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Concerning SH_0ES data: discrepant $W_{0,\,\mathrm{VI}}$ absolute magnitudes for Cepheids in the keystone galaxy NGC4258

Daniel Majaess ★

Mount Saint Vincent University, Halifax B3M2J6, Canada

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ABSTRACT

SH_0ES *VI*-band photometry for classical Cepheids in the keystone galaxy NGC4258 yield discrepant absolute magnitudes. Specifically, the 2016 and 2022 published SH_0ES Cepheid data for NGC4258 exhibit a substantial offset of $\Delta W_{0,\,\mathrm{VI}} \simeq 0^{\mathrm{m}}.3$. That adds to a suite of existing concerns associated with the SH_0ES analysis, which in sum imply that their relatively non-changing Hubble constant for nearly 20 years warrants scrutiny.

Key words: Cosmology – stars: variables: Cepheids – techniques: photometric.

1 INTRODUCTION

The SH_0ES results are leveraged to advocate that classical Cepheid distances yield an H_0 that is offset from the Planck CMB result (Riess et al. 2022). There are indeed concerns with ΛCDM, however, there exist errors and anomalies within SH_0ES data that provide sufficient pause when considering their conclusions, despite potentially being fortuitously correct. That includes inconsistent SH_0ES photometry for Cepheids in remote galaxies with inhomogeneous crowding and surface-brightness profiles (e.g. Efstathiou 2020; Freedman & Madore 2023), a suite of contested Leavitt law parameters such as slope, extinction law, metallicity (e.g. Madore & Freedman 2024), and changes in maser and Cepheid distances to the keystone galaxy NGC4258 (e.g. Majaess 2010, 2024). Yet, the SH_0ES $H_0 \simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ remained comparatively unaltered across approximately two decades. A subset of such disconcerting issues are highlighted further, and the new analysis is presented in Section 2.

Majaess (2010) argued that the W_{VI} slope of the Leavitt law for near-solar Cepheids determined by Riess et al. (2009, SH_0ES) exhibited a marked offset ($\alpha = -2.98 \pm 0.07$) from the consensus result ($\alpha \simeq -3.3$, see also Majaess, Turner & Gieren 2011; Riess et al. 2022). Majaess (2010) further remarked that a shallower W_{VI} slope may be indicative of incorrect photometric standardization or decontamination procedures (crowding/blending), and that certain SH_0ES V–I colours may be too blue (see also Efstathiou 2020). Freedman & Madore (2023) stressed that, "A simple comparison of the distance moduli tabulated in Riess et al. (2016, 2022) reveals an overall difference of $-0^{\mathrm{m}}.123$... That corresponds to a 6 per cent shift in H$_0$."

Efstathiou (2020) determined the following regarding the $W_{H-\mathrm{VI}}$ data of Riess et al. (2016, SH_0ES), "The LMC distance[1] together with the SH$_0$ES Cepheids is placing NGC4258 at a distance of 6.98 Mpc if metallicity effects are ignored, whereas the maser distance is 7.58 Mpc." Majaess (2024) conveyed that the Macri et al. (2006), Hoffmann et al. (2016, SH_0ES), and Yuan et al. (2022, SH_0ES) W_{VI} Cepheid data sets for NGC4258 are discordant, both *vis à vis* the mean distance and the impact of chemical composition on Cepheid distances. Macri et al. (2006) and Hoffmann et al. (2016, SH_0ES)[2] favoured a relatively stronger dependence of the W_{VI} Leavitt law zero-point on metallicity, while the Yuan et al. (2022, SH_0ES) data suggest otherwise (see fig. 3 in Majaess 2024). Udalski et al. (2001), Majaess et al. (2011), Wielgórski et al. (2017), and Madore & Freedman (2024) concluded that W_{VI} functions are relatively insensitive to metallicity,[3] whereas Riess & Breuval (2024, SH_0ES) advocate for a larger zero-point dependence by comparison (e.g. $\gamma = -0.22 \pm 0.04\,\mathrm{mag\,dex^{-1}}$). For example, Madore & Freedman (2024) relayed TRGB-Cepheid distances (their fig. 1) which contest that Riess & Breuval (2024, SH_0ES) finding. The reader can examine fig. 6 in Yuan et al. (2022, SH_0ES) and assess whether a constant (indicating a null-dependence) represents their latest NGC4258 analysis rather than the fits they overlaid, and pair that with an inspection of the extended metallicity baseline present in fig. 1 of Madore & Freedman (2024). Yuan et al. (2022, SH_0ES) determined that γ is $-0.07 \pm 0.21\,\mathrm{mag\,dex^{-1}}$. Moreover, Majaess (2024) added there is an alarming *I*-band (F814W) and W_{VI} discrepancy between Hoffmann et al. (2016, SH_0ES) and Yuan et al. (2022, SH_0ES), which is characterized by a considerable mean difference ($\gtrsim 0^{\mathrm{m}}.15$). That could stem from inhomogeneous photometry or crowding corrections, and Yuan et al. (2022, SH_0ES) stated, "many past works have not fully incorporated individual Cepheid crowding corrections (e.g. Macri et al. 2006, Hoffmann et al. 2016) as we have here, which will make the Cepheids fainter." Cepheids at smaller

