

## The Cepheids of Centaurus A (NGC 5128) and Implications for $H_0$

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### ABSTRACT

A VI Wesenheit and period–color analysis based on new OGLE observations reaffirms Ferrarese *et al.* discovery of 5 type II Cepheids in NGC 5128. The distance to that comparatively unreddened population is  $d = 3.8 \pm 0.4(\sigma_{\bar{x}})$  Mpc. The classical Cepheids in NGC 5128 are the most obscured in the extragalactic sample ( $n = 30$ ) surveyed, whereas groups of Cepheids tied to several SNe host galaxies feature negative reddening. Adopting an anomalous extinction law for Cepheids in NGC 5128 owing to observations of SN 1986G ( $R_V \simeq 2.4$ ) is not favored, granted SNe Ia may follow smaller  $R_V$ . The distances to classical Cepheids in NGC 5128 exhibit a dependence on color and CCD chip, which may arise in part from photometric contamination. Applying a color cut to mitigate contamination yields  $d \simeq 3.5$  Mpc ( $V - I \lesssim 1.3$  mag), while the entire sample's mean is  $d \simeq 3.1$  Mpc. The distance was established *via* the latest VI Galactic Wesenheit functions that include the 10 HST calibrators, and which imply a shorter distance scale than Sandage *et al.* (2004) by  $\gtrsim 10\%$  at  $P \simeq 25$  d. HST monitored classical Cepheids in NGC 5128, and the SNe hosts NGC 3021 and NGC 1309, follow a shallower VI Wesenheit slope than ground-based calibrations of the Milky Way, LMC, NGC 6822, SMC, and IC 1613. The discrepancy is unrelated to metallicity since the latter group share a common slope over a sizeable abundance baseline ( $\alpha = -3.34 \pm 0.08(2\sigma)$ ,  $\Delta[\text{Fe}/\text{H}] \simeq 1$ ). A negligible distance offset between OGLE classical Cepheids and RR Lyr variables in the LMC, SMC, and IC 1613 bolsters assertions that VI-based Wesenheit functions are relatively insensitive to chemical abundance. In sum, a metallicity effect (VI) is not the chief source of uncertainty associated with the Cepheid distance to NGC 5128 or the establishment of the Hubble constant, but rather it may be the admittedly challenging task of obtaining precise, commonly standardized, multiepoch, multiband, comparatively uncontaminated extragalactic Cepheid photometry.

**Key words:** Stars: variables: Cepheids – Galaxies: individual: NGC 5128 – distance scale

### 1. Introduction

Ferrarese *et al.* (2007) discovered at least 51 classical Cepheids and 5 type II Cepheid candidates in Centaurus A (NGC 5128). The comprehensive survey provides an opportunity to ascertain the distance to NGC 5128 from population I and II standard candles. That is particularly pertinent granted the classical Cepheid distance to NGC 5128 is inconsistent with independent indicators. The discrepancy

has been attributed to an anomalous extinction law and ambiguities surrounding the sensitivity of  $VI$ -based Cepheid relations to chemical abundance. Yet alternative rationale are favored in the present study.

Type II Cepheids continue to garner attention as a means of establishing the distances to globular clusters, the Galactic center, and galaxies (Kubiak and Udalski 2003, Majaess *et al.* 2009a, 2009c, Majaess 2010ab). Indeed, at least 21 type II Cepheids were observed beyond the local group in M106 (Macri *et al.* 2006, Majaess *et al.* 2009c). The distance inferred to that galaxy from type II Cepheids agrees with estimates established by masers and classical Cepheids ( $D_{\text{II}} \simeq 7.3$  Mpc, Herrnstein *et al.* 1999, Macri *et al.* 2006, Majaess *et al.* 2009c). Discovering type II Cepheids and RR Lyr variables in galaxies hosting classical Cepheids offers an opportunity to constrain the effects of chemical composition on their luminosities and intrinsic colors (Freedman and Madore 1996, Udalski *et al.* 2001, Majaess *et al.* 2009a, 2009c, Majaess 2010ab, see also the historic precedent outlined in Tammann *et al.* 2008). However, the statistics must be conducive to the task, while the degeneracies posed by other uncertainties mitigated (*e.g.*, photometric contamination *via* blending and crowding).

In this study, additional evidence is presented to secure membership for 5 type II Cepheid candidates observed by Ferrarese *et al.* (2007) in NGC 5128 (Section 2). In Section 3 distances are computed for that galaxy's population of classical and type II Cepheids, namely by employing: the latest  $VI$  Galactic calibration which includes the new HST parallaxes for 10 nearby classical Cepheids; and a calibration inferred from recent  $VI$  observations for 197 type II Cepheids in the LMC (OGLE). The associated uncertainties tied to the derived parameters are discussed, and pertain directly to the Cepheid distance scale and the establishment of  $H_0$ . It is advocated that an anomalous extinction law (Section 3) and variations in chemical composition amongst Cepheids (Section 4.1) are unrelated to a significant disparity between the Cepheid distance to NGC 5128 and independent indicators. The discrepancy may stem from the difficulties inherent to obtaining extragalactic Cepheid photometry (Section 4.2).

