On the metallicity dependence of classical Cepheid light amplitudes

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Abstract Classical Cepheids remain a cornerstone of the cosmic distance scale, and thus characterizing the dependence of their light amplitude on metallicity is important. Period-amplitude diagrams constructed for longer-period classical Cepheids in IC 1613, NGC 3109, SMC, NGC 6822, LMC, and the Milky Way imply that very metal-poor Cepheids typically exhibit smaller $V$-band amplitudes than their metal-rich counterparts. The results provide an alternate interpretation relative to arguments for a null and converse metallicity dependence. The empirical results can be employed to check predictions from theoretical models, to approximate mean abundances for target populations hosting numerous long-period Cepheids, and to facilitate the identification of potentially blended or peculiar objects.

Keywords Stars: oscillations · Stars: abundances · Stars: variables: Cepheids

1 Introduction

Establishing an empirically derived correlation between a classical Cepheid’s light amplitude, pulsation period, and chemical composition is important for several reasons. For example, such a pertinent link is needed to help constrain theoretical models. Model-generated period-amplitude diagrams are acutely sensitive to the input physics, the adopted mass-luminosity relation, the inclusion of convective overshooting (Bono et al. 2000a, their Fig. 6) and rotation, the spatial resolution of the ionization zones (Petroni et al. 2003, their Fig. 10), and the generated amplitudes once transformed to Johnson $V$ can be $\sim 20\%$ too large (Bono et al. 2000a, their Fig. 7). Bono et al. (2000a) found that metal-poor Cepheids typically exhibit larger amplitudes than their metal-rich counterparts, except for the $7\ M_\odot$ canonical and $9\ M_\odot$ convective overshooting models. Thus metal-rich $10-30\ M_\odot$ ($7-9\ M_\odot$) Cepheids may potentially exhibit larger amplitudes than their metal-poor counterparts. The availability of such testable model predictions is desirable, however, the diversity of opinion concerning the empirical picture (a partial account is provided below) hindered a comparison.

Figure 1 in Shapley (1942) highlights the sizable amplitude offset between $\sim 300+$ SMC and Galactic Cepheids. Shapley (1942) argued that the discrepancy may be tied to systematic errors, whereas Arp and Kraft (1961) suggested the offset was attributable to differences in chemical composition between SMC and Galactic Cepheids ($\Delta [\text{Fe/H}] \sim -0.75$, Luck et al. 1998; Romaniello et al. 2008). Schaltenbrand and Tammann (1970) instead noted a
general similarity among period-amplitude relations characterizing Cepheids in the Galaxy and Magellanic Clouds. van Genderen (1978, and references therein) argued otherwise, namely that longer-period metal-poor classical Cepheids exhibit smaller amplitudes than their metal-rich counterparts, thereby supporting the results of Arp and Kraft (1961). Berdnikov and Ivanov (1986) and Paczyński and Pindor (2000) corroborated the van Genderen (1978) conclusion concerning the amplitude-metallicity behavior of longer-period Cepheids. A recent analysis by Szabados and Klagyivik (2012) indicated that metal-poor classical Cepheids display slightly larger amplitudes than their metal-rich counterparts, a result inferred by correlating the latest abundance and photometric data for Galactic Cepheids (−0.4 ≤ [Fe/H] ≤ 0.4). Szabados and Klagyivik (2012) found the correlation strongest for shorter-period Cepheids, whereas the impact of metallicity on radial velocity and B-band amplitudes for longer-period Cepheids was less pronounced, and the coefficient for the latter was not significant (their Table 2 and Fig. 4).

At present the template lightcurve repository used to analyze sparse extragalactic Cepheid observations features a mix of SMC, LMC, and Galactic Cepheids (Stetson 1996; Tanvir et al. 2005; Yoachim et al. 2009), without regard for metallicity spread among the calibrating and parent galaxies. Tanvir et al. (2005) and Yoachim et al. (2009) hinted that an amplitude offset between the samples could be linked to metallicity, whereas Stetson (1996) suggested that a minor offset might be exaggerated in part by selection effects tied to Galactic Cepheids (see also Shapley 1942; Szabados 2003a), and indeed, results presented in Sect. 2 confirm that an offset is difficult to discern between relatively metal-rich Galactic and LMC Cepheids. Extending the comparison to include very metal-poor galaxies such as the SMC and IC 1613 is thus desirable, since the amplitude offset presumably increases in concert with the metallicity baseline established. Ultimately, constraining the amplitude-metallicity relation may help mitigate uncertainties associated with fitting lightcurve templates to sparsely observed (HST) Cepheids.

