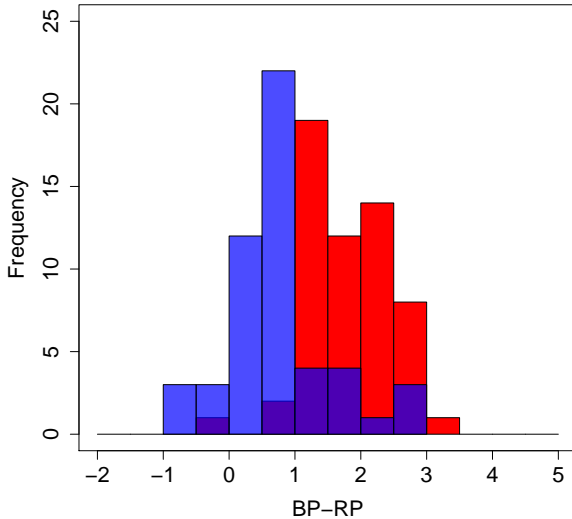
**Fig. 17.** Histogram of the apparent magnitudes of known Tycho-2 RR Lyrae stars (blue) and classical Cepheids (red) not included in the TGAS catalog.

less than 5 transits or extreme red or blue colour indices. The cut in the number of transits results in a loss of sources with projected positions near the ecliptic that should not bias our samples in any respect. Biases will appear if there is a correlation between the position in the celestial sphere and the brightness of the sources, such that the sources missed due to an insufficient number of transits were predominantly bright or faint (we discard direct correlations with the period). In principle, the number of transits depends on the scanning law and hence, any correlation if present should be negligible.

The selection of sources based on the estimated  $G_{BP}-G_{RP}$  can be very simplistically reduced to rejection of sources outside the range  $[0.5, 3.5]$  mag (but see Gaia Collaboration et al. 2016a, for details). This may result in a loss of stars in the highest extinction regions of the disk. If periods are not taken into account and only the instability strip is considered, the brighter stars will be redder and thus, more prone to be rejected by the photometric reduction pipeline due to interstellar reddening beyond the 3.5 mag limit. In principle, this should only affect significantly the sample of Cepheids (because RR Lyrae stars are not concentrated in the disk where most of the extinction occurs). For these samples of brightest sources and a fixed period however, the brighter sources are at the blue edge of the instability strip, so at any given period in the  $PL$ ,  $PW$  or  $PLZ$  relations, we are more likely to lose the fainter stars. In summary, we may expect a bias present in the bright part of the  $PL$  relations in the sense of an underrepresentation of the fainter pulsators.

We have estimated the  $G$ ,  $G_{BP}$  and  $G_{RP}$  magnitudes for Tycho-2 sources missing from TGAS using the photometric relations by Jordi et al. (2010). Figure 18 shows the distribution of estimated  $G_{BP} - G_{RP}$  colour indices for the samples of classical Cepheids (red) and RR Lyrae stars (blue). As expected, all values are bluer than the 3.5 mag limit and hence, reddening is not responsible for the exclusion of this sources from the catalog. On the opposite side, however, the TGAS catalog misses at least 16 RR Lyrae (but only one Cepheid) type pulsators with colour indices bluer than 0.5. This should affect more strongly





**Fig. 18.** Histogram of the estimated  $G_{BP}-G_{RP}$  colour indices of known Tycho-2 RR Lyrae stars (blue) and classical Cepheids (red) missing from the TGAS catalog.

the fainter members of the instability strip that are, on average, bluer.

Finally, sources with astrometric uncertainties beyond 1 mas/yr in proper motion, 20 mas in position, or 1 mas in parallax are also excluded from the TGAS catalog. All these uncertainties depend on the source colour and apparent magnitude, and the complex TDI-gating scheme makes a more detailed quantification of the effects very difficult. In general, the fainter and/or redder the star, the larger the uncertainty, with the apparent magnitude having a much stronger effect on the uncertainties (see e.g. de Bruijne et al. 2005). We see from simulations that the net effect is a bias that affects predominantly the long period end of the  $PL$ ,  $PW$  or  $PLZ$  distributions in the sense of shifting the average absolute magnitude for a fixed period towards brighter (more negative) values. Hence, it has the opposite effect of the Malmquist bias which tends to flatten the slope of the  $PL$  relations. Indeed, we see from these simulations that in some cases, the two biases cancel their effects on the slope and only a zero point shift remains as the net result of the two biases.

### 3.1.2. Selections caused by availability of external data

So far, we have analysed the effects of the Malmquist bias already present in the Tycho-2 sample, and those emerging from the various truncations/censorships of the Tycho-2 sample carried out in the generation of the TGAS catalog. In this work we apply a last filter to retain only sources in TGAS with  $V$ ,  $I$ ,  $J$ ,  $K_s$  or  $W1$  magnitudes and periods available (hereafter, external data, see Sections 4, 5, 6). Therefore, the effect of this last filter remains to be discussed. If the filter left the distribution of TGAS pulsators unchanged, then no further bias would be introduced in the analyses. In the following paragraphs we study the differences under the light of the available data.

We have compared the one-dimensional empirical distributions in parallax, absolute magnitudes, and periods (with respect to OGLE distributions of the LMC fundamental mode classical Cepheids and the LMC and Galactic bulge RR Lyrae stars). In

the following, we will apply the Anderson-Darling test (Anderson & Darling 1952) which is a frequentist approach to a problem that would be better approached using Bayesian methods. Unfortunately, the frequentist approach (with all its limitations) will have to suffice until we can put forward a reasonable parametric model of the biases.

For the RR Lyrae parallaxes, the Anderson-Darling test yields a p-value of 0.00008, well below any reasonable significance level. The main difference between the two distributions is a clear excess of parallaxes greater than 2 mas in the sample of TGAS sources without external data. When the uncertainties are taken into account using bootstrapping, the net result is that 42% (80%) of the experiments falls below the common 0.01 (0.05) significance level.

If we remove sources with negative parallaxes, we can apply the Anderson-Darling test to check if the two samples of absolute magnitudes could have been drawn from the same distribution. The result is a p-value equal to  $9 \cdot 10^{-7}$ , with the set of stars without external data showing a median absolute G magnitude ( $1.2^{+0.8}_{-0.7}$  with the uncertainties quoting the first to third quantile range) fainter than the sample used for the  $PL$  relations ( $0.7 \pm 0.5$ ). The bootstrapping experiment performed to include the uncertainties into the analysis yields a 38% (68%) of experiments with values below the 0.01 (0.05) significance level.

In both cases (parallaxes and absolute magnitudes), the evidence for a difference seems inconclusive when the uncertainties are taken into account, but there are very significant hints that indicate an underrepresentation of faint sources in the TGAS sample. This evidence is made more robust if we re-estimate the p-values using absolute magnitudes derived from distance estimates obtained along the lines suggested by Bailer-Jones (2015). In this latter case we use the prior for the distance derived from the Bayesian models of the  $PL$  relationships (in the hierarchical model, this prior is inferred as part of the model as explained in Section 3.2). The final p-value obtained with these absolute magnitudes is 0.003, again below the two significance levels quoted above.

For the parallaxes of classical Cepheids, the Anderson-Darling test yields a p-value of 0.01. In this case again, the difference is the excess of large parallaxes in the sample of sources without external data with respect to the TGAS sample. The excess is much smaller than in the RR Lyrae case. When the uncertainties are taken into account, the result is that 11% (45%) of the experiments fall below the 0.01 (0.05) significance level.

For absolute magnitudes (and again, removing stars with negative parallaxes) we obtain a p-value of 0.22 (without bootstrapping the uncertainties) and 0.02% (0.002%) of bootstrap samples below the 0.01 (0.05) significance level. Hence, if the difference is real, we do not expect it to bias our  $PL$  inferences significantly.

Overall, the complexity in the censorships of the samples available this paper is not easy to interpret and makes it difficult to produce a reliable estimation of all possible biases introduced by them. We identified at least three clear sources of biases: (i) the loss of the bluest RR Lyrae stars, (ii) the absence in the Gaia DR1 of the sources with largest astrometric uncertainties (that is, the exclusion from the TGAS catalog of sources with uncertainties larger than 1 mas/yr in proper motion, 20 mas in position or 1 mas in parallax), and (iii) the selection of sources with external data available. Although we have assumed that the local systematic correlations described in Section 2.2 average out for the two stellar types discussed, the lack of a detailed description of these correlations prevents us from completely discarding potential biases in the case of classical Cepheids which are not distributed

uniformly in the celestial sphere. The results presented in this paper have then to be considered as preliminary, and to be superseded by results from further releases of Gaia data allowing the use of samples less affected by uncontrolled censorship effects.

### 3.2. Methods

An often, commonly used way to obtain the luminosity calibration (e.g. a  $PL$ ,  $PW$ ,  $PLZ$  or  $M_V - [\text{Fe}/\text{H}]$  relation) is the direct transformation to distance (and then absolute magnitude) by parallax inversion and then the least squares fit of the derived parameters. However, in the presence of parallaxes with errors larger than 10% this method has significant disadvantages that we discuss in the following.

The absolute magnitude of a star is calculated from its parallax by using the following relation:

$$M = m_0 + 5 \log(\varpi) - 10 \quad (1)$$

where  $M$  is the absolute magnitude,  $m_0$  is the apparent dereddened magnitude of the star, and  $\varpi$  is the parallax in mas. Notice that although the errors in the Gaia parallaxes are well behaved, approximately Gaussian and thus symmetrical, the errors in these derived magnitudes will not be so. The logarithm in the expression makes the derived error in  $M$  asymmetrical and can thus lead to biases. In particular, the application of the least squares method to a fit using these values is generally not advisable, since this method relies on the errors of the fitted values being Gaussian or at least symmetrical. Furthermore, negative parallaxes cannot be used in such fitting processes.

