Evidence for a Systematic Offset of \(-80 \mu\text{as}\) in the Gaia DR2 Parallaxes

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Abstract

We reprise the analysis of Stassun & Torres, comparing the parallaxes of the eclipsing binaries reported in that paper to the parallaxes newly reported in the Gaia second data release (DR2). We find evidence for a systematic offset of \(-82 \pm 33 \mu\text{as}\), in the sense of the Gaia parallaxes being too small, for brightnesses (\(G \lesssim 12\)) and for distances (0.03–3 kpc) in the ranges spanned by the eclipsing binary sample. The offset does not appear to depend strongly on distance within this range, though there is marginal evidence that the offset increases (becomes slightly more negative) for distances \(\gtrsim 1\) kpc, up to the 3 kpc distances probed by the test sample. The offset reported here is consistent with the expectation that global systematics in the Gaia DR2 parallaxes are below 100 \(\mu\text{as}\).

Key words: binaries: eclipsing – parallaxes – stars: distances

1. Introduction

The trigonometric parallaxes for \(\sim 10^9\) stars from the Gaia mission promise to revolutionize many areas of stellar astrophysics. For example, it will be possible to determine accurate radii and masses for tens of thousands of bright stars observed by the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015), by combining the Gaia parallaxes with the granulation “flicker” (Bastien et al. 2016) in the TESS light curves (Stassun et al. 2017, 2018).

In order to perform an independent assessment of the Gaia parallaxes, 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; the precision on the predicted parallaxes is \(\sim 190 \mu\text{as}\) on average. While this precision is poorer than that expected from the Gaia second data release (DR2), for which the global systematics are expected to be below 100 \(\mu\text{as}\) (Gaia Collaboration et al. 2018), the EB sample is large enough that it should be possible in principle to assess average systematics down to \(\sim 190/\sqrt{158} \approx 15 \mu\text{as}\).

In Stassun & Torres (2016b), we reported an initial assessment of the Gaia first data release (DR1) parallaxes, finding a significant average offset of \(-0.25 \pm 0.05\) mas, in the sense that the Gaia DR1 parallaxes were too small (i.e., the Gaia distances too long), at least within the range of distances probed by the overlap of the EB and Gaia DR1 samples (\(\lesssim 1\) kpc). That finding, which was consistent with the expected systematic error floor of 0.3 mas for Gaia DR1 (Brown et al. 2016), was corroborated by other authors on the basis of ground-based parallaxes of nearby M dwarfs (Jao et al. 2016) and asteroseismic stellar radii in the Kepler field (Huber et al. 2017). The study of Huber et al. (2017) found a somewhat smaller offset and also discussed potential biases in the stellar luminosities arising from systematics in the effective-temperature scale. Another analysis on the basis of stellar radii from granulation “flicker” (Bastien et al. 2013, 2016; Corsaro & De Ridder 2014) again corroborated the Stassun & Torres (2016b) offset (Stassun et al. 2018).

In this paper, we report the results of testing the Gaia DR2 parallaxes against the same Stassun & Torres (2016a) EB benchmark sample as we used in Stassun & Torres (2016b). Our intent is to provide an additional independent validation to those considered by the Gaia Mission team (Arenou et al. 2018), which finds evidence for a global parallax offset ranging from about \(-30 \mu\text{as}\) to about \(-50 \mu\text{as}\) for most of the benchmark samples they considered. Section 2 summarizes the EB and Gaia data used. Section 3 presents the key result of a systematic offset in the Gaia parallaxes relative to the EB sample. Section 4 considers potential trends in the parallax offset with other parameters. Section 5 concludes with a summary of our conclusions.

2. Data

We adopted the predicted parallaxes for the 158 EBs included in the study of Stassun & Torres (2016a). Of these, 151 have parallaxes available in Gaia DR2. We excluded from our analysis any parallaxes identified in the Gaia release as potentially problematic (ASTROMETRIC\_EXCESS\_NOISE\_SIG flag greater than 2; see Lindegren et al. 2012), leaving 89 EBs, none of which were flagged as potentially problematic by Stassun & Torres (2016a). Thus, our primary study sample is 89 EBs with good parallaxes from both the EB analysis and from Gaia DR2. These EBs are all relatively nearby, with parallaxes in the range \(\pi \approx 0.3–30\) mas. Finally, all 89 EBs have Gaia parallax errors better than 15\%, and thus the choice of prior on the parallax should not be important for inferring distances (e.g., Bailer-Jones 2015).