In this study period-amplitude diagrams are constructed for longer-period classical Cepheids in the Milky Way ([Fe/H] ~ 0), LMC ([Fe/H] ~ −0.33), NGC 6822 ([Fe/H] ~ −0.5), SMC ([Fe/H] ~ −0.75), and IC 1613 ([Fe/H] ~ −1). The galaxies span a sizable metallicity baseline (Δ[Fe/H] ~ −1), and the latest observational data for the comparatively uncrowded galaxies are analyzed (e.g., OGLE III). Longer-period very metal-poor classical Cepheids are found to typically exhibit smaller V-band amplitudes than their metal-rich counterparts. The difference is sufficiently discernible that the period-amplitude diagram may be employed in certain cases to approximate the mean metallicity for a target population containing numerous long-period classical Cepheids, provided the sample is relatively free from the effects of blending. The results may be employed to support metallicity estimates inferred from adjacent young stars and nebulae (e.g., NGC 3109, Sect. 3).

2 Analysis

2.1 Photometry

Only longer-period classical Cepheids (P > 10^4) are examined here, since for surveys of remote galaxies such stars typically exhibit smaller photometric uncertainties owing to their intrinsic brightness. Uncertainties introduced by misclassified short-period overtone pulsators and undersampled fainter objects are eliminated. Long-period classical Cepheids also appear less sensitive to blending (e.g., Macri et al. 2006, their Fig. 17). A Cepheid’s amplitude can be artificially reduced as a result of blending, so mitigating that effect is important.

Photometric parameters for Galactic Cepheids were derived from the expansive compilation of Berdnikov (2008) (see also Berdnikov et al. 2000), and supplemented in certain instances using observations acquired from the Abbey-Ridge Observatory (e.g., V396 Cyg, S Vul, etc., Lane 2008). Photometry for variables in IC 1613 and the Magellanic Clouds was taken from the OGLE survey (e.g., Udalski et al. 2001; Soszyński et al. 2008, 2010). Araucaria photometry for Cepheids in NGC 6822 was published by Pietrzyński et al. (2004). Following Klagyivik and Szabados (2009) and Szabados and Klagyivik (2012), peak-to-peak amplitudes were determined for the Cepheids (see also the pertinent discussion by Ngeow et al. 2003). The period-amplitude results derived for the Galactic sample are similar to those found in the comprehensive analysis by Klagyivik and Szabados (2009). V-band observations were selected as reliable B-band extragalactic data are sparse, and the amplitude diminishes with increasing wavelength (Madore and Freedman 1991, their Fig. 5). Johnson V is also common and well standardized, thus reducing uncertainties introduced by mismatched filters (e.g., U-band).

2.2 Amplitude-metallicity dependence

A comparison between classical Cepheids in the Galaxy and IC 1613 is particularly pertinent granted the abundance difference between the samples is sizable, and approximately Δ[Fe/H] ~ −1 (Luck et al. 1998; Tautvaišienė et al. 2007;
Bresolin et al. 2007). Figure 1 demonstrates that metal-poor Cepheids in IC 1613 typically have smaller $V$-band amplitudes than their Galactic counterparts, although a larger sample is desirable. However, 50+ simulations sampling the Milky Way data, such that the total number of Cepheids randomly drawn equals the sample size of IC 1613, yields a median amplitude ratio of: $0.80 \pm 0.05(\sigma)$ (IC 1613/MW, Fig. 2). That evaluation suggests, in concert with the results for the SMC, that the amplitude offset is probably not attributable to poor statistics. The median amplitude ratio can be approximated as:

