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Assessing potential cluster Cepheids from a new distance and reddening parametrization and Two Micron All Sky Survey photometry

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ABSTRACT

A framework is outlined to assess Cepheids as potential cluster members from readily available photometric observations. A relationship is derived to estimate colour excess and distance for individual Cepheids through a calibration involving recently published *Hubble Space Telescope* parallaxes and a cleaned sample of established cluster Cepheids. Photometric $V - J$ colour is found to be a viable parameter for approximating a Cepheid's reddening. The non-universal nature of the slope of the Cepheid period–luminosity relation for *BV* photometry is confirmed. By comparison, the slopes of the *VJ* and *VI* relations seem relatively unaffected by metallicity. A new Galactic Cepheid confirmed here, GSC 03729−01127 (F6-G1 Ib), is sufficiently coincident with the coronal regions of Tombaugh 5 to warrant follow-up radial velocity measures to assess membership. CCD photometry and O–C diagrams are presented for GSC 03729−01127 and the suspected cluster Cepheids AB Cam and BD Cas. Fourier analysis of the photometry for BD Cas and recent estimates of its metallicity constrain it to be a Population I overtone pulsator rather than a Type II s-Cepheid. AB Cam and BD Cas are not physically associated with the spatially adjacent open clusters Tombaugh 5 and King 13, respectively; the latter being much older ($\log \tau \simeq 9$) than believed previously. Rates of period change are determined for the three Cepheids from archival and published data. GSC 03729−01127 and AB Cam exhibit period increases, implying fifth and third crossings of the instability strip, respectively, while BD Cas exhibits a period decrease, indicating a second crossing, with possible superposed trends unrelated to binarity. More importantly, the observed rates of period change confirm theoretical predictions. The challenges and prospects for future work in this area of research are discussed.

Key words: stars: distances – stars: fundamental parameters – Cepheids.

1 INTRODUCTION

The All Sky Automated Survey (ASAS; Pojmanski 2000), the Northern Sky Variability Survey (NSVS; Woźniak et al. 2004) and The Amateur Sky Survey (TASS; Droege et al. 2006) have detected many new Cepheid variables through their photometric signatures, resulting in a valuable expansion of the Galactic Cepheid sample (Samus et al. 2004) once confirmed by spectroscopic observation. In the case of GSC 03729−01127 (TASSIV 6349369), a suspected Cepheid studied here, the variable may be an open cluster member and a potentially valuable calibrator for the Cepheid period–luminosity (PL) relation. Cepheids continue to provide the foundation for the universal distance scale, and such variables could serve as an efficient means of quantifying the extinction to Galactic and extragalactic targets.

The results of the seminal *Hubble Space Telescope* (*HST*) Key Project yielded a Hubble constant of $H_0 = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Freedman et al. 2001), a value supported by cosmological constraints inferred from *Wilkinson Microwave Anisotropy Probe* (*WMAP*) observations (Spergel et al. 2007). The *HST* results are tied to Large Magellanic Cloud (LMC) Cepheids, which advantageously provide a large sample of common distance. However, distance estimates for the LMC exhibit an unsatisfactorily large scatter (Freedman et al. 2001; Benedict et al. 2002), resulting in an uncertain zero-point. Moreover, there exists a difference in metallicity between LMC Cepheid variables relative to both Galactic Cepheids and those in galaxies used for calibrating secondary distance candles, the effects of which remain actively debated. Tammann, Sandage &

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Reindl (2003), for example, suggested that the LMC–Cepheid PL relation appears to characterize short-period Cepheids as too bright relative to their Galactic counterparts and long-period Cepheids as too faint. Conversely, van Leeuwen et al. (2007) and Benedict et al. (2007) suggested, on the basis of revised *Hipparcos* and newly derived *HST* parallaxes, that the slopes of the PL relations (V, I) for Cepheids in the Galaxy and the LMC are consistent within their cited uncertainties. Indeed, the results presented in Section 3.2, complementing in part those of Fouqué et al. (2007), appear to confirm ideas put forth in each of the above studies, namely that the slope of the PL relation is not universal in certain passbands, and for *VJ* and *VI* constructed relations, any putative difference in slope arising from metallicity effects appears negligible in comparison with other concerns and uncertainties related to extragalactic observations. Nevertheless, a consensus has yet to emerge, and a resolution to the above debate may be assisted by renewed efforts towards establishing Galactic Cepheids as cluster members, a connection that provides direct constraints on Cepheid luminosities, intrinsic colours, masses, metallicities and pulsation modes.

Turner & Burke (2002) compiled an extensive list of suspected cluster Cepheids based upon preliminary analyses, but only a few cluster/Cepheid pairs have been studied with the necessary detail to determine the parameters of the associated clusters accurately, or to obtain the necessary radial velocity measures needed to establish membership in cases where reliable proper motions are unavailable. Efforts to discover new Galactic open clusters (Alessi, Moitinho & Dias 2003; Moitinho, Alessi & Dias 2003; Kronberger et al. 2006) and Cepheid variables (Pojmanski 2000; Woźniak et al. 2004; Droege et al. 2006) have also resulted in a welcome increase to the number of suspected cluster Cepheids. This paper outlines a framework to assess the viability of such cases efficiently, with an intent to highlight cases requiring further attention and focus. Section 3 develops a relationship to estimate colour excesses and distances for individual Cepheids from several photometric parameters. Section 4 presents CCD photometry, spectroscopic results and O–C analyses for the suspected cluster Cepheids BD Cas (Tsarevsky, Ureche & Efremov 1966; Turner & Burke 2002), AB Cam (van den Bergh 1957; Tsarevsky et al. 1966) and a new Galactic Cepheid confirmed here, GSC 03729−01127. Distances, colour excesses and ages are also derived for the associated open clusters Tombaugh 5 and King 13 from Two Micron All Sky Survey (2MASS) photometry (Cutri et al. 2003).

2 DATA ACQUISITION AND REDUCTIONS

Light curves for the Cepheids presented here were constructed from CCD photometry obtained with the 0.3-m Schmidt–Cassegrain telescope of the Abbey Ridge Observatory (ARO), an automated facility located outside of Halifax, Nova Scotia. A description of the facility, its equipment and the data reduction procedures used for the observations are given elsewhere (Majaess et al. 2008). Low-dispersion spectra at 120 Å mm^{-1} were obtained for the Cepheids with the Dominion Astrophysical Observatory's 1.8-m Plaskett telescope in 2006 October using the SITe-2 CCD detector. The spectra were reduced and analysed using the National Optical Astronomy Observatory's routines in IRAF, along with software packages by Christian Buil (IRIS), Valerie Desnoux (VSPEC) and Robert H. Nelson (RAVEREC).

