The Astrophysical Journal Letters, 907:L33 (4pp), 2021 February 1 https://doi.org/10.3847/2041-8213/abdaad

Parallax Systematics and Photocenter Motions of Benchmark Eclipsing Binaries in Gaia EDR3

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Received 2020 December 29; revised 2021 January 9; accepted 2021 January 12; published 2021 January 29

Abstract

Previous analyses of various standard candles observed by the Gaia satellite have reported statistically significant systematics in the parallaxes that have improved from ∼250 μas in the first data release (DR1) to 50–80 μas in the second data release (DR2). Here we examine the parallaxes newly reported in the Gaia early third data release (EDR3) using the same sample of benchmark eclipsing binaries (EBs) we used to assess the DR1 and DR2 parallaxes. We find a mean offset of -37 ± 20 μas (Gaia − EB), which decreases to -15 ± 18 μas after applying the corrections recommended by the Gaia Mission team; global systematics in the Gaia parallaxes have clearly improved and are no longer statistically significant for the EB sample, which spans $5 \lesssim G \lesssim 12$ in brightness and 0.03–3 kpc in distance. We also find that the Renormalized Unit Weight Error (RUWE) goodness-of-fit statistic reported in Gaia DR3 is highly sensitive to unresolved companions (tertiaries in the case of our EB sample) as well as to photocenter motion of the binaries themselves. RUWE is nearly perfectly correlated ($r^2 = 0.82$) with photocenter motions down to $\lesssim$0.1 mas, and surprisingly this correlation exists entirely within the nominal "good" RUWE range of 1.0–1.4. This suggests that RUWE values even slightly greater than 1.0 may signify unresolved binaries in Gaia, and that the RUWE value can serve as a quantitative predictor of the photocenter motion.

Unified Astronomy Thesaurus concepts: Eclipsing binary stars (444); Stellar parallax (1618); Stellar distance (1595)

1. Introduction

The trigonometric parallaxes for $\sim 10^9$ stars from the Gaia mission have heralded a new era of precision astrophysics for stars, exoplanets, and the Milky Way. It is essential to assess these parallaxes for potential biases, particularly in light of the experience from Hipparcos, which suffered a significant bias in at least the case of the Pleiades cluster (e.g., Pinsonneault et al. 1998). Such a check requires a set of benchmark stars whose parallaxes are determined independent of the Gaia parallaxes, and preferably independent of parallaxes altogether.

To this end, Stassun & Torres (2016a) assembled a sample of 158 eclipsing binary stars (EBs) whose radii and effective temperatures are known empirically and precisely, such that their bolometric luminosities are determined to high precision (via the Stefan–Boltzmann relation) and therefore independent of assumed distance. Stassun & Torres (2016a) also measured the bolometric fluxes for these EBs which, together with the precisely known bolometric luminosities, yielded the EB distances. While the precision on the predicted EB parallaxes is ≈190 μas on average, the EB sample is large enough that it should be possible in principle to assess average systematics down to $\sim 190/\sqrt{158} \sim 15$ μas.

In Stassun & Torres (2016b) we reported an initial assessment of the Gaia first data release (DR1) parallaxes, finding a significant average offset of -250 ± 50 μas, in the sense that the Gaia DR1 parallaxes were too small. That finding, which was consistent with the expected systematic error floor of 300 μas for Gaia DR1 (Gaia Collaboration et al. 2016), was corroborated by other authors on the basis of ground-based parallaxes of nearby M dwarfs (Jao et al. 2016), asteroseismic stellar radii in the Kepler field (Huber et al. 2017), and stellar radii from granulation "flicker" (Stassun et al. 2018). We reprised that analysis for the Gaia DR2 parallaxes in Stassun & Torres (2018), finding a much smaller offset of about −80 μas, comparable to the offsets averaging about −60 μas found by a number of other studies (e.g., Arenou et al. 2018; Kounkel et al. 2018; Riess et al. 2018; Zinn et al. 2019).

In this paper we apply the same benchmark EB sample of Stassun & Torres (2016a) to the Gaia early third data release (EDR3). Section 2 summarizes the EB and Gaia data used. Section 3 presents the key finding that we no longer observe a statistically significant global offset in the Gaia parallaxes. Section 4 discusses the implications of a correlation that we find between photocenter motion and Gaia reported goodness-of-fit statistics for the identification of unresolved binaries throughout the Gaia catalog. Section 5 concludes with a summary of our findings.

