Type II Cepheids as Extragalactic Distance Candles

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ABSTRACT

Extragalactic type II Cepheids are tentatively identified in photometric surveys of IC 1613, M33, M101, M106, M31, NGC 4603, and the SMC. Preliminary results suggest that type II Cepheids may play an important role as standard candles, in constraining the effects of metallicity on Cepheid parameters, and in mapping extinction.

Key words: *Cepheids – Stars: Population II – distance scale*

1. Introduction

Type II Cepheids were often cited as potential distance indicators, yet the possibility of a non-unique period–luminosity relation and their comparative faintness relative to classical Cepheids often precluded their use. Recent advances in the field are challenging such perceptions, however. The OGLE survey of the LMC and Galactic bulge secured a statistically valid sample of type II Cepheids that facilitated the establishment of viable period–magnitude relations (Udalski *et al.* 1999, Kubiak and Udalski 2003, Soszyński *et al.* 2008, Majaess *et al.* 2009). The distances inferred to the Galactic center and innumerable globular clusters from type II Cepheids agree with estimates found in the literature (Pritzl *et al.* 2003, Matsunaga *et al.* 2006, Groenewegen *et al.* 2008, Feast *et al.* 2008, Matsunaga *et al.* 2009, Majaess *et al.* 2009). Furthermore, type II Cepheids were observed beyond the Local Group alongside classical Cepheids in the galaxy M106 (Macri *et al.* 2006). That finding, in tandem with the possible discovery of type II Cepheids in NGC 3198 and NGC 5128 (Kelson *et al.* 1999, Ferrarese *et al.* 2007, Majaess *et al.* 2009), motivated the present study which expands the search for extragalactic type II Cepheids.

Type II Cepheids may be identified in galaxies that do not contain young massive stars like classical Cepheids (Turner 1996), since the variables originate from

an older low mass population (Wallerstein 2002). It follows that statistical uncertainties in recent estimates of H_0 might be reduced through an increase in the number of galaxies used for calibration (Freedman and Madore 1996, Freedman *et al.* 2001). Type II Cepheids also offer an empirical resolution to the debate surrounding the effect of metallicity on the distances and colors of classical Cepheids. The distance and reddening determined for a particular galaxy from classical Cepheids, type II Cepheids, and RR Lyr variable stars should be comparable, with any identifiable differences possibly linked to metallicity effects. Similarly, parameters (d, E_{B-V}) established for globular clusters from RR Lyr variable stars and type II Cepheids may be compared to estimates that are insensitive to metallicity.

This study employs reddening-free Cepheid relations to highlight the potential membership of type II Cepheids in surveys of IC 1613 (Udalski *et al.* 2001), M106 (Macri *et al.* 2006), M33 (Macri *et al.* 2001a, Hartman *et al.* 2006, Bersier *et al.* 2008, Scowcroft *et al.* 2009), M101 (Kelson *et al.* 1996, Stetson *et al.* 1998), M31 (Bonanos *et al.* 2003), NGC 4603 (Zepf *et al.* 1997, Newman *et al.* 1999), and the SMC (Udalski *et al.* 1999). The effects of metallicity on the determination of a Cepheid's color and distance are discussed.

2. Extragalactic Type II Cepheids

Wesenheit reddening-free parameterizations for classical Cepheids pulsating in the first overtone (OT) and fundamental mode (FU), and for type II Cepheids (TII) can be deduced from OGLE observations of the LMC (Udalski *et al.* 1999, Soszyński *et al.* 2008):

$$W_{VI} = V - \beta(V - I)$$
$$W_{VI}(FU) = -(3.29 \pm 0.02)(\log P) + (15.82 \pm 0.01)$$
$$W_{VI}(OT) = -(3.37 \pm 0.02)(\log P) + (15.32 \pm 0.01) \tag{1}$$
$$W_{VI}(TII^*) \simeq -2.7 \times \log P + 17.4$$

