Cluster Cepheids with High Precision Gaia Parallaxes, Low Zero-point Uncertainties, and Hubble Space Telescope Photometry

Adam G. Riess1,2, Louise Breuval2, Wenlong Yuan2, Stefano Casertano1, Lucas M. Macri3, J. Bradley Bowers2, Dan Scolnic2, Tristan Cantat-Gaudin2, Richard I. Anderson6, and Mauricio Cruz Reyes6

1 Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
2 Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
3 George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics & Astronomy, Texas A & M University, College Station, TX 77843, USA
4 Department of Physics, Duke University, Durham, NC 27708, USA
5 Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
6 Institute of Physics, Laboratory of Astrophysics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland

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Abstract

We present Hubble Space Telescope (HST) photometry of 17 Cepheids in open clusters and their cluster mean parallaxes from Gaia EDR3. These parallaxes are more precise than those from individual Cepheids ($G < 8$ mag) previously used to measure the Hubble constant because they are derived from an average of $>300$ stars per cluster. Cluster parallaxes also have smaller systematic uncertainty because their stars lie in the range ($G > 13$ mag) where the Gaia parallax calibration is the most comprehensive. Cepheid photometry employed in the period–luminosity relation was measured using the same HST instrument (WFC3) and filters (F555W, F814W, F160W) as extragalactic Cepheids in Type Ia supernova hosts. We find no evidence of residual parallax offset in this magnitude range, $\mu_p = -3 \pm 4$ mas, consistent with the results from Lindegren et al. and most studies. The Cepheid luminosity (at $P = 10$ d and solar metallicity) in the HST near-infrared, Wesenheit magnitude system derived from the cluster sample is $M_{W,1}^H = -5.902 \pm 0.025$ mag and $-5.890 \pm 0.018$ mag with or without simultaneous determination of a parallax offset, respectively. These results are similar to measurements from field Cepheids, confirming the accuracy of the Gaia parallaxes over a broad range of magnitudes. The SH0ES distance ladder calibrated only from this sample gives $H_0 = 72.9 \pm 1.3$ and $H_0 = 73.3 \pm 1.1$ km s$^{-1}$ Mpc$^{-1}$ with or without offset marginalization; combined with all other anchors we find $H_0 = 73.01 \pm 0.99$ and $73.15 \pm 0.97$ km s$^{-1}$ Mpc$^{-1}$, respectively, a 5% or 7% reduction in the uncertainty in $H_0$ and a $\sim 5.3\sigma$ Hubble tension relative to Planck + $\Lambda$CDM. It appears increasingly difficult to reconcile two of the best-measured cosmic scales, parallaxes from Gaia and the angular size of the acoustic scale of the cosmic microwave background, using the simplest form of $\Lambda$CDM to connect the two.

Unified Astronomy Thesaurus concepts: Hubble constant (758); Cepheid distance (217)

1. Introduction

Trigonometric parallaxes of Milky Way Cepheids measured by the ESA Gaia mission, in concert with their fluxes measured with the Hubble Space Telescope (HST), offer the only route at present to reach a 1% geometric calibration of a distance ladder used to measure the Hubble constant. The Gaia EDR3 data release provided parallaxes with $\sim 25$ μas precision for 75 Cepheids photometrically with HST to reach a 1.1% geometric calibration including marginalization over the Gaia parallax offset term (Riess et al. 2021a, hereafter R21). These were used in the recent SH0ES measurement of $H_0$ (Riess et al. 2021b, hereafter R22) and in other studies (Brout et al. 2022; Jones et al. 2022). However, it is possible to obtain parallaxes with still greater individual precision and lower systematic uncertainty for Cepheids that reside in Milky Way open clusters (Turner 2010).

The precision of the mean parallax of a cluster of stars can greatly exceed that of its individual members. (Breuval et al. 2020, hereafter B20) confirmed this for 13 Milky Way cluster Cepheids with parallaxes from Gaia DR2. Although cluster parallax uncertainties do not scale as the square root of the number of stars in a Cepheid-hosted cluster due to the angular covariance of Gaia parallax measurements (Lindegren et al. 2021, hereafter L21), a mean cluster parallax uncertainty including the angular uncertainty is approximately 3 times smaller (on average) than that of the Cepheid it hosts and thus each cluster Cepheid has the weight of approximately nine field Cepheids.

However, Cepheids are rarely found in star clusters. Although born in young clusters, their ages ($\sim 100$ Myr) greatly exceed the dissipation timescale of open clusters ($\sim 10$ Myr; Lada & Lada 2003; Dinnbier et al. 2022), so that Cepheids hosted by clusters comprise only a few percent of the Cepheid population (Anderson et al. 2013). Nevertheless, their unique leverage makes even a modest sample significant and valuable.