3. Results

Figure 1(a) shows the direct comparison of the EB parallax predictions from Stassun & Torres (2016a) versus the Gaia DR2 parallaxes for the study sample. The least-squares linear best fit, weighted by the measurement uncertainties in both quantities (Press et al. 1992), is \(\pi_{\text{EB}} = 0.062 \pm 0.047 + 1.015 \pm 0.007 \times \pi_{\text{Gaia}}\). To first order, the agreement between the Gaia DR2 and EB parallaxes is excellent. However, the linear fit coefficients do indicate that the EB parallaxes may be
larger on average than the Gaia parallaxes; moreover, the deviation from a one-to-one agreement in Figure 1(a) hints at the relative difference becoming somewhat larger at smaller parallaxes (see also Figure 1(b)).

Figure 2 presents the overall distribution of parallax differences in the sense of \( \pi_{\text{Gaia}} - \pi_{\text{EB}} \). The distribution appears roughly symmetric and normally distributed, with perhaps a sharper peak and more extended wings than a Gaussian, and there is a clear offset relative to zero. The weighted mean offset is \( \Delta \pi = -82 \pm 33 \mu \text{as} \), where the quoted error is the uncertainty of the mean for 89 measurements. Note that the weighted mean offset for the full sample is similar, \( \Delta \pi = -107 \pm 28 \mu \text{as} \), though, to be clear, we do not quote this as our main result due to the Gaia parallaxes being reported as unreliable for many of these (see Section 2).

4. Discussion

The official Gaia DR2 documentation states\(^4\): “Parallax systematics exist depending on celestial position, magnitude, and colour, and are estimated to be below 0.1\( \mu \text{as} \). There is a significant average parallax zero-point of about \(-30 \mu \text{as} \).” Our finding of a mean parallax offset of \( \Delta \pi \approx -82 \pm 33 \mu \text{as} \) (Section 3; Figure 2) is consistent with this expectation of a systematic error floor below 0.1\( \mu \text{as} \).

In principle, this offset could be due to systematics in one or more of the EB parameters from which the EB distances are determined. If so, one might suspect in particular the EB \( T_{\text{eff}} \) values; unlike the stellar radii, for example, which are determined from simple geometry, the \( T_{\text{eff}} \) values are determined from spectral analysis and/or spectral typing and/or color relations. The slope of the fitted relation in Figure 1 would imply an error in the EB distance scale of \( \sim 1.5\% \), which in turn would require a systematic error in \( T_{\text{eff}} \) of \( \sim 0.75\% \) (because \( d \sim L_{\text{bol}}^{1/2} \sim T_{\text{eff}}^{2} \)) or \( \sim 50 \text{ K} \) given the typical \( T_{\text{eff}} \) of the EB sample. The sense of the offset is that the EBs would have to be systematically too cool.

This possibility was also considered in our previous study of the DR1 parallax offset (Stassun & Torres 2016b) and was discounted as unlikely for multiple reasons, including comparison to the Hipparcos parallaxes and the fact that the various EBs in our study sample have had their \( T_{\text{eff}} \) determined by different methodologies and different calibrations, making it very unlikely that any individual biases should produce a net systematic offset in a sample of 89 EBs spanning a large range of \( T_{\text{eff}} \). Finally, we have directly examined the degree to which \( \Delta \pi \) correlates with \( T_{\text{eff}} \) in the EB sample (Figure 1). It is true

\(^4\) \text{http://www.cosmos.esa.int/web/gaia/dr2}
that the hotter stars tend to have the largest fractional $\Delta \pi$; however, this is most likely a consequence of the fact that the hotter (more luminous) EBs tend to be at larger distances and that a constant $\Delta \pi$ is fractionally largest at small $\pi$. Moreover, fractionally large $\Delta \pi$ also occur among cool EBs in Figure 1.

We also examined possible correlations of $\Delta \pi$ with stellar brightness, color, and position on sky. No statistically significant patterns were found; however, the sample here may not be large enough to detect low-level, multivariate dependencies on these parameters; the Gaia DR2 documentation suggests that such low-level dependencies are likely to be present (Arenou et al. 2018). Indeed, the EBs in our sample are all relatively bright, $G \lesssim 12$, and thus may not adequately probe magnitude-dependent effects.