BL Her, W Vir, and RV Tau variables do not follow the same simple Wesenheit function (see Soszyński *et al.* 2008). Consequently, the aforementioned equations were only used to identify type II and classical Cepheids by their locations in reddening-free period–magnitude diagrams (van den Bergh 1968, Madore 1982, Opolski 1983). The distances were then computed from the reddening-free Cepheid distance relationship of Majaess *et al.* (2008a, 2009). A correction term was derived by Majaess *et al.* (2009) to permit the determination of distances to the RV Tau subclass of type II Cepheids, in addition to stars occupying the BL Her and W Vir regimes. The reddening-free Cepheid distance relationships were obtained *via* least squares techniques applied to specific samples of calibrators. For classical Cepheids the sample consisted of Galactic cluster Cepheids (*e.g.*, Turner and Burke 2002) and Cepheids with new HST parallaxes (Benedict *et al.* 2007). Defining the relation strictly as a Galactic calibration is somewhat ambiguous given that
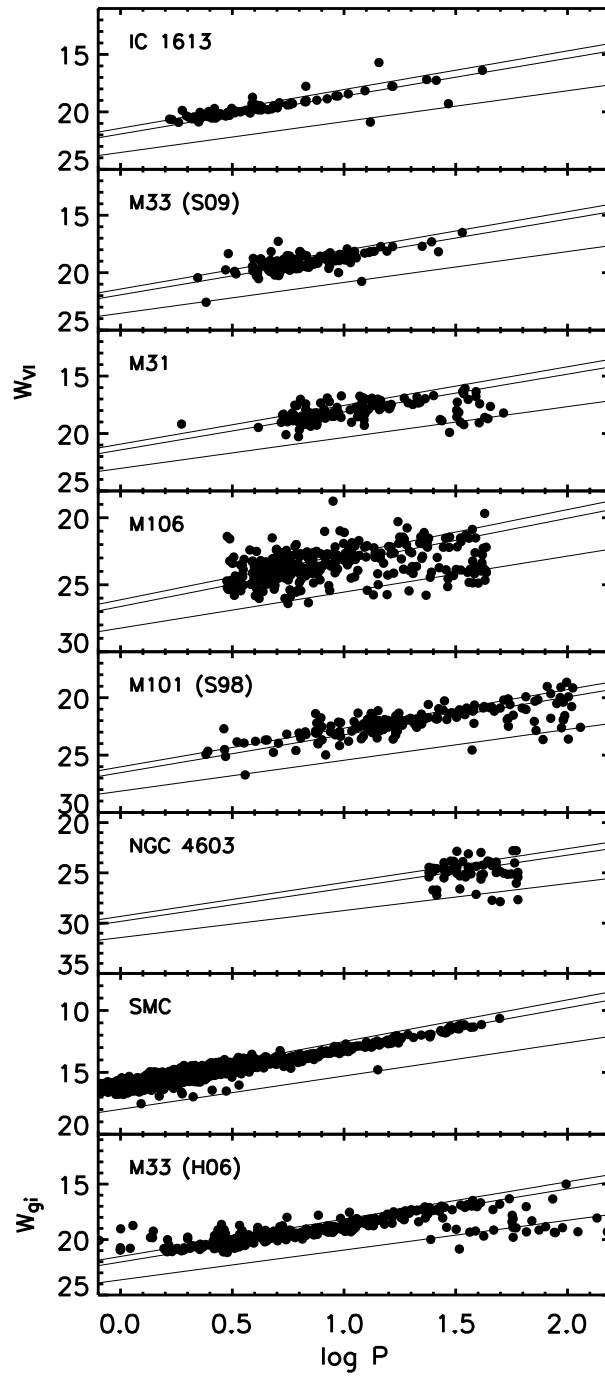
Fig. 1. Wesenheit period–magnitude diagrams for the galaxies studied. Solid lines indicate the Wesenheit functions for classical Cepheids pulsating in the overtone and fundamental modes, and type II Cepheids.

Milky Way Cepheids appear to follow a galactocentric metallicity gradient (Andrievsky *et al.* 2002). The Majaess *et al.* (2008a) relation is tied to Galactic classical Cepheids that exhibit near solar abundances (Andrievsky *et al.* 2002). For type II Cepheids the calibrators were LMC variables observed by OGLE (Udalski *et al.* 1999, Soszyński *et al.* 2008).

The color coefficient for the Wesenheit relations used here, $\beta = 2.55$, is that employed by Fouqué *et al.* (2007). The slopes of the W_{VI} relations do vary between galaxies, and shall be elaborated upon in a separate study. The Wesenheit functions were shifted in tandem by the same zero-point to correct for a difference in modulus between the calibrating galaxy (the LMC) and the target galaxy under inspection. It is noted that the formal uncertainties cited for the Wesenheit functions are optimistic (Eq. 1).

Classical and type II Cepheid candidates in the survey of M33 by Hartman *et al.* (2006) and Bersier *et al.* (2008) were identified by constructing a Wesenheit function for g' and i' magnitudes. A sizeable type II Cepheid population exists in that survey, of which a small subsample is plotted in Fig. 1. Further results by their research group are eagerly anticipated.

T a b l e 1

A sample of variables lying near the type II Cepheid Wesenheit relation

Galaxy	Star ID	P [days]	V [mag]	I [mag]	Photometry
IC 1613	[UWP2001] 10421	29.31	21.099	20.389	(1)
IC 1613	[UWP2001] 17473	13.12	21.887	21.498	(1)
M33	118019	11.99021	22.0394	21.5377	(2)
M33	D33J013348.9+304823.0	77 (SR?)	20.83	19.16	(3)
M33	D33J013402.5+302907.5	89.1 (SR?)	21.52	19.7	(3)
M33	D33J013410.6+303750.9	89.1	20.77	19.55	(3)
M33	D33J013357.1+304455.2	69.4	21.47	20.02	(3)
M33	D33J013427.3+304407.3	76.6	21.46	20.26	(3)
M31	D31J004338.6+414327.8	138.4659 (SR?)	20.16	18.5	(4)
M31	D31J004443.9+414642.5	40.4597	21.39	19.83	(4)
M31	D31J004421.5+413636.1	45.1998	18.94	18.43	(4)
M31	D31J004344.8+413705.8	31.9068	21.47	20.1	(4)
M31	D31J004454.4+414528.6	32.6462	21.53	20.21	(4)
M31	D31J004432.7+414601.0	51.7285	19.87	19.22	(4)
M31	D31J004336.6+415207.8	31.9668	19.31	19.01	(4)
M31	D31J004440.8+413346.0	42.6421	21.1	20.12	(4)
M31	D31J004306.6+414734.7	44.067	21.26	20.26	(4)
M31	D31J004426.5+414210.5	26.9212	21.87	20.66	(4)
M31	D31J004339.4+413925.8	27.4462	21.9	20.72	(4)
M31	D31J004435.4+414237.8	33.1692	21.18	20.33	(4)
M31	D31J004441.2+413700.4	40.2412	20.65	20.03	(4)
M31	D31J004454.4+415133.9	34.374	21.22	20.44	(4)
M31	D31J004325.7+414338.1	12.3263	21.59	20.69	(4)