In order to include stars with negative parallax measurements and to avoid non-linear transformations when fitting the  $PL$ ,  $PW$ ,  $PLZ$  or  $M_V - [\text{Fe}/\text{H}]$  relations, we follow the prescription of Arenou & Luri (1999), who define an astrometric based luminosity (ABL) as

$$a = 10^{0.2M} = \varpi 10^{0.2m_0-2} \quad (2)$$

where  $M$  is the absolute magnitude,  $\varpi$  the parallax in mas, and  $m_0$  the extinction corrected apparent magnitude. Using the ABL instead of the absolute magnitude is preferable, as the parallax is used linearly, leading to symmetrical error bars as the parallax errors themselves. Additionally, there is no additional Lutz-Kelker bias due to sample truncation, as stars with negative parallax can be included (though biases due to earlier sample selection will remain present, see Sec. 3.1). For example, assuming that the stars follow a relation between period and absolute magnitude of the form:

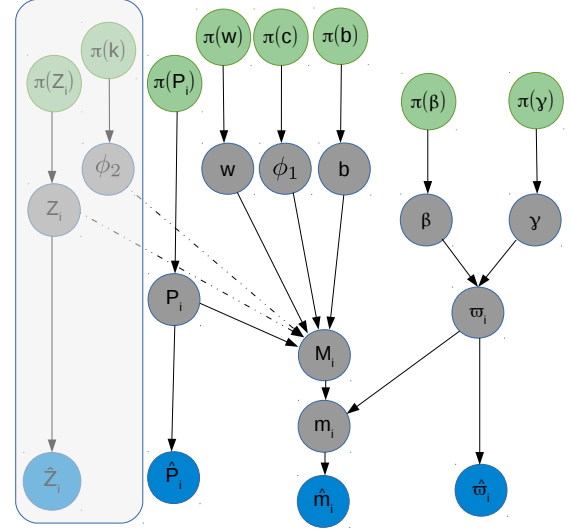
$$M = \alpha \log P + \rho \quad (3)$$

where  $P$  is the period and  $\alpha$  and  $\rho$  are the slope and zero point of the  $PL$  and  $PW$  relations, we fit

$$10^{0.2(\alpha \log P + \rho)} = \varpi 10^{0.2m_0-2} \quad (4)$$

using the weighted non-linear least squares. The same approach could be used to fit the  $PLZ$  and  $M_V - [\text{Fe}/\text{H}]$  relations of RR Lyrae stars. We just apply the non-linear least squares fit to the equations:

$$10^{0.2(\alpha \log P + \beta [\text{Fe}/\text{H}] + \rho)} = \varpi 10^{0.2m_0-2} \quad (5)$$



**Fig. 19.** Directed Acyclic Graph that represents the forward model used to infer the  $PL(Z)$  relation coefficients.

and

$$10^{0.2(\alpha [\text{Fe}/\text{H}] + \rho)} = \varpi 10^{0.2m_0-2} \quad (6)$$

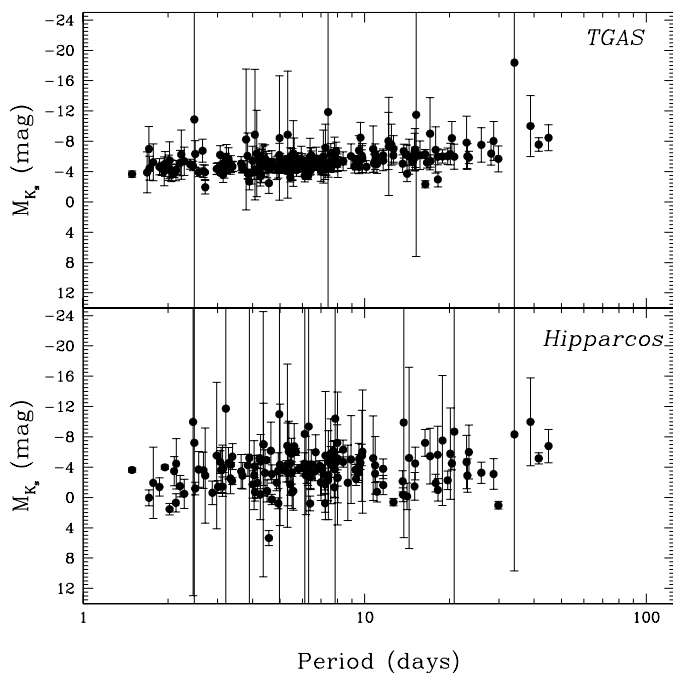
Finally, the use of a Bayesian approach to fit the  $PL$ ,  $PW$ ,  $PLZ$  or  $M_V - [\text{Fe}/\text{H}]$  relations followed by the variable stars, provides an excellent alternative option. The Bayesian estimate of the  $PL(Z)$  relationships is accomplished by means of a hierarchical model (that will be described elsewhere, but see Sesar et al. 2016, for a similar approach) encoded in the directed acyclic graph shown in Fig. 19. It shows the measurements at the bottom level: periods ( $\hat{P}_i$ ), apparent magnitudes ( $\hat{m}_i$ ), metallicities (when appropriate,  $\hat{Z}_i$ ) and parallaxes ( $\hat{\varpi}_i$ ). The subindex  $i$  runs from 1 to the total number of stars  $N$  in each sample. Our model assumes that the measurements (denoted by  $\{\hat{d}_i = (\hat{m}_i, \hat{P}_i, \hat{\varpi}_i, \hat{Z}_i); i : 1, 2, \dots, N\}$ ) are realizations from normal distributions centred at the true (unknown) values (denoted as  $P_i, Z_i, m_i$ , and  $\varpi_i$ ) and with standard deviations given by the measurement uncertainties. We express the most general  $PLZ$  relation as

$$M = b + c \cdot \log(P) + k \cdot Z + \epsilon \quad (7)$$

where  $\epsilon$  is a Gaussian distributed random variable

$$\epsilon \sim \mathcal{N}(0, w) \quad (8)$$

that represents the intrinsic dispersion of the relation (not due to measurement uncertainties).



**Fig. 20.** Classical Cepheid  $PM_{K_s}$  relations using TGAS (upper panel) and Hipparcos (lower panel) parallaxes, respectively. The upper panel shows the absolute magnitudes,  $M_{K_s}$ , of 221 classical Cepheids with positive parallaxes from TGAS. The lower panel shows 156 classical Cepheids with positive Hipparcos parallaxes.

The parallaxes are assumed to be drawn from a log-normal prior of parameters  $\beta$  and  $\gamma$ . The model is hierarchical in the sense that this prior is inferred as part of the model, and  $\beta$  and  $\gamma$  are themselves prescribed by their own priors (see Table 2 for a full list of priors).

We have tried several prior definitions and the results are insensitive to the prior choice except for unreasonable setups.

In the following analysis we apply all three methods: (i) the direct transformation of the parallaxes to absolute magnitudes (Eq. 1) and the weighted linear least squares fitting (LSQ) in the period-absolute magnitude plane ( $PL$ ,  $PW$ ,  $PLZ$  relations) and the absolute magnitude-metallicity plane ( $M_V - [\text{Fe}/\text{H}]$  relation); (ii) the use of the ABL to perform the non-linear weighted least squares fit of Eqs. 4-6; (iii) the realization of the Bayesian fitting approach. The Bayesian solution corresponds to the maximum a posteriori (MAP) values, and the r.m.s. represents the dispersion of the unweighted residuals with respect to this MAP solution. The ABL and Bayesian methods are preferred to avoid biases and we include the LSQ fitting for comparison purposes and to also allow comparison with published results using this method.

#### 4. Classical Cepheids

TGAS parallaxes are available in *Gaia* DR1 for 331 Galactic classical Cepheids. We have collected from the literature  $V$ ,  $I$  and 2MASS  $K_s$  photometry,  $E(B - V)$  reddening values, period and classification for the whole sample, making an effort to assemble an as much as possible uniform and homogeneous catalogue. For the mean magnitudes whenever available we collected intensity-averaged mean  $V$ ,  $I$ ,  $K_s$  magnitudes based on a complete sampling of the light curves, in several cases we computed ourselves the intensity-averaged mean values from the light curves published in the literature. Period and  $V$ ,  $I$ ,  $K_s$  photometry values have been taken from different sources, among which primar-

ily Groenewegen (1999), Berdnikov et al. (2000), Fernie et al. (1995, DDO Database of Galactic Classical Cepheids), Ngeow (2012), the GCVS (Samus et al. 2007-2015) and the ASAS3 catalogue (Pojmanski 2002).  $E(B - V)$  reddening values and related errors were taken from Fernie et al. (1995), Groenewegen (1999), Turner et al. (2001), Fouqué et al. (2007) and Pejcha & Kochanek (2012). In a few cases we specifically estimated the reddening for this study from the available photometry. Metal abundances were mainly taken from Genovali et al. (2014) and for a few stars from Ngeow (2012). Information about duplicity is from Klagyivik & Szabados (2009) and Anderson et al. (2016).

We found in the literature period values for 312 classical Cepheids (94%) of our sample,  $E(B - V)$  reddening values for 276 stars (83%), photometry in the  $V$ ,  $I$  and  $K_s$  bands for 297 (90%), 250 (76%) and 292 (88%) classical Cepheids, respectively. We provide the complete dataset of the 331 Galactic classical Cepheids in Table 7. Hipparcos parallaxes are available for 248 of them. Among the 248 classical Cepheids with parallax measured by both Hipparcos and *Gaia* we selected 228 with  $K_s$  magnitude, reddening and period available in the literature. To correct the  $K_s$  magnitudes for extinction we used the extinction law of Cardelli et al. (1989) and adopted for the ratio of total to selective extinction the value  $R_V = 3.1$ , thus deriving  $K_{s,0} = K_s - 0.35E(B - V)$ . We then transformed the TGAS and Hipparcos parallaxes to absolute  $M_{K_s}$  magnitudes applying Eq. 1. This transformation was possible only for stars with positive parallax values, namely, 221 out of 228 stars with TGAS parallax and only 156 out of 228 for Hipparcos. The corresponding  $PM_{K_s}$  relations are shown in the upper and lower panels of Fig. 20 for the TGAS and Hipparcos parallaxes, respectively. The improvement produced by the TGAS parallaxes is impressive. The scatter is very much reduced, the sample is about 30% larger and, although error bars are still very large, a clear  $PM_{K_s}$  relation can now be seen in the data. Since other factors (e.g. multiplicity, see Sec. 4.1), besides errors in the parallax measurements, may contribute to the large dispersion seen in the upper panel of Fig. 20, we cleaned the sample from binary systems and retained for analysis only single, fundamental mode, classical Cepheids.