The other important advantage of Cepheid cluster parallaxes from Gaia comes from the better initial calibration of their parallax offset. This term was determined for EDR3 by L21 from a combination of a million QSOs ($G > 13$ mag), millions of LMC stars ($G > 12$ mag), and a smaller number ($\sim 7000$) of physically bound pairs with a bright companion ($G > 6$ mag) as seen in Figure 1. Because the offset is a function of magnitude
and was calibrated from sources that match the $12 < G < 19$ mag range of cluster stars as seen in Figure 1, the offset calibration for these parallaxes is optimal. The offset is less well constrained at $G < 9$ mag (typical of Milky Way Cepheids) due to the smaller number of calibrating sources, requiring the simultaneous constraint of the offset at this brighter range and the Cepheid luminosity. This doubles the uncertainty in the latter, as described in (Riess et al. 2018a, hereafter R18b) and in R21. Figure 2 shows constraints on the residual (from L21) parallax offset as a function of source magnitude as determined by external studies. As expected, there is a good consensus for little to no residual offset, $\z_p$, at $G > 13$ ($\z_p < 5 \mu$as).

While the Gaia EDR3 parallaxes of cluster Cepheids would support the target $\approx 1\%$ goal, reaching it also requires these Cepheids to be observed on the same HST photometric system as those in Type Ia supernova (SN Ia) hosts, as systematic disparities (i.e., between the ground and space in the NIR), empirically seen to be 0.03–0.04 mag (Riess et al. 2018b, 2019a, hereafter R18b and R19a), would otherwise dominate the other error terms. While we could estimate these Cepheid magnitudes in the three-band HST system synthetically by applying transformations using ground-based photometry, B20 showed that the statistical errors from transformations are a factor of 3 worse than was achieved with HST (0.06 mag from the ground versus 0.02 mag per Cepheid with HST, surpassing the mean of 0.05 mag distances errors of the EDR3 parallaxes) and the additional systematic uncertainty of 0.04 mag between ground and HST zero-points would still limit the resulting calibration of $H_0$ to $> 2\%$.

Here we present observations of 17 Cluster Cepheids measured with HST using the same instrument and three filters as other Cepheids on the SH0ES team distance ladder obtained with the same spatial-scanning protocols used in R18b and R21. In Section 2 we present the measurements, and in Section 3 we use these data to constrain the Cepheid period–luminosity ($P$–$L$) relation, the scale of the distance ladder, and $H_0$, with discussion of the results in Section 4.

2. Data

2.1. Clusters

The Cepheid cluster sample was initially selected as the set of 13 fundamental-mode Cepheids (including a beat or double mode Cepheid V367-SCT using the period of its fundamental pulsation) with $P > 4d$ identified by B20 to be in clusters with high confidence. These associations were determined by comparing angular positions, proper motions, parallaxes, and ages between the Ripepi et al. (2019) Cepheid catalog and the open cluster catalog derived from Gaia DR2 by Cantat-Gaudin et al. (2018). Five of these Cepheids (DL Cas, U Sgr, XZ Car, and S Nor) were previously photometrically measured with HST by R18b and R21. The other nine were targeted in a Cycle 29 HST program, GO 16676 (PI Riess) to collect this cluster sample and are presented here for the first time.

Subsequently, Breuval (2021), Zhou & Chen (2021), and Cruz Reyes & Anderson (2022, hereafter CR22) identified a few additional Cepheids hosted by open clusters using Gaia EDR3. Three of these, WX Pup, SV Vul, and X Pup were previously measured with HST by R18b and one, X Vul, was targeted for new observations in the Cycle 29 program. Thus the full sample we consider is 17 Cepheid and cluster pairs.

From the most recent studies which use Gaia EDR3, there is strong agreement between studies on the association of a specific Cepheid and cluster for 14 of the 17 variables we consider, which we will refer to as the “Gold” sample. The remaining three objects (which we call the “Silver” sample) warrant additional consideration due to their greater spatial separation from the cluster centers, which would place them outside the cores but inside the cluster coronae, which extend up to 10–farther in radius (Kharchenko et al. 2005).

These objects are:

- **WX Pup**—located $\sim 26'$ from the center of UBC 231, though all other properties (radial separation, proper motion, age) are in concordance.
- **X Pup**—CR22 identified a new open cluster association, CL X Pup, which is $\sim 30'$ from this variable with otherwise consistent measures.
- **XZ Car**—B20 associated this variable with NGC 3496 with a large angular separation from the core; 52' (or 35 pc) placing it plausibly in the clusters’ corona. All other measures are consistent.\footnote{CR22 associate XZ Car with lower-than-full confidence (Silver) with a previously undiscovered cluster, CL XZ Car. This newly identified cluster is still far from XZ Car at 20' (or 14 pc), though half the separation as NGC 3496. However, this cluster is also less rich than NGC 3496, likely equalizing the difference in association advantage. Further the new cluster is more discrepant in proper motion and photometric parallax, the latter implying a $\sim 250\pm 70$ pc radial separation. For these reasons we retain the B20 association though we assign this association a Silver category confidence.}