## 2. Type II Cepheids in NGC 5128

Ferrarese *et al.* (2007) identified several potential type II Cepheids in NGC 5128, with an emphasis placed on the following variables that exhibit Cepheid-like light curves: C43, C50, C52, C54, and C56. However, the absence of a  $VI$  calibrating dataset hampered efforts to secure the classification (footnote 9, Ferrarese *et al.* 2007). The relevant data would be published a year later by the OGLE consortium who observed 197 type II LMC Cepheids in  $V$  and  $I$  (Soszyński *et al.* 2008a). The candidates highlighted by Ferrarese *et al.* (2007) may now be reassessed *via*  $VI$  Wesenheit and period–color diagrams (Fig. 1). There are drawbacks to applying only the aforementioned diagnostics to secure a type II Cepheid designation

(Majaess *et al.* 2009c). The former diagnostic is degenerate since variables of separate classes may overlap the type II Cepheid Wesenheit relation, like semi-regulars (Soszyński *et al.* 2007, 2008a, 2009b, Pellerin *et al.* 2009, Majaess *et al.* 2009c). The latter diagnostic is problematic owing to differential reddening displacing a variable from the intrinsic or mean type II Cepheid trend. A strict adherence to the mean period–color criterion led Majaess *et al.* (2009c) to reduce their preliminary sample of  $\gtrsim 100$  extragalactic type II Cepheids (excluding the LMC) by nearly  $\simeq 50\%$ . Additional diagnostics are needed which include period–amplitude and Fourier analyzes of the light curves. Yet RV Tau stars, which constitute the brightest subclass of type II Cepheids (Szabados 2010) and are therefore often detected in extragalactic surveys, exhibit somewhat chaotic and non-unique light curves that hamper efforts to secure a designation. The matter is exacerbated since observations for type II Cepheid candidates in remote galaxies are typically sparse and uncertain, particularly since the stars are often sampled fortuitously near the limiting magnitude of surveys seeking to discover brighter classical Cepheids.

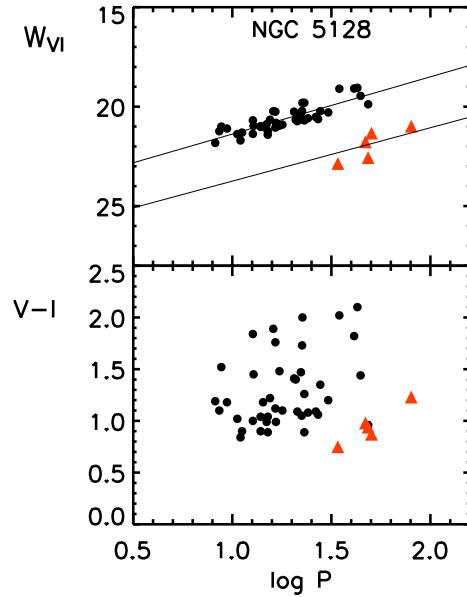


Fig. 1. VI Wesenheit and period–color diagrams confirm Ferrarese *et al.* discovery of five type II Cepheids in NGC 5128. Type II and Classical Cepheids are indicated by red triangles and black dots accordingly, and are distinctly separated by  $\simeq 2$  magnitudes in Wesenheit space. The Wesenheit magnitudes were evaluated as  $W_{VI} = V - R_{VI} \times (V - I)$ , where  $R_{VI} = 2.55$  is the canonical extinction law. The slopes of the Wesenheit functions are variants of the LMC calibration (Majaess *et al.* 2009c, OGLE photometry). Long-period classical Cepheids in NGC 5128 exhibit a sizeable color excess.

All the candidates highlighted by Ferrarese *et al.* (2007) fall on the VI Wesenheit relation characterizing type II Cepheids (Fig. 1). The Wesenheit function is defined and discussed in van den Bergh (1968), Madore (1982), Opolski (1983,

1988), Madore and Freedman (1991, 2009), and Turner (2010). The relation is reddening-free and relatively insensitive to the width of the instability strip. The population of type II and classical Cepheids are distinctly separated by  $\simeq 2$  magnitudes in Wesenheit space. BL Her, W Vir, and RV Tau stars do not follow the same linear VI Wesenheit function (Soszyński *et al.* 2008a, although see Matsunaga *et al.* 2006, 2009, Feast 2010). However, the linear relations displayed in Fig. 1 merely identify and segregate the Cepheid populations (Majaess *et al.* 2009c). A separate relation that accounts for the reputed non-linearity of the VI type II Cepheid Wesenheit function is employed to establish distances (Majaess *et al.* 2009a).

The VI period–color diagram demonstrates that the type II Cepheid candidates exhibit apparent colors that are analogous to or somewhat bluer than their classical Cepheid counterparts (Fig. 1). That agrees with the trend noted for classical and type II Cepheids in the LMC and M31 (Majaess *et al.* 2009c, photometry: Udalski *et al.* 1999, Bonanos *et al.* 2003). Semi-regulars, by contrast, are typically redder than Cepheids. The sparse sampling results in large uncertainties for the deduced mean magnitudes, periods, and hence classifications for the type II Cepheid candidates. The variables exhibit pulsation periods likely matching an RV Tau sub-classification. RV Tau stars may display alternating minima and maxima (see Wils and Otero 2008), however, that effect cannot be detected in the present data owing to the limited sampling and uncertainties (one cycle  $\simeq 44$  d).

