

CONCERNING THE CLASSICAL CEPHEID VI_C WESENHEIT FUNCTION'S STRONG METALLICITY DEPENDENCE

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ABSTRACT

Evidence is presented which supports findings that the classical Cepheid VI_C period Wesenheit function is relatively insensitive to metallicity. The viability of a recently advocated strong metallicity dependence was evaluated by applying the proposed correction ($\gamma = -0.8 \text{ mag dex}^{-1}$) to distances established for the Magellanic Clouds via a Galactic VI_C Wesenheit calibration, which is anchored to 10 nearby classical Cepheids with measured *Hubble Space Telescope* (*HST*) parallaxes. The resulting γ -corrected distances for the Magellanic Clouds (e.g., Small Magellanic Cloud, $\mu_{0,\gamma} \sim 18.3$) are in significant disagreement with that established from a mean of >300 published estimates (NED-D), and a universal Wesenheit template featuring 11 δ Scuti, SX Phe, RR Lyrae, and Type II Cepheid variables with *HST/Hipparcos* parallaxes. Conversely, adopting a null correction (i.e., $\gamma = 0 \text{ mag dex}^{-1}$) consolidates the estimates. In tandem with existing evidence, the results imply that variations in chemical composition among Cepheids are a comparatively negligible source of uncertainty for W_{VI_C} -based extragalactic distances and determinations of H_0 . A new approach is described which aims to provide additional Galactic Cepheid calibrators to facilitate subsequent assessments of the VI_C Wesenheit function's relative (in) sensitivity to abundance changes. VVV/UKIDSS/Two Micron All Sky Survey *JHK_s* photometry for clusters in spiral arms shall be employed to establish a precise galactic longitude–distance relation, which can be applied in certain cases to determine the absolute Wesenheit magnitudes for younger Cepheids.

Key words: distance scale – galaxies: distances and redshifts – stars: variables: Cepheids

1. INTRODUCTION

Classical Cepheids are integral to the establishment of Galactic and extragalactic distance scales (Pietrzyński & Gieren 2004; Turner 2010) and the selection of a cosmological model (Macri & Riess 2009; Freedman & Madore 2010). Consequently, it is imperative to assess the effect of metallicity on VI_C Wesenheit classical Cepheid relations. In particular, are abundance differences between Cepheids comprising the calibration and target population important? Certain researchers advocate that a sizable correction is necessary when establishing the distance to benchmark metal-poor classical Cepheids in the Magellanic Clouds via a VI_C Wesenheit calibration tied to solar-abundance Galactic Cepheids. The dependence of the VI_C Wesenheit function on chemical composition is typically assessed by doing the following:

1. Evaluating the Wesenheit slopes inferred from classical Cepheids in galaxies spanning a sizable abundance baseline. A pertinent example is to examine solar to metal-poor classical Cepheids in the Milky Way, Large Magellanic Cloud (LMC), NGC 6822, Small Magellanic Cloud (SMC), and IC 1613. The galaxies are listed in order of decreasing metal abundance and span $\Delta[\text{Fe}/\text{H}] \sim 1$ (Luck et al. 1998; Udalski et al. 2001; Mottini et al. 2006; Tautvaišienė et al. 2007).
2. Comparing whether the VI_C Wesenheit magnitude offset between differing classes of pulsating stars is insensitive to the galaxy sampled. That may be evaluated by examining differences in Wesenheit space between RR Lyrae variables, δ Scuti variables (SX Phe variables), Type II Cepheids, and classical Cepheids in the Galaxy, LMC, SMC, and IC 1613. Equivalent offsets in the absence of metallicity corrections imply that VI_C Wesenheit functions are insensitive to

abundance changes. Similarly, comparing the mean color-excess inferred from various standard candles at a common zero point (e.g., IC 1613) likewise enables a determination of the impact of metallicity on that parameter, although marginal differences may arise since classical Cepheids (population I objects) are often located in dustier regions. Furthermore, extinction estimates inferred from period-reddening (VI_C) relations can be compared to DIRBE/*IRAS* dust maps to constrain the metallicity dependence.