★ E-mail: daniel.majaess@gmail.com

[1] Pietrzyński et al. (2019)

[2] See the broader companion study of Riess et al. (2016, SH_0ES).

[3] Breuval et al. (2022) provide a rebuttal that the reader can consider in their subsection 5.5, and see also their Table 1. Disagreements likewise exist from the important perspective of modelling (Bono et al. 2008; Anderson et al. 2016).

Table 1. The Hoffmann et al. (2016, SH_0ES) and Yuan et al. (2022, SH_0ES) data for classical Cepheids in the keystone galaxy NGC4258 provide discordant absolute magnitudes ($W_{0,\,\mathrm{VI}}$). The Reid et al. (2019) maser distance was adopted following SH_0ES.

W_{VI} data set	β (equation (2))
Hoffmann et al. (2016, SH_0ES)	-2.97 ± 0.04
Yuan et al. (2022, SH_0ES)	-2.66 ± 0.05

galactocentric radii can feature enhanced chemical abundances and be projected upon an increased stellar density and high-surface brightness background. That degeneracy has compromised certain determinations of the impact of metallicity on Cepheid distances (section 5 of Macri et al. 2001; Majaess et al. 2011, and references therein), and photometric contamination has propagated a systematic uncertainty into H_0 determinations and the cosmic distance scale (e.g. Stanek & Udalski 1999; Mochejska et al. 2004; Majaess et al. 2012).

Majaess (2020) readily identified blended LMC RR Lyrae variables, whereas brighter Cepheids were more challenging to differentiate in that respect, and thus it was emphasized that the SH_0ES approach to decontamination of more remote Cepheids must be independently verified, since they applied significant crowding corrections (e.g. $0^{\mathrm{m}}.22$, Table 2 in Riess et al. 2011). Independently, Freedman & Madore (2024) relayed an analysis by I. Jang regarding the Riess et al. (2012, SH_0ES) crowding data, noting, "With a median correction of $\sim 0^{\mathrm{m}}.25$, which corresponds to a 10 per cent difference in H_0 of $>7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$... there remains the potential for a hidden systematic effect that may be difficult to identify and account for."

In this study, additional points of concern are highlighted regarding SH_0ES, with a focus on the incompatible absolute magnitudes ($W_{0,\,\mathrm{VI}}$) implied for NGC4258 Cepheids across the following studies: Hoffmann et al. (2016, SH_0ES) and Yuan et al. (2022, SH_0ES).