Rates of period change for the Cepheids studied here were determined through O–C analyses using light curves constructed primarily from the data derived from visual scanning of images in the Harvard College Observatory Photographic Plate Collection. Software tailored for the analysis of Cepheid light curves (see Turner & Berdnikov 2004) was used to determine the offsets in phase and magnitude space that minimize the χ^2 statistic when matching input light curves to a standard template.

3 CEPHEID–DISTANCE RELATION

The distance to a Cepheid can be established through adoption of intrinsic parameters from published PL ($\langle M_V \rangle$ versus $\log P$) and period–colour [$(B - V)_0$ versus $\log P$] relations, although such estimates typically idealize the result to an object located near the centre of the instability strip. Neglect of the intrinsic scatter inherent to such relationships can affect estimates of colour excess and distance to individual Cepheids made from them, since the variable may lie anywhere within the strip (e.g. towards the red or blue edge). Large calibrating data sets are therefore required when constructing strict two-parameter Cepheid relations to ensure a reasonably even sampling of both sides of the strip and to avoid a least-squares solution biased towards pre-dominantly red or blue edge objects, an important consideration that is often overlooked.

A distance relation applicable to Cepheid variables is formulated here, motivated by the work of Opolski (1983, 1988). Consider the canonical distance modulus equation

$$5 \log d = V - A_V - M_V + 5, \qquad (1)$$

where $A_V = R_V \times E_{B-V}$ and $E_{B-V} = (B - V) - (B - V)_0$. The standard PL–colour relation for Cepheids can be expressed as

$$M_V = a \log P + b(B - V)_0 + c.$$

Equation (1) can therefore be rewritten as

$$5 \log d = V - a \log P - b(B - V) + (b - R_V)E_{B-V} - c + 5,$$

or

$$5 \log d = V + \alpha \log P + \beta(B - V) + \delta E_{B-V} + \gamma. \qquad (2)$$

A calibrating set (Table 1) consisting of established cluster Cepheids and Cepheids with parallaxes measured recently with the *HST* (Benedict et al. 2007) was used to determine the coefficients in equation (2) that minimize the χ^2 statistic, yielding an optimum solution given by

$$5 \log d = V + 3.77 \log P - 2.40(B - V) - E_{B-V} + 7.03.$$

The resulting relationship reproduces the distances for the calibrating set with formal average uncertainties of ±3 per cent (Fig. 1). The true scatter applying to use of the relationship for individual Cepheids shall be larger.

The colour excess term can also be characterized in terms of observable parameters as

$$E_{B-V} = \eta \log P + \lambda(V - J) + \phi, \qquad (3)$$

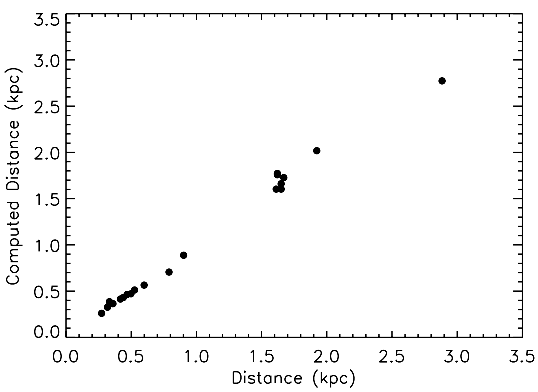
where $(V - J)$ colour appears to be a viable surrogate for determining colour excess, although *H*- or *K*-band photometry could be substituted for *J*. A test of the colour excess relation using $(V – H)$ and $(V–K)$ produced slightly larger χ^2 statistics than when $(V–J)$ was used as the colour index, so the latter was adopted in the present study.

Suitable infrared and optical photometry for the calibrating Cepheids (Table 1) was obtained from Laney & Stobie (1992), Groenewegen (1999) and sources identified by Fouqué et al. (2007)

Table 1. Calibrating data set.

Cepheid	Period (d)	Cluster	Distance (pc)	E_{B-V}	Source
EV Sct	4.39	NGC 6664	1612	0.64	(1)
CF Cas	4.88	NGC 7790	2884	0.57	(2,3)
CV Mon	5.38	van den Bergh 1	1650	0.75	(4)
QZ Nor	5.47	NGC 6067	1621	0.35	(5)
V Cen	5.49	NGC 5662	790	0.31	(6)
V367 Sct	6.29	NGC 6649	1650	1.27	(7,8)
U Sgr	6.75	IC 4725	599	0.43	(9,10)
DL Cas	8.00	NGC 129	1670	0.47	(11)
S Nor	9.75	NGC 6087	902	0.17	(12)
TW Nor	10.79	Lyngå 6	1923	1.22	(13,14,10)
V340 Nor	11.29	NGC 6067	1621	0.35	(5)
RT Aur	3.73	...	417	0.051	(15)
T Vul	4.44	...	526	0.064	(15)
FF Aql	4.47	...	356	0.224	(15)
δ Cep	5.37	...	273	0.092	(15)
Y Sge	5.77	...	469	0.205	(15)
X Sgr	7.01	...	333	0.197	(15)
W Sgr	7.59	...	439	0.111	(15)
β Dor	9.84	...	318	0.044	(15)
ζ Gem	10.15	...	360	0.018	(15)
ℓ Car	35.55	...	498	0.17	(15)

Data sources: (1) Turner (1976), (2) Pedreros, Madore & Freedman (1984), (3) Takala (1988), (4) Turner et al. (1998), (5) Walker (1985b), (6) Clariá, Lapasset & Bosio (1991), (7) Madore & van den Bergh (1975), (8) Turner (1981), (9) Pel (1985), (10) Turner & Burke (2002), (11) Turner, Forbes & Pedreros (1992), (12) Turner (1986), (13) Madore (1975), (14) Walker (1985a) and (15) Benedict et al. (2007).



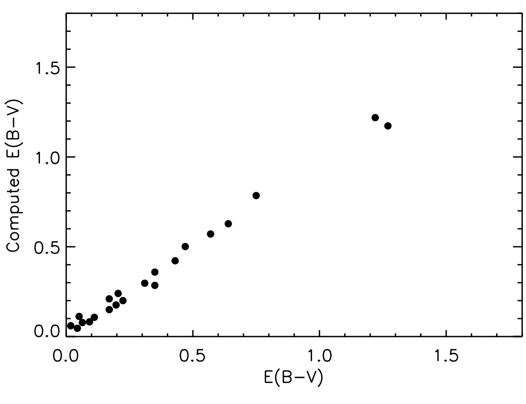


Figure 1. A comparison of the output from the Cepheid relations developed in Section 3 with literature values.