3. Exploiting the galactocentric metallicity gradient to deduce the Wesenheit magnitude offset between classical Cepheids observed in the outer (metal-poor) and central (metal-rich) regions of a particular galaxy. However, a degeneracy emerges which complicates the analysis since the surface brightness and stellar density increase toward the central (metal-rich) regions, and thus photometric contamination (blending/crowding) becomes significant. Indeed, it is argued here that the (spurious) brightening (W_{VI_C}) of extragalactic Cepheids as a function of decreasing galactocentric distance (Kennicutt et al. 1998) is direct empirical evidence of photometric contamination.
4. Evaluating published metallicity corrections by applying them to distances established for the Magellanic Clouds using a Galactic classical Cepheid calibration (e.g., Majaess et al. 2009a). The aim is to assess whether the metallicity corrected distances match expectations for the Magellanic Clouds as established from $\geq 3 \times 10^2$ published estimates (e.g., SN1987A, eclipsing binaries, RR Lyrae variables, etc.).

In this study, evaluation (4) is conducted using the sizable metallicity effect³ ($\gamma \sim -0.8 \text{ mag dex}^{-1}$) proposed

³ Gerke et al. (2011) likewise favor a sizable metallicity dependence. The reader is referred to their comprehensive survey.

by Shappee & Stanek (2011). Shappee & Stanek (2011) inferred that estimate by comparing the Wesenheit magnitudes of classical Cepheids occupying metal-rich and metal-poor fields in M101. Evaluation (1) is employed to assess whether the slope of the VI_C Wesenheit function characterizing Cepheids in M101 may be sensitive to abundance changes (see discussion in Shappee & Stanek 2011 and their Table 10 and Figure 28). Mager et al. (2009) analyzed the *Hubble Space Telescope* (*HST*) images for M101 and reached alternate conclusions,⁴ namely, that there is no significant dependence on metallicity for the slope, and a comparatively small dependence on the zero point of the P - L relation exists (see also Freedman et al. 2001; Storm et al. 2011b). Published results for other galaxies (e.g., NGC 5253; Gibson et al. 2000) are likewise interpreter/sample selection/pipeline dependent, thereby highlighting an often uncharacterized source of uncertainty.

The dissenting (alternate) view conveyed here concerning a sizable γ -correction does not mitigate the broader significance of the Shappee & Stanek (2011) and Gerke et al. (2011) results. Shappee & Stanek (2011) discovered $\sim 10^3$ classical Cepheids in M101, thereby exceeding existing records for the number of extragalactic Cepheids detected in a particular galaxy beyond the Local Group. Indeed, it is hoped that their approach may be applied to discover countless Cepheids in additional galaxies. Gerke et al. (2011) demonstrated the pertinence of the Large Binocular Telescope for fostering extragalactic Cepheid research. Both studies present seminal results.

2. EVIDENCE FOR THE ABSENCE OF A METALLICITY EFFECT IN VI_C

First, evidence hitherto which indicates the relative insensitivity of VI_C intrinsic color and Wesenheit functions to abundance changes is summarized, namely, since such pertinent evidence is often overlooked.

The results for evaluation (1) indicate that classical Cepheids in the Milky Way, LMC, NGC 6822, SMC, and IC 1613 follow a common VI_C Wesenheit slope (Majaess 2010c, see also Pietrzyński et al. 2004; Pietrzyński & Gieren 2004; Majaess et al. 2008, 2009a; Soszyński et al. 2010) to within the uncertainties (Figure 1). The galaxies span a sizable abundance baseline, thereby permitting a reliable determination of any trend. Conversely, classical Cepheids in the Milky Way and SMC exhibit differing BV Wesenheit slopes (Majaess et al. 2008, 2009a, see also Caldwell & Coulson 1985). The latter dependence appears tied to increased line blanketing in BV (Caldwell & Coulson 1985, and references therein).