### 3. The Cepheid Distance to NGC 5128

The distance to the type II Cepheids in NGC 5128 may be ascertained *via* the VI reddening-free relation established by Majaess *et al.* (2009a) from OGLE LMC calibrators (Udalski *et al.* 1999, Soszyński *et al.* 2008a). Likewise, the distance to the classical Cepheids may be computed using a VI Galactic Cepheid calibration (Majaess *et al.* 2008). That calibration is based primarily on the efforts of fellow researchers who established classical Cepheids as members of Galactic open clusters (*e.g.*, Sandage 1958, Madore and van den Bergh 1975, Turner *et al.* 1992) or secured precise trigonometric parallaxes (HST, Benedict *et al.* 2007). The resulting mean distance to the classical and type II Cepheids in NGC 5128 is:  $D_{\text{TI}} = 3.06 \pm 0.07(\sigma_{\bar{x}}) \pm 0.54(\sigma)$  Mpc and  $D_{\text{TII}} = 3.8 \pm 0.4(\sigma_{\bar{x}}) \pm 0.8(\sigma)$  Mpc<sup>1</sup>. The classical Cepheid distance is essentially that determined by Ferrarese *et al.* (2007), assuming the canonical extinction law ( $D_{\text{TI}} \simeq 3.1$  Mpc, see their Table 6). The agreement is expected granted the Galactic classical Cepheid calibration yields a distance to the LMC of  $\mu_0 \simeq 18.45$  (Majaess *et al.* 2008, Majaess 2010a, photometry: Udalski *et al.* 1999, Sebo *et al.* 2002, Soszyński *et al.* 2008b), which is comparable to the zero-point of the distance relation they employed. Ferrarese *et al.*

<sup>1</sup>  $\sigma_{\bar{x}}$  and  $\sigma$  are the internal standard error and standard deviation. Ferrarese *et al.* 2007 error budget is provided in their Table 7. Note that the Cepheid distances deviate as a function of color and CCD chip by upwards of  $\simeq 0.4$  Mpc (Section 4.2, Fig. 5).

(2007) consider and invariably adopt an anomalous extinction law for NGC 5128's Cepheids based on observations of supernova 1986G ( $R_V = 2.4$ , Hough *et al.* 1987), thereby increasing their estimate to  $D_{\text{TI}} \simeq 3.4$  Mpc, which is the distance cited throughout the literature. Yet recent observations indicate that SNe Ia may follow smaller  $R_V$  than the canonical extinction law (Elias-Rosa *et al.* 2006, Wang *et al.* 2006, Goobar 2008, Nobili and Goobar 2008). Riess *et al.* (2009b) cite a consensus value of  $R_V \simeq 2.5$  for SNe Ia which is consistent with that found by Hough *et al.* (1987) for the supernova in NGC 5128 (SN 1986G). Adopting an anomalously low extinction law for Cepheids in NGC 5128 based solely on observations of SN 1986G is not favored.

The mean classical Cepheid distance to NGC 5128 disagrees with other indicators by  $\gtrsim -20\%$  (Harris *et al.* 2009, see also the NASA/IPAC Extragalactic Database (NED) master list of galaxy distances<sup>2</sup> by Madore and Steer 2007). The distances cited above should be interpreted cautiously, irrespective of the aforementioned discrepancy. The type II Cepheid estimate presently exhibits small statistics and large uncertainties, as expected. The distances computed for the classical Cepheids display a dependence on color and CCD chip (Section 4.2, Fig. 5). Additional concerns arise because that population is amongst the most obscured in the extragalactic sample (Section 4.2).

#### 4. Uncertainties Associated with the Cepheid Distance to NGC 5128

##### 4.1. The (Null) Role of Metallicity

It has been argued that metal-rich classical Cepheids may exhibit a shallower (and steeper) Wesenheit slope than metal-poor ones, thereby introducing a potential source of uncertainty into the present analysis since the chemical composition of the Cepheids in NGC 5128 is unknown. However, a plot of the Wesenheit slopes inferred from ground-based observations of classical Cepheids in the Milky Way, LMC, NGC 6822, SMC, and IC 1613, demonstrates that the galaxies are characterized by a common  $VI$  slope over a sizeable abundance baseline (Fig. 2,  $\alpha = -3.34 \pm 0.08(2\sigma)$  and  $\Delta[\text{Fe}/\text{H}] \simeq 1$ ). The slope of the  $VI$  Wesenheit function is therefore insensitive to metallicity to within the uncertainties. The contrasting interpretations and evidence presented by Tammann *et al.* (2008) and Riess *et al.* (2009a) should be considered.

The Galactic calibration employed to secure the distance to NGC 5128 and construct Fig. 2 is based in part on Benedict *et al.* (2007) HST parallaxes for 10 nearby classical Cepheids, which anchored the Milky Way calibration. Tammann *et al.* (2008) questioned the reliability of the HST parallaxes as the resulting period– $M_{V,I}$  relations inferred from that sample do not match their functions, which were constructed from the best available data at the time (Tammann *et al.* 2003, Sandage

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<sup>2</sup><http://nedwww.ipac.caltech.edu/level5/NED1D/intro.html>

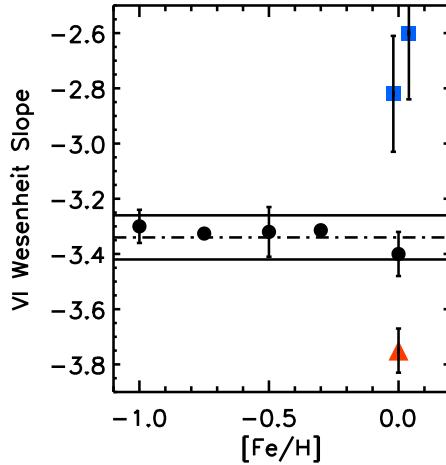


Fig. 2. The slope of the  $VI$  classical Cepheid Wesenheit relation is relatively insensitive to metallicity. HST observations of classical Cepheids in NGC 5128, NGC 1309 and NGC 3021 (blue squares) follow a shallow slope by comparison to the latest ground-based observations of variables in the Milky Way, LMC, NGC 6822, SMC, and IC 1613 (black dots,  $\alpha = -3.34 \pm 0.08(2\sigma)$ ). The slope of Sandage *et al.* 2004 Galactic calibration, based upon the best available data at the time of derivation and represented by the red triangle, disagrees with that inferred from the new HST parallaxes and (revised) cluster Cepheids ( $\alpha \simeq -3.4$ ).

