DISTANCE-DEPENDENT OFFSETS BETWEEN PARALLAXES FOR NEARBY STARS AND *GAIA* DR1 PARALLAXES

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ABSTRACT

We use 612 single stars with previously published trigonometric parallaxes placing them within 25 pc to evaluate parallaxes released in *Gaia's* first data release (DR1). We find that the *Gaia* parallaxes are, on average, 0.24 ± 0.02 mas smaller than the weighted mean trigonometric parallax values for these stars in the solar neighborhood. We also find that the offset changes with distance out to 100 pc, in the sense that the closer the star, the larger the offset. We find no systematic trends in the parallax offsets with stellar V magnitude, $V - K$ color, or proper motion. We do find that the offset is roughly twice as large for stars south of the ecliptic compared to those that are north.

Key words: astrometry – solar neighborhood – stars: distances

Supporting material: machine-readable table

1. INTRODUCTION

The first wave of results from the *Gaia* astrometry mission was released on 2016 September 14, in what is known as the *Gaia* First Data Release (hereafter DR1; Brown et al. 2016). With this release, astrometry has entered a new era, where a few lines of SQL script yield millions of parallaxes, rather than tens of thousands from *Hipparcos*, or thousands from over a century of painstaking work from both the ground and space that produced parallaxes for individually targeted stars. Because of the new rich data set, the *Gaia* results will undoubtedly change the way astronomers investigate the stellar population of the Milky Way and how they create samples of stars for in-depth studies. Because of the broad utility of the *Gaia* results, it is important to check that the new measurements are consistent with what came before. In this Letter, we compare DR1 results to the fundamental sample of nearby stars, which motivated the pursuit of trigonometric parallaxes in the first place.

2. MATCHING STARS AND PARALLAX COMPARISONS

To compare the new *Gaia* parallaxes to previously measured values, we first used the available DR1 search tools to extract stars with parallaxes placing them within 40 pc. The SQL script used was *SELECT * FROM gaiadr1.tgas_source WHERE parallax > = 25*. This query resulted in 3402 stars within 25 pc. We use this result to match 3806 systems within 25 pc collected by us in the past 10 years (Henry & Jao 2015). This list contains all stars with published, accurate (uncertainty ⩽10 mas), trigonometric parallaxes placing them within 25 pc as of 2015 January 1. This 25 pc horizon was previously defined by the Catalog of Nearby Stars (Gliese & Jahreiss 1995) and has been widely used in nearby populations studies. Presumably, single stars with no known stellar, brown dwarf, or planetary companions in this list were selected to reduce contamination of the data set by stars with parallaxes suffering from astrometric perturbations. The search in DR1 was extended to

40 pc for cross-matching to ensure that stars beyond 25 pc in DR1 would be included. Stars with *Hipparcos* identifiers were matched first. If a star had no *Hipparcos* identifier, coordinate matching was used with a radius of 1′, after adjusting for proper motions between the DR1 epoch of 2015 and the epoch of 2000 of these nearby stars. The resulting list of 612 stars[5] and both sets of parallaxes used for the comparisons is given in Table 1.

For the pre-*Gaia* measurements, if multiple trigonometric measurements were published for a given star, a weighted mean parallax value was calculated. Because parallaxes come from various sources, we make three comparisons here: (1) DR1 versus weighted mean trigonometric parallaxes from all available sources, (2) DR1 versus *Hipparcos* parallaxes (van Leeuwen 2007), and (3) DR1 versus YPC parallaxes from *The General Catalog of Trigonometric Parallaxes* (van Altena et al. 1995), sometimes called the Yale Parallax Catalog, or simply YPC. The first two columns in Table 1 are coordinates in epoch and equinox 2000, followed by three columns of identifiers. Columns 6–8 list proper motions, position angles of the proper motions, and their references. The majority of proper motions are from the Tycho-2 catalog (Høg et al. 2000). A few are from *Hipparcos* or our SuperCOSMOS-RECONS survey (Hambly et al. 2001), the latter of which are presented here for the first time. Columns 9 and 10 are Johnson V magnitudes and references. Note that some stars without Johnson V have values converted from Tycho B_T and V_T.[6] The 2MASS K_s (99.99 indicates no value in 2MASS) and *Gaia* G magnitudes are listed in columns 11 and 12. Columns 13–16 give weighted mean parallaxes, parallax errors, the number of parallaxes in the weighted means, and references. The DR1 parallaxes and errors are listed in the final two columns.