2. Data

We adopted the predicted parallaxes for the 151 EBs from Stassun & Torres (2016a) that were also included in our previous analysis of the Gaia DR2 parallaxes (Stassun & Torres 2018), all of which have parallaxes available in Gaia EDR3. The EBs are all bright, with Gaia magnitudes in the range $5 \lesssim G \lesssim 12$, and extend out to ∼3 kpc, with parallaxes in the range of $\pi \approx$ 0.3–30 mas. In addition, all of the EBs have distance uncertainties better than 15%, and thus the choice of prior on the EB distance should not be important for inferring their parallaxes (e.g., Bailer-Jones 2015).

Stassun & Torres (2016a) identified 32 of the EBs as having known or suspected tertiary companions from the original EB analysis and/or from subsequent follow-up studies. We flag those systems separately in our analysis as part of our examination of the effects of such companions. To that end, we use the Renormalized Unit Weight Error (RUWE) statistic

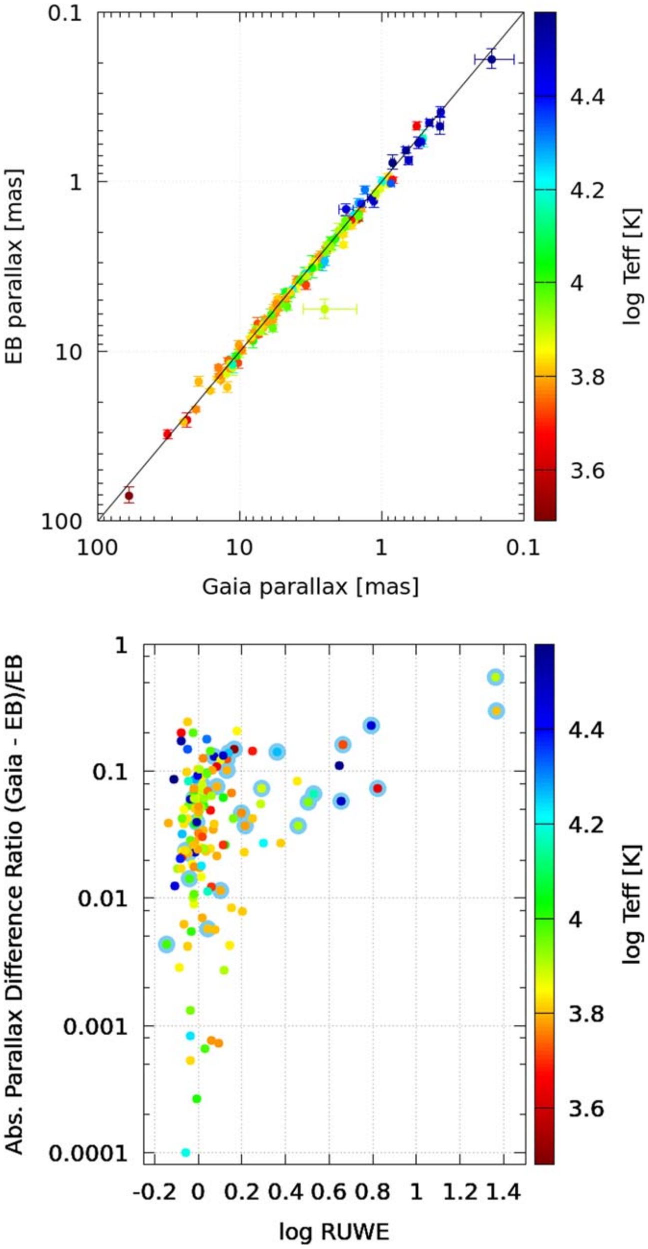

Figure 1. (Top) Direct comparison of predicted parallaxes from the eclipsing binary sample of Stassun & Torres (2016a, π_{EB}) vs. the parallaxes from the Gaia early third data release (π_{Gaia}). The one-to-one line is shown in black, and color represents T_{eff} for the EBs as a proxy for system color. (Bottom) The absolute fractional parallax difference $|(\pi_{\mathrm{Gaia}} - \pi_{\mathrm{EB}})/\pi_{\mathrm{EB}}|$ vs. the Gaia astrometric goodness-of-fit statistic (RUWE). Blue halos identify EBs known or suspected to have unresolved tertiary companions that could affect the Gaia astrometric solution; indeed, the upper-right portion of the diagram, representing EBs with large parallax differences relative to Gaia and exhibiting large RUWE in Gaia, is populated almost entirely by these systems.

reported in Gaia EDR3 as the primary astrometric goodness-of-fit indicator.