$\langle AV / AV_{MW} \rangle \sim -0.1[Fe/H]^2 + 0.1[Fe/H] + 1$

($10 \leq P \leq 30^d, -1 \leq [Fe/H] \leq 0$)  \hspace{1cm} \text{(1)}$

That equation will require updating as new data become available. Figures 1 and 2 may be used in unison to gauge the impact of high and low-amplitude outliers. Cepheids in the SMC and NGC 6822 are likewise more metal-poor than Galactic Cepheids, and the amplitudes of Cepheids in the SMC are noticeably smaller than those of their Galactic counterparts. Similar to IC 1613, a comparison between Galactic and SMC classical Cepheids is pertinent granted the abundance difference between the two samples is large, $\Delta[Fe/H] \sim -0.75$ (Mottini et al. 2006). Differences are not readily apparent between Milky Way and LMC Cepheids (Figs. 2, 3), a fact which is explained in part by the metallicity overlap between those populations (Mottini et al. 2006; Luck et al. 2011). Figures 2 and 3 may be consistent in part with findings inferred from Szabados and Klagyivik (2012), and indicate that amplitudes for longer-period Cepheids in the $[Fe/H] \gtrsim -0.4$ regime may display a marginal dependence on metallicity (note that Fig. 2 is described by a converging polynomial: Eq. (1)).

The rationale behind the impact of metallicity on Cepheid light amplitudes is complicated (see also Schaltenbrand and Tammann 1970; Szabados and Klagyivik 2012, and discussion therein). It is unclear whether very metal-poor longer-period Cepheids are preferentially sampling the red-edge of the instability strip, where the pulsation is damped owing to convection. In older stellar evolutionary models increased metallicity depressed high surface temperature excursions for lower-mass ($< 5 \ M_\odot$) stars during the blue-loop stage following core helium ignition (Becker and Cepheids 1985). However, the extent of blue-loops may likewise depend on CNO abundances in the envelopes (Xu and Li 2004), which are governed in part by rotation and meridional mixing during the main-sequence stage (Maeder 2001; Turner and Berdnikov 2004). The empirical approach (e.g., Fig. 1) provides important insights that enable certain model

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**Fig. 1** Period-amplitude diagrams for classical Cepheids in IC 1613 (red, $[Fe/H] \sim -1$), SMC (purple, $[Fe/H] \sim -0.75$), NGC 6822 (orange, $[Fe/H] \sim -0.5$), and the LMC (black, $[Fe/H] \sim -0.33$). The galaxies are listed in order of increasing metal abundance (the shaded gray region characterizes Milky Way Cepheids, $[Fe/H] \sim 0$). The results imply that longer-period metal-rich classical Cepheids (e.g., Milky Way) typically exhibit larger $V$-band amplitudes than their very metal-poor counterparts (e.g., SMC). Overlaid red lines trace an approximate mean upper bound to the distribution, which appears to increase in tandem with metallicity up to the LMC. Cepheids deviating from the lower-envelope delineated by the bulk distribution may be peculiar or suffer from blending (binarity or crowding).

**Fig. 2** To assess the impact of the differing sample sizes on the perceived amplitude offset, Cepheids were randomly drawn from the Milky Way (MW) dataset until the total typically equalled that of the comparison dataset (e.g., IC 1613, $[Fe/H] \sim -1$). Median amplitude ratios were subsequently inferred from 50+ simulations, and were evaluated relative to MW Cepheids. The uncertainties displayed are the standard deviations ($\sigma[Fe/H] = 0.15$ dex was assumed for IC 1613 and NGC 6822). Longer-period metal-rich Cepheids typically exhibit larger $V$-band amplitudes than their very metal-poor counterparts.
solutions to be eliminated. The empirical trends for > 30 d Cepheids (Fig. 1) should presently be interpreted cautiously owing to poor statistics, however, certain models predict that a turnover may occur near that boundary whereby metal-poor Cepheids exhibit the larger amplitudes.

It is desirable to extend the analysis of Luck et al. (1998) and Mottini et al. (2006) to establish direct abundances for Cepheids in NGC 6822 and IC 1613. Abundance estimates by those authors were inferred from Cepheid spectra, which consequently obviates concerns regarding whether abundances deduced from nebulae (or otherwise) are representative of the Cepheid population (see also Bresolin et al. 2009; Bresolin 2010). For example, the abundance estimate for NGC 6822 stems from two A-type supergiants in that galaxy (Venn et al. 2001, [Fe/H] = −0.49 ± 0.20). Abundances inferred from nebulae seem to confirm the Venn et al. (2001) result that young stars in NGC 6822 are more metal-rich than their SMC counterparts. Yet nebular abundances are also uncertain, as evidenced by the debate concerning the galactocentric metallicity gradients in M33 and M106 (Bono et al. 2008; Majaess 2010; Bresolin 2011a, 2011b).

2.3 Blending

Setting a lower envelope to the period-amplitude diagram reveals that several stars in the Magellanic Clouds appear peculiar or blended, although the bulk of the sample appear typical.