T a b l e 1

Concluded

Galaxy	Star ID	P [days]	V [mag]	I [mag]	Photometry
M101	[SSF98] V42	54.4	24.53	23.73	(5)
M101	[SSF98] V119	71.03	23.85	23.15	(5)
M101	[SSF98] V223	95.72 (SR?)	24.81	23.68	(5)
M101	[SSF98] V102	72.33	25.53	24.48	(5)
M101	[SSF98] V209	94.01 (SR?)	24.38	23.69	(5)
SMC	OGLE SMC-SC2 81443	1.2356	19.088	18.454	(6)
SMC	OGLE SMC-SC5 235485	2.11321	18.728	18.012	(6)
SMC	OGLE SMC-SC3 130452	1.48964 (AC?)	18.734	17.993	(6)
SMC	OGLE SMC-SC11 100	1.88761	18.471	17.763	(6)
SMC	OGLE SMC-SC8 148923	1.87772	18.127	17.511	(6)
SMC	OGLE SMC-SC3 157235	2.97155	18.499	17.688	(6)
SMC	OGLE SMC-SC5 111664	2.56919	17.21	16.897	(6)
SMC	OGLE SMC-SC8 3848	3.38938	17.29	16.776	(6)
SMC	OGLE SMC-SC7 83050	14.1664	16.432	15.762	(6)
M106	[MSB2006] I-117359	15.69	26.987	25.927	(7)
M106	[MSB2006] I-139045	26.66	26.317	25.302	(7)
M106	[MSB2006] I-098414	20.38	26.468	25.564	(7)
M106	[MSB2006] I-088850	37.64	25.911	24.862	(7)
M106	[MSB2006] I-071968	41.44	25.333	24.561	(7)
M106	[MSB2006] O-31291	28.62	26.602	25.538	(7)
M106	[MSB2006] O-38462	14.22	26.481	25.899	(7)
M106	[MSB2006] I-139786	31.75	26.349	25.372	(7)
M106	[MSB2006] I-078417	33.31	26.395	25.417	(7)
M106	[MSB2006] O-07822	39.55	25.855	25.004	(7)
M106	[MSB2006] I-005860	36.7	25.857	25.067	(7)
M106	[MSB2006] I-239712	24.31	26.849	25.906	(7)
M106	[MSB2006] I-052900	42.4	25.634	24.925	(7)
M106	[MSB2006] I-120571	42.01	25.913	25.09	(7)
M106	[MSB2006] O-28609	35.69	26.439	25.51	(7)
M106	[MSB2006] I-095468	29.86	26.706	25.781	(7)
M106	[MSB2006] O-29582	30.92	26.605	25.706	(7)
M106	[MSB2006] I-106574	29.2	26.442	25.702	(7)
M106	[MSB2006] I-139636	41.12	26.411	25.456	(7)
M106	[MSB2006] O-11134	38.33	26.075	25.333	(7)
M106	[MSB2006] I-082122	43.16	26.305	25.387	(7)
NGC 4603	1165	60	27.24	26.53	(8)
NGC 4603	2848	59	26.9	26.56	(8)
NGC 4603	2862	33	27.72	27.28	(8)
NGC 4603	2547	26	27.57	27.23	(8)
NGC 4603	1545	25	27.55	27.22	(8)