(see discussion in their section 2.1), with J-band measures being standardized on the 2MASS system. The coefficients of equation (3) that minimize the χ^2 statistic are

$$E_{B-V} = -(0.270)\log P + (0.415)(V-J) - 0.255. \quad (4)$$

The coefficients of the same equation that minimize the χ^2 statistic for $(V-H)$ and $(V-K)$ are

$$E_{B-V} = -(0.33)\log P + (0.37)(V-H) - 0.27$$

and

$$E_{B-V} = -(0.30)\log P + (0.34)(V-K) - 0.27.$$

Equation (4) reproduces the reddenings for the calibrating Cepheids with an average uncertainty of ± 0.03 mag (Fig. 1), although the true scatter applying to use of the relationship for individual Cepheids will be larger. The relation makes use of V- and J-band photometry (2MASS) that are widely available, and should provide a first-order estimate in the absence of reddenings determined by means of BVI_c photometry (Laney & Stobie 1994; Laney & Caldwell 2007), spectroscopic analyses (Kovtyukh et al. 2008) or space reddenings (Laney & Caldwell 2007; Turner et al., in preparation). Alternatively, a reddening-free distance relation analogous to the Wesenheit function (van den Bergh 1968; Madore 1982) can be constructed by setting $\delta = 0$ (equation 3), which results in a negligible increase in the χ^2 statistic relative to the optimum solution in equation (3). A reanalysis of the coefficients then yields

$$5\log d = V + (4.42)\log P - (3.43)(B-V) + 7.15$$

$$5\log d = V + (3.43)\log P - (2.58)(V-I) + 7.50$$

$$5\log d = V + (3.30)\log P - (1.48)(V-J) + 7.63.$$

Published results raise questions about the pulsation modes of the s-Cepheids EV Sct and QZ Nor (Coulson & Caldwell 1985; Moffett & Barnes 1986; Bono et al. 2001). With the relationship derived here, the memberships of EV Sct in the cluster NGC 6664 (Mermilliod, Mayor & Burki 1987) and QZ Nor in the cluster NGC 6087 (Coulson & Caldwell 1985; Mermilliod et al. 1987), as established by radial velocity measures, imply that EV Sct and QZ Nor are overtone pulsators. Otherwise, equation (3) with the assumption of fundamental mode pulsation results in anomalous luminosities for the Cepheids, namely values that differ from those resulting from implied cluster membership by several times the mean uncertainties. Such conclusions are sensitive, however, to the distances adopted for both clusters in Table 1.

3.1 Determining ⟨*J*⟩

Reliable estimates for a Cepheid's colour excess from equation (4) require the availability of precise mean J-band magnitudes. Infrared light curves are readily available for the calibrating set (Table 1), but in most instances only single-epoch 2MASS photometry exists. The derivation of mean magnitudes from single- epoch observations is complicated by several issues. First, Cepheids undergo rapid period changes (Szabados 1977, 1980, 1981; Berdnikov 1994; Berdnikov et al. 1997; Glushkova, Berdnikov & Turner 2006; Turner et al. 2006), so a significant time lapse between single-epoch observations and those of the reference optical light curve can result in correspondingly large phase offsets. On the other hand, most Cepheids with periods between 5 and 10 d exhibit relatively slow period changes, as confirmed observationally in Section 4. Secondly, the mean magnitude deduced from single-epoch observations is less certain because the morphological structure of the light curve can

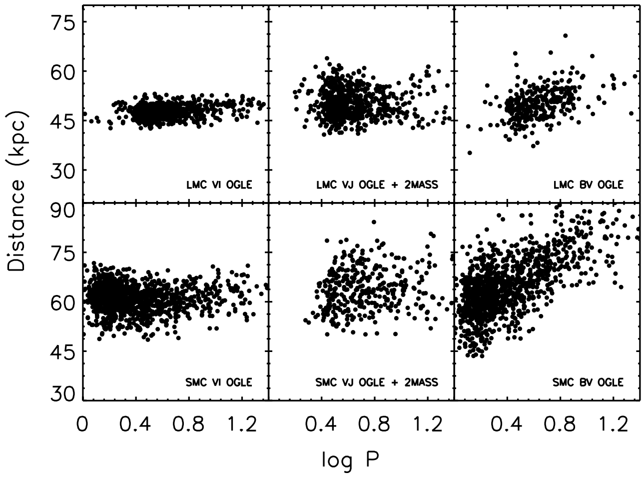


Figure 2. Cepheid distance diagrams constructed for the Magellanic Clouds (see text for details).

change between the optical and infrared (e.g. SV Vul); the former traces the temperature and the latter the radius. Deriving colour excesses for stars lacking multiple observations is undoubtedly less precise, especially for large amplitude Cepheids and those exhibiting a significant, yet usually unknown, period change.

The mean J magnitude $\langle J \rangle$ can be approximated by

$$\langle J \rangle \simeq J_{\mathrm{JD}} - \left[\frac{|\, V(\phi_J) - V_{\max} \,|}{V_{\mathrm{a}}} - 0.5 \right] J_{\mathrm{a}},$$

where J_{JD} is the magnitude for the single-epoch observation, $V(\phi_J)$ is the visual magnitude at the same phase as J_{JD}, $V_{\max}$ is the V-band magnitude of the star at maximum brightness, and V_{a} and J_{a} are the light amplitudes of the Cepheid in the visual and J band, respectively. For the V to J amplitude relation outlined by Welch et al. (1984) and Soszyński, Gieren & Pietrzyński (2005) of $J_{\mathrm{a}} \simeq 0.37 \times V_{\mathrm{a}}$, the equation becomes

$$\langle J \rangle \simeq J_{\mathrm{JD}} - \left[\frac{|\, V(\phi_J) - V_{\max} \,|}{V_{\mathrm{a}}} - 0.5 \right] 0.37 V_{\mathrm{a}}. \quad (5)$$

A derivation of the mean magnitude for the cluster Cepheids DL Cas, CV Mon, QZ Nor, V340 Nor and EV Sct, which are not saturated in the 2MASS survey and have been observed at a fairly recent epoch by ASAS, thereby minimizing the effects of period change, yields an average difference of ± 0.03 mag relative to mean J-band magnitudes found in the literature. That may be an optimistic estimate given that the light curves for Cepheids in the above sample are primarily sinusoidal and of small amplitude. In spite of the cited uncertainties for single-epoch 2MASS observations ($\Delta J \simeq \pm 0.03$ mag) and the above considerations, equation (5) proves to be a satisfactory approximation for determining $\langle J \rangle$.