2 ANALYSIS

The Hoffmann et al. (2016, SH_0ES) and Yuan et al. (2022, SH_0ES) data sets are compared with respect to the absolute magnitudes implied by the Araucaria distance to the LMC (Pietrzyński et al. 2019), and the maser distance to NGC4258 (Reid, Pesce & Riess 2019). Those are anchor points adopted by SH_0ES. However, such oft-cited distances may be incorrect, and there are LMC estimates with relatively low-cited uncertainties (e.g. Steer 2020, and references therein, and the reader should likewise weigh the conclusions of Schaefer 2008).

First, the apparent Wesenheit (W_{VI}) magnitude is given by

$$W_{VI} = F814W - 1.45(F555W - F814W). \quad (1)$$

The colour coefficient represents the extinction law adopted by OGLE and Hoffmann et al. (2016, SH_0ES). The form for the absolute $W_{0,\,\mathrm{VI}}$ magnitude is

$$W_{0,VI} = \alpha \log P + \beta. \quad (2)$$

The distance modulus follows as

$$W_{VI} - W_{0,VI} = \mu_0. \quad (3)$$

The coefficient and zero-point can be determined by combining the expressions

$$F814W - 1.45(F555W - F814W) = \alpha \log P + \beta + \mu_0. \quad (4)$$

The Riess et al. (2019) data for LMC Cepheids, in tandem with their adopted $\mu_0 = 18.477 \pm 0.026$ (Pietrzyński et al. 2019), yield the following results via minimization:

$$\beta = -2.65 \pm 0.04, \alpha = -3.34 \pm 0.03, \quad (5)$$

where β is the zero-point of the absolute Wesenheit magnitude, and which shall be compared to that inferred from NGC4258 data. Note the slope α is comparable to that determined by Majaess (2010) and Majaess et al. (2011) for Local Group Cepheids, and across a sizable metallicity baseline. That starkly contrasts earlier findings by Riess et al. (2009, SH_0ES). The Hoffmann et al. (2016, SH_0ES) data for NGC4258 Cepheids, in tandem with the Reid et al. (2019) maser distance ($\mu_0 = 29.397 \pm 0.032$), yield the following results via minimization:

$$\beta = -3.26 \pm 0.05, \alpha = -3.09 \pm 0.03. \quad (6)$$

Critically, those findings vastly differ from equation (5). Hereon, the LMC slope will be adopted following the Majaess (2010) and Majaess et al. (2011) results, whose analysis relied in part on Araucaria, OGLE, and Benedict et al. (2007) data. Redoing the analysis with the LMC slope and NGC4258 maser distance yields

$$\beta = -2.97 \pm 0.04. \quad (7)$$

Note the substantial difference ($\simeq 0^{\mathrm{m}}.3$) relative to the LMC determined absolute magnitude (equation (5)), or that of Yuan et al. (2022, SH_0ES) (equation (8)). Even if the Riess & Breuval (2024, SH_0ES) metallicity effect was adopted ($\gamma = 0.22 \pm 0.04\,\mathrm{mag\,dex^{-1}}$), despite arguments to the contrary (e.g. Madore & Freedman 2024): the ensuing $<0^{\mathrm{m}}.1$ correction is far from reconciling the absolute magnitudes. Efstathiou (2020) examined the $W_{H-\mathrm{VI}}$ function and discovered a $0.177 \pm 0^{\mathrm{m}}.051$ discrepancy when comparing distance moduli established for NGC4258 using the Riess et al. (2016, SH_0ES) observations, the Riess et al. (2019) LMC observations, and anchor points for those galaxies (Pietrzyński et al. 2019; Reid et al. 2019).

The more recent W_{VI} SH_0ES analysis by Yuan et al. (2022, SH_0ES) of NGC4258 Cepheids essentially eliminates the aforementioned $\simeq 0^{\mathrm{m}}.3$ deviation tied to the earlier SH_0ES photometry (Hoffmann et al. 2016), and the minimization procedure yielded