References: (1) Udalski *et al.* 2001, (2) Scowcroft *et al.* 2009, (3) Macri *et al.* 2001a, (4) Bonanos *et al.* 2003, (5) Stetson *et al.* 1998, (6) Udalski *et al.* 1999, (7) Macri *et al.* 2006, (8) Newman *et al.* 1999.
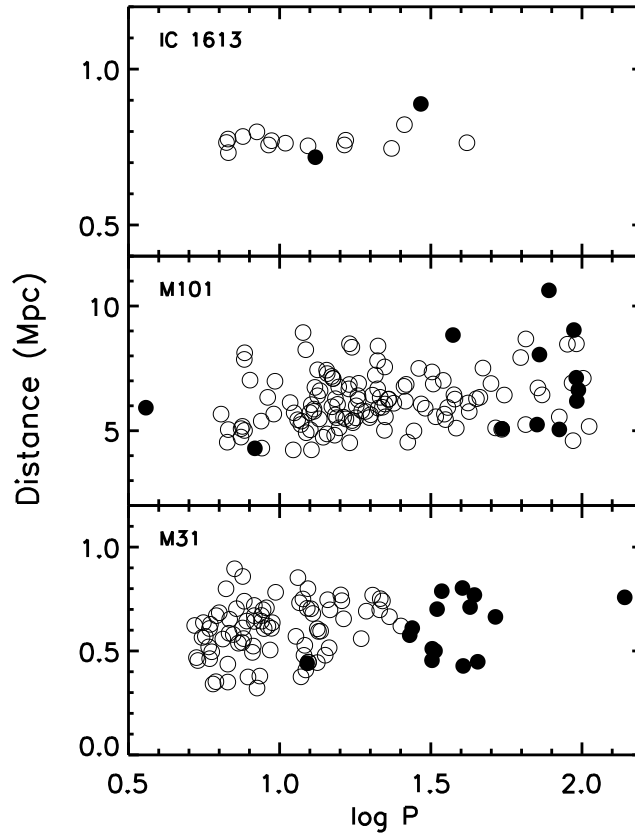
Fig. 2. Cepheid period–distance diagrams for the galaxies IC 1613, M101, and M31. Filled circles identify stars analyzed using the type II Cepheid distance relation. Open circles identify stars analyzed with the classical Cepheid distance parametrization.

Type II Cepheid candidates were tentatively identified in IC 1613 (Udalski *et al.* 2001), M106 (Macri *et al.* 2006), M33 (Macri *et al.* 2001a, Hartman *et al.* 2006, Bersier *et al.* 2008, Scowcroft *et al.* 2009), M101 (Kelson *et al.* 1996, Stetson *et al.* 1998), M31 (Bonanos *et al.* 2003), NGC 4603 (Newman *et al.* 1999), and the SMC (Udalski *et al.* 1999). Data for a subsample of type II Cepheid candidates are presented in Table 1. Once classifications were established from a Wesenheit analysis (Fig. 1), period–distance diagrams were constructed using reddening-free *VI* classical and type II Cepheid distance relations (Majaess *et al.* 2008a, 2009). A subsample is provided as Fig. 2. Parameters for the galaxies are summarized in Table 2, where (i) and (o) denote the inner and outer regions of the galaxies. Inadequate sampling is a concern and may result in systemic offsets whenever small statistics are present (IC 1613, SMC, M33). The SMC sample may be biased by anomalous Cepheids or the limiting magnitude of the survey. The distance was therefore weighted toward stars near the center of the type II Cepheid relation.

Lastly, the distance cited to Cepheids in the DIRECT M31-Y field is nearer than the canonical estimate for the Andromeda galaxy. That may be related in part to standardization offsets in the photometry (see Figs. 2, 3 and Section 3.1, Bonanos *et al.* 2003). An analysis of the remaining five DIRECT fields is underway.

T a b l e 2

Distance moduli for the sample galaxies

Galaxy	$(m-M)_0$ (TI)	$(m-M)_0$ (TII)	No. TII	Photometry
IC 1613	24.35 ± 0.09	24.52 ± 0.16	2	1
SMC	18.93 ± 0.10	18.85 ± 0.11	9	2
M33	24.43 ± 0.14 (i)	24.54	1	3
	24.67 ± 0.07 (o)	$\cdots$	$\ldots$	3
	24.40 ± 0.17 (i)	24.5 ± 0.3	5	4
M31 (Y-field)	23.93 ± 0.24	23.93 ± 0.24	17	5
M106	29.09 ± 0.14 (i)	29.20 ± 0.18	15	6
	29.20 ± 0.12 (i)	$\cdots$	$\ldots$	6
	29.34 ± 0.09 (o)	29.43 ± 0.14	6	6
	29.46 ± 0.16 (i)	$\cdots$	$\ldots$	7
M101	28.89 ± 0.17 (i)	28.9 ± 0.4	6	8
	29.29 ± 0.20 (o)	$\cdots$	$\ldots$	9
NGC 4603	32.3 ± 0.4	31.6 ± 0.3	5	10

References: (1) Udalski *et al.* (2001), (2) Udalski *et al.* (1999), (3) Scowcroft *et al.* (2009), (4) Macri *et al.* (2001a), (5) Bonanos *et al.* (2003), (6) Macri *et al.* (2006), (7) Newman *et al.* (2001), (8) Stetson *et al.* (1998), (9) Kelson *et al.* (1999), (10) Newman *et al.* (1999).

Soszyński *et al.* (2008) discovered a set of 16 rather interesting and peculiar LMC type II Cepheids of the W Vir subclass. The stars exhibit periods of pulsations ranging from $\simeq 4-10$ days, and were interpreted as more luminous binary systems (Soszyński *et al.* 2008). Indeed, the enigmatic IX Cas may be the Galactic analog (Harris and Welch 1989, Turner *et al.* 2009). Such stars occupy a small fraction ($\approx$ 10%) of the overall type II Cepheid population in the LMC, mitigating the impact on conclusions derived here owing to misclassified W Vir pulsators. However, depending on the limiting magnitude of the survey, caution is warranted since such stars may be preferentially sampled owing to their increased luminosities relative to regular W Vir pulsators.