3.2 Extragalactic comparisons

The distance to the LMC and Small Magellanic Cloud (SMC) can be established by adopting the reddening-free relations highlighted earlier and utilizing V and I photometry from Optical Gravitational Lensing Experiment (OGLE) (Udalski et al. 1999), V and J photometry from a combined set of OGLE and 2MASS data compiled by the authors (see Fig. 2),[1] and B and V photometry from OGLE. The first two methods yield distance moduli to the LMC of 18.39 ± 0.09 and 18.49 ± 0.19. The distance moduli to the SMC derived from *VI* and *VJ* photometry are 18.93 ± 0.14 and 19.02 ± 0.22.

The diagrams constructed from reddening-free *VI* and *VJ* relations remain generally unbiased towards redder colours, but there is an obvious bias for the *BV* distances that may be attributed to line blanketing effects arising from metallicity differences among Milky Way, LMC and SMC Cepheids. The effect is more pronounced for the SMC, an expected trend given that SMC Cepheids exhibit a lower metallicity than those of the LMC (e.g. Mottini 2006). The results confirm that the slope of the PL relation is not universal when based on *BV* photometry, while by comparison, the slopes for the *VJ* and *VI* relations seem relatively unaffected by metallicity. The derived distances are consistent with values found in the literature (see Laney & Stobie 1994; Benedict et al. 2002), although distances cited in other studies are preferred since a putative zero-point metallicity correction was not addressed here. The *VJ* result establishes the viability of 2MASS photometry in such analyses in spite of the survey's single-epoch observations. Indeed, the uncertainty in the *VJ* result could be reduced by approximating the mean $\langle J \rangle$-band magnitude according to the prescription described earlier or that described by Soszyński et al. (2005). Lastly, it is noted that biases towards redder colours may also result from standardization problems (see fig. 14 of Zaritsky et al. 2002).

The giant elliptical galaxy NGC 5128 hosts large numbers of Cepheids, and Ferrarese et al. (2007) derived a distance of 3.1 ± 0.1 Mpc to the galaxy using the Wesenheit PL calibration (see table 6 and section 5.3 in their paper). The distance to NGC 5128 established with the reddening-free *VI* relation formulated in Section 3 is 3.1 ± 0.5 Mpc. Star C 43 in table 5 of Ferrarese et al. (2007) is presumably not a Type I Cepheid. Similarly, Phelps et al. (1998) derived a distance of 12.03 ± 0.9 Mpc to NGC 2090 from Cepheids, while the reddening-free *VI* relation given here yields a comparable distance of 11.8 ± 1.3 Mpc. A broader analysis including a larger sample of galaxies is needed to draw any meaningful conclusions, but to first order the results are in agreement.

4 POTENTIAL CLUSTER CEPHEIDS

4.1 GSC 03729−01127

The Cepheid-like variations of GSC 03729−01127 were noted by Mike Sallman and Wils & Greaves (2004) while inspecting TASS and NSVS observations, respectively. Preliminary analysis of the TASS data produced a period of $P \simeq 5.074$ d, a value closely approximated by our observations, which yield $P = 5.065 \pm 0.008$ d. A period analysis of the photometry was carried out in the PERANSO software environment (Vanmunster 2007) using the algorithms ANOVA (Schwarzenberg-Czerny 1996), FALC (Harris et al. 1989) and CLEANEST (Foster 1995). The phased light curve (Fig. 3) has an amplitude of $\Delta V \simeq 0.72$ mag ($\Delta B \simeq 1.09$ mag in the blue) and displays a typical Cepheid signature with a rapid rise from minimum to maximum.

Spectroscopy confirms that the variable is indeed a Cepheid, displaying spectral variations from F6 Ib to G1 Ib over its cycle. All-sky *BV* photometry for GSC 03729−01127 was obtained on several nights, with extinction coefficients derived using techniques outlined by Henden & Kaitchuck (1998) and Warner (2006). The photometry was standardized to the Johnson system using stars in the nearby open cluster NGC 225 (Hoag et al. 1961). The mean magnitude and colour are $\langle V \rangle \simeq 10.90$ and $\langle B - V \rangle \simeq 1.67$, which,

[1] The OGLE + 2MASS data set for the LMC and SMC is available online at the Vizier data base.

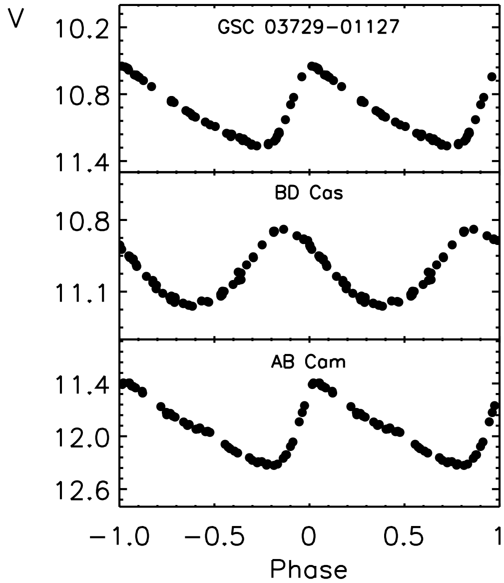


Figure 3. The light curves for the Cepheids GSC 03729−01127, BD Cas and AB Cam, constructed from differential photometry obtained at the ARO. Standard deviations across check stars in the Cepheid fields typically range from ±0.006 to ±0.008 mag.

with the formulation of Section 3, result in an estimated distance of $d = 1230 \pm 120$ pc and a colour excess of $E_{B-V} = 1.05 \pm 0.05$. The Cepheid is assumed to be pulsating in the fundamental mode, as inferred from the morphological structure of its light curve (see Beaulieu 1995; Welch et al. 1995; Beaulieu & Sasselov 1998).

The Cepheid lies 21.9 arcmin from the core of Tombaugh 5 (Tombaugh 1941), an open cluster estimated to be ∼1.8 kpc distant (Reddish 1954). Maciejewski & Niedzielski (2007) provided a more recent estimate of $d = 1.33 \pm 0.33$ kpc, which is smaller than $d = 1.75 \pm 0.15$ kpc derived by Lata et al. (2004) from multiband photometry. The data of both groups imply a reddening of $E_{B-V} \simeq 0.8$. An analysis of 2MASS photometry for the field, fitted with a solar isochrone (Fig. 4) from the Padova data base of stellar isochrones (Bonatto, Bica & Girardi 2004), implies a cluster age of $\log\tau = 8.35 \pm 0.15$, a distance of $d = 1.66 \pm 0.20$ kpc and a reddening of $E_{J-H} = 0.22 \pm 0.02$ ($E_{B-V} \simeq 0.81$ according to the relations established in Section 5).