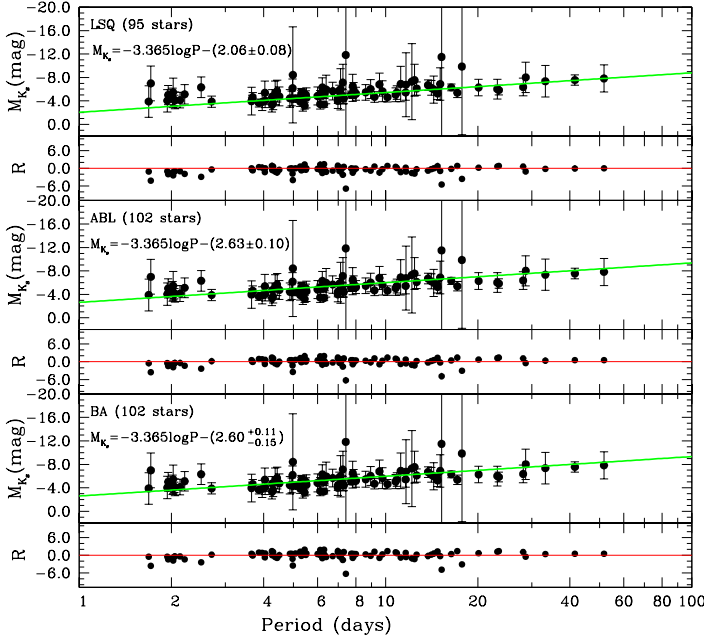
##### 4.1. Binarity-multiplicity among Cepheids

Classical Cepheids are Population I stars, therefore occurrence of binaries among them is a common phenomenon. However, it is not easy to detect the presence of a companion because it is the supergiant Cepheid that dominates the system. For brightest (naked-eye) Cepheids, the frequency of binaries (including systems consisting of more than two stars) exceeds 50%, and there is a selection effect towards fainter visual magnitudes that results in a deficit in known binaries (Szabados 2003). For classical Cepheids in the MW, there exists an on-line data base developed and maintained at the Konkoly Observatory<sup>7</sup> in which one can find the actual list of known binaries involving a Cepheid component. A few further binary Cepheids are known from Anderson et al. (2016). When performing astrometric reduction of the *Gaia* data, these stars have to be treated as binary systems because the orbital motion (if not taken into account) falsifies the resulting trigonometric parallax (Szabados 1997). Moreover, the brightness of the Cepheid ( $G$ ,  $G_{BP}$ , and  $G_{RP}$  magnitudes) has to be corrected for the photometric contribution of the companion star. If the available photometric, spectroscopic, and astromet-

<sup>7</sup> <http://www.konkoly.hu/CEP/intro.html>

$$\begin{aligned}
p(m_i|\varpi_i, \phi_1, b, \phi_2, w, P_i, Z_i) &\sim \mathcal{N}(m_i|\tan(\phi_1) \cdot \log_{10}(P_i) + \tan(\phi_2) \cdot Z_i + b - 5 \cdot \log_{10}(\varpi_i) - 10, w) \\
p(\varpi_i|\beta, \gamma) &\sim \ln \mathcal{N}(\varpi_i|\beta, \gamma) \\
\pi(\gamma) &\sim \exp(1) \\
p(\beta) &\sim \mathcal{N}(0, 2) \\
\pi(\phi_1) &\sim \mathcal{N}(0, 3.14/2) \\
\pi(\phi_2) &\sim \mathcal{N}(0, 3.14/2) \\
\pi(b) &\sim \mathcal{N}(0, 10) \\
\pi(w) &\sim \exp(10) \\
\pi(Z_i) &\sim \mathcal{N}(Z_i|0, 5) \\
\pi(P_i) &\sim \mathcal{N}(P_i|0, 3)
\end{aligned}$$

**Table 2.** Prior ( $\pi$ ) definitions for the hierarchical Bayesian model of the  $PL(Z)$  relations. The symbol  $\sim$  has to be read as "is distributed according to". The exp expression has to be interpreted not as the exponential analytical function but as the exponential probability density distribution. We use the  $\pi$  symbol to refer to the prior probability and use 3.14 to refer to the half-length of the circle.



**Fig. 21.** Classical Cepheid  $PL$  relations in the  $K_s$ -band obtained i) by linear least squares fitting the stars' absolute magnitudes inferred from direct transformation of the TGAS parallaxes (upper panel); ii) via non-linear least squares fit and the ABL method (middle panel); and iii) using a Bayesian approach (bottom panel). The slope of the fit is adopted from Fouqué et al. (2007). The bottom part of each panel shows the residuals from the best fit line.

ric data are insufficient to characterize the binary system or get reliable apparent and absolute magnitudes of the Cepheid component, that particular Cepheid cannot be used as a calibrator in determining the zero point of the  $PL$  relationship. Combining information from the on-line data base of the Konkoly Observatory, Klagyivik & Szabados (2009) and Anderson et al. (2016) we find that 198 (60%) of the 331 classical Cepheids in our sample are binaries. They were not used to compute the  $PL$  relations. Once known binaries are discarded our sample reduces to 133 non-binary classical Cepheids. The selection for binarity we have operated may sound very strict, however, the reduced scatter of the comparison with photometric parallaxes obtained with the Baade-Wesselink technique (see Fig. 15) when binary Cepheids are discarded indicates that ours is a safe approach.

#### 4.2. Derivation of the classical Cepheid $PL$ and $PW$ relations

We found information on the period,  $V$ ,  $I_c$ ,  $K$  photometry and reddening only for 125 of the 133 non-binary classical Cepheids. Furthermore, three of them, namely, BB Her, EV Aql and V733 Aql are classified as Type II Cepheids in the McMaster Cepheid Photometry and Radial Velocity Data Archive<sup>8</sup>. We discarded them from the sample of classical Cepheids but did not include them in the list of Type II Cepheids since their classification is uncertain. After this additional cleaning we are left with a sample of 122 bona-fide classical Cepheids.

Fundamental mode (F) and first-overtone (FO) classical Cepheids follow different  $PL$  relations. Information on the pulsation mode of the 122 classical Cepheids in the clean sample is available from the studies by Udalski et al. (1999), Sziládi et al. (2007), Klagyivik & Szabados (2009), Molnár & Szabados (2014) and Inno et al. (2015), by which it turns out that our sample contains 102 fundamental mode classical Cepheids. In order to remove any scatter caused by mixing multiple  $PL$  relations and given the small number of FO pulsators (20), in the following analysis we have considered only the F classical Cepheids. The error distribution of the TGAS parallaxes for the 102 F classical Cepheids is shown by the magenta histogram in Fig. 1. Relevant information (*Gaia*/Hipparcos/Tycho-2 Ids,  $G$ ,  $\langle V \rangle$ ,  $\langle I \rangle$ ,  $\langle K_s \rangle$  magnitudes, period, reddening, metallicity, parallax and parallax errors) for them is summarised in the first 102 rows of Table 7. Typical errors of the  $V$ ,  $I$ ,  $K_s$  apparent mean magnitudes are estimated to be of about 0.02 mag.

We note that  $G$ -band magnitudes are available for all the classical Cepheids in our sample, however, we decide to not compute  $G$ -band  $PL$ s primarily because *Gaia*  $G$ -band has a too large throughput (330 - 1050 nm) encompassing roughly from the  $U$  to the  $Y$  spectral ranges. The intrinsic width of the classical Cepheids instability strip varies significantly going from  $U$  to  $K$  passbands and the dispersion of the Cepheids  $PL$  varies accordingly, being tightest in the NIR (Sec. 1 and, e.g. fig. 4 of Madore & Freedman 1991) in this making the  $K$ -band the best choice for testing TGAS parallaxes with the classical Cepheid  $PL$  relations. Furthermore, the  $G$ -band magnitudes available for TGAS classical Cepheids in *Gaia* DR1 are the straight average of, often, only a few measurements unevenly sampling the cyclic light variation of these stars, hence further enhancing the scatter of the  $G$ -band  $PL$ . The situation will improve significantly with *Gaia* DR2 because both better sampled  $G$ -band light curves will be released for the TGAS Cepheids and, more importantly, because

<sup>8</sup> <http://crocus.physics.mcmaster.ca/Cepheid/>

$G_{RP}$  magnitudes (640 - 1050 nm) will become available, allowing the *Gaia*  $G_{RP}$   $PL$  relation to be built for classical Cepheids.