Finally, we consider an alternate interpretation to a constant systematic error (zeropoint offset). We can reframe the linear fit shown in Figure 1(a) in terms of both a zeropoint offset and an error in scale. The fitted relation between $\pi_{EB}$ and $\pi_{Gaia}$ in Section 3 can be rewritten as $\pi_{Gaia} = \pi_{EB} - 0.061 \pm 0.015 \times \pi_{EB}$. Note that for sufficiently distant stars, $\pi_{EB}$ is necessarily more precise than $\pi_{Gaia}$, since the relative precision on EB-based parallaxes does not depend on distance (Stassun & Torres 2016a). Thus, the intercept of the linear fit ($-0.061$ mas) becomes the estimator of the zeropoint offset in the $\pi_{Gaia}$ parallaxes. In that case, the fitted slope coefficient ($0.015$) would correspond to an error in scale, which could in principle be produced by systematics in the EB parameters (e.g., $T_{eff}$ is systematically too small; see above) and/or by magnitude- or color-dependent systematics in Gaia, if magnitude or color are correlated with distance in the sample. Indeed, as noted above (see Figure 1), the EB sample does indeed possess some correlation between color and distance, due simply to the fact that the hottest EBs have the highest luminosities and therefore can be observed at larger distances. In any event, the zeropoint offset in this case—in which there is both an offset error and a scale error—would be $-61 \pm 46$ mas. This offset is somewhat smaller than (and less statistically significant), but consistent with, the value of $-82 \pm 33$ mas that we found above (Section 3) as a global mean offset.

In comparison to our findings reported here, a recent analysis of the Gaia DR2 parallaxes relative to a sample of benchmark Cepheids finds evidence for a global offset of $-46 \pm 13$ mas (Riess et al. 2018). Similarly, a concurrent independent analysis by Zinn et al. (2018) finds a nearly identical systematic offset of $-52.8 \pm 2.4$ mas (statistical) $\pm 1$ mas (systematic) using a large sample of more than 3000 stars with asteroseismically determined radii. These results are perhaps in better agreement with the offset of $-61 \pm 46$ mas that we find above when considering both zeropoint and scale terms; indeed, the Zinn et al. (2018) preliminary analysis suggests that the offset may increase somewhat at larger distances (smaller parallaxes), similar to the hint of such a trend that we observe among the handful of EBs at distances beyond $\sim 1$ kpc (Figure 1), which again may suggest a small error in scale in addition to a zeropoint systematic error. Alternatively, we note that in the Zinn et al. (2018) sample, the brighter stars with $G < 11$ (more similar in brightness to our EB sample) appear to exhibit a larger systematic offset of $\approx 80$ mas, similar to the global offset that we find. Finally, an analysis by Kounkel et al. (2018) of 55 young stars with Very Large Baseline Array parallaxes finds an offset of $-74 \pm 34$ mas, with mild evidence for a scale error term (at 1σ confidence). In any case, our finding of a simple global offset of $\Delta \pi = -82 \pm 33$ mas is fully consistent with these other reports and is, we believe, a reasonably good estimate of the offset for relatively bright ($G \lesssim 12$) and nearby ($d \lesssim 1$ kpc) stars as represented by our EB sample.

5. Summary and Conclusions

Here, we present evidence of a small but systematic offset in the average zeropoint of the parallax measurements recently released by the Gaia Mission of about $-82 \pm 33$ mas, in the sense that the Gaia values are too small. To apply the correction, this (negative) offset must be subtracted from the reported Gaia DR2 parallaxes. Because the benchmark sample that we use is mainly within $1$ kpc, we can only confirm that the offset is statistically valid for relatively large parallaxes, $\pi \gtrsim 1$ mas. In addition, the sample used here is relatively bright, with $G \lesssim 12$.

The reference for this determination is a set of 89 independently inferred parallaxes from a benchmark sample of well-studied eclipsing binaries with a wide range of brightnesses and distributed over the entire sky. This paper presents evidence of a difference between the Gaia and EB parallaxes, which we have interpreted here as a systematic error in Gaia after discussing the alternative. In particular, we have considered the possibility of a systematic offset in the EB effective temperature scale as a possible, but unlikely alternative explanation. Other authors who have performed concurrent, independent analyses with different benchmark samples (Kounkel et al. 2018; Riess et al. 2018; Zinn et al. 2018) report similar offsets in the range from $-46$ mas to $-74$ mas. We have also discussed, and cannot rule out, the possibility that there exists a small error in scale as well as an error in zeropoint; in that case, the zeropoint offset becomes $-61 \pm 46$ mas for the EB sample studied here.

Finally, the parallax offset independently reported here is a testament to the quality of the vetting of the Gaia Mission. The $-80$ mas offset we find here is perfectly consistent with the 100 mas systematic error floor reported by the Gaia Mission for DR2 (Arenou et al. 2018; Gaia Collaboration et al. 2018).

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