The VI_C Wesenheit results imply that the source for the following discrepancies is unrelated to a metallicity effect: the slope of the VI_C Wesenheit function varies as a function of galactocentric distance for classical Cepheids in M101 and M106 (e.g., Shappee & Stanek 2011, their Figure 28); the slope of the VI_C Wesenheit function inferred from the Sandage et al. (2004) Galactic calibrating sample⁵ is too steep, yielding distances for longer-period Cepheids which are artificially too large (Majaess 2010c, see also Benedict et al. 2007; van Leeuwen et al. 2007; Storm et al. 2011a), and conversely, classical Cepheids in several supernova (SN) host galaxies

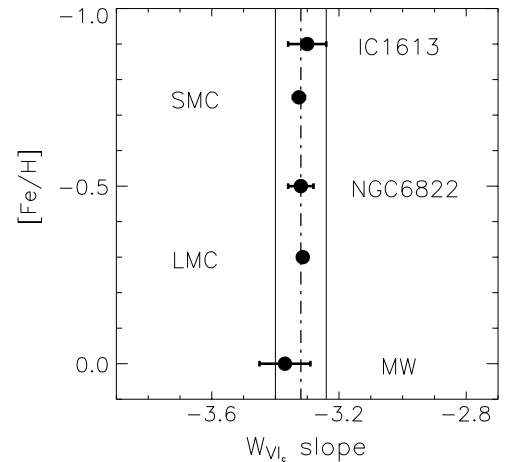


Figure 1. Slope of the VI_C Wesenheit function as inferred from ground-based photometry of classical Cepheids in the Milky Way (Equation (2)), LMC, NGC 6822, SMC, and IC 1613. The slope of the VI_C Wesenheit function is insensitive to metallicity over the range examined.

exhibit too shallow a VI_C Wesenheit slope and negative mean reddenings (IC 4128, NGC 1309, NGC 3021, Majaess 2010c, and references therein).

Regarding evaluation (2), the Wesenheit magnitude offset between RR Lyrae variables and classical Cepheids in the LMC, SMC, and IC 1613 agree to within the uncertainties (Majaess 2010c, see also Udalski et al. 2001; Pietrzyński & Gieren 2004; Pietrzyński et al. 2004). Distances and extinction estimates inferred for RR Lyrae, Type II Cepheid, and classical Cepheid variables in countless galaxies and globular clusters via metallicity-uncorrected period-based relations are comparable, and agree with results from DIRBE/*IRAS* dust maps (e.g., M33 and M54, Majaess et al. 2009a; Majaess 2010b).

Concerning evaluation (3), results by several authors imply that the (spurious) brightening (W_{VI_C}) of extragalactic Cepheids as a function of decreasing galactocentric distance stems from the associated increase in photometric contamination, rather than as a result of increasing metal abundances (Mochejska et al. 2000; Macri et al. 2001; Mochejska et al. 2004; Bono et al. 2008; Majaess et al. 2009a; Majaess 2010c; Bresolin 2011). The surface brightness and stellar density increase near the central region, and hence the effects of crowding and blending cannot be ignored. Further evidence presented below bolsters that assertion. Shappee & Stanek (2011) note that blending, in tandem with other factors, is a concern (see their discussion).

3. EVALUATING THE VIABILITY OF $\gamma \sim -0.8 \text{ mag dex}^{-1}$

The viability of a sizable metallicity correction ($\gamma \sim -0.8 \text{ mag dex}^{-1}$) is now evaluated by applying it to distances inferred from classical Cepheids in the Magellanic Clouds via the Galactic calibration. Benedict et al. (2007) cite a Galactic VI_C Wesenheit function characterizing 10 nearby classical Cepheids with *HST* parallaxes as

$$W_{VI_C,0} = (-3.34 \pm 0.17) \log P_0 - 2.52, \quad (1)$$

where $W_{VI_C,0}$ is the absolute Wesenheit magnitude and $\log P_0$ is the pulsation period tied to the fundamental mode. Benedict et al. (2002a, 2007) established *HST* parallaxes for the classical Cepheids RT Aur, T Vul, FF Aql, δ Cep, Y Sgr, X Sgr, W Sgr, β Dor, ζ Gem, and ℓ Car. Turner (2010) noted that the period-luminosity relation inferred from classical Cepheids

⁴ Taken verbatim from their published AAS abstract.