We computed  $PL$  relations in the  $V$ ,  $I$  and  $K_s$  bands (hereinafter,  $PM_V$ ,  $PM_I$ ,  $PM_{K_s}$  and  $(V, V-I)$ ,  $(K_s, V-K_s)$   $PW$  relations [ $PW(V, V-I)$ ,  $PW(K_s, V-K_s)$ ] relations for the 102 F classical Cepheids in our sample. To correct for extinction the  $V$ ,  $I$  and  $K_s$  magnitudes we adopted the extinction relations from Cardelli et al. (1989) and  $R_V = 3.1$ , thus obtaining:  $V_0 = V - 3.1E(B-V)$ ,  $I_0 = I - 1.48E(B-V)$  and  $K_{s,0} = K_s - 0.35E(B-V)$ . The Wesenheit magnitudes used in this paper are defined as follows:  $W(V, I) = V - 2.55(V-I)$  (Fouqué et al. 2007) and  $W(V, K_s) = K_s - 0.13(V-K_s)$  (Ripepi et al. 2012). As pointed out in Sec. 1, the  $PW$  relations have several advantages with respect to normal  $PL$  relations, because the effect of errors on the reddening estimates is in principle removed, in practice greatly mitigated, and because the colour term in the  $W$  magnitude definition takes into account and partially corrects for the finite colour width of the instability strip, thus reducing the associated uncertainty on the distance determinations. It is also worth noticing that in the case of the  $W(V, K_s)$ , the  $PW$  is equivalent to the  $PLC$  relation in the same filters (see, e.g. Ripepi et al. 2012). Since errors of the TGAS parallax are large we did not attempt to derive both slope and zero point but fixed the slope of the  $PL$  and  $PW$  relations and used the TGAS parallaxes just to estimate the zero points. We adopted the slopes from Fouqué et al. (2007) for the  $PM_V$ ,  $PM_I$ ,  $PM_{K_s}$  and  $PW(V, V-I)$  relations and from Ripepi et al. (2012) for the  $PW(K_s, V-K_s)$  relation.

The  $PL$  and  $PW$  relations obtained applying the three different approaches described in Sec. 3.2 to the various passbands considered in this paper ( $V$ ,  $I$  and  $K_s$ ) are reported in Table 3 and shown in Fig. 21 for the case of the  $PK_s$  relations. Specifically, the upper panel of Fig. 21 shows the weighted least squares fit of the absolute  $M_{K_s}$  magnitudes obtained by direct transformation of the parallaxes (Eq. 1, hereinafter referred to as LSQ). The fit was possible only for 95 classical Cepheids in the sample for which TGAS parallaxes have positive values. The  $PM_V$ ,  $PM_I$ ,  $PM_{K_s}$ ,  $PW(V, V-I)$  and  $PW(K_s, V-K_s)$  relations were then computed using the ABL method and a weighted non-linear least squares fit in the form of Eq. 4. Using the ABL approach the whole sample of 102 classical Cepheids, without discarding stars with negative parallaxes, could be used. The  $PM_{K_s}$  relation derived with the ABL method is shown in the middle panel of Fig. 21. Finally, we used our Bayesian approach to fit the  $PL$  and  $PW$  relations of the whole sample of 102 classical Cepheids, the resulting  $PM_{K_s}$  relation is presented in the bottom panel of Fig. 21. Comparison of the results in Table 3 shows that the ABL and Bayesian approaches are generally in good agreement to each other and provide brighter absolute magnitudes (hence longer distances) than the direct transformation of parallaxes and the LSQ fit which absolute magnitudes are about  $\sim 0.5$  mag systematically fainter. However, we also note that the r.m.s. scatter of all relations is very large, due to the large parallax uncertainties. The r.m.s. of the Bayesian solution is particularly large as it represents the unweighted residuals with respect to the maximum a posteriori solution.

## 5. Type II Cepheids

Type II Cepheids are pulsating variables that belong to the Population II star family. They have been studied by several authors (Wallerstein & Cox 1984, Gingold 1985, Harris 1985, Bono, Caputo & Santolamazza 1997, Wallerstein 2002, Feast et al. 2008, Matsunaga et al. 2011, Soszyński et al. 2008, Ripepi et al. 2015) and are usually divided in three classes: BL Herculis (BL Her)

with periods between 1 and 4 days, W Virginis (W Vir) with period from 4 to 20 days and RV Tauri (RV Tau) with periods from 20 to 150 days. The light curves of BL Her and W Vir stars can be almost sinusoidal or highly non-sinusoidal, those of RV Tauri have alternating minima. It is believed that BL Her variables are low-mass stars ( $0.5-0.6 M_\odot$ ) that start the central He burning on the blue side of the RR Lyrae star gap and crossing the instability strip at about 0.5-1.5 mag brighter than the RR Lyrae stars (hence the longer periods). Hydrodynamic models indicate that they pulsate in the fundamental radial mode (see e.g. Marconi & Di Criscienzo 2007, and references therein). The W Vir variables, instead, cross the instability strip during their blue-loop excursions (“blue-nose”) from the asymptotic giant branch (AGB) during helium-shell flashes. They are  $\sim 2-4$  mag brighter than the RR Lyrae stars. As the BL Her, also the W Vir stars are thought to pulsate in the radial fundamental mode (see, e.g. Lemasle et al. 2015, and references therein).

The RV Tau are post-AGB stars that cross the instability strip at high luminosity during their path to the white dwarf cooling sequence. It is still unclear whether it is appropriate to include them in the same class as the BL Her and W Vir stars, since they have different evolutionary histories (Wallerstein 2002). In addition to the three above types, Soszyński et al. (2008) suggested the existence of the so-called peculiar W Vir (pW Vir) stars. They exhibit peculiar light curves and, at constant period, are generally brighter than normal Type II Cepheids. Although their true nature remains uncertain, it is likely that the pW Vir are part of binary systems.

It has been known since a long time that the Type II Cepheids follow a  $PL$  relation (Nemec et al. 1994) in the optical. Kubiak & Udalski (2003) later found that all Type II Cepheids with periods in the range of 0.7 to about 10 days in the OGLE II (Udalski et al. 1992) sample follow the same  $PL$  relation as then also confirmed by Pritzl et al. (2003) and Matsunaga et al. (2006) for Type II Cepheids in Galactic globular clusters, by Groenewegen et al. (2008) for Type II Cepheids in the Galactic bulge, and by Soszyński et al. (2008) for the LMC sample, on the basis of OGLE III data. Matsunaga et al. (2011) using single-epoch data showed that the Type II Cepheids follow tight  $PL$  relations in the  $J$ ,  $H$ ,  $K_s$  passbands. This result has been confirmed by Ripepi et al. (2015) based on multi-epoch  $J$ ,  $K_s$  photometry for 130 Type II Cepheids observed in the LMC by the *VISTA survey of the Magellanic Clouds system*, VMC (Cioni et al. 2011). These authors found that unique  $PL$  and  $PW$  relations holds both for BL Her and W Vir variables, whereas RV Tau stars follow different and more dispersed relationships. In light of this and the different evolutionary history we have not considered the RV Tau stars in our analysis. Ripepi et al. (2015) also found that the metallicity dependence of the Type II Cepheid  $PL$  and  $PW$  relations is small, if any. Therefore, the metallicity was neglected in our analysis.

The sample of 31 Type II Cepheids that have TGAS parallax (see Section 2) contains 12 BL Her, 14 W Vir and 5 RV Tau stars. Excluding the RV Tau variables we are left with a sample of 26 stars spanning the period range from 1.16 to 30.0 d. The error distribution of the TGAS parallaxes for these 26 Type II Cepheids is shown by the grey histogram in Fig. 2.  $J$  and  $K_s$  photometry for them was taken from the 2MASS catalogue (Cutri et al. 2003), pulsation periods from the GCVS (Samus et al. 2007-2015),  $E(B-V)$  reddening values and related errors were taken from the NASA/IPAC Infrared Science Archive<sup>9</sup>, which is based on the reddening maps of Schlafly & Finkbeiner

<sup>9</sup> <http://irsa.ipac.caltech.edu/applications/DUST/>



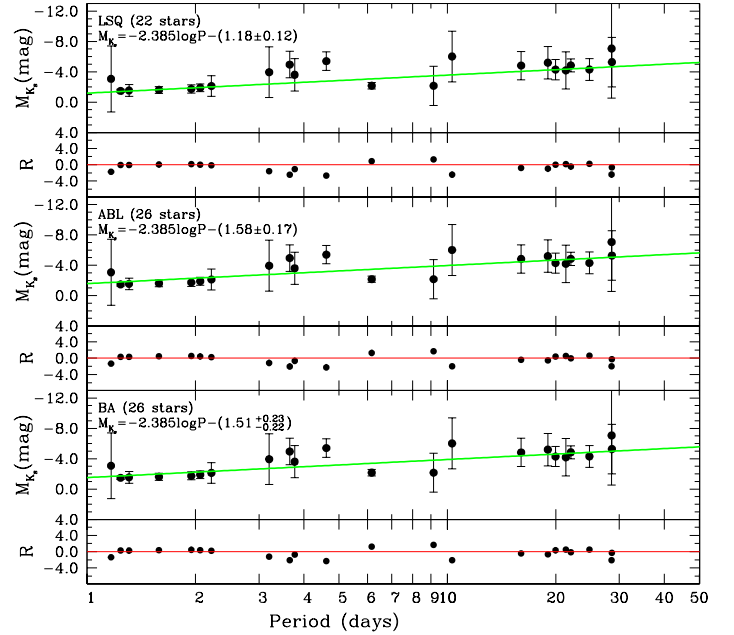
**Table 3.** *PL* and *PW* relations for classical Cepheids with zero point based on TGAS parallaxes.