2.2. Cluster Parallaxes

Cluster parallaxes were determined from the average of stars identified as likely members following the procedure Cantat-Gaudin et al. (2018). The inverse of the parallax uncertainties given in EDR3 were used to weight the mean parallaxes. We provide the properties of these Cepheids and their cluster hosts in Table 1. The cluster star parallaxes include the L21 zero-point offset calibration term as a function of their magnitude,
The statistical uncertainty derived from the mean of the cluster stars is exceedingly small, ranging from 1 to 4 μas. However, Gaia parallaxes have an angular covariance that reduces the available precision for clustered sources. Knowledge of the angular covariance has been derived (Lindegren et al. 2021; Maíz Apellániz et al. 2021) on small scales (with numerous independent patches of <15′ where the angular covariance is seen to be ∼62 μas²) using the

Figure 2. External calibrations of the residual Gaia parallax offset relative to L21 measured by external sources as a function of source magnitude, collated by L21. We added to this the measurement from Cluster Cepheids and highlight both sets of Cepheid measurements in red. The gray regions at ΔZ = (G − 22) μas with bands of ±5 and 10 μas shows a simplistic, approximate 68% and 95% confidence intervals representing a “consensus” of the external measurements tabulated in Lindegren (2021). Measures in the negative direction imply parallaxes that are overestimated by L21. Points from Zinn (2021, private communication, 2022) are at ν = 1.48, the mean color of the Cepheids.

Table 1
Cluster Data for Cepheid Hosts

| Cluster  | Cepheid | R.A.   | Decl.   | N   | Size  | πa (μas) | σb   | stat | ac | tot |
|----------|---------|--------|---------|-----|-------|----------|------|------|----|-----|
| Berkeley 58 | CG-CAS  | 0.0579 | 60.9421 | 206 | 5.3   | 335.9    | 2.0  | 8.2  | 8.4 |
| NGC 129   | DL-CAS  | 7.5629 | 60.2252 | 469 | 16.3  | 558.6    | 1.0  | 7.0  | 7.1 |
| FSR 0951  | RS-ORI  | 95.5796| 14.6391 | 240 | 13.9  | 594.0    | 1.8  | 7.0  | 7.2 |
| vdBerg 1  | CV-MON  | 99.2807| 3.0779  | 66  | 3.4   | 578.6    | 4.2  | 8.8  | 9.7 |
| CL X-PUP  | X-PUP   | 113.3532| −20.4798| 125 | <5    | 363.0    | ...  | ...  | 7.1 |
| UBC 231   | WX-PUP  | 115.5583| −26.2943| 35  | 7.8   | 355.9    | 3.5  | 7.5  | 8.2 |
| Ruprecht 79 | CS-VEL | 145.2566| −53.8477| 267 | 4.5   | 274.1    | 1.5  | 8.4  | 8.5 |
| NGC 3496  | XZ-CAR  | 164.8822| −60.3360| 554 | 7.3   | 439.0    | 0.8  | 7.6  | 7.7 |
| NGC 5662  | V-CEN   | 218.7455| −56.6592| 259 | 21.3  | 1322.1   | 1.4  | 7.0  | 7.2 |
| Lynga 6   | TW-NOR  | 241.2089| −51.9538| 163 | 4.8   | 408.2    | 2.5  | 8.3  | 8.7 |
| NGC 6067  | V340-NOR| 243.2930| −54.2264| 1234| 9.3   | 495.5    | 0.8  | 7.3  | 7.3 |
| NGC 6087  | S-NOR   | 244.7350| −57.9140| 279 | 16.8  | 1056.8   | 1.5  | 7.0  | 7.2 |
| IC 4725   | U-SGR   | 277.9490| −19.1125| 516 | 23.0  | 1540.0   | 1.1  | 7.0  | 7.1 |
| NGC 6649  | V367-SCT| 278.3591| −10.3966| 628 | 4.7   | 507.9    | 1.7  | 8.3  | 8.5 |
| UBC 130   | SV-VUL  | 298.0507| 27.4452 | 98  | 8.7   | 427.8    | 2.0  | 7.3  | 7.6 |
| UBC 129   | X-VUL   | 298.9809| 26.4709 | 254 | 44.8  | 885.8    | 1.2  | 7.1  | 7.2 |
| NGC 7790  | CF-CAS  | 359.6092| 61.2159 | 248 | 5.5   | 331.0    | 1.7  | 8.1  | 8.3 |

Notes.

a Includes L20 parallax offset.
b Total uncertainty (in last column) is the quadrature sum of the statistical uncertainty and the angular covariance (ac).
c Data from CR22.
random-phase photometry, which is independent of filter zero-points as it depends on magnitude differences, was corrected to mean phase following the same procedures given in R18a, R18b, and R21 and is provided in Table 2. The sources of the light curves used to measure the phase corrections are given in Tables 3 and 4.