*et al.* 2004). Their relations were derived prior to the publication of the HST parallaxes and the parameters for longer-period classical Cepheids tied to Galactic associations have since been revised (Turner 2010), although continued work is needed to secure new calibrators and revise existing ones<sup>3</sup>. The implied assertion that the HST parallaxes are awry is not supported by the results of Turner (2010) or Fig. 2. A central conclusion of Turner (2010) was that the classical Cepheid period–luminosity relation tied to the HST sample is in agreement with that inferred from cluster Cepheids. Moreover, the slope of the  $VI$  Wesenheit function inferred from the HST parallaxes matches that of ground-based observations of classical Cepheids in the LMC, NGC 6822, SMC, and IC 1613, whereas the relations employed by Tamman *et al.* (2003) and Sandage *et al.* (2004) differ (Fig. 2). The  $VI$  Galactic Wesenheit functions of Fouqué *et al.* (2007), Majaess *et al.* (2008), and Turner (2010) establish a distance scale which is  $\gtrsim 10\%$  nearer than Sandage *et al.* (2004) at  $P \simeq 25$  d (Fig. 3). The  $VI$  Galactic Wesenheit calibration established by Fouqué *et al.* (2007), partly on the basis of infrared surface brightness and interferometric Baade–Wesselink parallaxes, matches Turner (2010) hybrid HST/cluster Cepheid based relation within  $\lesssim 5\%$  (Fig. 3). Lastly, regarding the construction of Fig. 2, it is noted that the slope characterizing longer period Cepheids in IC 1613 is steeper than that describing the short period regime. Moreover, the SMC exhibits a significant break in the  $VI$  Wesenheit function (see also Soszyński *et al.* 2010,

<sup>3</sup>Facilitated by surveys initiated at the VISTA and OMM (Minniti *et al.* 2010, Artigau *et al.* 2010).

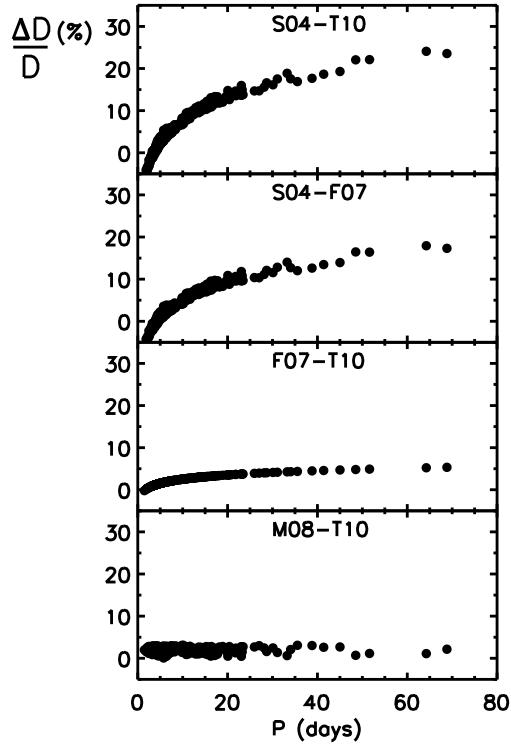


Fig. 3. A comparison of the distances established to Galactic classical Cepheids *via* the VI Wesenheit calibrations of Sandage *et al.* (2004) – S04, Fouqué *et al.* (2007) – F07, Majaess *et al.* (2008) – M08, and Turner (2010) – T10. The latter three calibrations include Benedict *et al.* (2007) HST trigonometric parallaxes for 10 nearby classical Cepheids. The Sandage *et al.* (2004) distance scale diverges from that of Fouqué *et al.* (2007) and Turner (2010) by  $\gtrsim +10\%$  at  $P \simeq 25$  d.

and references therein). The LMC displays a separate trend, and efforts continue to characterize the discrepancy and its source. The reader is likewise referred to the research of Ngeow *et al.* (2009).

Kennicutt *et al.* (1998), Macri *et al.* (2006), and Scowcroft *et al.* (2009) suggest that the classical Cepheid VI Wesenheit relation exhibits a zero-point dependence on metallicity (see also the review of Romaniello *et al.* 2005, 2008), again introducing a potential source of uncertainty into the present analysis since the chemical composition of the Cepheids in NGC 5128 is unknown. The aforementioned researchers endeavored to ascertain the influence of chemical composition by examining the distance offset between classical Cepheids located in the central (metal-rich) and outer (metal-poor) regions of a particular galaxy (M101, M106, M33). However, a degeneracy emerges (photometric contamination) since the stellar density and surface brightness often increase toward the central region. Macri *et al.* (2001) noted that a substantial fraction of the difference in distance moduli between classical Cepheids occupying the inner and outer regions of M101 could arise