⁵ Sandage et al.'s (2004) Galactic Cepheid calibration relied upon the best available data prior to the release of the *HST* parallaxes (Benedict et al. 2007). Moreover, Turner (2010) and Storm et al. (2011a) subsequently revised the Galactic calibration, and continued revisions will invariably ensue.

Table 1
Distances for the Magellanic Clouds

| Galaxy | [Fe/H] ^a | $\mu_0(\gamma \sim 0 \text{ mag dex}^{-1})^b$ | $\mu_0(\gamma \sim -0.8 \text{ mag dex}^{-1})^b$ | NED-D ^c | $\mu_{0,uvt}$ ^d |
|--------|---------------------|---|--|---|------------------------------------|
| LMC | -0.33 ± 0.13 | 18.4 | 18.1 | $18.46 \pm 0.01(\sigma_{\bar{x}}) \pm 0.15(\sigma)$ | $18.40 \pm 0.08(\sigma_{\bar{x}})$ |
| SMC | -0.75 ± 0.08 | 18.9 | 18.3 | $18.86 \pm 0.02(\sigma_{\bar{x}}) \pm 0.18(\sigma)$ | ... |

Notes.

^a Mean Cepheid abundances from Mottini et al. (2006), which agree with the earlier determinations by Luck et al. (1998).

^b Metallicity (γ) corrected distances established from a VI_C Galactic classical Cepheid Wesenheit function (Equation (1)).

^c Distances for the Magellanic Clouds tabulated from $>3 \times 10^2$ published estimates (NED-D). A mean LMC distance derived from additional published estimates is forthcoming (I. Steer et al. 2011, in preparation).

^d Inferred from a universal Wesenheit template featuring 11 nearby δ Scuti, SX Phe, RR Lyrae, and Type II Cepheids variables with *HST/Hipparcos* parallaxes.

in open clusters (e.g., DL Cas/NGC 129; Turner et al. 1992) matches that established from the Benedict et al. (2007) sample. Moreover, the *HST* parallaxes were likewise corroborated by van Leeuwen et al. (2007) using revised *Hipparcos* parallaxes. Majaess et al. (2011b) established precise JHK_s zero-age main-sequence distances to seven of nine benchmark open clusters that agree with the revised *Hipparcos* estimates (van Leeuwen 2009). In summary, the reliability of the *HST* parallaxes is supported by independent means.

Majaess et al. (2011c) supplemented the *HST* calibration with 21 Galactic cluster Cepheids (Turner 2010) and obtained

$$W_{VI_c,0} = (-3.37 \pm 0.08) \log P_0 - (2.48 \pm 0.08). \quad (2)$$

The hybrid Galactic Wesenheit function includes the revised parameters for the classical Cepheid TW Nor in the open cluster Lyngå 6, which stemmed from an analysis of new VVV JHK_s photometry for the cluster (Minniti et al. 2010; Moni Bidin et al. 2011; Majaess et al. 2011c). That result agrees with the revised distance established from the infrared surface brightness technique (Storm et al. 2011a). The short period classical Cepheid SU Cas was excluded from the derivation since its parameters are being revised by Turner (see also discussion in Storm et al. 2011a).