Star counts were made for Tombaugh 5 from 2MASS data, relative to a cluster centre at 03:47:56, +59:04:59 (J2000) found from strip counts on the Palomar survey E-plate of the field. The data (Fig. 5) imply a nuclear radius for the cluster of $r_{\rm n} \simeq 8$ arcmin and a coronal radius of $R_{\rm c} \simeq 23$ arcmin in the notation of Kholopov (1969). GSC 03729−01127 lies close to the cluster's tidal limit, which raises questions about its possible association with Tombaugh 5. The progenitor mass of GSC 03729−01127 can be estimated from its pulsation period as $\sim 4\,{\rm M}_{\odot}$ (see Turner 1996), consistent with the implied turnoff mass for Tombaugh 5 and a possible physical association.

Although the star count evidence is only marginally consistent with membership of GSC 03729−01127 in Tombaugh 5, the similarity of the distance estimates and evolutionary ages for Cepheid and cluster are sufficient to warrant follow-up radial velocity measures, which are needed before reaching any conclusions regarding membership. A list of likely cluster members has been tabulated for such a purpose (Table 2), with membership inferred from a correlation between a star's position in the 2MASS colour–colour and colour–magnitude diagrams.

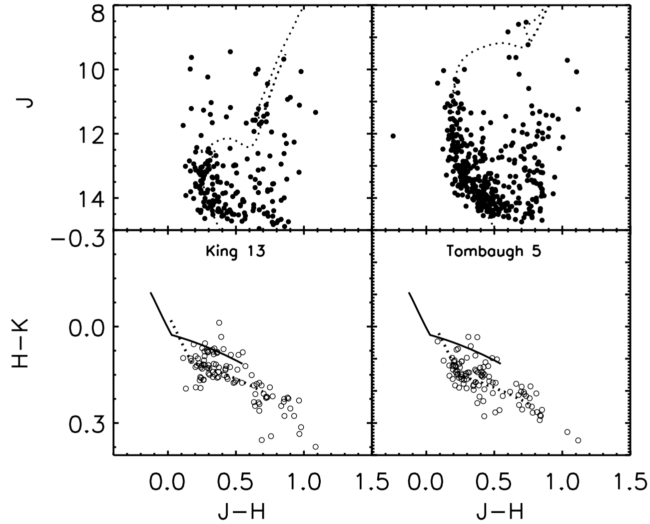


Figure 4. Colour–colour and colour–magnitude diagrams for King 13 (left-hand panel) and Tombaugh 5 (right-hand panel) constructed from 2MASS data. Clearly visible sequences of AF-type stars (King 13) and late-B-type stars (Tombaugh 5) produce reddenings of $E_{J-H} = 0.14 \pm 0.02$ ($E_{B-V} \simeq 0.52$) and $E_{J-H} = 0.22 \pm 0.02$ ($E_{B-V} \simeq 0.81$), respectively. King 13 and Tombaugh 5 have inferred ages of $\log\tau = 9.0 \pm 0.2$ and $\log\tau = 8.35 \pm 0.15$, and distances of $d = 2.55 \pm 0.50$ and 1.66 ± 0.20 kpc, respectively (see text). A reddening relationship of $E_{J-H} = 1.72 \times E_{H-K}$ was adopted from Bica & Bonatto (2005) and Dutra et al. (2002).

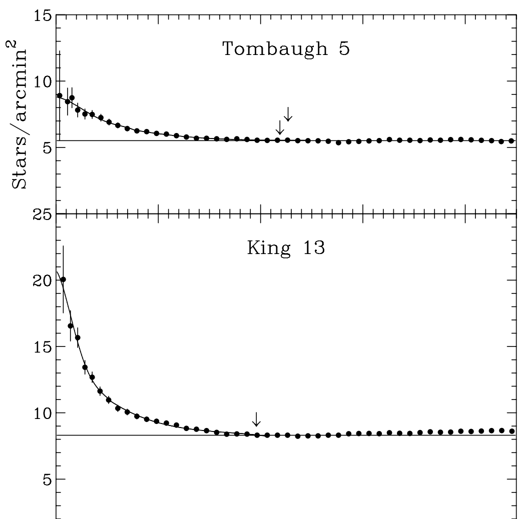


Figure 5. Star counts for the open clusters Tombaugh 5 and King 13, compiled from 2MASS observations. Arrows indicate the locations of GSC 03729−01127 and AB Cam (inner and outer points, upper figure) and BD Cas (lower figure) relative to their respective cluster centres.

The Cepheid's evolutionary history was examined through O–C analysis (Fig. 6 and Table 3), based primarily upon photographic light curves obtained from the examination of archival images in the Harvard College Observatory Photographic Plate Collection, supplemented by CCD observations from NSVS, TASS, ASAS, the ARO and data from a continuing program of Cepheid monitoring at

Table 2. Likely evolved B-type members of Tombaugh 5.

2MASS designation	J
03473515+5907588	10.307
03482167+5903410	11.607
03481681+5901295	11.321
03471767+5904333	11.542
03473265+5901398	11.589
03481650+5905219	12.018

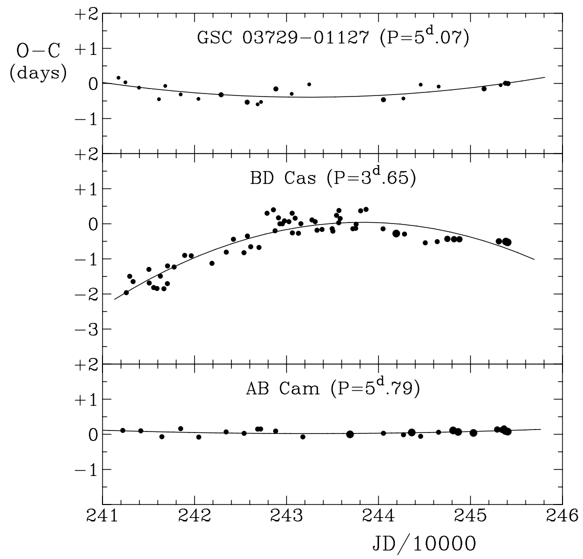


Figure 6. The O–C diagrams for GSC 03729−01127, BD Cas and AB Cam (from top to bottom panel), including observations compiled by Szabados (1977, 1983). The size of each data point is proportional to the weight assigned in the analysis, and the parabola in each case represents a regression fit.