[5] There are a total of 869 systems in this list with new DR1 parallaxes.

[6] Details of the conversions will be discussed in a future paper that outlines how we construct template stars to get these conversions; for converted V values we list the reference as "this work."

Table 1
Stars within 25 pc with Parallaxes from GAIA-DR1 and Other Sources

R.A. (2000.0)	Decl. (2000.0)	Name	HIP	*Gaia* source_id	μ (″/yr)	P.A. (deg)	Ref	*V* (mag)	Ref	K_s (mag)	*G* (mag)	$\varpi_{\rm weighted}$ (mas)	$\varpi_{\rm err}$ (mas)	# of ϖ	Ref	ϖ_{Gaia} (mas)	$\varpi_{\rm err}$ (mas)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
00:05:17.68	−67:49:57.4	GJ 0003	436	4706630496753986944	0.571	191.9	8	8.48	2	5.71	8.00	62.970	0.709	2	23, 26	61.142	0.3358
00:06:19.19	−65:50:25.9	LHS 1019	523	4899957901143352576	0.586	160.5	8	12.17	13	7.63	10.92	59.850	2.640	1	26	57.100	0.3270
00:06:36.77	+29:01:17.4	GJ 0005	544	2860924685628241024	0.420	115.1	8	6.06	1	4.31	5.82	73.100	0.558	2	23, 26	72.627	0.5204
00:08:27.29	+17:25:27.3	HIP 000687	687	2772804841615919616	0.110	233.8	8	10.80	19	6.98	9.89	45.980	1.930	1	26	46.386	0.3303
00:12:50.25	−57:54:45.4	GJ 2001	1031	4918476357015844352	0.123	286.8	8	7.23	13	5.38	6.96	49.530	0.580	1	26	48.461	0.3542

References. (1) This work, (2) Bessell (1990), (3) Dahn et al. (1988), (4) Dittmann et al. (2014), (5) Fabricius & Makarov (2000), (6) Harrington & Dahn (1980), (7) Harrington et al. (1993), (8) Høg et al. (2000), (9) Ianna et al. (1996), (10) Jao et al. (2005), (11) Khovritchev et al. (2013), (12) Kilkenny et al. (2007), (13) Koen et al. (2010), (14) Riedel et al. (2010), (15) Shkolnik et al. (2012), (16) Subasavage et al. (2009), (17) Weis (1987), (18) Weis (1988), (19) Weis (1993), (20) Weis (1996) (21) Weis et al. (1999), (22) Winters et al. (2015), (23) van Altena et al. (1995), (24) Weis (1991), (25) Weis (1991), (26) van Leeuwen (2007).

(This table is available in its entirety in machine-readable form.)

(a)

(b)

(c)