3. Results

Figure 1 (top) shows the direct comparison of the EB parallax predictions from Stassun & Torres (2016a) versus the Gaia EDR3 parallaxes for the study sample. To first order, the agreement between the Gaia EDR3 and EB parallaxes appears excellent.

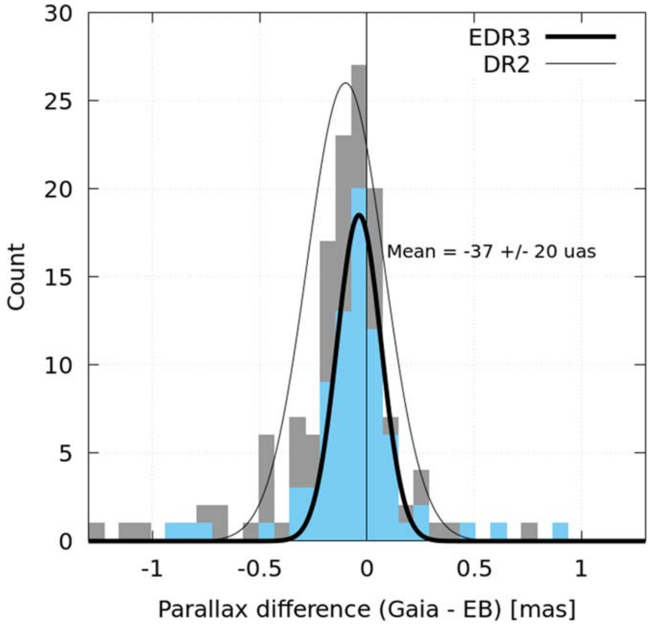

Figure 2. Distribution of $\Delta\pi$ (Gaia – EB) for the entire EB sample (gray histogram) and for the subset we use to evaluate the global offset (blue histogram; see the text), with a Gaussian fit to the latter (thick black curve). The thin black curve represents the Gaussian fit to the $\Delta\pi$ distribution that we found for DR2 (Stassun & Torres 2018), scaled to the height of the gray histogram for visual comparison.

A closer examination of the differences between the Gaia parallaxes (π_{Gaia}) and the EB parallaxes (π_{EB}) shows that while the vast majority agree to within a few percent, the differences range from as small as 0.01% in the best cases to as large as ~50% in the worst cases (Figure 1, bottom). Importantly, we observe that the parallax differences are very strongly correlated with the Gaia RUWE goodness-of-fit statistic, and that the sources with RUWE > 1.4 tend to be those with known or suspected tertiaries (points with blue halos in the upper-right of Figure 1, bottom). A Kendall's τ test yields a probability of 0.0004 for the null hypothesis of no correlation between parallax difference and RUWE. And while the correlation does not appear to be simply linear, a simple linear correlation alone can account for 56% of the variance between the two quantities (i.e., $r^2 = 0.56$).

Figure 2 presents the overall distribution of parallax differences in the sense of $\pi_{\mathrm{Gaia}} - \pi_{\mathrm{EB}}$. The distribution appears roughly symmetric and normally distributed, with perhaps a sharper peak and more extended wings than a Gaussian. In comparison to the distribution of parallax differences that we found in our DR2 analysis (Stassun & Torres 2018, thin black curve in Figure 2), the distribution now is markedly narrower, indicating that the scatter in the Gaia EDR3 parallaxes is improved relative to the DR2 parallaxes.

Based on the finding above that the RUWE statistic is correlated with the presence of a tertiary companion and thus with larger parallax differences, we only consider the subset of EBs with RUWE < 1.4 and that are not known or suspected of possessing tertiaries. We moreover consider only those with photocenter motions smaller than 0.1 mas (see Section 4.2), leaving 76 EBs as our best sample to assess the global parallax offset (blue histogram in Figure 2). The mean offset from a simple (unweighted) Gaussian fit is $\Delta\pi = -37 \pm 20$ μas, where the quoted uncertainty is the standard error of the mean (i.e., $\sigma_{\mathrm{rms}}/\sqrt{76}$).