VI_C Wesenheit functions determined by Soszyński et al. (2008, 2010) that characterize $\geq 10^3$ fundamental mode classical Cepheids in the Magellanic Clouds are

$$\begin{aligned} W_{VI_c}(\text{LMC}) &= (-3.314 \pm 0.009) \log P_0 + (15.838 \pm 0.006) \\ W_{VI_c}(\text{SMC}) &= (-3.326 \pm 0.019) \log P_0 + (16.383 \pm 0.014). \end{aligned} \quad (3)$$

An analogous slope describes Galactic and Magellanic Cloud classical Cepheids which span $[\text{Fe}/\text{H}] \sim 0 \rightarrow -0.33 \rightarrow -0.75$ (Equations (2) and (3), Figure 1). The coefficients and zero points of the functions were confirmed by Majaess et al. (2009a) and Ngeow et al. (2009). The distance modulus follows from subtracting the Wesenheit function inferred for a target population from the Galactic calibration:

$$\begin{aligned} W_{VI_c,0} &= W_{VI_c} - \mu_0 \\ \mu_0 &= W_{VI_c} - W_{VI_c,0}. \end{aligned} \quad (4)$$

Evaluating μ_0 for the LMC and SMC by subtracting Equation (3) from Equation (1) yields $\mu_0 \sim 18.4$ and $\mu_0 \sim 18.9$, accordingly. Mottini et al. (2006) cite mean abundance estimates for classical Cepheids in the Magellanic Clouds as $[\text{Fe}/\text{H}]_{\text{LMC}} = -0.33 \pm 0.13$ and $[\text{Fe}/\text{H}]_{\text{SMC}} = -0.75 \pm 0.08$

(see also Luck et al. 1998; Romaniello et al. 2008). The resulting distance modulus corrections owing to abundance differences between Galactic and Magellanic Cloud classical Cepheids are $\Delta\mu_{0,\gamma}(\text{LMC}) \sim -0.26$ and $\Delta\mu_{0,\gamma}(\text{SMC}) \sim -0.60$, for $\gamma \sim -0.8 \text{ mag dex}^{-1}$ (Shappee & Stanek 2011). The metallicity corrected distance estimates for the LMC and SMC are therefore $\mu_{0,\gamma} \sim 18.1$ and $\mu_{0,\gamma} \sim 18.3$, respectively. The results are concerning since they imply that the Magellanic Clouds are $\sim 20\%$ nearer than inferred from a mean of >300 published estimates, including the independent distance determined below from a universal Wesenheit template. Furthermore, the separation between the Clouds ($\Delta\mu_{0,\gamma} \sim 0.2$) is approximately half the canonical estimate.

A consensus distance for the LMC may be derived using the NASA/IPAC Extragalactic Database NED-D (Madore & Steer 2007). That compilation features redshift-independent distances for 10^4 galaxies. NED-D contains $>3 \times 10^2$ distance estimates for the Magellanic Clouds, excluding those established from classical Cepheids (e.g., Storm et al. 2011b). The mean values for the LMC and SMC are $\mu_0 = 18.46 \pm 0.01(\sigma_{\bar{x}}) \pm 0.15(\sigma)$ and $\mu_0 = 18.86 \pm 0.02(\sigma_{\bar{x}}) \pm 0.18(\sigma)$. The results disagree with the metallicity corrected distances established using $\gamma \sim -0.8 \text{ mag dex}^{-1}$ (Table 1). By contrast, the results inferred from NED-D agree with the W_{VI} -based distances uncorrected for metallicity differences between Magellanic Cloud and Galactic classical Cepheids (Table 1).

The distance to the LMC established via a universal Wesenheit template (Majaess et al. 2011a, 2011b) featuring 11 nearby δ Scuti, SX Phe, RR Lyrae, and Type II Cepheids variables with *HST/Hipparcos* parallaxes is $\mu_0 = 18.40 \pm 0.08(\sigma_{\bar{x}})$. The prototypes RR Lyrae and SX Phe are included in the calibration owing to the availability of *HST* and revised *Hipparcos* parallaxes (Benedict et al. 2002b; van Leeuwen 2007). The distance was inferred by matching the calibrated Wesenheit template to OGLE observations of LMC variables (e.g., Poleski et al. 2010, for δ Scuti stars). The impetus for the universal Wesenheit template is to employ the statistical weight of the entire variable star demographic to establish precise distances, constrain pulsation modes, and to provide a broader context for identifying peculiarities among certain variables (Majaess et al. 2011a, 2011b). The reddening-free nature of the Wesenheit approach obviates the propagation of uncertainties tied to tentative total/differential extinction corrections, ensuring that further calibration may ensue directly from published or forthcoming geometric-based distances (masers, *HST*, Very Long Baseline Array, *Gaia*). The distance established to the LMC from the Wesenheit template matches that from NED-D and a calibration based on classical Cepheids only (Equations (1) and (2)).