(d)
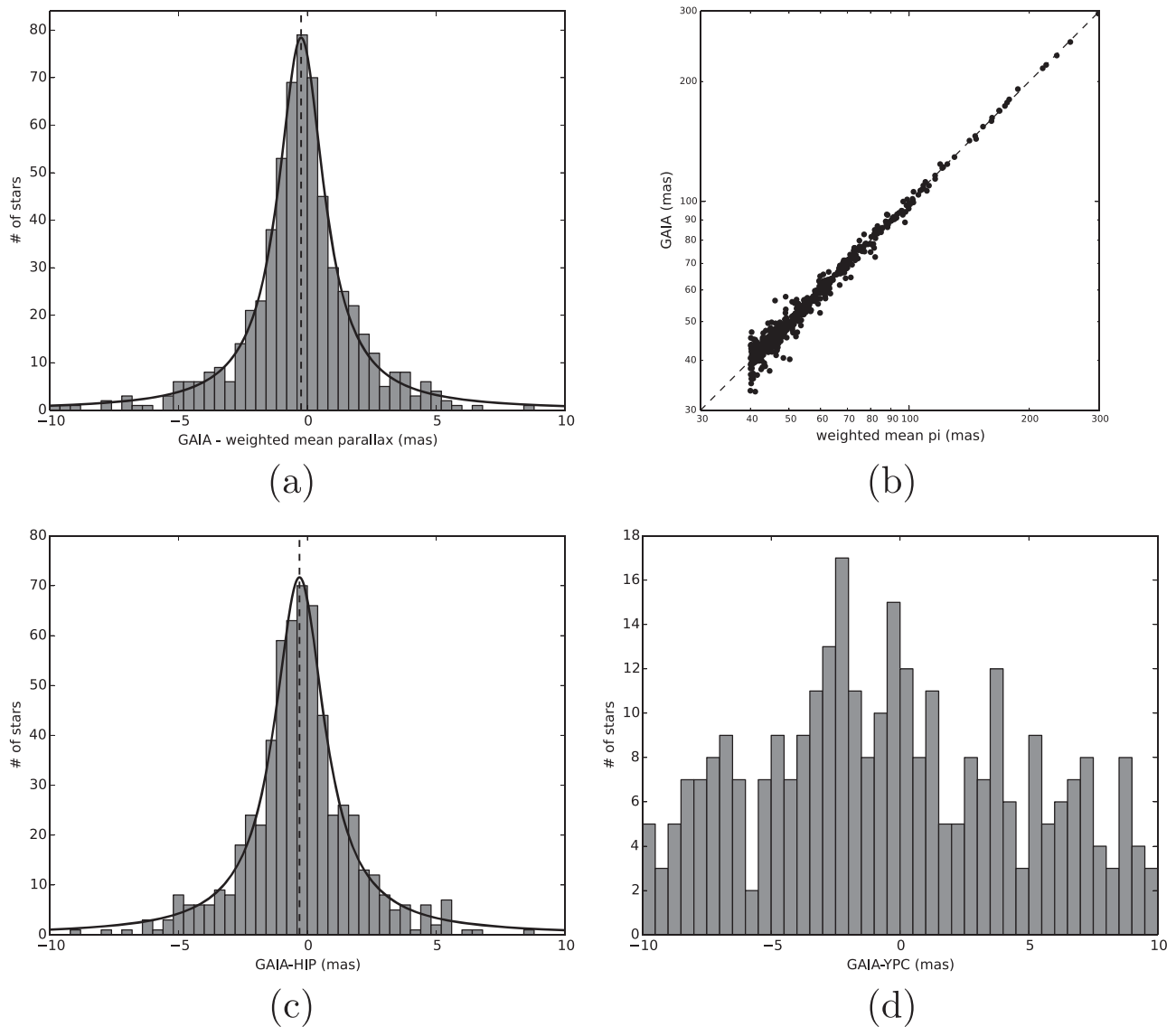
Figure 1. Parallax comparisons. (a) A histogram of parallax differences, $(\Delta\varpi)$, between values in *Gaia*-DR1 and weighted mean values for 612 single stars within 25 pc is shown. The bin size is 0.4 mas, and a Lorentz distribution is shown, rather than a Gaussian. The dashed line indicates the offset of -0.24 mas between the two data sets. (b) This log–log plot shows a one-to-one comparison between the DR1 and the weighted mean parallaxes. The mean parallax errors for all points in DR1 and these 612 stars are -0.29 mas for DR1 and 2.33 mas for weighted mean parallaxes. (c) A similar histogram to that shown in panel (a) is shown with a bin size of 0.4 mas, but for DR1 vs. revised *Hipparcos* catalog parallax values. The vertical line indicates an offset of -0.30 mas. (d) A DR1 vs. YPC comparison is shown with a bin size of 0.5 mas. The distribution is much more stretched than for the weighted mean and *Hipparcos*-only distributions because of the larger YPC parallax errors. Consequently, no fit has been made.