We combine the bands into the same reddening-free Wesenheit index used for all recent SH0ES analyses (R22),

$$m_W^I = m_{F160W} - 0.386 (m_{F555W} - m_{F814W}).$$

The reddening ratio of 0.386 is derived from the Fitzpatrick (1999) reddening law with $R_V = 3.3$. Following the SH0ES convention, we correct the $m_W^I$ magnitudes for the count rate nonlinearity of WFC3 relative to faint extragalactic Cepheids (0.0077 mag dex$^{-1}$; Riess et al. 2019b) by applying this term to the Cepheids in anchors so they are directly comparable to the (uncorrected by convention) extragalactic Cepheids in SN Ia hosts. The mean difference between the Milky Way (MW) Cepheids and the sky limit, a floor for count rate, is 6.3 dex for an addition of 0.048 $\pm$ 0.004 mag, which are added, by convention, only to the Wesenheit magnitudes in Table 2. We also include individual [Fe/H] metallicity measurements as compiled by Groeneeweg (2018) for use in the Cepheid $P$–$L$ relation which span a range of $-0.01$ to $+0.33$ dex with a mean of $+0.08$ dex and a dispersion of $0.07$ dex, to which we add 0.06 dex to convert from [Fe/H] to [O/H] (Romaniello et al. 2022).

3. Constraining the $P$–$L$ Relation

Briefly, to relate Cepheid luminosity to period, it is useful to define an extinction-free distance modulus from the difference in an apparent and absolute Wesenheit magnitude, $m_0 = m_W^I - M_W^I$. This is standardized for Cepheids using the

## Table 2

| Cepheid Cycle 29 | log P | F555W | F814W | F160W | $m_W^I$ | $m_{FL}^I$ | $\pi_\text{R22}$ | $\sigma$ | Cluster | Sample |
|------------------|-------|-------|-------|-------|---------|-----------|--------------|--------|---------|--------|
| CF-CAS           | 0.688 | 11.30 | 0.023 | 9.693 | 0.026   | 8.261     | 0.027        | 7.684  | 0.030   | −0.01  | 308.4  | 4.3  | NGC 7790 | Gold |
| CG-CAS           | 0.640 | 11.56 | 0.024 | 9.843 | 0.026   | 8.315     | 0.027        | 7.694  | 0.034   | 0.06   | 330.2  | 5.1  | Berkeley 38 | Gold |
| CS-VEL           | 0.771 | 11.87 | 0.015 | 10.04 | 0.019   | 8.375     | 0.027        | 7.710  | 0.029   | 0.09   | 268.5  | 3.5  | Ruprecht 79 | Gold |
| CV-MON           | 0.731 | 10.45 | 0.024 | 8.587 | 0.018   | 6.924     | 0.027        | 6.250  | 0.029   | 0.09   | 559.4  | 7.6  | vdBergh 1 | Gold |
| RS-ORI           | 0.879 | 8.553 | 0.016 | 7.239 | 0.027   | 6.110     | 0.027        | 5.652  | 0.030   | 0.11   | 588.3  | 8.0  | FSR 0951 | Gold |
| TW-NOR           | 1.033 | 11.84 | 0.028 | 9.193 | 0.020   | 8.677     | 0.027        | 5.900  | 0.030   | 0.27   | 415.2  | 5.8  | Lynga 6 | Gold |
| V-CEN            | 0.740 | 7.006 | 0.012 | 5.802 | 0.010   | 4.723     | 0.027        | 4.311  | 0.028   | 0.12   | 1347.2 | 17.3 | NGC 5662 | Gold |
| V340-NOR         | 1.064 | 8.533 | 0.024 | 7.137 | 0.018   | 5.852     | 0.027        | 5.363  | 0.029   | 0.07   | 507.1  | 6.9  | NGC 6067 | Gold |
| V367-SCT         | 0.799 | 11.75 | 0.043 | 9.194 | 0.030   | 7.112     | 0.050        | 6.171  | 0.054   | 0.12   | 1618.0 | 21.0 | IC 4725 | Gold |
| U-SGR            | 0.829 | 6.886 | 0.018 | 5.388 | 0.011   | 4.143     | 0.027        | 3.619  | 0.027   | 0.14   | 1067.2 | 6.7  | NGC 6087 | Gold |
| V338-SCT         | 0.799 | 11.30 | 0.023 | 7.161 | 0.017   | 5.219     | 0.007        | 6.372  | 0.016   | 0.10   | 426.5  | 1.9  | NGC 3496 | Silver |
| S-NOR            | 0.989 | 6.578 | 0.011 | 5.410 | 0.012   | 4.391     | 0.012        | 3.994  | 0.014   | 0.10   | 1067.2 | 6.7  | NGC 6087 | Gold |
| XZ-CAR           | 1.221 | 8.773 | 0.017 | 7.217 | 0.006   | 5.770     | 0.007        | 5.219  | 0.010   | 0.03   | 246.5  | 1.9  | NGC 3496 | Silver |
| WX-PUP           | 0.951 | 9.191 | 0.030 | 7.944 | 0.012   | 6.807     | 0.010        | 6.372  | 0.016   | 0.01    | 378.2  | 2.8  | UBC 231 | Silver |
| SV-VUL           | 1.653 | 7.267 | 0.047 | 5.648 | 0.033   | 4.214     | 0.027        | 3.643  | 0.035   | 0.11   | 457.3  | 7.4  | UBC 130 | Gold |
| X-PUP            | 1.414 | 8.695 | 0.019 | 7.128 | 0.010   | 5.628     | 0.008        | 5.073  | 0.012   | 0.02   | 340.2  | 1.8  | CL XPUP  | Silver |