Lindegren et al. (2020) have provided a prescription for small parallax corrections as a function of brightness, color, and position on the sky; those corrections average ∼20 μas for the EB sample, and applying them (on a star-by-star basis) yields a corrected mean parallax offset of $\Delta\pi = -15 \pm 18$ μas (not shown in Figure 2), calculated as above. These corrections thus appear promising.

4. Discussion

4.1. Accuracy of the Eclipsing Binary Parallaxes

As of the Gaia early third data release (EDR3), we no longer observe a statistically significant global offset in the Gaia parallaxes relative to the sample of benchmark eclipsing binaries from Stassun & Torres (2016a). The analysis of Section 3 suggests an upper limit to any remaining global offset of -33 μas (in the sense of Gaia − EB), after adjusting the Gaia EDR3 parallaxes by the small corrections prescribed by Lindegren et al. (2020). Even without those corrections, our finding here of no significant global offset continues the trend of improvement in the Gaia parallaxes, from -250 μas in DR1 to -80 μas in DR2 to -37 μas in EDR3. This latest estimate is now comparable to the fundamental accuracy attainable by the EB sample (see Section 1); thus, absent a major enlargement of the benchmark EB sample, it appears that comparisons of the Gaia parallaxes to these EBs have reached the limit of their utility.

At the same time, the steady improvement of the Gaia parallaxes relative to the EB sample down to the nominal limits of the EB accuracy serves as a validation of certain assumptions built into the EB sample, in particular the effective temperature scale. As we noted in our previous analyses of the Gaia DR1 and DR2 parallaxes (Stassun & Torres 2016b, 2018), in principle the offsets we reported could have been due to systematics in the EB $T_{\rm eff}$ values: unlike the EB stellar radii, for example, which are determined from simple geometry, the $T_{\rm eff}$ values are determined from spectral analysis and/or spectral typing and/or color relations. For example, the global parallax offset of -80 μas that we reported in Stassun & Torres (2018) would require a systematic error in $T_{\rm eff}$ of ∼50 K in the sense that the EBs would have to be systematically too cool. This possibility was discounted by Stassun & Torres (2018) for multiple reasons, including comparison to the Hipparcos parallaxes (Stassun & Torres 2016a) and the fact that the various EBs in our study sample have had their $T_{\rm eff}$ determined by different methodologies and different calibrations, making it very unlikely that any individual biases should produce a net systematic offset in a large sample of EBs spanning a large range of $T_{\rm eff}$.

4.2. Unresolved Companions and Photocenter Motion

We observed in Figure 1 (bottom) that the Gaia RUWE astrometric goodness-of-fit statistic is clearly sensitive to the presence of unresolved companions (tertiaries, in the case of the EB sample). Nearly all of the EBs with RUWE > 1.4 (typically used as the threshold suggesting a poor astrometric solution; see, e.g., Lindegren 2018) are previously known or suspected triples (see Stassun & Torres 2016a, and references therein). Consequently, we suggest that the few EBs with RUWE > 1.4 that are not flagged as triples in Figure 1 (bottom) are in fact triples but have simply not been previously identified as such. Our finding that the RUWE is sensitive to the presence of unresolved companions is consistent with the results of Belokurov et al. (2020) for Gaia DR2.

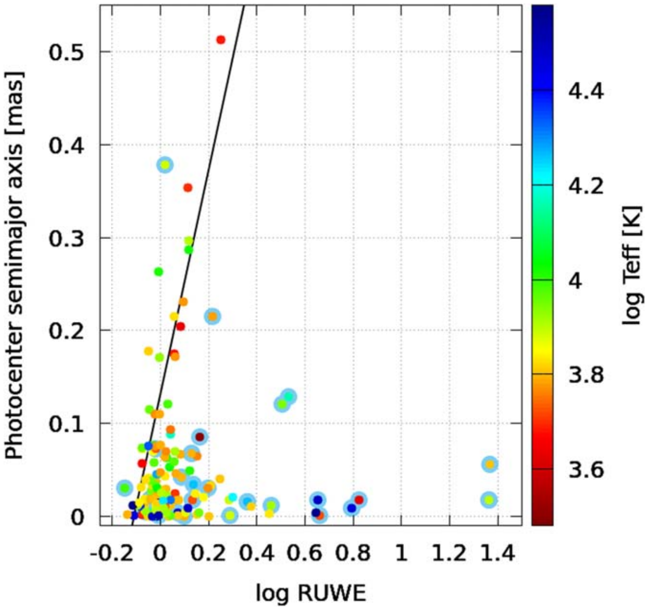

Figure 3. Same as Figure 1 (bottom), except the ordinate now represents the predicted photocenter motion of the EBs. The solid black line represents a linear least-squares fit of photocenter motion vs. $\log_{10}$ RUWE for EBs with RUWE < 1.4, photocenter semimajor axis $\geqslant$0.1 mas, and that are not known or suspected of possessing tertiary companions (blue halos).