The Figure 1(a) shows binned results of the differences between the DR1 and the weighted mean parallaxes, in the sense $\Delta\varpi = \varpi_{\mathrm{DR1}} - \varpi_{\mathrm{weighted\ mean\ parallax}}$. Figure 1(b) compares the parallax values along a one-to-one correspondence line. This histogram shows that the $\Delta\varpi$ distribution is not symmetric about zero, but centered around -0.24 ± 0.02 mas, indicating that the DR1 parallaxes are somewhat smaller than measured previously for nearby stars. Because of the unusually wide wings of the distribution, an unweighted Lorentz distribution was fit instead of a Gaussian distribution that represents random sampling. The offset indicates that the DR1 results place nearby stars systematically slightly further away than the current measurements. Our result is virtually identical to the systematic offset of -0.25 mas reported in Stassun & Torres (2016), who compared DR1 parallaxes to orbital parallaxes derived for 108 eclipsing binary systems. In contrast,

a comparison of DR1 parallaxes to photometrically estimated parallaxes for 212 Galactic Cepheids (Casertano et al. 2016) does not show a systematic offset, instead finding that the DR1 parallaxes are in "remarkably" good agreement with the estimates from the period–luminosity relation (Riess et al. 2011). We note, however, that the result for Cepheids involves photometric parallax *estimates*, rather than trigonometric parallax *measurements*.

To probe possible sources of the offset, we also compared DR1 to *Hipparcos* and YPC results independently, as shown in Figures 1(c) and (d). In Figure 1(c), we see that the offset between DR1 and the revised *Hipparcos* results (van Leeuwen 2007) for 600 stars common to both samples is -0.30 ± 0.03 mas, similar to, and in the same direction as the offset seen for the weighted mean parallaxes. Again, a Lorentz profile has been fit to the distribution. As shown in Figure 1(d),

the much larger errors in the YPC parallaxes for 402 stars in common to both samples (offsets for 98 stars are beyond the edges of the panel) makes it difficult to reach any clear interpretation about offsets between DR1 and YPC parallaxes. Apparently, most of the differences seen between DR1 and weighted mean parallaxes are due to offsets between *Gaia* and *Hipparcos* results.

Lindegren et al. (2016) also discussed parallax differences between *Hipparcos* values and the DR1 in their Appendix C. They found that the median parallax difference ($\varpi_{DR1} - \varpi_{Hipparcos}$) is −0.089 mas based on 86,928 sources, roughly one-third of the offset we have found. Although they did not outline the distance distribution of these 86,928 stars, analysis of their Figure B.1 for ~87,000 stars shows that the majority have parallaxes between 0 and 10 mas. Apparently, when the parallax comparison is done using stars beyond 100 pc, the discrepancy is very small.

We also investigated the parallax differences in terms of *V* magnitude, (*V* − *K*) color, and proper motion to reveal whether or not any of these attributes may be linked to the systematics. Figure 2 shows no clear trends between the DR1/weighted mean parallax offset and any of these three parameters. The only evident correlations seen are expected—stars fainter in *V* and redder in *V* − *K* show larger offsets than brighter, bluer stars simply because their previously measured parallaxes have larger errors in general. In the DR1, the primary data set contains excess source noises for each source, and the excess noises represent the modeling errors (Lindegren et al. 2016). We found that the parallax difference is not a function of the excess noise. We also note the Lutz–Kelker bias has a negligible effect on this systematic offset reported here.

3. SYSTEMS WORTHY OF NOTE

Among the 612 stars used for our comparisons, there are two with parallax differences larger than 20%: GJ 723 and LTT 7370.