4. CONCLUSION AND FUTURE RESEARCH

A sizable metallicity correction ($\gamma \sim -0.8 \text{ mag dex}^{-1}$) was evaluated by applying it to distances established for classical Cepheids in the Magellanic Clouds via the Galactic W_{VI_C} function (Equation (1), Table 1). The ensuing metallicity corrected distances for the Magellanic Clouds are in significant disagreement with estimates from countless indicators (Table 1). In tandem with the evidence summarized in Section 2, the results indicate that variations in chemical composition among Cepheids are a comparatively insignificant source of uncertainty for W_{VI} -established distances and determinations of H_0 . Metallicity corrections seem unnecessary for W_{VI_C} -based distances, and consequently the observed apparent brightening (W_{VI_C}) of extragalactic Cepheids with decreasing galactocentric distance (Kennicutt et al. 1998; Shappee & Stanek 2011) likely stems from the associated increase in surface brightness and stellar density toward the galaxy center (Majaess et al. 2009a; Majaess 2010c, see also Mochejska et al. 2000; Macri et al. 2001; Mochejska et al. 2004; Bono et al. 2008; Bresolin 2011). The disagreement with Shappee & Stanek (2011) regarding the nature of the VI_C Wesenheit function's metallicity dependence does not mitigate the significant accomplishments achieved in their comprehensive analysis of M101. Shappee & Stanek (2011) discovered $\sim 10^3$ classical Cepheids using hybrid and modified variable search routines. Furthermore, the results for M101 provide additional empirical constraints on photometric contamination (blending/crowding), which in harmony with the challenges of establishing precise, standardized, multi-epoch, multi-band photometry constitute a significant source of uncertainty for extragalactic Cepheid distances.

Future research shall aim to assess the viability of establishing classical Cepheid calibrators from their membership in spiral arms, which are likewise delineated by young open clusters (e.g., Majaess et al. 2009b, 2009c). An ℓ -distance relation, where ℓ is the galactic longitude, can be inferred from open clusters with precise parameters derived via VVV/UKIDSS/Two Micron All Sky Survey JHK_s photometry (Lucas et al. 2008; Minniti et al. 2010). The dispersion for the ℓ -distance relation is particularly limited for certain sight lines, such as toward the Carina arm (Majaess et al. 2009b, 2009c; Majaess 2010a). The ℓ -distance relation may be subsequently applied to classical Cepheids which are spiral arm members, e.g., SZ Vel and RY Vel. The aforementioned classical Cepheids exhibit pulsation periods of 14 and 28 days accordingly, and would bolster the longer period regime of the Galactic calibration which is comparatively undersampled (see Benedict et al. 2007 or Figure 3 in Majaess et al. 2011c). Securing additional long-period calibrators would mitigate present uncertainties associated with the slope of the Galactic Wesenheit function (Equation (2)) and permit a more reliable determination of the parameter's insensitivity to chemical composition (Figure 1). Moreover, longer period classical Cepheids are particularly important since they are most often sampled in remote galaxies owing to their increased luminosity relative to shorter period Cepheids. The Hubble flow dominates proper motions for remote galaxies, thereby minimizing uncertainties tied to the latter parameter and hence H_0 . Indeed, the debate surrounding the SN Ia scale and H_0 (Freedman et al. 2001; Sandage et al. 2004) centers in part around the intrinsic parameters of longer period Cepheids (e.g., see Figure 3 in Majaess 2010c).

The results presented here emphasize the importance of characterizing and correcting spurious (e.g., contaminated) photometry tied to distant Cepheids when determining the

metallicity dependence on W_{VI_C} and H_0 . Admittedly, additional research on the topic is required.

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