Notes.

$^a$ Does not include addition of 0.0075 $\pm$ 0.006 mag dex$^{-1}$ to correct CRNL for 5 to 6.5 dex between MW and extragalactic Cepheids.

$^b$ Includes addition of CRNL to convert direct extrapolation to extragalactic Cepheids in R22 that do not include any CRNL correction.

$^c$ $\pi_\text{R22} = 10^{-2.030 \times 0.1 - 0.0085}$ where $\mu = m_H^I - M_H^I$ and $M_H^I$ is the absolute Wesenheit magnitude determined from the Cepheid period and the distance scale from Riess et al. (2019b) where $b_w = -3.30$, $Z_w = -0.22$ mag dex$^{-1}$, and $M_H^I = -5.90$ mag, which results in $H_0 = 73.04$ km s$^{-1}$ Mpc$^{-1}$ as discussed in the text.

$^d$ [Fe/H] from Groeneeweg (2018).
Table 3
Ground Data Sources for Phase Determination

| Identifier | Phase Determination | References\(^a\) |
|------------|---------------------|------------------|
| CF Cas     | 3–10, 13, 15, 24, 25, 33, 34 | 3–10, 13, 15, 24, 25, 33, 34 |
| CG Cas     | 4, 5, 9, 13, 15, 22, 33, 34, 36 | 4, 5, 9, 13, 15, 22, 33, 34 |
| CS Vel     | 16, 25, 33–35 | 25, 33–35 |
| CV Mon     | 1, 3, 7, 9–11, 13, 16, 20, 21, 31, 34, 35 | 3, 7, 9–11, 13, 20, 21, 31, 34, 35 |
| RS Ori     | 1, 3, 20, 21, 31, 34, 35, 34, 35 | 3, 7, 9–11, 13, 20, 21, 31, 34, 35 |
| TW Nor     | 1, 25, 26, 33–35 | 25, 26, 33–35 |
| V Cen      | 1, 11, 16, 23, 34 | 11, 23, 34 |
| V0340 Nor  | 34, 36 | 34, 36 |
| V0367 Scl\(^b\) | 3–6, 8, 9, 11, 12, 15, 16, 27–31, 33, 34 | 3–6, 8, 9, 11, 12, 15, 16, 27–31, 33, 34 |
| X Vul      | 3, 4, 6, 9, 10, 21, 31, 34 | 3, 4, 6, 9, 10, 21, 31, 34 |

Notes.
\(^a\) Labels are described in Table 4. NA: no ground data available.
\(^b\) Light curves were modeled with two periods.

Table 4
References for the Labels in Table 3

| ID | Reference | Comments | ID | Reference | Comments |
|----|-----------|----------|----|-----------|----------|
| 1  | Pel (1976) | McMaster | 2  | Welch et al. (1984) | McMaster |
| 3  | Moffett & Barnes (1984) | McMaster | 4  | Berdnikov (1992e) | McMaster |
| 5  | Berdnikov (1992f) | McMaster | 6  | Berdnikov (1992a) | McMaster |
| 7  | Berdnikov (1992c) | McMaster | 8  | Berdnikov (1992d) | McMaster |
| 9  | Berdnikov (1992b) | McMaster | 10 | Berdnikov (1993) | McMaster |
| 11 | Berdnikov & Turner (1995) | McMaster | 12 | Berdnikov & Turner (1995) | McMaster |
| 13 | Berdnikov & Vosyakova (1995) | McMaster | 14 | Szabados (1981) | McMaster |
| 15 | Berdnikov (1986) | McMaster | 16 | Laney & Stobie (1992) | McMaster |
| 17 | Barnes et al. (1979) | McMaster | 18 | Szabados (1977) | McMaster |
| 19 | Henden (1980) | McMaster | 20 | Szabados (1991) | McMaster |
| 21 | Szabados (1980) | McMaster | 22 | Henden (1996) | McMaster |
| 23 | Gieren (1981) | McMaster | 24 | Berdnikov (1987) | McMaster |
| 25 | Harris (1980) | McMaster | 26 | Madore & van den Bergh (1975) | McMaster |
| 27 | Berdnikov & Ibragimov (1994b) | McMaster | 28 | Berdnikov et al. (1995) | McMaster |
| 29 | Madore & van den Bergh (1975) | McMaster | 30 | Berdnikov & Ibragimov (1994a) | McMaster |
| 31 | Pojmanski (1997) | ASAS | 32 | Alfonso-Garzón et al. (2012) | I-OMC |
| 33 | Kochanek et al. (2017) | ASAS-SN | 34 | Berdnikov et al. (2000) | McMaster |
| 35 | Berdnikov et al. (2015) | McMaster | 36 | This work | This work |