	Relation	RMS (mag)
$PM_V$ 95 objects (LSQ)	$-2.678 \log P - (1.00 \pm 0.08)$	0.74
$PM_V$ 102 objects (ABL)	$-2.678 \log P - (1.54 \pm 0.10)$	0.85
$PM_V$ 102 objects (BA)	$-2.678 \log P - (1.49^{+0.12}_{-0.11})$	1.31
$PM_I$ 95 objects (LSQ)	$-2.98 \log P - (1.28 \pm 0.08)$	0.78
$PM_I$ 102 objects (ABL)	$-2.98 \log P - (1.84 \pm 0.10)$	0.87
$PM_I$ 102 stars (BA)	$-2.98 \log P - (1.80^{+0.13}_{-0.12})$	1.33
$PM_{K_s}$ 95 objects (LSQ)	$-3.365 \log P - (2.06 \pm 0.08)$	0.74
$PM_{K_s}$ 102 objects (ABL)	$-3.365 \log P - (2.63 \pm 0.10)$	0.88
$PM_{K_s}$ 102 stars (BA)	$-3.365 \log P - (2.60^{+0.11}_{-0.15})$	1.33
$PW(V, V - I)$ 95 objects (LSQ)	$-3.477 \log P - (2.21 \pm 0.08)$	0.77
$PW(V, V - I)$ 102 objects (ABL)	$-3.477 \log P - (2.82 \pm 0.11)$	0.90
$PW(V, V - I)$ 102 stars (BA)	$-3.477 \log P - (2.63 \pm 0.13)$	1.36
$PW(K_s, V - K_s)$ 95 objects (LSQ)	$-3.32 \log P - (2.32 \pm 0.08)$	0.73
$PW(K_s, V - K_s)$ 102 objects (ABL)	$-3.32 \log P - (2.87 \pm 0.10)$	0.87
$PW(K_s, V - K_s)$ 102 stars (BA)	$-3.32 \log P - (2.81^{+0.14}_{-0.12})$	1.33

(2011). To de-redden the  $K_s$  and  $J$  magnitudes we applied the extinction laws  $A_J = 0.87E(B - V)$  and  $A_K = 0.35E(B - V)$  from Cardelli et al. (1989), adopting  $R_V = 3.1$ . We also calculated the Wesenheit magnitude  $W(K_s, J) = K_s - 0.69(J - K_s)$  and fitted the  $PM_{K_s}$ ,  $PM_J$  and  $PW(K_s, J - K_s)$  relations adopting the slopes derived by Ripepi et al. (2015) for BL Her and W Vir stars in the LMC. For the Type II Cepheids we only have single-phase 2MASS  $J$  and  $K_s$  magnitudes instead of magnitudes averaged over the whole pulsation cycle, which introduced additional uncertainty. The typical amplitude of the Type II Cepheids in these bands is  $\sim 0.3$  mag, hence, we adopted mean errors of the apparent  $J$  and  $K_s$  magnitudes of 0.15 mag. The sample of 26 Type II Cepheids contains four stars with negative parallaxes. Hence, we performed the linear least squares fitting of the absolute magnitudes only for the 22 Type II Cepheids with a positive parallax, while the ABL and Bayesian methods were applied to the whole sample of 26 Type II Cepheids. As with the classical Cepheids, we show graphically in Fig. 22 only the  $PM_{K_s}$  relation and summarise in Table 4 the relations obtained in all various bands considered in the paper. Similarly to what we found for classical Cepheids, the r.m.s. of all relations is fairly large, the ABL and Bayesian approaches are generally in good agreement to each other and, on average, about 0.4 mag brighter than found with the LSQ fit.

## 6. RR Lyrae stars

TGAS parallaxes are published in *Gaia* DR1 for 364 MW RR Lyrae stars. Photometry and metallicity for most of these stars is available in the literature, although sparse through many different papers and catalogues. Dambis et al. (2013) have collected and homogenised the literature data of 403 MW RR Lyrae stars for which they publish period, pulsation mode, interstellar visual absorption ( $A_V$ ), iron abundance ([Fe/H]) on the Zinn & West (1984) metallicity scale (for 402 stars), and intensity-averaged mean magnitudes in the Johnson  $V$ , 2MASS  $K_s$  and Wide-field Infrared Survey Explorer (*WISE*)  $W_1$  ( $3.4 \mu\text{m}$ ) passbands for 384, 403 and 398 stars, respectively. The pulsation pe-

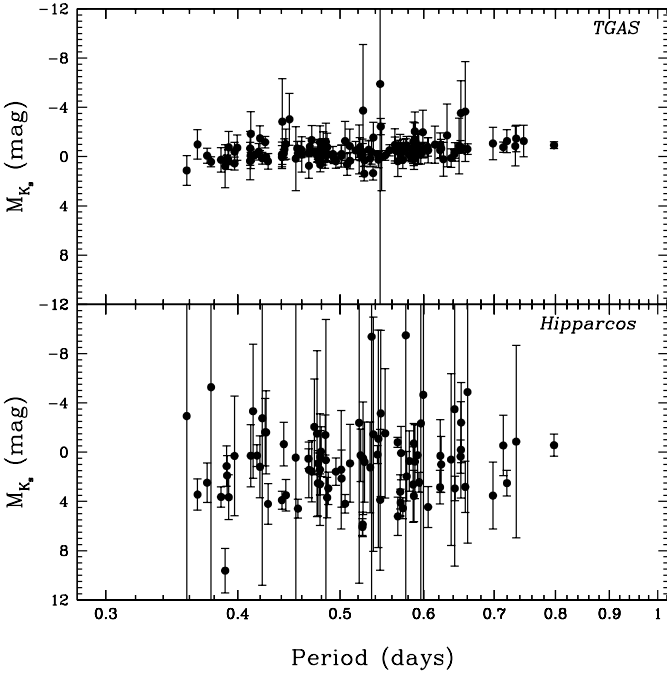


**Fig. 22.** *PL* relation in the  $K_s$  band of the Type II Cepheids obtained i) by linear least squares fit of the stars' absolute magnitudes inferred by direct transformation of the TGAS parallaxes (upper panel); ii) via non-linear least squares fit and the ABL method (middle panel), and iii) using the Bayesian approach (bottom panel). The slope of the fit is adopted from Ripepi et al. (2015). The bottom part of each panel shows the residuals from the best fit line.

riods are taken from the ASAS3 (Pojmanski 2002, Maintz 2005) and GCVS (Samus et al. 2007-2015) catalogues. The interstellar extinction values are estimated from the three-dimensional model by Drimmel et al. (2003). These authors do not provide individual errors for the extinction values but compared their extinction estimates with those derived from near-infrared colour-magnitude diagrams of different MW fields based on 2MASS data, finding differences smaller than 0.05 mag. We adopt this value as the mean uncertainty of the extinction. The mean  $V$

**Table 4.** *PL* and *PW* relations for Type II Cepheids based on TGAS parallaxes.

	Relation	RMS (mag)
$PM_J$ 22 objects (LSQ)	$-2.19 \log P - (0.97 \pm 0.13)$	0.88
$PM_J$ 26 objects (ABL)	$-2.19 \log P - (1.50 \pm 0.20)$	1.25
$PM_J$ 26 objects (BA)	$-2.19 \log P - (1.36^{+0.26}_{-0.25})$	1.15
$PM_{K_s}$ 22 objects (LSQ)	$-2.385 \log P - (1.18 \pm 0.12)$	0.81
$PM_{K_s}$ 26 objects (ABL)	$-2.385 \log P - (1.58 \pm 0.17)$	1.10
$PM_{K_s}$ 26 objects (BA)	$-2.385 \log P - (1.51^{+0.23}_{-0.22})$	1.14
$PW(K_s, J - K_s)$ 22 objects (LSQ)	$-2.52 \log P - (1.34 \pm 0.10)$	0.80
$PW(K_s, J - K_s)$ 26 objects (ABL)	$-2.52 \log P - (1.59 \pm 0.13)$	1.04
$PW(K_s, J - K_s)$ 26 objects (BA)	$-2.52 \log P - (1.66^{+0.21}_{-0.22})$	1.13


**Fig. 23.** RR Lyrae star  $PM_{K_s}$  relations using TGAS (upper panel) and Hipparcos (lower panel) parallaxes, respectively. The upper panel shows the absolute magnitudes,  $M_{K_s}$ , of 143 RR Lyrae stars with positive TGAS parallaxes. The lower panel shows 91 RR Lyrae stars with positive Hipparcos parallaxes.

magnitudes were calculated from nine overlapping sets of observations (see details in Dambis et al. 2013 and references therein); the  $K_s$ -band mean magnitudes from 2MASS single-epoch observations of Cutri et al. (2003) and applying the phase-correction procedure described in Feast et al. (2008)<sup>10</sup>. Mean magnitudes in the mid-infrared  $W1$  passband are calculated from the *WISE* single-exposure database. We cross-matched our sample of 364 RR Lyrae stars with TGAS parallaxes against the catalogue of Dambis et al. (2013) and found 200 sources in common. They span the period range from 0.27 to 0.80 d. The error distribution of the TGAS parallaxes for these 200 RR Lyrae stars is shown by the blue histogram in Fig. 3. The complete dataset (*Gaia*/Hipparcos/Tycho-2 Ids, period, pulsation mode,  $G$ ,  $\langle V \rangle$ ,

$\langle K_s \rangle$ ,  $\langle W1 \rangle$  magnitudes,  $A_V$  and  $[\text{Fe}/\text{H}]$  values) along with TGAS parallaxes and errors for the total sample of 364 RR Lyrae stars is presented in Table 9. For the first 200 entries in the table, the literature values are from Dambis et al. (2013), for the remaining 164 sources the literature information is mainly taken from the GCVS (Samus et al. 2007-2015).

Both Hipparcos and TGAS parallaxes are available for 145 RR Lyrae stars out of 200. As for the classical Cepheids we transformed the TGAS and Hipparcos parallaxes to absolute  $M_{K_s}$  magnitudes applying Eq. 1. This transformation was possible only for stars with positive parallax values, namely, 143 out of 145 stars with TGAS parallax and only 91 out of 145 for Hipparcos. We “fundamentalized” the periods of the RRc stars by adding 0.127 to the  $\log P$ . The corresponding  $PM_{K_s}$  relations are shown in the upper and lower panels of Fig. 23 for TGAS and Hipparcos parallaxes, respectively. The former shows the significant improvement of the TGAS parallaxes for RR Lyrae stars. This is much more impressive than for classical Cepheids and reveals a  $PM_{K_s}$  relation which becomes markedly visible if compared to Hipparcos’.