$$\beta = -2.66 \pm 0.05. \quad (8)$$

Perhaps the revised SH_0ES approach was motivated in part by criticisms concerning photometry, crowding, blending, and the resulting offsets (e.g. equation (3.5) in Efstathiou 2020), and possibly by the Yuan et al. (2020) recognition that Cepheids in high-surface brightness regions of the Seyfert 1 galaxy NGC4151 exhibited a systematic shift (their fig. 9, right panel). Nevertheless, the SH_0ES photometry for the keystone galaxy NGC4258 is discrepant across time. Admittedly, both the maser and Cepheid distances to NGC4258 feature a discouraging history, with early estimates of the former (6.4 ± 0.9 and 7.2 ± 0.3 Mpc, Miyoshi et al. 1995; Herrnstein et al. 1999) being extensively nearer than the Reid et al. (2019) result of $7.576 \pm 0.082 \pm 0.076$ Mpc. Majaess (2024) conveyed that the suite of W_{VI} Cepheid data sets for NGC4258 exhibited divergent results (Maoz et al. 1999; Newman et al. 2001; Macri et al. 2006; Fausnaugh et al. 2015; Hoffmann et al. 2016; Yuan et al. 2022).

The Hoffmann et al. (2016, SH_0ES) and Yuan et al. (2022, SH_0ES) data for NGC4258 provide irreconcilable absolute magnitudes. That result likewise holds when adopting an $\alpha(\log P - 1)$ framework for equation (2).

3 CONCLUSION

$W_{\rm VI}$ photometry of Cepheids in NGC4258 is inconsistent between Hoffmann et al. (2016, SH_0ES) and Yuan et al. (2022, SH_0ES), in terms of the mean implied distance, the impact of metallicity, and with respect to the absolute magnitude constrained by LMC and NGC4258 (M106) distances adopted by the SH_0ES team (Table 1). The latter $\simeq 0^{\rm m}.3$ discrepancy is too large to be explained by the contested metallicity effect proposed by SH_0ES (Riess & Breuval 2024, see also the replies within Efstathiou 2020). More broadly, there are numerous inconsistencies endemic to SH_0ES data over time, as outlined previously (e.g. Freedman & Madore 2023; Majaess 2024). The following overarching conclusions regarding Cepheids are worth re-emphasizing, namely

(i) the dawn of precision cosmology seemingly occurs in an era where a lack of agreement exists concerning fundamentals associated with the Leavitt law, owing in part to degeneracies (e.g. crowding, blending, metallicity, and extinction law). Additional research on the latter topic tied to variations in the extinction law is of particular interest (e.g. Turner 2012; Fausnaugh et al. 2015).

(ii) A $W_{\rm VI}$ metallicity effect is not a chief source of uncertainty associated with Cepheid distances or the establishment of H_0, but rather it is the challenging task of obtaining precise, commonly standardized, multi-epoch, multiband, comparatively uncontaminated extragalactic Cepheid photometry.

(iii) A consensus framework to assess photometric contamination should be pursued, in concert with an elaborate characterization of the difference in approach to crowding adopted by Yuan et al. (2022, SH_0ES) relative to previous work (Riess et al. 2009, 2011; Hoffmann et al. 2016; Riess et al. 2016), especially given Table 1 and the passage on crowding from Yuan et al. (2022, SH_0ES) restated verbatim in Section 1, and owing to anomalies described in the literature (e.g. Majaess 2010; Efstathiou 2020; Freedman & Madore 2023; Majaess 2024). Indeed, the entire suite of raw *HST* images must be reassessed by independent researchers to benchmark SH_0ES assertions throughout the project's history, since confirmation bias can unwittingly impact conclusions. Examining the veracity of prior SH_0ES findings provides guidance on whether the cited Hubble constant and uncertainties are reliable. Importantly, the full Cepheid (unculled) data sets should be published (Efstathiou 2020).

Consequently, TRGB and JAGB distances in non-crowded regions are desirable (e.g. Madore & Freedman 2023; Freedman & Madore 2024).

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DATA AVAILABILITY

The data underlying this article are readily available via the Centre de Données astronomiques de Strasbourg (CDS), Hoffmann et al. (2016, SH_0ES), and Yuan et al. (2022, SH_0ES).

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