Table 3. O–C data for GSC 03729−01127.

JD_{max}	Cycles	O–C (d)	Data points	Weight	Source
241 1726.028	−8207	+0.162	13	1.0	(1)
241 2480.634	−8058	+0.031	13	1.0	(1)
241 3959.564	−7766	−0.121	25	1.0	(1)
241 6127.206	−7338	−0.450	11	1.0	(1)
241 6816.473	−7202	−0.070	22	1.0	(1)
241 8492.862	−6871	−0.312	19	1.0	(1)
242 0417.567	−6491	−0.440	24	1.0	(1)
242 2894.642	−6002	−0.321	8	1.0	(1)
242 5720.892	−5444	−0.536	8	1.0	(1)
242 6855.472	−5220	−0.595	28	1.0	(1)
242 7225.308	−5147	−0.529	11	1.0	(1)
242 8841.526	−4828	−0.157	27	1.0	(1)
243 0563.605	−4488	−0.298	15	1.0	(1)
243 2463.383	−4113	−0.026	14	1.0	(1)
244 0537.114	−2519	−0.463	13	1.0	(1)
244 2710.182	−2090	−0.430	27	1.0	(1)
244 4584.756	−1720	−0.036	24	1.0	(1)
244 6534.863	−1335	−0.089	34	1.0	(1)
245 1478.579	−359	−0.154	69	3.0	(2)
245 3284.296	−3	−0.049	94	3.0	(3)
245 3808.799	+101	+0.005	18	3.0	(4)
245 4087.385	+156	−0.003	49	3.0	(5)

Data sources: (1) Harvard collection, (2) NSVS, Woźniak et al. (2004), (3) TASS, Droege et al. (2006), (4) Burke-Gaffney Observatory and (5) Abbey Ridge Observatory.

the Burke-Gaffney Observatory of Saint Mary's University (Turner, Pedreros & Walker 1998; Turner, Horsford & MacMillan 1999; Turner et al. 2005). An adopted ephemeris of

$$JD_{max} = 245\,3297.1935 + 5.065\,35E,$$

where E is the number of elapsed cycles, was found to fit the observations reasonably well over the last century and was used to phase the data. GSC 03729−01127 appears to be undergoing a gradual period increase of $+0.272 \pm 0.088\,\mathrm{s\,yr^{-1}}$, confirming theoretical predictions on rates of period change for $P \simeq 5$ d Cepheids as outlined by Turner et al. (2006). The rate of period change indicates that the Cepheid is evolving towards the red edge of the instability strip in the third or fifth crossing (Turner et al. 2006). There is some ambiguity, given the Cepheid's small pulsation amplitude, but that is resolved from the reddening derived here. GSC 03729−01127 appears to lie on the cool (red) edge of the instability strip, in which case its rate of period increase and small pulsation amplitude imply that it is in the fifth crossing of the strip.

4.2 BD Cas

BD Cas is a small-amplitude, sinusoidal, 3.65 d Cepheid ($\Delta V \simeq 0.33$; Fig. 3) discovered by Beljawsky (1931). Increased sampling and precision photometry indicate that the variations are not purely sinusoidal (Fig. 3), although the star could still qualify as an s-Cepheid. There is some uncertainty regarding the variable's pulsation mode and population type (Kienzle et al. 1999, see references and discussion therein). Kienzle et al. (1999) examined the structure of the Cepheid's radial velocity curve in Fourier space using CORAVEL measures and data from Gorynya, Rastorguev & Samus (1996) and noted that the values of A_1 and R_{21} are consistent with overtone pulsation, whereas ϕ_{21} is not. They argued that the analysis was hampered by large uncertainties because of undersampling, with further observations needed to constrain the pulsation mode unambiguously.

A Fourier analysis of the new ARO photometry yields an amplitude ratio of $R_{21} = 0.113 \pm 0.010$ and $\phi_{21} = 3.50 \pm 0.09$, which imply overtone pulsation by the criteria of Beaulieu & Sasselov (1998) and Zabolotskikh et al. (2005). The Cepheid's near-solar metallicity of [Fe/H] $= -0.07$ (Andrievsky et al. 2002) and Galactic location ($\ell, b = 118, -1$) are consistent with other Population I variables, which suggests that BD Cas is a classical Cepheid pulsating in the first overtone. The Cepheid's spectral type exhibits only small variations, from F6 II to F7 Ib. It should also be noted that a viable framework for discriminating a Cepheid's population type by means of Fourier analysis is yet to emerge (Fernie & Ehlers 1999).

BD Cas lies 19.6 arcmin from the open cluster King 13 (King 1949) and ~16 arcmin from the suspected cluster Czernik 1 (Czernik 1966). Marx & Lehmann (1979) examined King 13 using photographic *UBV* photometry and derived a distance of $d = 1730 \pm 200$ pc and a reddening of $E_{B-V} = 0.38$. Subramaniam & Bhatt (2007) obtained a larger reddening of $E_{B-V} = 0.82 \pm 0.02$, a larger distance of $d = 3100 \pm 300$ pc and a cluster age of $\log\tau = 8.5$ from CCD photometry, while Maciejewski & Niedzielski (2007) obtained an age of $\log\tau = 8.4$, a distance of $d = 3670 \pm 1300$ pc and a reddening of $E_{B-V} = 0.86 \pm 0.12$ by similar means. An analysis of 2MASS photometry for the field, fitted with an isochrone from the Padova data base of stellar isochrones (Bonatto et al. 2004), results in a distance of $d = 2550 \pm 500$ pc and a reddening of $E_{J-H} = 0.15 \pm 0.02$ ($E_{B-V} \simeq 0.56$ according to the relations derived in Section 5). The colour–colour and colour–magnitude diagrams are dominated by AF dwarfs (Fig. 4) and the reddening solution is well established. Moreover, the structure of the main-sequence turnoff and the clustering of red giant members (Fig. 4) indicate an age near $\log \tau = 9.0 \pm 0.15$. The distance estimate should be viewed cautiously because it is tied to stars lying near the limiting magnitude of the 2MASS survey. However, the age and reddening estimates are tied more directly to the colours of main-sequence stars, and are consequently more reliable.