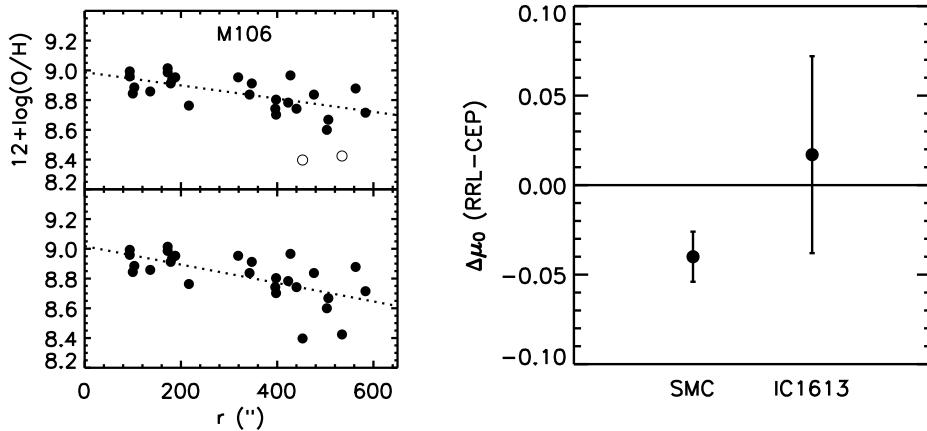


Fig. 4. *Left*, Riess *et al.* (2009a) abundance gradient for M106 implies that initial estimates of the VI classical Cepheid metallicity effect ( $\gamma_i \simeq -0.3$  mag/dex) nearly double. The exclusion of two data points implies an even larger value (*left, top panel*). A sizeable metallicity effect contradicts evidence presented by a direct comparison of classical Cepheids, type II Cepheids, and RR Lyr variables at common zero-points. *Right*, the distance offset between RR Lyr variables and classical Cepheids in the SMC and IC 1613 is nearly negligible. The base set of equations employed to compute the distances are OGLE VI Wesenheit functions of LMC classical Cepheids and RR Lyr variables. The comparison is independent of zero-point and uncertainties tied to extinction corrections. The results, in tandem with those of Fig. 2, imply that the primary source of uncertainty tied to the Cepheid distance to NGC 5128 is unrelated to variations in chemical composition amongst Cepheids.

from blending. Macri *et al.* (2006) and Scowcroft *et al.* (2009) employed criteria to mitigate the impact of photometric contamination so to enable an unbiased determination of the metallicity effect from observations of classical Cepheids in M106 and M33, and the reader is encouraged to consider their evidence. Yet the result inferred from variables in M106 was provided an alternative rationale by Bono *et al.* (2008) and Majaess *et al.* (2009c), who noted that the observed offset was too large to be attributed to variations in chemical composition. Indeed, Riess *et al.* (2009a) abundance gradient for M106 implies that initial estimates of the classical Cepheid metallicity effect ( $\gamma_i \simeq -0.3$  mag/dex) nearly double (Fig. 4, or see Table 12 in Riess *et al.* 2009a). A comparably sizeable result is obtained when examining the offset between Stetson *et al.* (1998) distance to classical Cepheids occupying the inner region of M101 and Kelson *et al.* (1996) distance to classical Cepheids in the outer region of that same galaxy, which sample metal-rich and metal-poor variables accordingly ( $\gamma \simeq -0.5$  mag/dex, see also Majaess *et al.* 2009c). The results for M101 and M106 are larger than that cited for M33 ( $\gamma \simeq -0.3$  mag/dex). The results differ in yet another manner, namely that the slope of the VI Wesenheit function inferred from classical Cepheids sampling the inner region of M106 differs from the outer region, while the classical Cepheids of M33 (inner and outer) exhibit a comparable slope. The discrepancies are manifold and the proposed metallicity effect is nonetheless too large.

The sizeable distance offset between classical Cepheids occupying the outer and inner regions of the galaxies arises from photometric contamination and other source(s). Consider the following example, in tandem with the results of Fig. 2, which compares the distances to classical Cepheids and RR Lyr variables at a common zero-point (*e.g.*, LMC, SMC, and IC 1613). The VI Wesenheit functions inferred from OGLE LMC classical Cepheids and RR Lyr variables are adopted as the calibrating set (Udalski *et al.* 1999, Soszyński *et al.* 2003). RR Lyr variables likewise follow scatter reduced VI Wesenheit functions (Kovács and Jurcsik 1997, Soszyński *et al.* 2003, 2009a, Di Criscienzo *et al.* 2007, Majaess 2010ab). The distance offset between classical Cepheids and RR Lyr variables in the SMC as established *via* the OGLE LMC Wesenheit relations is:  $\Delta\mu_0 \simeq -0.04$  (Fig. 4). The distance offset between classical Cepheids and RR Lyr variables in IC 1613 as established *via* the OGLE LMC Wesenheit relations is:  $\Delta\mu_0 \simeq +0.02$  (Fig. 4). The distances inferred from the standard candles agree to within the uncertainties, despite the neglect of metallicity corrections for variable types sampling different temperature, radius, and density regimes. Hence the evidence does not support a sizeable metallicity effect. The comparison between the variable types is independent of zero-point and uncertainties tied to extinction corrections. Admittedly, additional VI observations of extragalactic RR Lyr variables are desirable and the Wesenheit function characterizing that population as inferred from pulsation models, the Magellanic Clouds, and globular clusters are marginally discrepant (Kovács and Walker 2001, Di Criscienzo *et al.* 2004, 2007, Soszyński *et al.* 2009a). Further work is needed.

In sum, metallicity does not significantly alter the VI Wesenheit slope or zero-point (Figs. 2 and 4, *see also* Udalski *et al.* 2001, Pietrzynski *et al.* 2004, Majaess *et al.* 2008, 2009a, 2009c, Bono *et al.* 2008, Majaess 2010ab). Therefore, concerns are allayed pertaining to chemical composition being a sizeable source of uncertainty tied to the Cepheid distance for NGC 5128, or the establishment of  $H_0$ . By contrast, caution should be exhibited when employing *BV* relations for Cepheids and RR Lyr variables of differing abundance (Majaess *et al.* 2009c, and references therein). Caution is likewise urged when deriving a galaxy's distance and reddening *via* a multi wavelength approach which relies on Cepheid *B*-band data.