Interestingly, and somewhat surprisingly, we find that RUWE values below 1.4 are not devoid of astrophysical information. As shown in Figure 3, RUWE values in the range 1.0–1.4 are very strongly correlated with the predicted photocenter motions of the EBs. The photocenter semimajor axis of a binary in angular units is related to the angular semimajor axis of the orbit by $a_{\rm phot}'' = a''(B - \beta)$ (e.g., van de Kamp 1967), in which $B = M_2/(M_1 + M_2)$ and $\beta = \ell_2/(\ell_1 + \ell_2)$ are the secondary's fractional mass and fractional light at the wavelength of the observation (the Gaia G band). With the approximation that the fractional light in G is equal to the fractional bolometric luminosity $L_2/(L_1 + L_2)$, we computed the latter with the Stefan–Boltzmann law using the known effective temperatures and radii of each EB component. B follows from the known masses, and a'' from Kepler's third law with the masses and Gaia parallax, and the known orbital periods.

For EBs with RUWE < 1.4, photocenter semimajor axis $a_{\rm phot}'' \geqslant 0.1$ mas, and that are not known or suspected of possessing tertiary companions, we find that a simple linear correlation accounts for fully 82% of the variance ($r^2 = 0.82$), and a Kendall's τ test returns a probability of 0.0001 for the null hypothesis of no correlation. The correlation is of the form

$$a_{\rm phot}''\ (\mathrm{mas}) = 1.204 \times \log_{10}\mathrm{RUWE} + 0.13$$

for $1.0 \leqslant$ RUWE $\leqslant 1.4$. The fact that the EB with the largest photocenter semimajor axis also appears to follow the relation suggests that the relation may apply to RUWE as large as ∼1.8.

5. Summary and Conclusions

We have found that the systematic offsets previously reported in the average zero-point of the Gaia DR1 and DR2 parallax measurements are no longer statistically significant in the Gaia early third data release (EDR3). Formally, the parallax offset that we measure is -15 ± 18 μas (or an upper limit of -33 μas) after applying the small parallax corrections prescribed by Lindegren et al. (2020). The reference for this determination is the set of independently inferred parallaxes from the Stassun & Torres (2016a) benchmark sample of well-studied eclipsing binaries with a wide range of brightnesses ($5 < G < 12$), distances up to 3 kpc, and distributed over the entire sky.

That the systematic offset we measured has steadily improved from $-250\,\mu$as in Gaia DR1 (Stassun & Torres 2016b) is a testament to the quality of the vetting of the Gaia Mission and an affirmation of the fundamental accuracy of the benchmark eclipsing binaries, whose predicted parallaxes have remained unchanged. At the same time, any remaining systematics in the Gaia parallaxes are now at or below the fundamental accuracy limit of the benchmark eclipsing binary sample. Other standard candles such as RR Lyrae variables can provide additional constraints (e.g., Bhardwaj et al. 2021).

Finally, we find that the Gaia RUWE astrometric goodness-of-fit statistic is highly sensitive to unresolved companions (tertiaries in the case of the eclipsing binaries) as well as to photocenter motion of the binaries themselves. In fact, setting aside the EBs with tertiary companions, RUWE is very strongly correlated ($r^2 = 0.82$) with photocenter motions down to 0.1 mas, and remarkably this correlation exists within the nominal "good" RUWE range of 1.0–1.4. This somewhat surprising finding implies that RUWE values even slightly greater than 1.0 may in general signify unresolved binaries throughout the Gaia catalog, and the RUWE value can serve as a quantitative predictor of the photocenter motion.

This work has made use of the Filtergraph data visualization service (Burger et al. 2013). We thank the anonymous referee for the helpful comments. K.G.S. acknowledges partial support from NASA XRP grant 80NSSC18K0445. G.T. acknowledges partial support from NSF grant AST-1509375. This work has made use of data from the European Space Agency (ESA) mission Gaia (http://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, http://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

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