Abstract Riess et al (2018c, R18c) have claimed there exist seven problems in the analyses presented by Shanks et al (2018, S18) where we argue that there is enough uncertainty in Cepheid distances and local peculiar velocity fields to explain the current tension in $H_0$. Here, we take each of the R18c points in turn and suggest that either they do not apply or that the necessary caveats are already made by S18. We conclude that the main point to be inferred from our analyses still stands which is that previous claims by Riess et al (2018b) that Gaia parallaxes confirm their Cepheid scale are, at best, premature in advance of further improvements in the Gaia astrometric solution.

1 Gaia parallaxes and the Cepheid scale

1. The inclusion of Cepheids in open clusters. R18c criticise our inclusion of Cepheids whose distances were estimated by main-sequence fitting open clusters of which they are members because “These distances have never been used in modern $H_0$ determination, and their values are thus irrelevant in the context of distance scale.” It is true that they are not used in the distance scale of Riess et al (2016, 2018b) but they have played a crucial role in the distance scale for the past $\approx 60$ years. (see eg Irwin 1955; Feast 1957; Feast & Walker 1987; Laney & Stobie 1993 Feast 2003; Hoyle, Shanks & Tanvir 2003; Sandage & Tammann 2006; An et al 2007; Turner et al 2008; Anderson, Eyer and Mowlavi 2013; Chen, de Grijs & Den 2017; Lohr et al 2018). Indeed, it was noticing that the Gaia estimates of these open cluster/Cepheid distances were significantly longer than previously estimated that prompted the start of our study. We clearly state in our paper that these open cluster Cepheids give ‘contextual evidence that the Gaia distances imply a longer Cepheid scale’, while looking to another route to provide the most direct comparison with the scale of Riess et al (2016, 2018b).

2. The inclusion of Cepheids with saturated Gaia magnitudes. R18c criticise our comparison of the HST FGS sample of Benedict et al (2007) due to their having saturated magnitudes with $G < 6$, saying “the Gaia Team strongly recommends parallaxes for saturated objects in DR2 not be used, calling them ‘unreliable’ (Lindegren et al. 2018)”. In fact, Lindegren et al make the less strong statement that “The bright limit is $G \approx 3$, although stars with $G < 6$ generally have inferior astrometry due to calibration issues.” Moreover, in their selection of an astrometrically clean $< 100$pc sample Lindegren et al also include stars in the $3 < G < 6$ range (see their Fig. C2 (left)). We also excluded the 3 stars with the lowest parallax/error ratio and the remaining 5 all had distances within 600pc. Nevertheless, we acknowledge that stars with $G < 6$ may still have systematic uncertainties and Riess et al (2018b) take this view, arguing from their Fig. 4 that there is a much larger Gaia offset from their parallaxes at brighter $G$ mags than fainter $G$ mags. However, replotting the data of Fig. 1 of S18 where we now look at corrected Gaia distance modulus minus the previous modulus versus $G$ mag (see Fig. 1 below), we show that the fractional distance difference is roughly constant with magnitude. This is consistent with the fractional difference being as large at $G > 6$ as at $G < 6$, which could be interpreted as any systematic error due to saturation being sub-dominant at these low distances and large parallaxes.

3. The Gaia parallax offset. R18c criticise S18 for assuming the basic -29$\mu$as quasar offset. In the Riess et al (2018b) analysis of a sample of 46 Cepheids with distances estimated from their P-L relation based on HST photometry and then converted into a ‘photometric parallax’, they prefer to compare with Gaia parallaxes by fitting for a scale error and offset between the two. They find a result consistent with unit slope (ie no scale error) and an offset of -46$\mu$as. They interpret this result as the unit slope confirming their Cepheid scale (and $H_0$) while attributing the offset to Gaia. Riess et al (2018b) argue that the fact that in their Figs. 5, 6 they clearly statistically determine that the difference between the Gaia parallaxes and their own estimates is almost wholly an offset with the comparison giving almost exactly unit slope, means that their $H_0$ is confirmed. However, we see no reason for attributing all of the offset error to Gaia which essentially amounts to calibrating the Gaia...
offset on the previous Cepheid scale. Thus as a counter-example, let us now assume that actually Gaia measures parallaxes perfectly and that the above fit results of slope and offset still apply. On the argument of Riess et al the unit slope would argue that their Cepheid scale and $H_0$ is confirmed. Yet all the perfect Gaia parallaxes would still be a constant amount smaller than those of Riess et al. This would force the conclusion that some other problem affected the Riess et al parallaxes that mimicked a constant offset. So, for example, even if all their 46 photometric Cepheids had the same period, there could still be a problem, perhaps in their de-reddening since more distant Milky Way Cepheids tend to be more dust absorbed. Clearly, a constant offset between parallaxes is suggestive of a Gaia parallax problem but not a proof. This potential circularity of the Riess et al (2018b) argument is then repeated in Fig. 1 of R18c where they now argue for a magnitude dependent Gaia parallax offset solely on the basis of a comparison with their own Cepheid scale.