Admittedly, stars highlighted in Table 1 may be semi-regulars or variables of differing classes that overlap the Wesenheit relation describing type II Cepheids (Soszyński *et al.* 2007, 2008, 2009, Pellerin *et al.* 2009). An identification scheme based solely on a variable's position within the Wesenheit diagram is inadequate (Fig. 1). The initial sample presented in the Wesenheit and period–distance diagrams (Figs. 1, 2) were subsequently purged of variables exhibiting apparent colors significantly redder than the Cepheids. Semi-regulars, for example, are typ-

ically redder and may be magnitudes fainter than Cepheids (Udalski *et al.* 1999, Soszyński *et al.* 2007, 2008, 2009). Classical and type II Cepheids exhibit similar colors at a given period, but diverge in particular toward longer periods where RV Tau stars appear bluer than classical Cepheids. Applying the period–color diagnostic reduced the number of type II Cepheid candidates by $\approx 50\%$. No account for differential reddening was made. Additional work is needed here, as a rigorous analysis based on complete data should include a multifaceted approach to highlight contaminators using: Fourier parameters for the light-curves, color–magnitude, period–amplitude, period–color, and Wesenheit diagrams.

3.   Cepheid Metallicity Effect

3.1.   *Effects on Color*

Precise metallicity independent distance estimates for the sample of galaxies studied here are rare, for example the maser distance to M106 (Herrnstein *et al.* 2005). That complicates efforts to constrain the effect of metallicity on Cepheid distances. Conversely, reddenings are readily available and established by a set of autonomous methods. The intrinsic color of a Cepheid, and hence its temperature, are considered sensitive to metallicity (see references in the review by Feast 1999). Consequently, a classical Cepheid *VI* color-excess relation (see Section 4, Eq. 2) calibrated with Galactic variable stars in the solar neighborhood should yield a spurious estimate of reddening for classical Cepheids in the metal-poor galaxy IC 1613 (Udalski *et al.* 2001). The two samples exhibit a sizeable metallicity difference, namely $\Delta[\text{Fe/H}] \simeq 1$. However, the reddening of classical Cepheids in IC 1613 established from Eq. (2) agrees with that obtained by metallicity independent means (see Table 3). It follows that to within the uncertainties a classical Cepheid's intrinsic $(V-I)$ color must be relatively insensitive to metallicity. The color-excess relation (Eq. 2) also appears to provide a reasonable estimate of reddening for type II Cepheids (RV Tau subclass excluded), and an additional test for metallicity effects. That is demonstrated by the good agreement of computed reddenings for type II Cepheids in the globular clusters NGC 6441 (Pritzl *et al.* 2003), M54 (Pritzl *et al.* 2003), M15 (Corwin *et al.* 2008), and the LMC with metallicity independent determinations (Table 3). No metallicity corrections were applied despite a sizeable range in abundance spanning $[\text{Fe/H}] \approx -0.3$ to -2.3 (Table 3). A unique period–reddening relation for type II Cepheids shall be developed in a follow-up study since Eq. 2 inadequately characterizes the entire period regime. Nevertheless, the present results are confirmed by an ongoing parallel study that is establishing reddenings for a subsample of galaxies and globular clusters in Table 3 from RR Lyr variable stars. The statistics are larger and shall bolster confidence in the results. Lastly, the 2MASS reddenings highlighted in Table 3 should be viewed as first-order estimates.

Table 3

Reddenings for galaxies and globular clusters

Object	[Fe/H]	Cep I	Cep II	Schlegel *et al.* (1998)	Harris (1996)	2MASS 2MASS
LMC	−0.3	0.14 ± 0.04	0.14 ± 0.04	–	–	–
NGC 6441	−0.5	–	0.55 ± 0.03	0.63	0.45	0.66 ± 0.05
IC 1613	−1.0	0.05 ± 0.03	–	0.03	–	0.10 ± 0.05
M54	−1.6	–	≃ 0.16	0.15	0.15	–
M15	−2.3	–	≃ 0.14	0.11	0.09	0.14 ± 0.04

Metallicities from Harris (1996), Udalski *et al.* (2001), Mottini (2006). LMC and IC 1613 cited metallicities are for classical Cepheids. Schlegel *et al.* (1998) reddenings computed *via* the NED extinction calculator. 2MASS reddenings determined by Turner following the prescription highlighted in Turner *et al.* (2008).