Star counts were made for King 13 from 2MASS data, relative to a cluster centre at 00:10:16.47, +61:11:29.2 (J2000) found from strip counts on the Palomar survey E-plate of the field. The data (Fig. 5) imply a nuclear radius for the cluster of $r_n \simeq 6$ arcmin and a coronal radius of $R_c \simeq 20$ arcmin. BD Cas therefore lies very close to the cluster's tidal limit. With the Cepheid relationship formulated in Section 3 and pertinent photometric parameters for BD Cas (Szabados 1977), the Cepheid has an estimated distance of $d = 1520 \pm 150$ pc and a reddening of $E_{B-V} = 0.99 \pm 0.05$, which places it well foreground to the cluster, but curiously with a larger reddening. The large reddening for BD Cas is confirmed by an independent spectroscopic reddening estimate of $E_{B-V} = 1.01$ (Kovtyukh et al. 2008). A possible physical association between the cluster and Cepheid is further negated by the cluster's age, which implies a main-sequence turnoff mass near $2\,M_\odot$. There are no other known Population I cluster Cepheids associated with such a correspondingly old cluster (Turner 1996).

Lyngä (1995) has questioned the existence of the open cluster Czernik 1, which was suggested as an alternate parent cluster for BD Cas by Tsarevsky et al. (1966). Our analysis of 2MASS photometry and limited *BV* photometry for the cluster is inconclusive in that regard, so a possible connection with Czernik 1 remains unproven.

The star's evolutionary history was examined through O–C analysis (Fig. 6) using light curves constructed from data obtained from archival plates in the Harvard collection, data compiled by Szabados (1977, 1983) and more recent photoelectric and CCD photometry (Table 4). An ephemeris given by

$$\mathrm{JD_{max}} = 244\,1932.0320 + 3.650\,90E$$

was found suitable for phasing the data. BD Cas is undergoing a period decrease amounting to -0.698 ± 0.048 s yr^{-1} (Fig. 6), which, in conjunction with its derived reddening and inferred overtone status, implies a second crossing of the instability strip (Turner et al. 2006) and a star lying towards the hot (blue) edge. The rate of period change was derived from a polynomial fit (see Fig. 6), but there are deviations in the O–C data derived from recent photoelectric and CCD photometry that may indicate non-evolutionary effects. The trends are unlikely to arise from binarity, since that would imply an unrealistically large mass for the companion. Yet, binarity is not precluded and is common among Cepheids (Szabados 1995, 2003). The trends observed here and in the O–C diagrams of other Cepheids are yet to be explained satisfactorily, and remain an active and interesting area of research. Whether the superposed variations are small, as in the Cepheid RT Aur (Turner et al. 2007), or are large as in the case of the Cepheid SV Vul, the mechanism is yet to be established.

Table 4. New O–C data for BD Cas.

$\mathrm{JD_{max}}$	Cycles	O–C (d)	Data points	Weight	Source
241 2584.617	−8038	−1.964	9	1.0	(1)
241 2952.110	−7937	−1.497	7	1.0	(1)
241 3325.649	−7835	−1.647	7	1.0	(1)
241 5070.128	−7357	−1.687	8	1.0	(1)
241 5558.129	−7223	−1.818	12	1.0	(1)
241 5922.588	−7124	−1.844	11	1.0	(1)
241 6287.608	−7024	−1.493	11	1.0	(1)
241 6670.007	−6919	−1.851	20	1.0	(1)
241 7044.552	−6816	−1.705	20	1.0	(1)
241 7778.542	−6615	−1.232	40	1.0	(1)
241 9650.202	−6103	−0.912	35	1.0	(1)
242 1893.150	−5488	−1.128	30	1.0	(1)
242 3454.303	−5061	−0.808	17	1.0	(1)
242 4225.733	−4849	−0.442	7	1.0	(1)
242 5372.119	−4535	−0.825	22	1.0	(1)
242 5744.076	−4433	−0.350	8	1.0	(1)
242 6109.087	−4333	−0.654	10	1.0	(1)
242 7007.120	−4088	−0.675	13	1.0	(1)
242 9772.037	−3330	+0.083	49	1.0	(1)
243 1560.580	−2840	+0.003	43	1.0	(1)
243 3312.640	−2360	−0.183	21	1.0	(1)
244 0495.195	−393	−0.144	19	1.0	(1)
244 1932.979	+0	−0.277	21	2.0	(2)
244 2829.249	+245	−0.294	66	1.0	(1)
244 5089.520	+865	−0.541	...	1.5	(3)
244 6379.817	+1218	−0.509	100	1.0	(1)
244 7482.216	+1520	−0.431	14	2.0	(4)
244 8218.562	+1721	−0.438	98	2.0	(5)
244 8797.229	+1880	−0.442	28	2.0	(5)
245 3086.229	+3055	−0.500	55	3.0	(6)
245 3858.027	+3266	−0.506	17	3.0	(7)
245 4047.561	+3318	−0.529	56	3.0	(8)

Data sources: (1) Harvard collection, (2) Szabados (1977, 1983), (3) Busquets (1986), (4) Schmidt (1991), (5) *Hipparcos*, Perryman et al. (1997), (6) TASS, Droege et al. (2006), (7) Burke-Gaffney Observatory and (8) ARO.

4.3 AB Cam

AB Cam is a large-amplitude, 5.79 d Cepheid ($\Delta V \simeq 0.94$; Fig. 3) discovered by Morgenroth (1934). The distance to AB Cam can be estimated from Johnson system photometry (Berdnikov, Dambis & Vozyakova 2000) with the Cepheid relationship formulated in Section 3. The implied distance is $d = 4470 \pm 450$ pc with a reddening of $E_{B-V} = 0.59 \pm 0.05$. The object's light-curve morphology (Fig. 3) is consistent with fundamental mode pulsation (Beaulieu 1995; Welch et al. 1995; Beaulieu & Sasselov 1998), which was assumed for estimating the distance. van den Bergh (1957) and Tsarevsky et al. (1966) examined the field of AB Cam in search of a host cluster with null results. Despite the Cepheid's apparent angular proximity to Tombaugh 5, the two are not physically related (see Fig. 5).

The star's evolutionary history was examined through O–C analysis (Fig. 6) using photographic light curves constructed with magnitude estimates from archival plates in the Harvard collection, supplemented by more recent photoelectric and CCD photometry (Table 5). An ephemeris given by

$$\mathrm{JD_{max}} = 243\,7400.6380 + 5.787\,45E$$

proved suitable for phasing the data. AB Cam appears to be undergoing a very gradual increase of $+0.069 \pm 0.025$ s yr^{-1}. The rate is again consistent with observed rates of period change for $P \simeq 6$ d

Table 5. O–C data for AB Cam.

