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The Cepheid $P-L$ Relation and Metallicity

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Abstract. Baade–Wesselink radii derived using $VJHK$ photometry are used to test the metallicity dependence of the Cepheid $P-L$ relation using three collections of metallicity estimates from the literature. The hypothesis that Cepheids at the LMC metallicity ($[Fe/H] \sim -0.2$) could be several tenths of a magnitude fainter than at solar metallicity is not supported by the evidence.

It has often been assumed that the *bolometric* Cepheid $P-L$ relation is essentially invariant with metallicity, in agreement with theoretical calculations by Iben & Renzini (1984), Chiosi, Wood, & Capitanio (1993) and Saio & Gautschy (1998). This is by no means universally accepted. According to model calculations by Bono et al. (1999), metal-poor Cepheids should be brighter at a given period, while Sekiguchi & Fukugita (1998) have argued that LMC Cepheids may be 0.4 mag fainter at a given period than Cepheids in the solar neighborhood. There have been few practical ways of testing the metallicity dependence of the Cepheid $P-L$ relation. LMC and SMC Cepheids show little evidence of any great spread in composition (Caldwell & Coulson 1985ab, Luck et al. 1998), and the samples in M31 (Freedman & Madore 1990) have been shown by Feast (1991) to yield rather inconclusive results. There were also, until recently, few sufficiently precise metallicity measurements of Cepheids in our own Galaxy, let alone in the Clouds or beyond. Recently, Fry & Carney (1997) have determined high-precision metal abundances for 23 galactic Cepheids. Other sets of [Fe/H] determinations by Luck & Lambert (1985), Luck (1994) and Klochkova & Panchuk (1991) have enough overlap with Fry & Carney to give some indication of systematic differences among these determinations, though the claimed accuracy for these older metallicities is rather lower.

If Cepheids are fainter by as much as 0.4 mag at the LMC metallicity, then metal-poor stars must have smaller radii or lower surface brightness or both.

To test the effect of metallicity on radius, we need accurate radii, determined on a consistent system. Laney & Stobie (1995a,b = LS95a,b) calculated Baade–Wesselink (BW) radii for 49 galactic Cepheids using optical and JHK photometry; they showed that radii calculated using the K magnitude and the $J-K$ or $V-K$ colors appeared to be reasonably free of systematic errors. Since that time, JHK data have been obtained for 44 additional Cepheids, and Barnes et al. (1997) have published JHK photometry for 22 northern Cepheids. Radii have been calculated using the methods of LS95a for 30 of these objects, and improved radii have been calculated for QZ Nor, EV Sct, SZ Tau, CV Mon, ℓ Car

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and β Dor. For a few stars of exceptionally low amplitude, only the $(K, V-K)$ solution has been used here. Otherwise the $(K, V-K)$ and $(K, J-K)$ solutions have been averaged where both are available.

A combined Galaxy/LMC/SMC period–radius relation for fundamental pulsators gives (with 68 galactic and 9 MC Cepheids)

$$\begin{aligned} \log R &= 1.830 + 0.721(\log P - 1) + 0.018(\mathrm{LMC}) + 0.004(\mathrm{SMC}) \quad \sigma = 0.038. \\ &\quad \pm 0.005 \pm 0.014 \qquad\qquad \pm 0.020 \qquad\quad \pm 0.022 \end{aligned}$$

Likely overtone pulsators and stars with relatively uncertain radii (see LS95a) have been excluded in this solution. Note that systematic differences between galactic and MC radii are less than 1σ, in a direction implying that MC Cepheids are brighter than galactic Cepheids by a few hundredths of a magnitude.

VJHK photometry and radial velocities currently available allow the calculation of BW radii for 20 of the stars studied by Fry & Carney (FC), 18 of those studied by Luck & Lambert and Luck (LL), and 13 of those studied by Klochkova & Panchuk (KP). For the 20 FC Cepheids, one can apply the above zero point and slope to find that

$$\begin{aligned} \Delta \log R &= -0.008 - 0.086(\mathrm{overtones}) + 0.108[\mathrm{Fe/H}] \quad \sigma = 0.038, \\ &\quad \pm 0.009 \pm 0.027 \qquad\qquad \pm 0.077 \end{aligned}$$

where $\Delta \log R$ is the log of the predicted minus the log of the empirical radius. For the 18 LL Cepheids the coefficient of [Fe/H] is 0.029±0.085; for the 13 KP stars the coefficient of [M/H] is −0.054±0.109. Using values of the LL and KP metallicities shifted into mean agreement with FC for the stars in common, a joint solution for all 51 gives 0.033±0.047. Using the FC stars together with the LL stars not included in FC, and the KP stars not included in FC or LL (a hierarchy reflecting my opinion of their relative precision) gives a coefficient of 0.081±0.065 for 31 Cepheids (Fig. 1). For an LMC [Fe/H] of −0.2, the log of the radius will be larger by 0.02±0.02 (magnitude brighter by 0.11) from the FC data alone, and by 0.02±0.01 (magnitude brighter by 0.08) from the 31-star result. *Given the uncertainties, all of these are consistent with a bolometric $P-L$ relation which has no metallicity dependence.* The marginal (1σ) trend seen in the deviations from the mean $P-R$ relation would again imply that metal-poor Cepheids are slightly bright for their periods.