Blending arising from contamination by neighboring stars in crowded extragalactic fields (or via bina-

2∼10.5 d Cepheids exhibit an amplitude minimum owing to the Hertzsprung progression (see also Bono et al. 2000b; Klagyivik and Szabados 2009), which may be metallicity dependent.

3Evans (1995), Szabados (2003b), see also http://konkoly.hu/CEP/intro.html.
Fig. 4  Top panels, DSS images for NGC 6822 and IC 1613. The red dots represent brighter Cepheids sampled by the Araucaria and OGLE surveys. Approximate locations for the HST WFPC2 and ACS samplings are likewise shown for IC 1613. A ~26d Cepheid (IC 1613) residing away from the edge of the CCD detector exhibits both OGLE and ACS LCID photometry, and appears comparatively unblended ($\Sigma F_{s,V}/F_{Cep,V} < 1\%$). Bottom panels, relative Wesenheit computed distances plotted as a function of the galactocentric distance. The slopes of the best-fit trends are insignificant, yielding $0.008 \pm 0.008$ and $-0.005 \pm 0.019$ for NGC 6822 and IC 1613, respectively. Blending does not appear to be the principal source behind the amplitude trends highlighted in Figs. 1 and 2.

where the stellar density and surface brightness are comparatively low. There are 23 ACS-detected stars neighboring the Cepheid which fall well within the OGLE seeing, where the HST ACS photometry is from the LCID (Local Cosmology from Isolated Dwarfs) project (Bernard et al. 2010; Monelli et al. 2010). The sum of the $V$-band flux for those stars, divided by the mean Cepheid $V$-band flux ($\Sigma F_{s,V}/F_{Cep,V}$), yields a ratio less than 1%. That indicates blending has a negligible impact on the amplitude of that Cepheid. Several significantly fainter short-period Cepheids ($P < 3.1^d$) exhibit HST ACS and OGLE photometry, and ~15% of the flux measured for ~2–3$d$ Cepheids appears to stem from blending. The shortest-period Cepheid ($\sim10.45^d$) used in Fig. 1 is $\sim1^m.5$ brighter than those 2–3$d$ Cepheids. The median flux contributed by blending for the 2–3$d$ sample reduces the amplitude of the 10.45$d$ Cepheid by $0^m.03$, which is insufficient to account for the offset observed in Fig. 1. Yet there exist blended long-period Cepheids in each galaxy investigated (Fig. 1), and that includes the 14.33$d$ Cepheid in IC 1613, which appears overly bright for its period and displays an amplitude well below the lower-bound approximated in Fig. 1.

Another pertinent test is to evaluate whether computed distance moduli for Cepheids in IC 1613 and NGC 6822 exhibit a galactocentric dependence (Fig. 4). Distance moduli calculated for classical Cepheids in M33 and M106 exhibit such a positional dependence (Majaess et al. 2009, their Fig. 4). Cepheids in those galaxies appear brighter as the cluster core is approached, in concert with the increased star density and surface brightness. An inspection of the distance moduli estimated for brighter Cepheids in IC 1613 and NGC 6822 reveals no significant trend (Fig. 4), where relative distances were computed via the Wesenheit function:

$$W_{VIc} - W_{VIc,0} = \mu_0$$

$$V - R_{VIc} (V - Ic) - \alpha \log P_0 - \beta = \mu_0 + \beta = \Delta \mu$$

$$R_{VIc} = 2.55$$ is the ratio of total to selective extinction (Fouqué et al. 2007, and references therein), $\alpha \sim -3.32$ is the slope of the Wesenheit function (Benedict et al. 2007; Soszyński et al. 2008, 2010; Ngeow et al. 2009; Majaess et al. 2011a), and $\beta$ is chosen to be arbitrary (relative distance).
Majaess (2010) note that $V_{Ic}$ period-colour and period-Wesenheit relations can be employed, in tandem with other methods, to facilitate the identification of spurious photometry and blending. Bono et al. (2010) and Majaess et al. (2011b, and references therein) argue that such functions are comparatively insensitive to variations in chemical composition. It follows that negative mean reddenings inferred for Cepheid samples from $V_{Ic}$ period-colour relations, or mean reddenings that are less than foreground estimates (IRAS dust maps), may be indicative of photometric problems (Fig. 6 in Majaess 2010). Of similar note, significant deviations from the $V_{Ic}$ Wesenheit slope of $\alpha \sim -3.32$ may also be suggestive of problematic photometry. For example, ground-based photometry of Cepheids near the crowded core of M33 follow $\alpha \sim -2.8$ (see also the pertinent discussion in Pellerin and Macri 2011; Chavez et al. 2012, concerning the impact of blending on M33 Cepheid photometry). The mean reddenings and Wesenheit slopes inferred from ground-based photometry for Cepheids in the Local Group galaxies analyzed here do not display such troubling trends (Majaess 2010).