#### 4.2. *Extragalactic Cepheid Photometry*

Alternate sources that may explain the discrepancy between the Cepheid distance to NGC 5128 and independent indicators are now considered. Of particular concern is the correlation between the computed distances to classical Cepheids in NGC 5128, their colors, and the sampling CCD (Fig. 5). The origin of the bias may be manifold.

The excess reddening detected for a sizeable fraction of the classical Cepheids in NGC 5128 may be an indication of photometric contamination (Fig. 1), which subsequently causes the affected stars to appear brighter and nearer (Stanek and

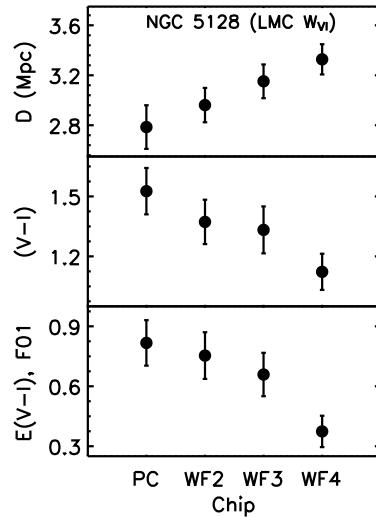


Fig. 5. The distances of classical Cepheids in NGC 5128 exhibit a color and CCD chip dependence, owing partly to photometric contamination. A color limited sample yields  $D \simeq 3.5$  Mpc ( $V - I \lesssim 1.3$  mag, see Fig. 1). A VI Wesenheit relation based on new OGLE-III observations (LMC,  $\mu_0 = 18.5$ ) was applied to infer the distance.

Udalski 1999, Mochejska *et al.* 2000, 2001, Mochejska 2002). The most obscured Cepheids in the sample are issued the nearest distances. Applying a color cut as indicated by Fig. 1 yields  $d \simeq 3.5$  Mpc ( $V - I \lesssim 1.3$  mag). The classical Cepheids of NGC 5128 exhibit the largest mean color excess of the extragalactic sample examined (Fig. 6). By contrast, negative mean reddenings were obtained for NGC 3021, NGC 1309, and IC 4182, galaxies which host classical Cepheids and SNe (Fig. 6, see also Saha *et al.* 2006). The reddenings for the extragalactic sample (including NGC 5128) were established *via* the period–color relations employed by Freedman *et al.* (2001) and Abrahamyan (2003). Applying Sandage *et al.* (2004) period– $M_{V,I}$  relations would shift additional SNe–Cepheid calibrating galaxies into the negative absorption regime (see also Saha *et al.* 2006). That calibration yields a mean color excess of  $E_{V-I} \simeq -0.17$  mag for classical Cepheids in NGC 1309. Period–color relations do not account for the temperature dependence in the strip at a given period. Consequently, reddenings computed for classical Cepheids on the hot edge of the strip will be overestimated, while reddenings computed for classical Cepheids on the cool edge of the strip will be underestimated. The photometric errors inherent to extragalactic observations, in addition to internal differential reddening, exacerbate the perceived spread. Period–color relations shall yield negative reddenings for Cepheids on the cool edge of the strip that are observed through negligible extinction, yet the mean for an entire sample of classical Cepheids should be null within the uncertainties owing to the even distribution of variables within the strip (Turner 2001). Suspicion should be cast upon photometry (and the period–color relations