Since Dambis et al. (2013) provide a homogeneous dataset for a fairly large sample of RR Lyrae stars we used their sample to study the *PL* relations in the  $K_s$  and  $W1$  passbands, the *PLZ* relation in the  $K_s$  band and the optical  $M_V - [\text{Fe}/\text{H}]$  relation adopting the three different approaches described in Sec. 3.2. The occurrence of RR Lyrae stars in binary systems is an extremely rare event. Only one RR Lyrae star, TU UMa, is confirmed to be a member of a binary star system with an orbital period of approximately 23 yr (Wade et al. 1999). Hence, we do not expect extra-scatter in the RR Lyrae relations due to this effect. Indeed, TU UMa is in the sample of 200 RR Lyrae stars that we used to derive the relations for the RR Lyrae stars described in the following sections and it is found to fall very nicely on the best fit line of the various relations.

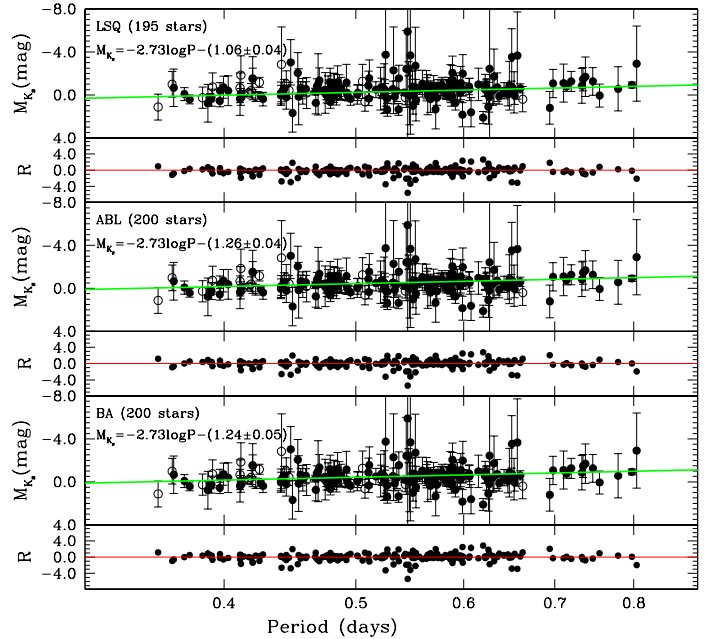
We note that we did not use the  $G$ -band magnitudes to compute the *PL*, *PLZ* or the  $M_V - [\text{Fe}/\text{H}]$  relations of the RR Lyrae stars, the reason being the same as discussed for classical Cepheids in Sec. 4.2 and even more so for the RR Lyrae stars. In fact, as clearly shown by fig. 2 in Catelan et al. (2004), the slope of the RR Lyrae *PL* relation changes from positive to negative values moving from the blue to the red edges of *Gaia*  $G$  passband, being roughly zero at its center. Hence, such a large passband should not be used to derive the RR Lyrae *PL* and  $M_V - [\text{Fe}/\text{H}]$  relations.

<sup>10</sup> For 32 RR Lyrae stars in Dambis et al. (2013) sample the 2MASS magnitudes do not have phase correction, however, only one of them falls in our sample of 364.

### 6.1. Derivation of the RR Lyrae stars $PL$ and $PLZ$ relations in the $K_s$ passband

The near-infrared  $PM_{K_s}Z$  relation of RR Lyrae stars has been studied by many different authors and, as summarised in Section 1, coefficients and zero point of the relation differ significantly from one study to the other, with the literature values for the dependence of  $M_{K_s}$  on period ranging from  $-2.101$  (Bono et al. 2003) to  $-2.73$  (Muraveva et al. 2015) and the dependence on metallicity ranging from  $0.03$  (Muraveva et al. 2015) to  $0.231$  (Bono et al. 2003). We used the sample of 200 RR Lyrae stars with TGAS parallaxes along with  $K_s$  magnitudes, period and metallicity values from Dambis et al. (2013) to fit the  $PM_{K_s}$  and  $PM_{K_s}Z$  relations. The  $K_s$  magnitudes were dereddened using the  $V$ -band absorption values ( $A_V$ ) in Dambis et al. (2013) and Cardelli et al. (1989)'s  $A_K/A_V = 0.114$  extinction law for the  $K$  band. The periods of the first overtone RR Lyrae stars (RRc) were “fundamentalized” as described in the previous section. As with the Cepheids we did not attempt to derive both slope and zero point of the RR Lyrae relations but used the TGAS parallaxes only to estimate the zero points. Specifically, we adopted the slope of the  $PM_{K_s}$  relation from Muraveva et al. (2015), who studied RR Lyrae stars in the LMC. The upper panel of Fig. 24 shows the linear least squares fit of the absolute magnitudes inferred from the direct transformation of the TGAS parallaxes. Five RR Lyrae stars in the sample have a negative parallax value, hence, the least squares fit could be applied only to 195 RR Lyrae stars. Middle and bottom panels of Fig. 24 show the  $PM_{K_s}$  relations obtained with the ABL and the Bayesian approaches, respectively. The whole sample of 200 RR Lyrae stars was used with these two methods. The  $PM_{K_s}$  relations obtained with the three different approaches are summarised in the first three rows of Table 5. Once again, the r.m.s of all relations is significantly large, the zero-points obtained with the ABL and Bayesian approaches are in good agreement to each other and, on average, about 0.2 mag brighter than found with the LSQ fit. We also note that the zero-points obtained with the ABL and Bayesian approaches are in perfect agreement with the zero-point of the  $PM_{K_s}Z$  relation obtained in Muraveva et al. (2015) using the HST parallaxes of four RR Lyrae stars from Benedict et al. (2011), (eq. 6 in Muraveva et al. 2015).

To fit the RR Lyrae near-infrared  $PM_{K_s}Z$  relation we used the metallicities in Dambis et al. (2013), which are on the Zinn & West metallicity scale, and took the slope of the period term from Muraveva et al. (2015), who used the metallicity scale defined in Gratton et al. (2004). This is 0.06 dex systematically higher than the Zinn & West scale, hence, we transformed Dambis et al. (2013)'s metallicities accordingly. Furthermore, Dambis et al. (2013) do not provide errors for the metallicities. We assumed them to be of 0.2 dex for all stars, as an average between spectroscopic determinations, which uncertainties generally are of the order of 0.1 dex and photometric metallicities whose typical errors can be as large as 0.3 dex. The  $PM_{K_s}Z$  relations obtained with the three different approaches are provided in rows 4 to 6 of Table 5. The zero-points obtained with the ABL and Bayesian approaches are in good agreement to each other and, on average, about 0.1 mag brighter than found with the LSQ fit. The dependence of the  $M_{K_s}$  magnitude on metallicity is always found to be negligible considering the current uncertainties.



**Fig. 24.** RR Lyrae  $PL$  relation in the  $K_s$  obtained i) by linear least squares fitting the stars' absolute magnitudes inferred from direct transformation of the TGAS parallaxes (upper panel); ii) via non-linear least squares fit and the ABL method (middle panel), and iii) using the Bayesian approach (bottom panel). The slope of the fit is taken from Muraveva et al. (2015). Filled and empty circles represent fundamental-mode (RRab) and first overtone (RRc) stars, respectively. The bottom part of each panel shows the residuals from the best fit line.

### 6.2. Derivation of the RR Lyrae stars $PL$ relation in the $W_1$ passband.

The mid-infrared  $PW_1$  relation of RR Lyrae variables has been studied by Madore et al. (2013), Dambis et al. (2014), Klein et al. (2014) and Neeley et al. (2015), who found the slope of the  $PM_{W_1}$  dependence on period to range from  $-2.332$  (Neeley et al. 2015 for the *Spitzer* 3.6  $\mu\text{m}$  passband) to  $-2.44$  (Madore et al. 2013, for the WISE passbands). The metallicity dependence of the RR Lyrae  $PL$  relations is known to decrease with increasing the wavelength from near to mid infrared (see Section 1). Since in this paper the dependence on metallicity of the  $M_{K_s}$  magnitudes was found to be consistent with zero (see Section 6.1) we do not expect any dependence on metallicity of the  $PM_{W_1}$  relation to be detectable, given the current, large uncertainties. Hence to compute the  $PL$  relation in the  $W_1$  passband we adopt the slope of the  $PM_{W_1}$  relation from Madore et al. (2013) who neglect the metallicity term. Apparent  $W_1$  magnitudes are available, from Dambis et al. (2013), for 198 of the 200 RR Lyrae stars in our sample. Five of them have negative parallaxes, hence, when deriving the  $PM_{W_1}$  relation with the LSQ fit we could use only 193 stars. ABL and Bayesian approaches were applied instead to the whole sample of 198 stars. To correct for the extinction we used the relation  $A_{W_1}/A_V = 0.065$  from Madore et al. (2013). The  $PM_{W_1}$  relations obtained with the three different approaches are summarised in rows 7 to 9 of Table 5. The zero-point of the  $PM_{W_1}$  derived from the LSQ fit is 0.24 mag fainter than the zero-point in Madore et al. (2013) ( $-1.26 \pm 0.25$ ) which is based on the HST parallaxes of four RR Lyrae stars from Benedict et al. (2011), while the zero-points obtained with the ABL and Bayesian methods are about 0.2 mag brighter and well in agreement, within the errors, with Madore et al. (2013).