In sum, the principal amplitude offset shown in Figs. 1 and 2 likely results from variations in chemical composition, rather than blending. Ultimately, a solid conclusion awaits the acquisition of high-resolution HST photometry for the extragalactic fields monitored using ground-based telescopes (Fig. 4).

3 NGC 3109

NGC 3109 is located at the periphery of the Local Group, and features a classical Cepheid distance of $d = 1.30 \pm 0.02$ Mpc (Pietrzyński et al. 2006b; Soszyński et al. 2006). The mean abundance of the Cepheid population can be estimated using the amplitude trends defined in Sect. 2, and the $V$-band observations acquired by Pietrzyński et al. (2006b). A period-amplitude diagram (Fig. 5) confirms that Cepheids in NGC 3109 typically display smaller $V$-band amplitudes than their metal-rich counterparts in the Milky Way, and are analogous to Cepheids in very metal-poor galaxies (SMC and IC 1613). Fig. 1 and the median amplitude ratio (Fig. 2) can be employed in concert to estimate the mean abundance of the Cepheid population, thereby mitigating the impact of high and low-amplitude outliers. The resulting median amplitude ratio relative to the Milky Way sample is 0.81 ± 0.03, which together with the distribution displayed in Fig. 5, implies that Cepheids in NGC 3109 may potentially be more metal-poor than their SMC counterparts. However, uncertainties tied to the present analysis prevent a definitive determination, particularly granted shorter-period ($P < 19d$) Cepheids in NGC 3109 display increased scatter and blending appears more acute (Fig. 5). Abundances inferred from HII regions and 8 B-type supergiants corroborate the aforementioned assertion that NGC 3109 Cepheids are very metal-poor like those in the SMC and IC 1613 (Evans et al. 2007, and references therein). Thus, in the particular case of NGC 3109 the metallicity estimated from Cepheid pulsation matches that established by other means, to first order.

4 Conclusions

A period-amplitude analysis was conducted of longer-period classical Cepheids in the Milky Way, LMC, NGC 6822, SMC, NGC 3109, and IC 1613. That sample spans a sizable abundance baseline, thereby enabling the impact of metallicity on Cepheid light amplitudes to be assessed. On average, longer-period metal-rich classical Cepheids display larger $V$-band amplitudes than their counterparts in very metal-poor galaxies ($10 \leq P \leq 30d$, $-1 \leq [\text{Fe/H}] \leq 0$, Figs. 1, 2, 5). In particular, there is a readily discernible offset between relatively metal-rich (MW/LMC) and very metal-poor Cepheids (SMC/NGC 3109/IC 1613). The resulting empirically deduced amplitude-metallicity dependence agrees with prior findings by van Genderen (1978) and Berdnikov and Ivanov (1986), and should be useful for constraining theoretical models, identifying blended (owing to binarity or crowding) and peculiar Cepheids, inferring approximate mean abundances for target Cepheid populations (Sect. 3) provided the sample is large enough (see also

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4 For alternative interpretations and broader discussion see Romaniello et al. (2008), Feast (2011), Majaess et al. (2011b), and Matsunaga (2012).

5 That Araucaria-based Cepheid distance agrees with a mean inferred from 18 published estimates tied to other methods: $d = 1.33 \pm 0.08(\sigma_x) \pm 0.34(\sigma)$ Mpc (NED-D, Steer and Madore 2011).
van Genderen 1978; Tanvir et al. 2005), ensuring consistent Cepheid/nebular abundances (Bresolin 2010), and improving lightcurve template fits for Cepheids with limited observational data. The empirical results shown here lend support to models (e.g., Bono et al. 2000) indicating that metal-rich 10 − 30$^\text{d}$ Cepheids could exhibit larger amplitudes than their very metal-poor counterparts. Further research assessing the impact of blending on Cepheid distances and parameters is desirable, and indeed, the ramifications are grave if the principal amplitude trend described here stems from blending.

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