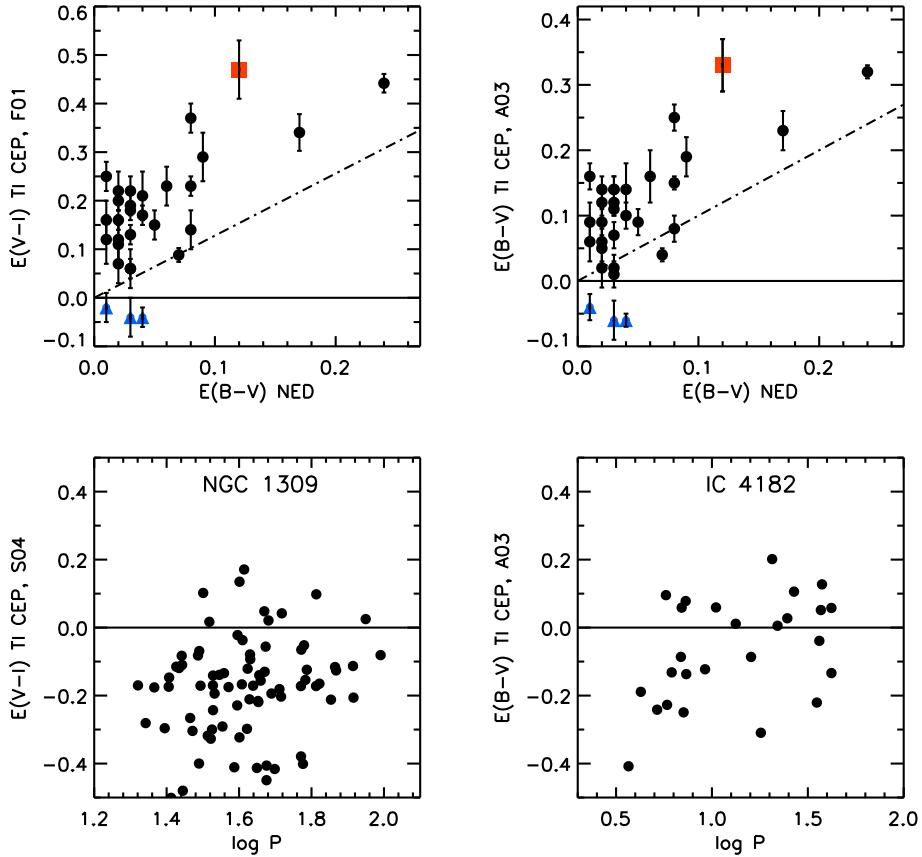


Fig. 6. *Top panels*, a comparison of the reddening established for a sample of galaxies (including NGC 5128) from classical Cepheids and the NED extinction calculator.  $E(V - I)$  is tabulated according to equations adopted by Freedman *et al.* (2001) – F01 and Sandage *et al.* (2004) – S04, whereas  $E(B - V)$  is computed following Abrahamyan (2003) – A03. Extragalactic classical Cepheid reddening lie above the relation describing unity (dashed line). The bulk of the data are offset  $A_V \simeq 0.3$  mag beyond the foreground estimate. Classical Cepheids in NGC 5128 (red square) display a sizeable mean color excess (see also Figs. 1, 5). By comparison, the Cepheid-SNe calibrating galaxies NGC 1309, NGC 3021, and IC 4182 (blue triangles) exhibit negative mean reddening (see also Saha *et al.* 2006).

employed) which yield a mean extinction significantly less than  $A_V \simeq 0.3$  mag beyond the foreground estimate (Fig. 6). Also note that Classical Cepheids observed in remote galaxies are preferentially the brightest (massive), and may be tied to star forming regions immersed in obscuring material (longer period classical Cepheids trace spiral arms: *e.g.*, Tammann 1970, Berdnikov and Efremov 1989, Majaess *et al.* 2009a, 2009b, Majaess 2010b).

The presence of floating photometric zero-points is a concern owing to the difficulties inherent to achieving a common standardization, particularly across a range in color and CCDs.

The Wesenheit relations (LMC or MW) applied to infer the distance to NGC 5128 exhibit a steeper slope. The Wesenheit slope describing classical Cepheids in NGC 5128 is  $\alpha \simeq -2.9 \pm 0.3$  (Fig. 1, sensitive to the sample and CCD chip chosen: Fig. 5). Riess *et al.* (2009a) remarked that a sample of classical Cepheids in metal-rich galaxies hosting supernovae are likewise characterized by a shallow Wesenheit slope. Photometric contamination, which may preferentially affect fainter short period Cepheids relative to brighter long period ones (*e.g.*, Fig. 17 in Macri *et al.* 2006), may bias the tilt of the inferred Wesenheit relation and could in part explain shallower slopes. Applying an LMC or Galactic calibration to galaxies that exhibit vastly differing Wesenheit slopes shall introduce a global bias. Consider two galaxies sharing a common distance (*e.g.*, the Leo I group) and spurious shallow Wesenheit slope, yet featuring variables of differing period distributions. The galaxy containing the classical Cepheids characterized by a shorter period distribution shall be issued a nearer distance. Moreover, an inhomogeneous period distribution across the CCD chips shall result in the propagation of artificial distance offsets across the detectors.

The effects described above may in sum conspire to produce Fig. 5, and the discrepancy between the Cepheid distance to NGC 5128 and that established by independent means. Admittedly, further work is needed to bolster the evidence.

Lastly, the period–reddening function derived previously by the author (Majaess *et al.* 2009c) was not employed here because it has become apparent that the purely numerical method pursued to derive the relation was swayed by poor calibrating statistics toward the long period regime (Majaess *et al.* 2008). The Galactic classical Cepheid calibration employed by the author (Majaess *et al.* 2008) exhibits an absence of long period variables save  $\ell$  Car, as perhaps too conservative a philosophy was imposed requiring cluster Cepheids enlisted in the calibration be secured *via* radial velocities or proper motions. A bias is introduced since  $\ell$  Car lies well toward the red edge of the instability strip (see Turner 2010). The author shall revisit the *VI* period–reddening formalism and subject elsewhere, an analysis that shall be facilitated by the recent establishment of spectroscopic reddening for a sizeable sample of Galactic classical Cepheids (Kovtyukh *et al.* 2008).

## 5. Summary and Future Research

The properties of classical and type II Cepheids in NGC 5128 are reinvestigated by employing calibrations featuring the latest OGLE and HST data. Sources beyond an anomalous extinction law or variations in chemical composition amongst Cepheids are proposed to rationalize the significant discrepancy between the Cepheid distance to NGC 5128 and other indicators.

Five type II Cepheid candidates discovered by Ferrarese *et al.* (2007) in NGC 5128 exhibit *VI* Wesenheit magnitudes and colors that are consistent with the proposed designation (Fig. 1). The pulsation periods could imply an RV Tau subclassification. RV Tau stars may exhibit alternating minima and maxima (see Wils and Otero 2008), however, the presence of that effect cannot be ascertained because

the observational baseline is only one cycle ( $\simeq 44$  d). The type II Cepheids are observed through marginal extinction, in contrast to their classical Cepheids counterparts (Figs. 1, 6).

The mean distance to the population of type II and classical Cepheids in NGC 5128 is:  $D_{\text{TII}} = 3.8 \pm 0.4(\sigma_{\bar{x}}) \pm 0.8(\sigma)$  Mpc and  $D_{\text{TI}} = 3.06 \pm 0.07(\sigma_{\bar{x}}) \pm 0.54(\sigma)$  Mpc. The latter estimate is essentially that obtained by Ferrarese *et al.* while employing the canonical extinction law ( $R_V \simeq 3.3$ , their Table 6). Adopting an anomalous extinction law for classical Cepheids in NGC 5128 owing to observations of SN 1982G ( $R_V \simeq 2.4$ ) is not favored. SNe Ia may follow smaller  $R_V$  than the canonical value (Elias-Rosa *et al.* 2006, Wang *et al.* 2006, Goobar 2008, Nobili and Goobar 2008). Small statistics presently dominate the uncertainty of the type II Cepheid distance to NGC 5128, mitigating the estimate's importance. The mean classical Cepheid distance to NGC 5128 ( $D_{\text{TI}} \simeq 3.1$  Mpc) disagrees with other indicators by  $\gtrsim -20\%$  (Harris *et al.* 2009).