The conversion of Gaussian parallax estimates to distance and magnitude as plotted on the P–L as functions of their inverse may result in biased likelihoods unless the signal-to-noise of the parallaxes is sufficiently high. An approximate result with a symmetric uncertainty can be obtained with an account of the Lutz–Kelker type bias (Lutz & Kelker 1973) (e.g., the volume bias; Bailey-Jones et al. 2021) that is still quite accurate. This is of less concern for the cluster parallaxes since their mean signal-to-noise ratio is very high at >50.
The Milky Way Cepheid period–luminosity relation in the HST NIR, reddening-free (Wesenheit) system as calibrated with three parallax samples. Parallaxes from HST spatial scanning (R18b) for eight Cepheids are in blue and yield 3% precision in the mean. The 66 points in gray (R21) using Gaia EDR3 Cepheid parallaxes with simultaneous calibration of the parallax offset. The red points come from cluster Cepheids and are less dependent on parallax offset calibration as they are measured in the range where Gaia is best calibrated. These samples differ in their parallax precision (inset) with the cluster parallaxes reaching ∼10 μas uncertainties leading to the low dispersion of σ = 0.07 mag for the cluster Cepheids. The dotted line (upper) shows the reference luminosity for the distance ladder.

We first optimize the value of

\[ \chi^2 = \sum (\pi_{\text{EDR3,i}} - \pi_{\text{phot,i}} + zp)^2 \sigma_i^{-2}, \]

(4)

where \( zp \) is a residual parallax offset after application of the L21-derived parallax offset and \( \pi_{\text{phot,i}} \) depends on the Cepheid P–L parameters in Equations (2) and (3), \( W, b_W, \) and \( M_{W,1}^W \). The individual \( \sigma_i \) are derived by adding in quadrature the photometric parallax uncertainty, the intrinsic width of the NIR Wesenheit P–L, and the parallax uncertainties in Table 1. For fits that can accommodate inaccuracies in the L21 zero-point offset calibration we assign a value for \( \sigma_{zp} \) as given below.

In Table 5 we give the results of these fits. R21 assigned a fairly large uncertainty prior of \( \sigma_{zp} = 10 \mu \text{as} \) due to the modest calibration sample available to L21 at this high brightness range (6 < \( G < 10 \)). In contrast (see Figure 1), the magnitudes of the stars used to measure the cluster parallaxes well match the bulk of those used by L21 to calibrate the offset. The mean \( G \) mag is 15.5 with a dispersion of 1.9 mag. So for these fits we assign a smaller, a priori uncertainty of \( \sigma_{zp} = 5 \mu \text{as} \) (L21 states the offset uncertainty to be “a few” μas in the magnitude and color range where it is well calibrated so our choice of \( \sigma_{zp} \) is relatively cautious). This would correspond to a 0.016 mag systematic uncertainty for the cluster sample.

The Cepheid cluster sample offers it is best constraints on the P–L intercept, \( M_{W,1}^W \). We therefore consider the best optimizations to be two-parameter fits for \( zp \) and \( M_{W,1}^W \) using constraints on the other P–L parameters (\( b_W \) and \( Z_W \)) obtained from the external Cepheid sample (used in R22) that well constrains these parameters as given in Table 5.

Our best fit to the full sample yields \( M_{W,1}^W = -5.902 \pm 0.026 \) mag and \( zp = -3 \pm 4 \mu \text{as} \) and \( M_{W,1}^W = -5.907 \pm 0.024 \) mag and \( zp = -4 \pm 4 \mu \text{as} \) for the Gold sample. The value of \( M_{W,1}^W \) is very close to the value derived from MW Cepheid parallaxes in R21, \(-5.903 \pm 0.024 \) mag, and to the mean value from three geometric anchors (LMC DEBs, NGC 4258 masers, and MW Cepheid parallaxes) of \(-5.894 \pm 0.017 \) mag in R22. The residual \( zp \) from L21 is small or undetected, consistent with the expectation it should be small in this magnitude range where Gaia is best calibrated. The listed uncertainty in \( b_W \) and \( Z_W \) is included but contributes less than 10% of the total variance of \( M_{W,1}^W \). Using this constraint as the sole anchor of the SH0ES distance ladder (R22) gives \( H_0 = 72.9 \pm 1.3 \) km s \(^{-1} \) Mpc \(^{-1} \) and \( H_0 = 73.3 \pm 1.1 \) km s \(^{-1} \) Mpc \(^{-1} \) with and without determination of the offset term, respectively, for either sample including systematic uncertainties in the SH0ES distance.
ladder (see Table 5). The Gold sample yields $H_0 = 72.7 \pm 1.3$ and $H_0 = 73.2 \pm 1.1$ with and without determination of the offset term.