GJ 723 = HIP 91557 is a nearby M dwarf with parallaxes from YPC and *Hipparcos*. The weighted mean parallax is 46.12 ± 5.81 mas, while the DR1 parallax is 56.483 ± 0.267 mas. The star has highly discrepant parallaxes with large errors in YPC and *Hipparcos*. The YPC parallax, 64.7 ± 8.6 mas, is a weighted mean of three independently measured parallaxes that are in reasonably good agreement. The original *Hipparcos* parallax of 29.70 ± 13.06 mas (Perryman 1997) was later revised to 30.49 ± 7.89 mas in the van Leeuwen (2007) re-reduction. This shows the YPC parallax is consistent with the DR1 parallax.

GJ 723 lies in a very crowded background star field, and the large errors in the stochastic *Hipparcos* solutions may be due to close proximity of GJ 723 to two other bright stars, 2MASS J18401792-1027481 and 2MASS J18401833-1027596. GJ 723 has proper motions in R.A. and decl. of (−130.4, −523.0), (−170.2, −525.2), (−167.69, −520.08), and (−143.6920, −557.0159) mas yr^{-1}, respectively, from the New Luyten Two Tenths (NLTT; Luyten & Hughes 1980), Tycho-2 (Høg et al. 2000), *Hipparcos* (van Leeuwen 2007), and DR1 catalogs. The photometric distance based on *VRIJHK* colors (Henry et al. 2004) puts the star at 21.46 pc, corresponding to a parallax of 46.59 mas that is larger than the *Hipparcos* value and smaller than the YPC and DR1 values. The distance to this star remains unclear.

LTT 7370 = HIP 91154 is a nearby K dwarf with a *Hipparcos* parallax of 46.46 ± 1.44 mas (van Leeuwen 2007).

(a)

(b)

(c)
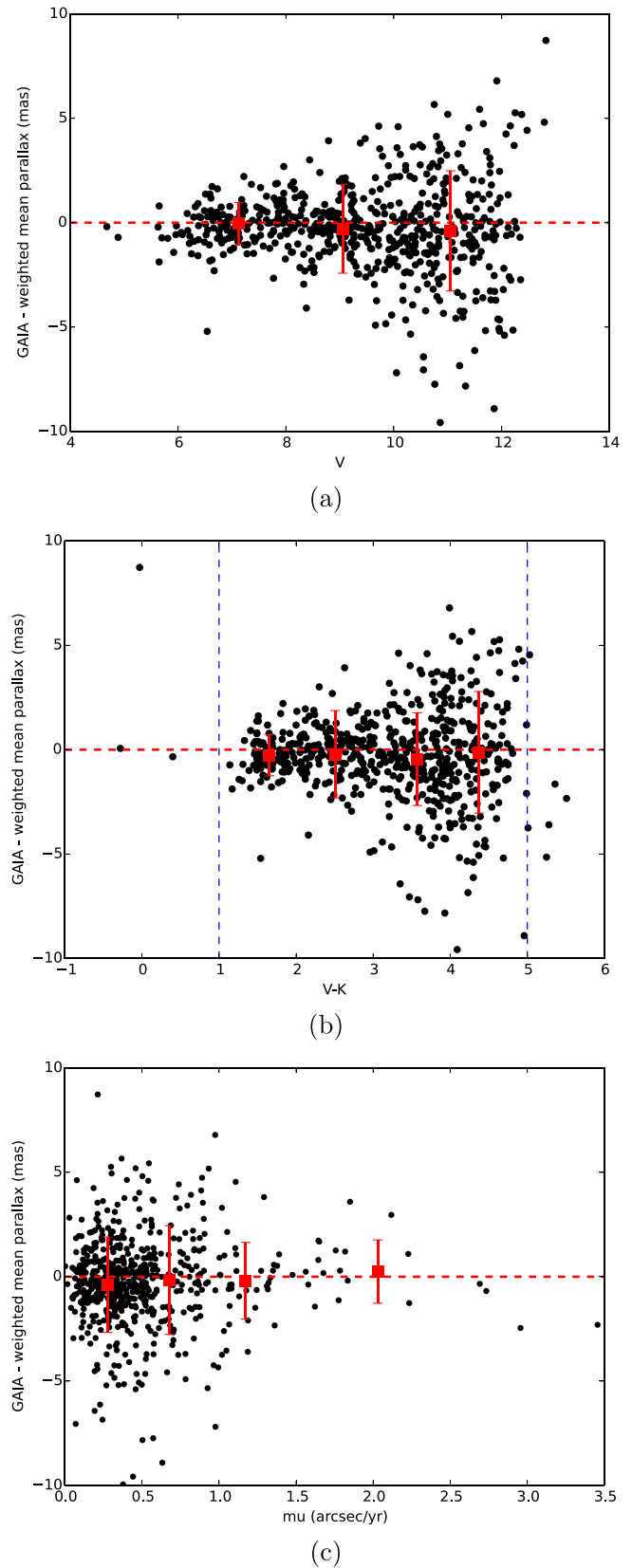
Figure 2. DR1–weighted mean parallax differences are plotted against *V*, *V* − *K*, and μ. The red dashed lines represent zero parallax differences. The squares on each plot represent the binned valued for each of the parameters. Because of the relatively large error bars, no obvious trends in parallax differences with any of these three attributes is evident. Stars outside of two blue vertical dashed lines in the middle panel are not included when deriving the binned points in *V* − *K*.