4. The error on the Gaia parallax offset. R18c criticise S18 for not quoting an uncertainty on our $-29\mu$as Gaia parallax offset. But here we are following Lindegren et al who treat the statistical uncertainty on this offset as negligible at $\pm 1\mu$as, given it is based on a standard error from $\approx 500000$ quasar parallax estimates. S18 also clearly state that there are possible systematic errors based on magnitude and colour but these are difficult to quantify at the present time. We then assumed no colour or magnitude systematics, broadly similar to Riess et al (2018b), and we simply assumed the most basic quasar offset as representing the first-order DR2 parallax verdict on the previous Cepheid scale, finding that generally Gaia distances are longer.

5. Other Cepheid calibrations. R18c note that Riess et al (2016) base their Cepheid calibration on detached eclipsing binaries and the water maser in NGC4258 as well as parallaxes. We also already note these other routes in our paper and say that it will be interesting to see how they fare as the Gaia astrometric solution improves (see Sect. 2 of S18). However, the main focus of S18 is the current Gaia DR2 parallaxes and the level to which they support the Cepheid scale of Riess et al (2016, 2018b). In their paper and elsewhere (see [https://www.nasa.gov/feature/goddard/2018/hubble-and-gaia-team-up-to-fuel-cosmic-conundrum], Riess et al (2018b) claim that the Gaia DR2 parallaxes confirm their previous Cepheid scale. We have argued above against this view and conclude that either the DR2 parallaxes are currently too uncertain for absolute Cepheid calibration or in their simplest form they give evidence against the previous scale. Thus deciding whether there is any inconsistency between parallax, the other two Cepheid calibration routes and the Cepheid scale in general must await improved Gaia astrometry.

2 The Local Hole

6. The Local Hole and the fit of the SNIa Hubble diagram. Here R18c claims that the SNIa Hubble diagram fit of S18 is worse with the Local Hole outflow effect included. But here R18c only compares to our fit with $\Omega_m$ kept fixed at its original value of $\Omega_m = 0.28$. When S18 fitted for both $H_0$ and $\Omega_m$ we found that including the effect of the Local Hole actually marginally improved the fit, reducing the total $\chi^2$ from 1035.7 to 1034.1. The fitted value of $\Omega_m$ only rose from 0.28 to 0.33 compared to the Planck value of 0.31 so we conclude the Local Hole outflow is consistent with the SNIa Hubble diagram.

7. Cosmic variance of Local Hole. Here R18c claim that our Local Hole model implies a $6\sigma$ fluctuation in a $\Lambda$CDM model based on the variances in simulations studied by Wu & Huterer (2017) and Oddershkov et al (2017), quoting an estimated 0.3% fluctuation in $H_0$. But Wu & Huterer report a standard deviation of 0.31 kms$^{-1}$Mpc$^{-1}$, a 0.46% fluctuation which makes our 1.8% rise a 3.9$\sigma$ fluctuation rather than $6\sigma$. Oddershkov et al emphasise the differences that different SNIa selections make quoting fluctuations in the range 0.3-0.96% for two previous SNIa surveys, so by the latter estimate the Local Hole significance could be as low as $\approx 1.9\sigma$. But note that we have previously accepted that if the Local Hole extends over a large fraction of the sky, it may start to challenge the standard cosmology at a similar $2.5 - 4\sigma$ level (Frith, Metcalfe & Shanks, 2006).
Figure 1: Data from S18 Fig. 1 to show how the difference between the +29µas corrected Gaia distance moduli and the previous distance moduli of Benedict et al (2007, FGS), Riess et al (2016, 2018a, WFC3) and Laney & Stobie (1993, LS) varies with $G$ magnitude. There is little evidence of magnitude dependence despite the FGS parallax stars of Benedict et al (2007) having saturated $G < 6$ magnitudes. Brackets show the 3 stars, l Car, W Sgr and RT Aur of Benedict et al (2007) that, as well as being saturated, have the lowest parallax/error ratio and were excluded by S18. For the remaining stars, the corrected Gaia distance moduli are $0.35 \pm 0.11$ mag larger or $17.6 \pm 5\%$ greater in distance.

3 Conclusions

We conclude that Gaia DR2 parallaxes do not immediately confirm the Cepheid scale of Riess et al (2018b). Indeed, the most direct interpretation of the new Gaia data is that they support an upwards revision of previous Cepheid distances by $\approx 7\%$ in the case of the Riess et al scale and by up to $\approx 18\%$ in other cases. We also conclude that there is strong evidence for a Local Hole that can cause a further $\approx 2\%$ reduction in $H_0$. We therefore stand by our conclusion that Gaia parallaxes, the Local Hole and associated uncertainties may potentially relieve the previous $H_0$ tension.

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