Adding this constraint to the latest SHOES measurement (R22) reduces the uncertainty in $H_0$ by $\sim$5% to $H_0 = 73.04 \pm 0.99 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with the full sample and $H_0 = 72.98 \pm 0.99 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for the Gold sample; simply summarized as $H_0 = 73.01 \pm 0.99 \text{ km s}^{-1} \text{ Mpc}^{-1}$. A tighter constraint on $M_{W,1}$ is found by fixing the parallax offset to the L21 value, i.e., $zp = 0$ (and $\sigma_{zp} = 0 \mu$as), yielding $-5.890 \pm 0.018$ mag for the full sample and $-5.892 \pm 0.017$ for the Gold sample. This reduces the uncertainty in the luminosity by 25% and improves the precision of $H_0$ by 7%. The improved calibration of Cepheids in the R22 distance ladder results in a $\sim5.3\sigma$ Hubble Tension with Planck + ΛCDM.

We also fit a different two-parameter model by fixing $zp$ to L21 and varying the slope, $b_w$, and the luminosity. The slopes are in fair agreement with the R22 mean ($-3.30 \pm 0.02$) with $-3.36 \pm 0.07$ for the full sample and $-3.44 \pm 0.08$ for the Gold sample. The values of $M_{W,1}$ are little changed though not directly useful for the determination of $H_0$ since they pertain to a different slope than that used in R22.

If we double the prior uncertainty in $\sigma_{zp}$ to 10 μas we find $-5.923 \pm 0.034$ mag and $H_0 = 72.90 \pm 1.01 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $zp = -8 \pm 7 \mu$as (if we discard any constraint on the zero-point from L21) the sample measures the offset to $zp = -9 \mu$as but without detecting a difference in $zp$ from L21). If we increase the cluster parallax errors by 30% we find $-5.905 \pm 0.028$ mag and $H_0 = 73.00 \pm 0.99 \text{ km s}^{-1} \text{ Mpc}^{-1}$. However, if these larger parallax errors are compensated by a smaller empirical intrinsic scatter (0.045 mag for the full sample to get $\chi^2_{red} = 1$) the result is $-5.905 \pm 0.023$ mag and $H_0 = 72.98 \pm 0.98 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

If we directly compare the 17 Cepheid and cluster parallaxes we find a mean difference of $8 \pm 5 \mu$as consistent with their independently measured, optimal zero-point difference of $11 \mu$as with the sense that the (uncorrected) Cepheid parallaxes are larger (shorter distances) than their clusters, which the analyses attribute to a significant residual offset applying only to the bright MW Cepheids in the less-well-calibrated range for Gaia.

In summary we find a much smaller sample of Cluster Cepheids observed with HST yields a similar constraint (value and uncertainty) as the full MW HST Cepheid sample. Most importantly, this constraint is measured with a different and smaller contribution to the systematic uncertainty from the Gaia parallax offset. In this way the two samples are complementary, demonstrating consistency in the Cepheid calibration in the presence of a significant (MW Cepheids) or negligible (Cluster Cepheids) nuisance term.

4. Discussion

The MW Cepheid field and cluster samples together provide an important check on the Cepheid calibration determined from Gaia parallaxes in light of uncertainties related to the parallax offset term. They pass this test at the present precision available increasing our confidence in the distance scale calibrated with Cepheid variables and further reduce options for evading the present “Hubble tension” via unrecognized, compounded systematic errors. Figure 4 shows the status of the first rung of the SHOES Cepheid distance ladder measured on the HST photometric system comparing geometric distances to Cepheids across 20 magnitudes, a range that exceeds the measured range of SN Ia. With future data releases, DR4 and DR5, it is reasonable to expect further improvements to the Gaia parallaxes that will support a <1% determination of $H_0$ via the Cepheid–SN Ia distance ladder.

We considered how variations in the reddening law could impact our constraints on the Cepheid luminosity. Using the intrinsic Cepheid period–color relation we find a mean color excess $E(V-I) = 1.1$ for the sample. Variations in the NIR reddening ratio ($R_H = 0.386$ from the Fitzpatrick 1999) of more than $\sigma_{R_H} \sim 0.05$ would induce a dispersion of $>0.06$ mag on the reddened $P-L$ relation to exceed the observed dispersion (accounting for the irreducible measurement errors) with no room left for the intrinsic dispersion of the relation, presenting an upper limit. The Fitzpatrick (1999) law also allows only small variations in $R_H$ for a large variation in $R_V$ with change of 0.015 in the former for 0.5 in the latter. The CCM89 law Cardelli et al. (1989) allows for larger changes. For a plausible but allowable variation of $\sigma_{R_V} \sim 0.03$ the one parameter luminosity uncertainty would increase from 0.018 to 0.020 mag.