Table 2
Parallax Offsets at Different Distances

	Method 1		Method 2		Method 3	
	Weighted Mean Horizon		*Gaia*-DR1 Horizon		*Gaia*-DR1 Horizon	
	$\varpi_{GAIA\text{-weighted}}$		$\varpi_{GAIA\text{-weighted}}$		$\varpi_{GAIA\text{-vLe07}}$	
parallax sets (mas)	# of stars	offset (mas)	# of stars	offset (mas)	# of stars	offset (mas)
$\varpi > 80$	85	-0.34 ± 0.11	80	-0.29 ± 0.10	128	-0.50 ± 0.08
$40 < \varpi \leqslant 80$	527	-0.23 ± 0.02	500	-0.17 ± 0.02	725	-0.16 ± 0.03
$20 < \varpi \leqslant 40$	…	…	…	…	3815	-0.08 ± 0.02
$10 < \varpi \leqslant 20$	…	…	…	…	11592	-0.06 ± 0.01
all	612	-0.24 ± 0.02	580	-0.19 ± 0.02	16260	-0.07 ± 0.01

Table 3
Parallax Offsets for Northern and Southern Stars

	offset (mas)	$\varpi_{\text{weighted}} > 80$ mas # of Stars	$80 \geqslant \varpi_{\text{weighted}} > 40$ mas # of Stars	Total # of Stars
North ($\beta > 0.$)	-0.17 ± 0.03	39	266	305
South ($\beta < 0.$)	-0.32 ± 0.04	46	261	307

No other previously published parallax is available for this star, whereas the new DR1 parallax is 26.083 ± 0.762 mas. The proper motions in R.A. and decl. from NLTT, Tycho-2, *Hipparcos*, and DR1 are $(-27.2, -389.0)$, $(-18.6, -424.1)$, $(-20.71, -424.84)$, and $(-22.3672, -424.9188)$ mas yr^{-1}, respectively. The photometric distance based on *VRIJHK* colors (Henry et al. 2004) places the star at 22.85 pc, corresponding to a parallax of 43.7 mas, which is consistent with the *Hipparcos* value, but not DR1's. This field is not crowded.

When checking coordinates from *Hipparcos*, 2MASS, *WISE*, and DR1, we found that these two stars move along their correct proper motion tracks, as generally supported by the agreement of the proper motion measurements given above. Thus, there is no evidence that DR1 has incorrect coordinates for these two stars.