JD_{max}	Cycles	O–C (d)	Data points	Weight	Source
241 2196.403	−4355	+0.110	16	1.0	(1)
241 4158.338	−4016	+0.099	22	1.0	(1)
241 6444.214	−3621	−0.068	28	1.0	(1)
241 8487.415	−3268	+0.163	15	1.0	(1)
242 0454.905	−2928	−0.079	24	1.0	(1)
242 3429.801	−2414	+0.068	13	1.0	(1)
242 5391.706	−2075	+0.027	16	1.0	(1)
242 6856.054	−1822	+0.149	26	1.0	(1)
242 7185.941	−1765	+0.152	20	1.0	(1)
242 8817.943	−1483	+0.093	26	1.0	(1)
243 1769.375	−973	−0.074	92	1.0	(1)
243 6902.916	−86	−0.002	28	3.0	(2)
244 0531.679	+541	+0.030	13	1.0	(1)
244 2713.505	+918	−0.012	26	1.0	(1)
244 3610.625	+1073	+0.053	14	3.0	(3)
244 4577.019	+1240	−0.057	24	1.0	(1)
244 6527.506	+1577	+0.059	34	1.0	(1)
244 8107.531	+1850	+0.111	13	3.0	(4)
244 8657.297	+1945	+0.069	9	3.0	(5)
245 0324.052	+2233	+0.038	13	3.0	(6)
245 2905.354	+2679	+0.137	18	2.0	(7)
245 3432.000	+2770	+0.126	26	2.0	(7)
245 3651.965	+2808	+0.167	19	2.0	(7)
245 3802.368	+2834	+0.096	12	3.0	(8)
245 4051.208	+2877	+0.076	45	3.0	(9)

Data sources: (1) Harvard collection, (2) Bahner, Hiltner & Kraft (1962), (3) Harris (1980), (4) Berdnikov (1992), (5) Schmidt & Seth (1996), (6) Berdnikov, Ignatova & Vozyakova (1998), (7) TASS, Droege et al. (2006), (8) Burke-Gaffney Observatory and (9) ARO.

Cepheids (Turner et al. 2006), and indicates, in conjunction with its large pulsation amplitude, a Cepheid in the third crossing of the instability strip lying towards the cool (red) edge. The object may be of added importance given that it falls near the lower bound for an undersampled locus of short-period third crossers in the rate of period change diagram (Turner et al. 2006).

5 OPTICAL TO INFRARED RELATIONS

Distance estimates for the open clusters studied in the preceding section were established using the following expression:

$$5 \log d = [J - M_J] - E_{J-H} \times R_j + 5.$$

The infrared colour excess E_{J-H} and the distance modulus $J - M_J$ can be derived by simultaneously fitting an intrinsic relation (Turner, unpublished) and isochrone (Bonatto et al. 2004) to the stars in a colour–colour and colour–magnitude diagram (see Fig. 4). A ratio of total to selective extinction of $R_j = 2.60$ was adopted (Dutra, Santiago & Bica 2002; Bica & Bonatto 2005), and the following relationship between reddening in the infrared to that in the optical was used to permit direct comparison of cluster reddenings derived from 2MASS photometry with more frequently cited optical results found in the literature:

$$E_{J-H} = (0.27 \pm 0.03) \times E_{B-V}. \quad (6)$$

Equation (6) was established from the calibrating set of open clusters in Table 1, and compares satisfactorily with relationships cited by Laney & Stobie (1993), Bica & Bonatto (2005) and Dutra et al. (2002). The coefficient derived here is smaller, however, and may be indicative of our visual fitting biases rather than a global relationship. We refer the reader to Laney & Stobie (1993) for a more rigorous discussion of the correlation.

6 DISCUSSION

The relationships highlighted in Section 3 yield reliable parameters when investigating short-period Cepheids ($P \leq 11$ d). Parameters determined for longer period Cepheids from such relations are less certain, primarily because of an absence of mid-to-long-period calibrators needed to identify a unique set of coefficients consistent over a broad-period baseline. At present, ℓ Car is the only established long-period calibrator (parallax) used in deriving the coefficients. A further drawback of the analysis rests in the adopted parameters for the calibrating clusters, which exhibit an unsatisfactory amount of scatter in the literature and in more recent analyses (e.g. Hoyle, Shanks & Tanvir 2003; An, Terndrup & Pinsonneault 2007). Refining distance estimates to the calibrating set of clusters by means of deep CCD photometry, analogous to the impressive results from the Canada–France–Hawaii Telescope Open Cluster Survey (Kalirai et al. 2001a,b), is a priority in moving forward. The framework is also tied to the *HST* sample of Cepheids with parallaxes and field reddenings established by Benedict et al. (2007). It is noted that the parallax measures for RT Aur and Y Sge differ significantly between *HST* and *Hipparcos* (van Leeuwen et al. 2007, see their table 1).

The framework outlined here should permit an efficient investigation of suspected cluster Cepheids (Turner & Burke 2002), including objects uncovered by cross-correlations between newly discovered Cepheids in the ASAS and TASS with open cluster data bases (i.e. WebDA). A potential goal is an expansion of the sample of cluster Cepheids, with particular emphasis on long-period cluster Cepheids. Of equal importance, however, is the task of purging line-of-sight coincidences from current lists promulgating the literature, something that is particularly acute given that high-precision data are needed to address the question of the universality of the PL relation.

Four longer term objectives exist. First is to use the new relations to determine Galactic parameters and map interstellar extinction. Second is to establish mean photometry for an entire calibrating set. Third is with regard to the universality of the PL relation and establishing long-period Cepheid calibrators; realistically these will be the highly anticipated results from the GAIA Space Mission (Crifo & The French Gaia Team 2006), a next-generation follow-up to the *Hipparcos* mission, that will provide the large and unbiased sample of Cepheid parallaxes needed to advance our knowledge of the field. In conjunction with a cleaned sample of cluster Cepheids, the Gaia sample should lead to a proper refinement of the relations outlined in Section 3, and consequently, the realization of the outlined objectives. Fourth is the longer term prospect of conducting extragalactic surveys using the James Webb Space Telescope (JWST) (Gardner et al. 2006) to determine the distances and extinction to, and within (equation 4), higher redshift galaxies. The aperture size and infrared sensitivity of the telescope will permit deeper sampling of extragalactic Cepheids, especially since the variables are bright in the infrared and the diminishment in flux from reddening is comparatively less than in the optical.

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