The distance to the classical Cepheids in NGC 5128 was determined by applying the latest *VI* Galactic Wesenheit calibrations which utilize Benedict *et al.* (2007) new HST trigonometric parallaxes for 10 nearby classical Cepheids (*e.g.*, Fouqué *et al.* 2007, Majaess *et al.* 2008, Turner 2010). The distance scale implied by the *VI* Galactic calibrations of Fouqué *et al.* (2007) and Turner (2010) are  $\gtrsim 10\%$  less than that advocated by Sandage *et al.* (2004) at  $P \simeq 25$  d (Fig. 3). The Tammann *et al.* (2003) and Sandage *et al.* (2004) relations were constructed prior to the publication of Benedict *et al.* (2007) HST parallaxes for 10 nearby classical Cepheids, which anchored the Milky Way calibration. Sandage *et al.* (2004) relation was employed to calibrate the SNe Ia scale and forms the basis for Sandage *et al.* (2006) estimate of  $H_0 \simeq 62$  km/(s · Mpc). That estimate is smaller than the value espoused by Freedman *et al.* (2001), and the discrepancy hampers efforts to constrain cosmological models (Riess *et al.* 2009b, Table 1). The difference amongst the *VI* Galactic calibrations cited above may explain the bulk of the disagreement between the estimates of  $H_0$ , however, that conclusion is somewhat presumptuous. Redetermining  $H_0$  to compliment the aforementioned estimates is desirable, but requires a scrupulous inspection of all the archived data while considering advances in the field and the assertions summarized here, an effort which may be pursued elsewhere. For example, added weight shall be given to calibrating galaxies which exhibit: a population of classical Cepheids that are characterized by a *VI* Wesenheit slope near  $\alpha \simeq -3.34 \pm 0.08(2\sigma)$  (Fig. 2), where the slope is not imposed upon the data unless reaffirmed by a least-squares fit; Cepheids that are observed through low obscuration, yet marginally greater than the foreground extinction estimate (Fig. 6); Cepheids that are issued consistent moduli across the CCD chips; Cepheids that are sampled in low density and low surface brightness environments so to mitigate photometric contamination, etc. Period–color relations and the slope of the *VI* Wesenheit function may be employed to screen photometry and assess quality (Figs. 1, 6).

The  $VI$  Wesenheit functions describing classical Cepheids in NGC 5128, and the SNe hosts NGC 3021 and NGC 1309, exhibit a shallower slope than calibrations of the Milky Way, LMC, NGC 6822, SMC, and IC 1613 (Fig. 2). The discrepancy is not tied to variations in metallicity since ground-based observations of classical Cepheids in the Milky Way, LMC, NGC 6822, SMC, and IC 1613 feature comparable  $VI$  Wesenheit slopes over a sizeable abundance baseline (Fig. 2,  $\alpha = -3.34 \pm 0.08(2\sigma)$ ,  $\Delta[\text{Fe}/\text{H}] \simeq 1$ ). The aforementioned galaxies exhibit the most precise photometry of all the Cepheid data inspected (Fig. 6). The distances computed for classical Cepheids in NGC 5128 display a dependence on color and CCD chip, which is likely attributable in part to photometric contamination (Figs. 1 and 5, see text). Applying a color cut to mitigate the effects of photometric contamination yields  $d \simeq 3.5$  Mpc ( $V - I \lesssim 1.3$  mag, see Fig. 1). The classical Cepheids otherwise exhibit the largest mean color excess of the extragalactic sample examined (Figs. 1, 6). By contrast, and perhaps disconcertingly, Cepheids tied to several galaxies hosting SNe feature negative (or near negligible) mean reddenings (Fig. 6, see also Saha *et al.* 2006). The extragalactic classical Cepheid sample displays a mean  $A_V \simeq 0.3$  mag offset beyond the foreground extinction estimate inferred from dust maps (Fig. 6). Fig. 6 reaffirms that reddening inferred from foreground dust extinction maps for distant galaxies are likely underestimated.

A zero-point metallicity correction is not the chief source of uncertainty tied to the  $VI$ -based Cepheid distance for NGC 5128, or the establishment of the Hubble constant ( $VI$  photometry). Riess *et al.* (2009a) abundance gradient for M106 implies that initial estimates of the classical Cepheid metallicity effect nearly double (Fig. 4). The resulting value is too large and contradicts a direct comparison of OGLE classical Cepheids and RR Lyr variables in the Magellanic Clouds and IC 1613, which exhibit a negligible distance offset ( $\Delta\mu_0 \simeq +0.01 \pm 0.06$ , Fig. 4). Moreover, the metallicity effect cited in the literature and inferred from observations of classical Cepheids in M33, M101, and M106 is discrepant *vis à vis* both the zero-point and slope dependencies. In sum, the evidence indicates that the slope and zero-point of the classical Cepheid  $VI$  Wesenheit function are largely insensitive to variations in chemical abundance (Figs. 2 and 4, see also Udalski *et al.* 2001, Pietrzynski *et al.* 2004, Majaess *et al.* 2008, 2009a, 2009c, Bono *et al.* 2008, Majaess 2010ab). A primary source of uncertainty tied to the Cepheid distance to NGC 5128, and that which hampers efforts to constrain cosmological models, may be the admittedly challenging task of obtaining precise, commonly standardized, multiepoch, multiband, comparatively uncontaminated extragalactic Cepheid photometry.

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