**Table 5.**  $PL$ , and  $M_V - [\text{Fe}/\text{H}]$  relations for RR Lyrae stars based on TGAS parallaxes.

	Relation	RMS (mag)
$PM_{K_s}$ 195 stars (LSQ)	$-2.73 \log P - (1.06 \pm 0.04)$	0.84
$PM_{K_s}$ 200 stars (ABL)	$-2.73 \log P - (1.26 \pm 0.04)$	0.90
$PM_{K_s}$ 200 stars (BA)	$-2.73 \log P - (1.24 \pm 0.05)$	1.02
$PM_{K_s}Z$ 195 stars (LSQ)	$-2.73 \log P - (0.01 \pm 0.07)[\text{Fe}/\text{H}] - (1.08 \pm 0.09)$	0.84
$PM_{K_s}Z$ 200 stars (ABL)	$-2.73 \log P + (0.07 \pm 0.07)[\text{Fe}/\text{H}] - (1.17 \pm 0.10)$	0.89
$PM_{K_s}Z$ 200 stars (BA)	$-2.73 \log P - (0.01^{+0.11}_{-0.07})[\text{Fe}/\text{H}] - (1.22^{+0.40}_{-0.09})$	1.02
$PM_{W_1}$ 193 stars (LSQ)	$-2.44 \log P - (1.02 \pm 0.04)$	0.82
$PM_{W_1}$ 198 stars (ABL)	$-2.44 \log P - (1.21 \pm 0.04)$	0.87
$PM_{W_1}$ 198 stars (BA)	$-2.44 \log P - (1.20 \pm 0.05)$	1.02
$M_V - [\text{Fe}/\text{H}]$ 195 stars (LSQ)	$0.214[\text{Fe}/\text{H}] + (1.01 \pm 0.04)$	0.82
$M_V - [\text{Fe}/\text{H}]$ 200 stars (ABL)	$0.214[\text{Fe}/\text{H}] + (0.82 \pm 0.04)$	0.87
$M_V - [\text{Fe}/\text{H}]$ 200 stars (BA)	$0.214[\text{Fe}/\text{H}] + (0.88^{+0.04}_{-0.06})$	1.21

### 6.3. Derivation of the optical $M_V - [\text{Fe}/\text{H}]$ relation of RR Lyrae stars

Finally, we used our sample of 200 RR Lyrae stars to compute the luminosity-metallicity relation,  $M_V - [\text{Fe}/\text{H}]$  that RR Lyrae stars conform to in the optical. Results are summarised in the bottom three rows of Table 5 for the LSQ fit, ABL method and Bayesian approach, separately. The direct transformation of the parallaxes to absolute magnitudes was possible only for 195 stars with positive parallaxes, while, the ABL and Bayesian approaches were applied to the whole sample of 200 RR Lyrae stars. We corrected the  $V$  apparent magnitudes for extinction using  $A_V = 3.1E(B - V)$  (Cardelli et al. 1989). We adopted the slope of Clementini et al. (2003) and Gratton et al. (2004) who studied the luminosity-metallicity relation of RR Lyrae stars in the LMC. As in Sec. 6.1, we transformed Dambis et al. (2013) metallicities to the scale adopted in Clementini et al. (2003) and Gratton et al. (2004). The  $M_V - [\text{Fe}/\text{H}]$  relation derived by the direct transformation of the TGAS parallaxes provides an absolute magnitude of  $M_V = 0.69 \pm 0.04$  mag for RR Lyrae stars with metallicity  $[\text{Fe}/\text{H}] = -1.5$  dex. This is significantly fainter than  $M_V = 0.45 \pm 0.05$  mag obtained for the same metallicity by Benedict et al. (2011) using HST parallaxes, while agrees, within the errors, with the value of  $M_V = 0.66 \pm 0.14$  mag derived by Cateilan & Cortes (2008) for RR Lyrae itself ( $[\text{Fe}/\text{H}] = -1.48$  dex).

The  $M_V - [\text{Fe}/\text{H}]$  relations obtained by applying the ABL and Bayesian approaches lead to  $M_V = 0.50 \pm 0.04$  mag and  $M_V = 0.56^{+0.04}_{-0.06}$  mag at  $[\text{Fe}/\text{H}] = -1.5$  dex, respectively, which is marginally consistent within the relative errors with the absolute magnitude derived by Benedict et al. (2011).

## 7. Comparison of results from different relations and conclusions

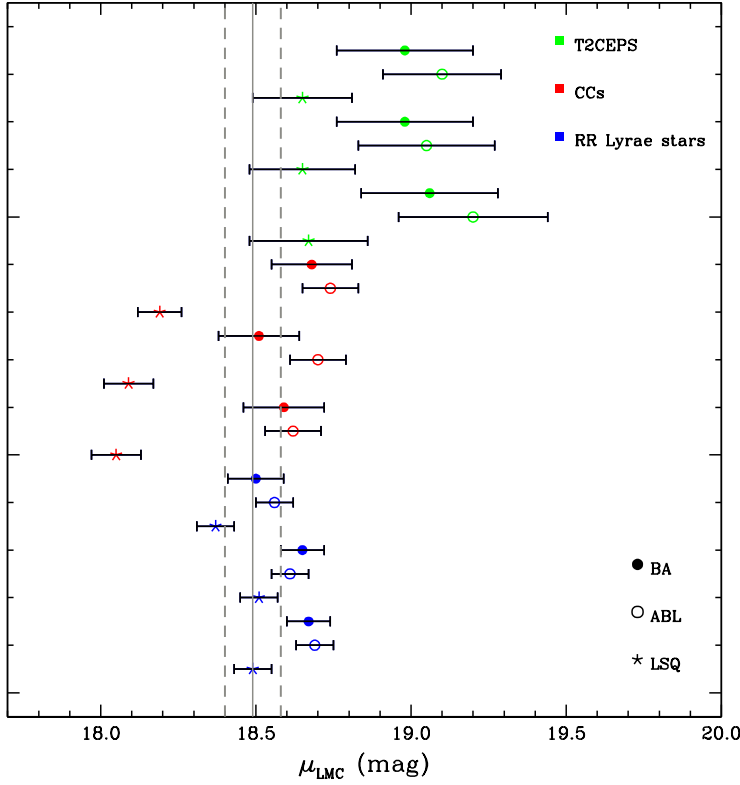
In this section we use the TGAS-based  $PL$ ,  $PW$ ,  $PLZ$  and  $M_V - [\text{Fe}/\text{H}]$  relations of classical Cepheids, Type II Cepheids and RR Lyrae stars derived with the three alternative fitting approaches presented in the previous sections to infer the distance to the LMC. We considered only the  $PM_{K_s}$ ,  $PW(V, I)$ ,  $PW(V, K_s)$  relations for the classical Cepheids and for the RR Lyrae stars only the  $PM_{K_s}$ ,  $PM_{K_s}Z$  and  $M_V - [\text{Fe}/\text{H}]$  relations, because they

are the most relevant in distance scale studies. This comparison may allow the user to apprehend potential and expected level of systematics of the TGAS parallaxes for these primary standard candles of the cosmological distance ladder. It also gives some perspective on the effects of handling parallaxes in parallax or distance (absolute magnitude) space.

The LMC is a fundamental anchor of the extragalactic distance ladder and its first step. Over the last couple of decades the distance modulus of the LMC has been measured countless times using different Population I and II distance indicators and many independent techniques (see e.g. Gibson 2000, Benedict et al. 2002, Clementini et al. 2003, Schaefer 2008 and a recent compilation of literature values by de Grijs et al. 2014), most of which are now converging on a median value of  $\mu_{\text{LMC}} = 18.49 \pm 0.09$  mag, that is well in agreement with the value of  $(m - M)_0 = 18.493 \pm 0.008$  (stat)  $\pm 0.047$  (syst) mag derived by Pietrzynski et al. (2013) using 8 eclipsing binaries in the LMC bar.

The distance moduli derived for the LMC from some of the various relations obtained in this paper are summarised in Table 6, with results for classical Cepheids, Type II Cepheids and RR Lyrae stars shown in the upper, middle and lower portions of the table, respectively. They were calculated according to the following procedure: for the classical Cepheids we adopted the  $PM_{K_s}$  and  $PW(V, I)$  relations derived for the LMC variables by Fouqué et al. (2007) (rows 4 and 2 from the bottom of their table 8) and the  $PW(V, K_s)$  relation by Ripepi et al. (2012) (their table 4). For the Type II Cepheids we used the LMC relations in table 5 of Ripepi et al. (2015). Finally, for the RR Lyrae stars we applied the relations from Muraveva et al. (2015) and Clementini et al. (2003). We then subtracted from the zero points of these relations, which are in apparent magnitude, our corresponding TGAS-based zero points. Finally, errors in the distance moduli were calculated as the r.m.s of our relations divided by the square root of the number of sources used in the fit. Different values are graphically compared in Fig. 25 where we adopt as a reference value the LMC distance modulus from Pietrzynski et al. (2013).