Perhaps not surprisingly, the slope of the *VI* reddening-free classical Cepheid distance relation appears relatively insensitive to metallicity (Udalski *et al.* 2001, Pietrzyński *et al.* 2004, Benedict *et al.* 2007, van Leeuwen *et al.* 2007, Fouqué *et al.* 2007, Majaess *et al.* 2008a). By contrast, the slope of a *BV* relation is sensitive to metallicity. Readers are referred to discussions in Caldwell and Coulson (1985), Chiosi *et al.* (1993), and Tammann *et al.* (2003). The aforementioned trends are confirmed when computing the distance to SMC Cepheids from relationships calibrated with Galactic Cepheids in the solar neighborhood (Fig. 3, see also Majaess *et al.* 2008a). Classical Cepheids in the SMC are metal poor in comparison with Cepheids in the LMC and solar neighborhood (Luck *et al.* 1998, Andrievsky *et al.* 2002, Mottini *et al.* 2006). *BV*-based Galactic classical Cepheid distance relations ineptly characterize SMC Cepheids (Fig. 3), and a break in slope is apparent. The ratio of total to selective extinction (R) can be adjusted to mitigate the bias noted in Fig. 3, but the value required to linearize the *BV* relation across all periods is unrealistic. A disadvantage of the Majaess *et al.* (2008a, 2009) Cepheid parameterizations is the ratio of total to selective extinction is fixed. It is also noted, in hindsight, that the color coefficient for the Majaess *et al.* (2008a) *BV* relation may be rather large. Further work is needed to consider the implications of anomalous values of R (*e.g.*, Macri *et al.* 2001b, Udalski 2003), and to examine why the Tammann *et al.* (2003) and Majaess *et al.* (2008a) Galactic *BV* relations do not match that of Fouqué *et al.* 2007 (Fig. 3). The latter finding is of particular concern, and a rigorous comparison of the Galactic calibrations shall ensue.

3.2. *Effects on Distance*

The data in Table 2 indicate that distance moduli for the inner regions of spiral galaxies in the sample derived from Cepheids are consistently smaller than the outer regions. The canonical explanation attributes the difference to a metallicity
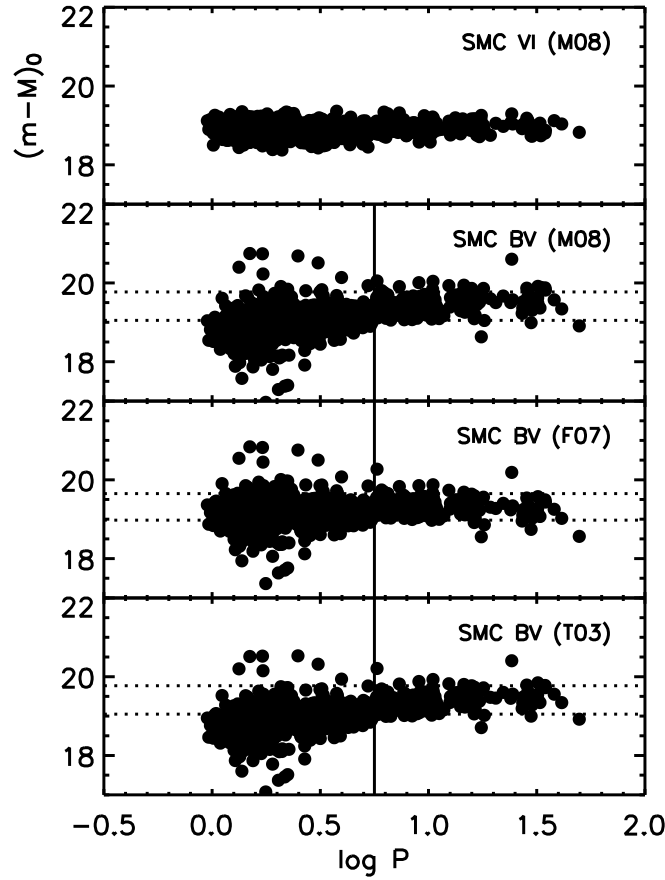
Fig. 3. Cepheid period–distance diagrams for the SMC. The slopes of classical Cepheid distance relations based on *BV* photometry are sensitive to the effects of metallicity. Conversely, the slopes of *VI*-based relations are relatively unaffected by comparison (*top*). The Galactic classical Cepheid relations ($Z_\odot$) of Majaess *et al.* (2008a, M08), Fouqué *et al.* (2007, F07), and Tammann *et al.* (2003, T03) were used.

gradient (Fig. 4, right). However, there are concerns regarding that assertion. For example, the distances computed to the two data sets that sample the inner regions of M106 (Newman *et al.* 2001, Macri *et al.* 2006), where the abundances are similar, differ by $(m - M)_0 \simeq 0.32$ mag (see Table 2). The discrepancy may reflect the difficulty of achieving a common photometric zero-point and the need to re-assess the error budget assigned to extragalactic Cepheid distance determinations. The distance to classical Cepheids occupying the inner region of M33 as established from the photometry of Macri *et al.* (2001a) and Scowcroft *et al.* (2009) are in agreement (Table 2). Likewise, the results highlighted in Table 2 for the inner and outer regions of M101 are consistent with that cited in Stetson *et al.* (1998). The implied difference in distance between the two regions of M33 and M101 are:

$\Delta(m-M)_{0,M33} \simeq 0.24$ mag and $\Delta(m-M)_{0,M101} \simeq 0.40$ mag. The observations by Macri *et al.* (2006) for M106 imply a difference of $\Delta(m-M)_{0,M106} \simeq 0.25$ mag (Fig. 4, $P \geq 7$ d), with the caveat that the results for M106 by Maoz *et al.* (1999) and Newman *et al.* (2001) are omitted. Applying a period-cut ($P \geq 12$ d) to the inner region's sample as indicated by Macri *et al.* (2006) reduces the offset to $\Delta(m-M)_{0,M106} \simeq 0.14$ mag (see also Fig. 17, Macri *et al.* 2006), however, an anomalous *VI* Wesenheit slope remains and is a concern. Nevertheless, evaluating $\delta(m-M)_0/\delta[O/H]$ by straight division rather than applying a linear fit to the data, an analysis of M106 indicates that the functional dependence of metallicity on distance appears more aptly characterized as non-linear (*e.g.*, a polynomial, Fig. 4), yields $\gamma \approx -0.5$ mag/dex. The required metallicity correction appears too large to account for the offset between the inner and outer regions of the galaxies examined.
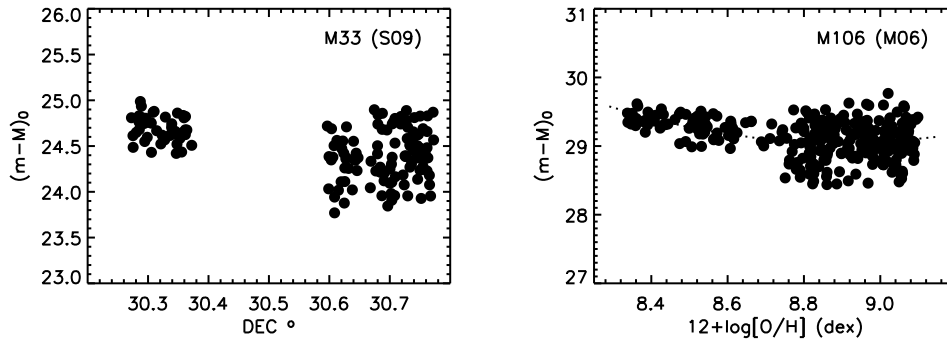

Fig. 4. Cepheid declination–distance and abundance–distance diagrams for the galaxies M33 (*left*, photometry from Scowcroft *et al.* 2009) and M106 (*right*, photometry from Macri *et al.* 2006). *Right*, the data can be represented by a polynomial fit.

Galactic classical Cepheids provide a metallicity-uncorrected distance to the LMC, SMC, and IC 1613 of $(m-M)_0 \simeq 18.45$ mag, 18.93 mag, 24.35 mag (*e.g.*, Majaess *et al.* 2008a and Table 2). Applying a more modest metallicity correction of $\gamma \simeq -0.3$ mag/dex reduces the distance to the LMC, SMC, and IC 1613 to $(m-M)_0 \simeq 18.35$ mag, 18.70 mag, 24.05 mag. The latter value for IC 1613 is especially disconcerting. However, yet again IC 1613 provides a unique opportunity to verify the proposed metallicity effect owing to the sizeable abundance difference between classical Cepheids in the Milky Way and that galaxy ($\Delta[Fe/H] \simeq 1$, see Section 3.1). Consider the following tests comparing distances to RR Lyr variable stars and Cepheids at a common zero-point (*e.g.*, IC 1613 and the SMC). Benedict *et al.* (2002) obtained a parallax for RR Lyr using the Hubble Space Telescope, which when averaged with the Hipparcos estimate yields an absolute magnitude of $M_V \simeq 0.54$ mag (van Leeuwen *et al.* 2007, Feast *et al.* 2008). The metallicity of RR Lyr is similar to variables of its class in IC 1613, namely $[Fe/H] \simeq -1.4$ (Dolphin *et al.* 2001, Benedict *et al.* 2002, Feast *et al.* 2008). Consequently, no

metallicity correction is required when evaluating the distance to RR Lyr variable stars observed in IC 1613. It follows that the distance to 14 RR Lyr variable stars observed in IC 1613 (Dolphin *et al.* 2001) is $(m-M)_0 = 24.33 \pm 0.08$ mag (assuming $M_V \simeq 0.54$ mag, $E_{B-V} = 0.05$ mag). That is in agreement with the classical Cepheid estimate (Table 2) and negates a sizeable metallicity effect. Likewise, the distance to RR Lyr variable stars observed in the SMC (Soszyński *et al.* 2002) is $(m-M)_0 = 18.87 \pm 0.13$ mag ($E_{B-V} = 0.08$ mag). Efforts are underway to secure a distance to the SMC and IC 1613 *via* a reddening-independent relation for RR Lyr variables.

In sum, the results provide the impetus to question a sizeable metallicity effect (see also Udalski *et al.* 2001, Pietrzyński *et al.* 2004, Majaess *et al.* 2009).