Gaia EDR3 parallaxes used to directly calibrate the luminosity of another standard candle, the tip of the red giant branch (TRGB), also point in the direction of growing “Hubble tension.” The parallaxes of stars in the globular cluster Omega Centauri yield $\mu_0 = 13.57-13.60$ mag (Soltis et al. 2021; Maíz Apellániz et al. 2021; Vasiliev & Baumgardt 2021), which

| Fit \( a \) | \( N \) | \( M_{W,1} \) (mag) | \( zp \) (μas) | \( b_w \) (mag/dex) | \( Z_w \) | \( \sigma_{zp} \) (mag) | \( H_0 \) CC only (km s\(^{-1}\) Mpc\(^{-1}\)) | \( H_0 \) all anchors (km s\(^{-1}\) Mpc\(^{-1}\)) |
|---|---|---|---|---|---|---|---|---|
| 2, G+S | 17 | $-5.902 \pm 0.026$ | $-3 \pm 4$ | $-3.299 \pm 0.015^{\text{b}}$ | $-0.217 \pm 0.046^{\text{b}}$ | 0.060 | 72.9 $\pm$ 1.3 | 73.04 $\pm$ 0.99 |
| 2, G | 14 | $-5.907 \pm 0.024$ | $-4 \pm 4$ | $-3.299 \pm 0.015^{\text{b}}$ | $-0.217 \pm 0.046^{\text{b}}$ | 0.047 | 72.7 $\pm$ 1.3 | 72.98 $\pm$ 0.99 |
| 2, G$S^{\text{e}}$ | 17 | $-5.893 \pm 0.018$ | 0$^{\text{d}}$ | $-3.36 \pm 0.07$ | $-0.217 \pm 0.046^{\text{b}}$ | 0.060 | ... | ... |
| 2, G$W$ | 14 | $-5.907 \pm 0.018$ | 0$^{\text{d}}$ | $-3.44 \pm 0.08$ | $-0.217 \pm 0.046^{\text{b}}$ | 0.047 | ... | ... |
| 1, G+S | 17 | $-5.890 \pm 0.018$ | 0$^{\text{d}}$ | $-3.299 \pm 0.015^{\text{b}}$ | $-0.217 \pm 0.046^{\text{b}}$ | 0.060 | 73.3 $\pm$ 1.1 | 73.16 $\pm$ 0.97 |
| 1, G | 14 | $-5.892 \pm 0.017$ | 0$^{\text{d}}$ | $-3.295 \pm 0.015^{\text{b}}$ | $-0.217 \pm 0.045^{\text{b}}$ | 0.047 | 72.3 $\pm$ 1.1 | 73.14 $\pm$ 0.97 |

Notes.

\( a \) Fit solutions are labeled by number of parameters (1 or 2) and samples (Gold, Silver); best solutions indicated with bold font.

\( b \) Fixed to R19a values.

\( c \) Cepheid luminosity not determined with same P-L parameter $b_w$ R22, so not directly applicable to determine $H_0$.

\( d \) Assuming no residual parallax offset in Gaia EDR3.
together with the extinction-corrected tip of $m_I = 9.63$ (Bellazzini et al. 2001; Bono et al. 2008) supports the fainter end of the TRGB luminosity range ($M_I = -4.0$) as do Gaia EDR3 parallaxes of field red giants (Li et al. 2022). While the limited precision of these calibrations still make them consistent with non-Gaia based results (e.g., Freedman 2021 at $-4.05$ and Anand et al. 2021 at $M_I = -4.00$), they offer an important indicator as subsequent releases from Gaia offer the only route to beat the 1.5% precision of the best alternative, the masers in NGC 4258. As relative distance measurements from primary and secondary distance indicators continue to improve, the ultimate test of the present Hubble tension and $\Lambda$CDM should come from the consistency or lack thereof between (final) parallaxes from Gaia and the angular size of the acoustic scale measured from the cosmic microwave background from Planck, two fundamental scale measurements of a cosmos for which there can be only one.

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ORCID iDs
灯笼 G. Riess © https://orcid.org/0000-0002-6124-1196
Louise Breuval © https://orcid.org/0000-0003-3889-7709
Wenlong Yuan © https://orcid.org/0000-0001-9420-6525

Lucas M. Macri © https://orcid.org/0000-0002-1775-4859
Dan Scolnic © https://orcid.org/0000-0002-4934-5849
Richard I. Anderson © https://orcid.org/0000-0001-8089-4419
Mauricio Cruz Reyes © https://orcid.org/0000-0003-2443-173X

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Figure 4. The first rung of the SH0ES distance ladder, geometry calibrating Cepheids. Points in gray are as presented in R22 and points in red are the cluster Cepheids presented here.
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