We find that there is a good consistency, within the errors, between results obtained with the ABL and Bayesian approaches for all three types of variables. On the other hand, the LSQ



**Fig. 25.** Values of the LMC distance modulus obtained from the  $PL$ ,  $PLZ$  and  $M_V - [\text{Fe}/\text{H}]$  relations for RR Lyrae stars (blue symbols), and some of the different TGAS-based  $PL$  and  $PW$  relations for classical (CCs; red symbols) and Type II Cepheids (T2CEPS; green symbols) derived in this paper. Asterisks, open circles and filled circles indicate results obtained using the linear least square fit (LSQ), the ABL method and the Bayesian approach, respectively. From bottom to top, RR Lyrae stars (blue symbols):  $PM_{K_s}$  relations for 195/200/200 stars (LSQ, ABL, BA methods) and slope from Muraveva et al. (2015);  $PM_{K_s}$  relations for 195/200/200 stars (LSQ, ABL, BA methods) and slope of the dependence on period from Muraveva et al. (2015);  $M_V - [\text{Fe}/\text{H}]$  relations for 195/200/200 stars (LSQ, ABL, BA methods) with slope from Clementini et al. (2003). For classical Cepheids (red symbols):  $PM_{K_s}$  and  $PW(V, V - I)$  relations for 95/102/102 stars (LSQ, ABL, BA methods) with slopes from Fouqué et al. (2007); and  $PW(K_s, V - K_s)$  relation for 95/102/102 stars (LSQ, ABL, BA methods) with slope from Ripepi et al. (2012). For Type II Cepheids (green symbols):  $PM_J$ ,  $PM_{K_s}$  and  $PW(K_s, J - K_s)$  relations for 22/26/26 stars (LSQ, ABL, BA methods) with slopes from Ripepi et al. (2015).

fit provides systematically shorter moduli. This discrepancy is larger (about 0.5-0.6 mag, on average) for the classical Cepheids, reduces to 0.4-0.5 mag for the Type II Cepheids, and is the smallest one, 0.2 mag, for the RR Lyrae stars. When compared with the LMC distance modulus of Pietrzynski et al. (2013), results from the Bayesian approach applied to classical Cepheids are always well consistent within the errors with the canonical value, the ABL results infer slightly longer distances than Pietrzynski et al. (2013), whereas results from the LSQ fit are 0.2-0.4 mag shorter than currently accepted in the literature. For the Type II Cepheids, all three methods provide longer moduli than the canonical value, by 0.3-0.5 mag the ABL and Bayesian approaches and by 0.2 mag the LSQ fit, hence being still consistent, within the errors, with Pietrzynski et al. (2013) estimate. The RR Lyrae stars used in this exercise are twice in number the classical Cepheids and more than 7 times the Type II Cepheids. The results obtained for the RR Lyrae stars show a much better agreement among the three methods and also a reasonably good agreement with the literature, once again confirming the impressive improvement in quality and statistics of the TGAS parallaxes for RR Lyrae stars compared to Hipparcos.

However, taken at face value the results summarised in Table 6 and Fig. 25 span an uncomfortable, large range of over one magnitude around the commonly accepted value of 18.5 mag for the distance modulus of the LMC. Because errors are still fairly

large, it is not clear, at this stage, whether this hints to some systematics in the parallax derivation that may affect in different way the different types of variables used in this paper. For instance, since no chromatic corrections were applied to derive the TGAS parallaxes, a colour effect could affect more classical Cepheids, which are both intrinsically redder and more reddened, than RR Lyrae stars or Type II Cepheids. Nevertheless, it is not easy to interpret these results unless in light of the still very large uncertainties affecting the TGAS parallaxes and, perhaps, the relatively small sample of variable stars that could be used, for instance in the analysis of the Type II Cepheids. We also remind the reader that the complexity in the censorships of the samples available prevented us from producing a more reliable estimation of the possible biases introduced by them. As such the results presented in this paper have to be considered as preliminary, and to be superseded by results from further releases of *Gaia* data allowing the use of samples with more accurate parallaxes and less affected by uncontrolled censorship effects.

**Table 6.** Distance moduli of the LMC obtained from some of the TGAS-based  $PL$ ,  $PW$ ,  $PLZ$  and  $M_V - [\text{Fe}/\text{H}]$  relations derived in this study.

Relation	$\mu$ (LSQ) (mag)	$\mu$ (ABL method) (mag)	$\mu$ (Bayesian method) (mag)
<b>Classical Cepheids</b>			
$PM_{K_s}$ for 95 (102) objects	$18.05 \pm 0.08$	$18.62 \pm 0.09$	$18.59 \pm 0.13$
$PW(V, V - I)$ for 95 (102) objects	$18.09 \pm 0.08$	$18.70 \pm 0.09$	$18.51 \pm 0.13$
$PW(K_s, V - K_s)$ for 95 (102) objects	$18.19 \pm 0.07$	$18.74 \pm 0.09$	$18.68 \pm 0.13$
<b>Type II Cepheids</b>			
$PM_J$ for 22 (26) objects	$18.67 \pm 0.19$	$19.20 \pm 0.24$	$19.06 \pm 0.22$
$PM_{K_s}$ for 22 (26) objects	$18.65 \pm 0.17$	$19.05 \pm 0.22$	$18.98 \pm 0.22$
$PW(K_s, J - K_s)$ for 22 (26) objects	$18.65 \pm 0.16$	$19.10 \pm 0.19$	$18.98 \pm 0.22$
<b>RR Lyrae stars</b>			
$PM_{K_s}$ for 195 (200) objects	$18.49 \pm 0.06$	$18.69 \pm 0.06$	$18.67 \pm 0.07$
$PM_{K_s} Z$ for 195 (200) objects	$18.51 \pm 0.06$	$18.61 \pm 0.06$	$18.65 \pm 0.07$
$M_V - [\text{Fe}/\text{H}]$ for 195 (200) objects	$18.37 \pm 0.06$	$18.56 \pm 0.06$	$18.50 \pm 0.09$

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**Table 7.** Dataset for the classical Cepheids

Name	ID <sub>Gaia</sub>	ID <sub>Hipparcos</sub>	ID <sub>Tycho2</sub>	$\varpi_{Hip}$ (mas)	$\sigma\varpi_{Hip}$ (mas)	$\varpi_{TGAS}$ (mas)	$\sigma\varpi_{TGAS}$ (mas)	P (days)	$G_{Gaia}$ (mag)	$\sigma_G$ (mag)	$\langle K_s \rangle$ (mag)	$\langle V \rangle$ (mag)	$\langle I \rangle$ (mag)	E(B-V) (mag)	[Fe/H] (dex)	Ref
AY Cen	5334506130758436352	55726		0.26	1.29	0.54	0.22	5.3098	8.431	0.013	6.249	8.813	7.693	0.38	0.05	1,2,3,8,9
BE Mon	3133819107955689984	31905		-0.10	2.44	0.53	0.24	2.7055	10.077	0.015	7.676	10.568	9.242	0.565	0.05	1,2,3,9,10,11
BR Vul	1827869808377481216	97309		-2.35	1.67	0.66	0.26	2.0462	10.036	0.017	7.136	10.686	9.021	0.911	-	1,3
CR Cep	2008504450538203776	112430		1.85	1.04	0.96	0.24	6.2332	8.906	0.011	5.873	9.647	7.974	0.709	0.0	1,2,3,7,9,10,11
CR Ser	4147381362033178624	89013		-2.95	2.27	0.63	0.30	5.3014	9.820	0.015	6.555	10.856	8.900	0.961	-	1,3,9,10,11

(1) van Leeuwen (2007b); (2) Genovali et al. (2014); (3) Samus et al. (2007-2015); (4) Sziládi et al. (2007); (5) Romaniello et al. (2008); (6) Lemasle et al. (2007) and Lemasle et al. (2008); (7) Luck et al. (2011); (8) Luck & Lambert (2011); (9) Berdnikov et al. (2000); (10) Groenewegen (1999); (11) Ngeow (2012). The first 102 entries are fundamental mode classical Cepheids that we used in the analysis described in Sec. 4.2.

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**Table 8.** Dataset for the Type II Cepheids

Name	ID <sub>Gaia</sub>	ID <sub>Hipparcos</sub>	ID <sub>Tycho2</sub>	$\varpi_{Hip}$ (mas)	$\sigma\varpi_{Hip}$ (mas)	$\varpi_{TGAS}$ (mas)	$\sigma\varpi_{TGAS}$ (mas)	P (days)	$G_{Gaia}$ (mag)	$\sigma_G$ (mag)	$K_s$ (mag)	E(B-V) (mag)
BL Her	4527596846604488448	88242	1562-1255-1	1.27	2.23	0.75	0.26	1.3075	10.144	0.016	9.116	0.07
RT Tra	5828480455598115584	81157	9042-226-1	1.26	1.5	1.03	0.24	1.9461	9.587	0.013	8.268	0.43
RU Cam	1108841774211669504	35681	4364-97-1	0.71	0.8	0.64	0.25	22.0000	8.186	0.004	6.154	0.08
SW Tau	3283721025728185728	20587	78-1341-1	2.80	1.44	1.27	0.25	1.5836	9.384	0.018	7.958	0.282
TX Del	1734124244402708608	102853	516-1779-1	0.04	1.69	1.20	0.22	6.1659	8.949	0.015	7.465	0.1

Note:  $K_s$  magnitudes from 2MASS (Cutri et al. 2003). Periods from Samus et al. (2007-2015). Colour excess from Harris (1985).

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**Table 9.** Dataset for the RR Lyrae stars

Name	ID <sub>Gaia</sub>	ID <sub>Hipparcos</sub>	ID <sub>Tycho2</sub>	$\varpi_{Hip}$ (mas)	$\sigma\varpi_{Hip}$ (mas)	$\varpi_{TGAS}$ (mas)	$\sigma\varpi_{TGAS}$ (mas)	P (days)	Mode	$G_{Gaia}$ (mag)	$\sigma_G$ (mag)	$\langle V \rangle$ (mag)	$\langle K_s \rangle$ (mag)	$A_V$ (mag)	[Fe/H] (dex)
AA CMi	3111925220109675136	35281	164-182-1	2.84	3.47	0.82	0.23	0.4764	AB	11.513	0.022	11.552	10.287	0.257	-0.55
AB UMa	1546016668386865792	59411	3455-362-1	0.14	1.94	0.93	0.27	0.5996	AB	10.733	0.010	10.899	9.623	0.068	-0.72
AE Boo	1234729395962169216	72342	1478-225-1	0.32	2.00	1.21	0.26	0.3150	C	10.526	0.015	10.664	9.730	0.07	-1.47
AF Vel	5360400626025377536	53213	8207-1400-1	1.45	2.18	1.16	0.25	0.5275	AB	11.394	0.010	11.389	10.042	0.407	-1.64
AL CMi	3143813565573130880		192-43-1	-	-	1.12	0.40	0.5506	AB	11.840	0.012	11.931	10.767	0.024	-0.85

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