A possible alternative to invoking the effects of metallicity to explain the observed offset in distance between the inner and outer regions is a changing ratio of selective to total extinction, or to consider the spurious photometric effects inherent to sampling the inner regions of galaxies. Cepheids sampling the inner crowded regions of M33 and M106 exhibit larger scatter than classical Cepheids sampling the outer region (Fig. 4). For the inner region of M106 the scatter arises in part from a shifting zero-point between shorter and longer-period Cepheids (see also Fig. 17, Macri *et al.* 2006). That may arise because of a different extinction law than adopted or photometric contamination. The distance to the inner regions of M33, M106, and M101 are approximately 10% smaller than values derived for Cepheids in the outer regions. The trend may be consistent with that expected from crowding and blending (Stanek and Udalski 1999, Mochejska *et al.* 2000, 2001). Macri *et al.* 2006 and Scowcroft *et al.* 2009 describe their efforts to assess and mitigate such effects for M106 and M33, and readers are referred to their studies. The debate surrounding the impact of blending and crowding is as contentious as that of metallicity, highlighting the importance of continuing efforts analogous to the aforementioned studies. It is tempting to invoke similarities in distance for type II and classical Cepheids (Table 2) as a measure of the effects of metallicity and photometric contamination. Presently, however, an analysis is hindered by small statistics and large uncertainties. Inevitably, determining the dependence of metallicity on Cepheid distances and colors using nearby galaxies (*e.g.*, SMC) shall break the degeneracy and facilitate an assessment regarding the effects of crowding and blending on Cepheids in distant galaxies. More work is needed here.

4.   Parametrization for Interstellar Extinction

A new photometric period–reddening relation based on *VI* photometry is derived to address concerns surrounding the effect of metallicity on Cepheid variables (Section 3). That relation shall also facilitate the mapping of interstellar reddening for regions of the Milky Way and beyond. A classical Cepheid's color excess can

be closely approximated (the instability strip exhibits width) by noting that:

$$E_{B-V} = \alpha \log P + \beta(m_{\lambda 1} - m_{\lambda 2}) + \phi$$

where α, β, and ϕ are coefficients that can be derived by minimizing the χ^2 statistic for a calibrating data set (Table 1 of Majaess *et al.* 2008a), and $m_{\lambda 1}$ and $m_{\lambda 2}$ are photometric magnitudes in different passbands. The optimum solution is:

$$E_{B-V} = -0.28 \log P + 0.74(V - I) - 0.27 \qquad (2)$$

which reproduces the calibrating set with an average uncertainty of ± 0.03 mag. The true scatter applying to use of the relationship for individual classical Cepheids shall be larger, particularly for extragalactic variables. *VJ*, *VH*, and *VK* relations are also practical alternatives for determining the color excess (Majaess *et al.* 2008a) and may provide first order estimates to complement reddenings derived by means of BVI_c photometry (Laney and Stobie 1994, Laney and Caldwell 2007), spectroscopic analyzes (Kovtyukh *et al.* 2008), and space reddenings (Turner 1984, Benedict *et al.* 2007, Turner *et al.* 2008).

5.   Summary and Discussion

60+ extragalactic type II Cepheid candidates were tentatively identified in the galaxies IC 1613, M106, M101, M33, M31, NGC 4603, and the SMC, complementing potential type II Cepheids found elsewhere in the LMC, NGC 3198, NGC 5128, etc. A subsequent study examining the extensive DIRECT and CFHT observations for M31 and M33 shall result in a sizeable increase to the statistics (Macri 2004, Bersier *et al.* 2008). A subsample of potential type II Cepheids is presented in Table 2. The list may be contaminated by variables of differing classes which overlap the Wesenheit relation characterizing type II Cepheids.

The distances established to a set of galaxies from type II Cepheids agree with estimates in the literature (Table 2). That sample includes several galaxies located beyond the Local Group (*e.g.*, M106, Macri *et al.* 2006). Presently, the uncertainties are large and identifications preliminary, yet the results are encouraging and underscore a pertinent role for type II Cepheids.

Type II Cepheids were likely purged from the final published results of classical Cepheid studies owing to their spurious positions on classical Cepheid period–magnitude relations. A re-examination of the original data may indeed be rewarding. Dedicated surveys of type II Cepheids (and RR Lyr variable stars) in nearby galaxies are also anticipated, analogous to that conducted of the LMC (Udalski 1999, Soszyński 2002, 2008). As demonstrated in Section 3, the continued discovery of type II Cepheids, RR Lyr variable stars, and classical Cepheids at a common zero-point shall result in direct constraints on the effects of metallicity on Cepheid distances and colors (*e.g.*, SMC and IC 1613). So too will the establishment of multiband photometry for type II Cepheids and RR Lyr variable stars in globular

clusters (Clement *et al.* 2001, Pritzl *et al.* 2003, Horne 2005, Matsunaga *et al.* 2006, Randall *et al.* 2007, Rabidoux *et al.* 2007, Corwin *et al.* 2008). A forthcoming study shall describe how such efforts are being pursued from the Abbey-Ridge Observatory (ARO) (Majaess *et al.* 2008b, Turner *et al.* 2009). Ongoing photometric monitoring from observatories like the ARO, in harmony with archival photometry from the Harvard College Observatory Plate Stacks (Grindlay *et al.* 2009), shall also enable the period evolution of these stars to be ascertained to support evolutionary models (Wallerstein 2002, Turner *et al.* 2006). A holistic approach shall be pursued and modest telescopes may serve a constructive role (Percy 1980, 1986, Szabados 2003, Paczyński 2006, Turner *et al.* 2009).

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