4. DISTANCE-DEPENDENT OFFSETS

The offset we describe above is a difference between DR1 and the weighted mean parallaxes of these 612 presumably single stars within 25 pc. We next investigated whether or not the offset depends on distance, i.e., the size of the measured parallax. We separated the 25 pc sample into two sets—stars with parallaxes between 40 and 80 mas and those with parallaxes larger than 80 mas—and performed the same histogram binning and Lorentz fitting routines for stars in these two sets. To reduce biases potentially caused by sample selection near the 40 mas cutoff, i.e., a subsample of stars beyond 25 pc in DR1 that were closer than 25 pc as measured previously, and vice versa, we created the new subsets two ways: Method 1 used the weighted mean parallaxes to define the parallax cutoff (612 stars) and Method 2 used DR1 (580 stars). Results for both methods are given in Table 2 and show offsets of roughly the same size and in the same direction. Note that Method 1 was used to derive the -0.24 ± 0.02 mas offset value described above.

We then stretched the sample out to 100 pc to provide an extended view of possible systematic offsets. We used the following SQL script to extract 16,260 parallaxes for stars within 100 pc in both van Leeuwen (2007) and DR1: "*SELECT parallax, parallax_error, pmra, pmdec, plx, e_plx, pm_ra, pm_de from gaiadr1.tgas_source, public.Hipparcos_newreduction WHERE gaiadr1.tgas_source.hip = public.Hipparcos_newreduction.hip AND parallax > 10.*" This is considered Method 3. Note that if stars are within 100 pc in van Leeuwen (2007), but not in DR1, they would not be extracted using this script. We then used parallaxes from DR1 to separate stars into different subsets corresponding to distance regimes of 25–50 pc and 50–100 pc, as presented in Table 2. There is a clear trend of changing offset in parallax with distance. It is important to note that we do not know the multiplicity status of the 16,260 stars used in Method 3. Hence, many unresolved companions may cause small perturbations and skew some *Gaia* measurements in DR1. It may be that the offset is much larger in Method 3 because unsolved perturbations cause larger offsets in the DR1 parallaxes. This table also implies why the offset reported in Lindegren et al. (2016) is only -0.089 mas because the majority of those $\approx 87,000$ stars are beyond 100 pc.

Although Lindegren et al. (2016) reported a relatively small offset of -0.089 mas between DR1 and the revised *Hipparcos* results, they found a north–south (N–S) asymmetry when dividing their sample at ecliptic latitude ($\beta = 0$): the northern stars have a larger offset (-0.13 mas) than the southern stars (-0.05 mas). We examined our sample of 612 stars within 25 pc for a N–S asymmetry, and also find a significant difference, *but in the opposite sense of* Lindegren et al. (2016): the southern star parallaxes are offset by -0.32 ± 0.04, whereas the northern stars are offset by only -0.17 ± 0.03 (see Table 3). There is no obvious explanation for this difference.

5. CONCLUSIONS

We have performed parallax comparisons between *Gaia*'s DR1 and previously available parallax measurements for single stars within 25 pc. We conclude that there is an offset of -0.24 ± 0.02 mas between DR1 and available weighted mean parallaxes, in the sense that the DR1 results place stars at slightly larger distances than previous measurements. We also

found that the Lutz–Kelker bias has a negligible effect on this systematic offset reported here. Although the offset is small, it is particularly important to resolve this discrepancy if it systematically affects stars at much greater distances, for which the parallax measurements will be less than a few milliarcseconds. We also found that the offset depends on how the samples are drawn. Nearby stars tend to have larger offsets than more distant stars, at least out to 100 pc. The offsets for the ensemble of stars within 25 pc is comparable to that reported in Stassun & Torres (2016), yet only 10% of their binaries were closer than 100 pc. We suspect that they have over-estimated their offset because most of their stars are much further away than our 612 single stars. Following the trend of smaller offsets at larger distances, more distant samples, like that in Lindegren et al. (2016), will exhibit smaller offsets. However, we expect the next *GAIA* data release will resolve this offset due to distances. Given the significant work that has gone into measuring their large parallaxes independently, the nearest stars, once again, can play a crucial role in understanding our Milky Way.

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