Are low-metallicity Cepheids cool for their periods, with a lower surface brightness? Laney & Stobie (1994) found that the temperature shift between galactic and SMC Cepheids was equivalent to a shift in $B-V$ at a given period of 0.081±0.016 (SMC bluer) after the effects of line blanketing had been removed. The same shift appears in every waveband, and for $V - I_C$:

$$\begin{aligned} (V-I)_0 &= 0.475 + 0.291 \times \log P - 0.031(\mathrm{LMC}) - 0.073(\mathrm{SMC}) \quad \sigma = 0.061, \\ &\quad \pm 0.014 \pm 0.013 \qquad\qquad \pm 0.011 \qquad\quad \pm 0.012 \end{aligned}$$

where $(V-I)_0$ is the dereddened magnitude mean, and s-Cepheids have been shifted into agreement with zero-point defined by the fundamental pulsators (129 galactic, 42 LMC and 46 SMC Cepheids). These temperature shifts with period are in good agreement with predictions by Iben & Renzini (1984). The

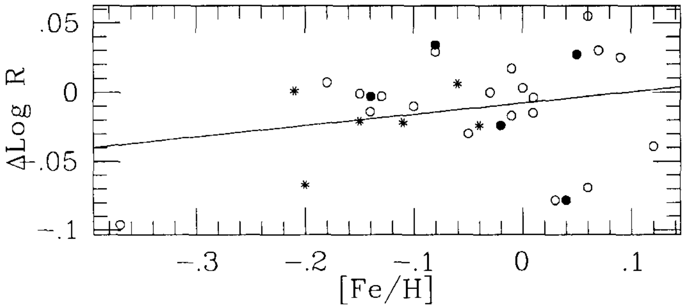

Figure 1. $\Delta \log R$ vs. [Fe/H], where $\Delta \log R$ ($\log R_{\mathrm{predicted}} - \log R_{\mathrm{observed}}$) has been calculated using the period–radius relation derived above. Overtone Cepheids have been shifted into zero point agreement with the fundamental pulsators. Cepheids with $VJHK$ radii and FC metallicities are shown as open circles; 6 Cepheids included by LL but not FC are represented by asterisks; 5 stars included by KP but not by LL or FC are represented by filled circles. The line is a least squares fit.

dereddened mean $V - I_C$ colors of galactic Cepheids with FC, LL or KP metallicities show no significant trend with metallicity. A formal composite solution (excluding the discrepant KP [Fe/H] for S Sge) indicates that Cepheids at LMC metallicity would be 0.006±0.015 bluer than at solar metal abundance.

If Cepheids at [Fe/H] of −0.2 were 0.4 mag fainter at a given period because of lower surface brightness, this would imply that the mean $V - I_0$ should be *redder* by roughly 0.13, in gross disagreement with the above. The BVI_C reddening scale assumed above can be calibrated using 33 Cepheids with known space reddenings, giving

$$E(B-V)_{(\text{space red.})} = \underset{\pm 0.01 \pm 0.01}{0.01 + 1.00 \times} E(B-V)_{(BVI_C)} \qquad \sigma = 0.03.$$

Metallicity corrections to BVI_C reddenings have been implemented as described by Caldwell & Coulson (1985ab = CC85ab). It is not yet clear whether more recent models and metal deficiency values than those adopted in CC85ab will make the dereddened colors of MC Cepheids redder or bluer, but the effect is unlikely to exceed 0.01 – 0.02 mag. Cepheid moduli determined using a single color (as in many HST studies) will still need a modest metallicity correction, as argued by Sasselov et al. (1997).

The suggestion by Sekiguchi & Fukugita (1998) – that LMC Cepheids may be fainter than galactic Cepheids at the same period by 0.4 mag – is inconsistent with the data by more than 6σ based on period–radius comparisons alone. Given that low-metallicity Cepheids appear to have hotter temperatures and higher surface brightnesses at a given period, it appears impossible to explain the discrepancy between the 'long' and 'short' distance scales in this way.

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Discussion

Christine Clement: In your plot of $\log R$ vs. $\log P$: did you show a significant difference in radius between overtone and fundamental pulsations?

David Laney: The overtone Cepheids are larger at a given period by 0.1 in $\log R$, as theory would predict.

Giuseppe Bono: 1. Are metal-poor Cepheids brighter than metal-rich ones? 2. What is the current accuracy of a reddening measurement?

David Laney: 1. All that can be said is that there is a formal low tendency for $\log R$ to be 0.081 ± 0.065 larger at $[Fe/H] = -0.2$ than at 0. The four measured SMC radii show no tendency to be larger for these periods and the $\Delta \log R/\Delta[Fe/H]$ trend for galactic Cepheids reverses if the overtone Cepheids are omitted. The safest answer is that the data are still consistent with a metallicity-independent $P-L$ relation, but not with Sekiguchi & Fukugita.
2. The scatter in $E(B-V)$ external vs. $E(B-V)_{BVI}$ is 0.03. Assuming equal errors, $E(B-V)_{BVI}$ is accurate to 0.02.

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