TWO NEW TESTS OF THE METALLICITY SENSITIVITY OF THE CEPHEID PERIOD–LUMINOSITY RELATION (THE LEAVITT LAW)

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ABSTRACT
We undertake a new test of the metallicity sensitivity of the Leavitt Law for classical Cepheids. We derive an empirical calibration of the apparent luminosities of Cepheids as measured from the optical through the mid-infrared (0.45–8.0 μm) as a function of spectroscopic [Fe/H] abundances of individual Cepheids in the Large Magellanic Cloud (LMC) from Romaniello et al. The cumulative trend over the entire wavelength range shows a nearly monotonic behavior. The sense of the trend is consistent with differential line blanketing in the optical, leading to stars of high metallicity being fainter in the optical. This is followed by a reversal in the trend at longer wavelengths, with the crossover occurring near the K band at about 2.2 μm, consistent with a subsequent redistribution of energy resulting in a mild brightening of Cepheids (with increased metallicity) at mid-infrared wavelengths. This conclusion agrees with that of Romaniello et al. based on a differential comparison of the mean V- and K-band Leavitt Laws for the Galaxy, Small Magellanic Cloud, and LMC, but is opposite in sign to most other empirical tests of the sensitivity of Cepheid distances to mean [O/H] Hα region abundances. We also search for a correlation of Cepheid host-galaxy metallicity with deviations of the galaxy’s Cepheid distance from that predicted from a pure Hubble flow. Based on Cepheid distances to 26 nearby galaxies in the local flow, only a very weak signal is detected giving δμα = −0.17(±0.31)([O/H] − 8.80) − 0.21(±0.10). This is in agreement with previous determinations, but statistically inconclusive.

Keywords: galaxies: distances and redshifts – Magellanic Clouds – stars: atmospheres – stars: variables: Cepheids

1. INTRODUCTION
The Cepheid period–luminosity relation (Leavitt Law) remains central in the determination of extragalactic distances and determination of the Hubble constant. An outstanding remaining issue in the calibration of the Cepheid distance scale is the effect of metallicity on Cepheid luminosities and colors. Early modeling efforts dating at least as far back as Robertson (1973) and Iben & Tuggle (1975) have investigated the role of metals in the atmospheres of Cepheid variables. More recent and extensive linear and nonlinear pulsation models by a number of groups have come to differing conclusions on both the sign and the magnitude of a metallicity effect (see Bono et al. 2008 and references therein for a recent discussion); hence empirical studies remain needed.

Over the past two decades we have proposed a number of tests for and calibrations of this effect on the Cepheid period–luminosity (PL) relation, hereafter referred to as the Leavitt Law. The first test (Freedman & Madore 1990) involved using Cepheids radially distributed across a single galaxy with a measured chemical composition gradient across its disk. By examining the change in the (reddening-corrected) distance moduli of individual Cepheids or groups of Cepheids as a function of galactocentric radius, one can test for the possible effects due to metallicity. The original test was applied to M31 where no statistically significant evidence for a metallicity effect was detected. A subsequent calibration was undertaken as part of the Hubble Space Telescope (HST) Key Project (Freedman et al. 2001) using Cepheids in M101 (Kennicutt et al. 1998) this time giving δ(m − M)H/δ[O/H] = −0.24 ± 0.16 mag dex−1. Another, more recent application of this technique can be found in Macri et al. (2006) in their study of radially distributed Cepheids in the nearby galaxy NGC 4258, where they find a slope of −0.29 ± 0.09 mag dex−1. And finally, Scowcroft et al. (2009) have examined Cepheids in four fields in the Local Group galaxy M33 and determined a metallicity sensitivity of −0.29 ± 0.11 mag dex−1.

The second test (Lee et al. 1993) proposed that a comparison of the tip of the red giant branch (TRGB) distances (Population II) with the Cepheid (Population I) distances could be used to look for a trend in the differential distance moduli as a function of the host galaxy (H II region) metallicity. This test was successfully deployed most recently by Sakai et al. (2004) where the slope of the metallicity relation was determined to be −0.24 ± 0.05 mag dex−1.

The conclusion from these two types of tests is that there is a mild sensitivity of the zero point of the Leavitt Law to metallicity with published values broadly centered around −0.25 mag dex−1, trending in the direction that more metal-rich Cepheids are intrinsically brighter than their metal-poor counterparts (at optical wavelengths). That is, using a low-metallicity calibration of the Leavitt Law to estimate distances to high-metallicity Cepheids would result in an underestimate of their true distances.

In a different approach, Romaniello et al. (2008) have obtained direct spectroscopic [Fe/H] abundances for a sample of Galactic, Large Magellanic Cloud (LMC), and Small Magellanic Cloud (SMC) Cepheids. They compare the Leavitt Law for samples of stars with different mean metallicities. In contrast to the studies above, they find that metal-rich Cepheids in the V band are fainter than metal-poor ones.

In the following we propose a further test using the published Romaniello et al. (2008) spectroscopic measurements of [Fe/H] to examine a correlation of the residuals in multi-wavelength photometry for individual Cepheids in the LMC. We also test the prediction that a metallicity effect will impose correlated scatter to the observed Hubble diagram.
2. TWO NEW TESTS

2.1. The LMC Spectroscopic Sample

Recently, Romaniello et al. (2008) published iron-line metallicities for 32 Galactic, 22 LMC, and 14 SMC Cepheids. They looked for a relation between the [Fe/H] abundance and the mean $V$-band and $K$-band residuals from the Freedman et al. (2001) and Persson et al. (2004) Leavitt Laws, respectively. In contrast with previous studies, they found an increasing dependence of the $V$-band residuals with [Fe/H] abundance; while at $K$, the existence of an effect was less clear.

In this paper, we explore the run of multi-wavelength ($UBV\ JHK$ and 3.6, 4.5, 5.8, and 8.0 $\mu$m) residuals from the Leavitt Law for the 22 individual LMC Cepheids\footnote{The SMC sample was not considered because of the large additional scatter imposed on all of the SMC Cepheid PL relations due to back-to-front geometric effects (e.g., Welch et al. 1987).} with measured [Fe/H] abundances derived by Romaniello et al. (2008) from high-resolution ($R = 30,000$) VLT UVES spectra.

2.1.1. Multi-wavelength Solutions

Before searching for a potential sensitivity of Cepheid magnitudes to metallicity, we first test for a correlation of metallicity with period. A correlation of this type could be sample induced; that is accidental, because of small-number statistics. Or, there could plausibly be an age effect, where metallicity increases with time, since periods are thearcs of age for Cepheids (e.g., Efremov 1978; Magnier et al. 1997; Bono et al. 2005). In any event, as Figure 1 shows, neither of these effects appear to be significant; there is no obvious correlation of metallicity with period.

We now undertake a test for metallicity, enabled for the first time by this new spectroscopic data set, in combination with existing multi-wavelength photometry. The $UBV$ photometry for the Cepheids is from Madore (1985), the $JHK$ photometry is from Persson et al. (2004), and the mid-infrared (3.6–8.0 $\mu$m) photometry is from Madore et al. (2009). For each individual Cepheid at each wavelength, we plot its magnitude residual from the mean PL relation (as defined by the Cepheids themselves in each of these samples) as a function of its measured atmospheric [Fe/H] metallicity. Then for each wavelength set, we solve for the linear sensitivity of that magnitude residual to Cepheid metallicity. The data and the regression fits are given in Table 1 and plotted in Figure 2. We also show the residuals for the reddening-free magnitude $W = V - R_V(B - V)$. We note that the correlation of residuals with metallicity is almost flat at the $H$ band, as well as for $W$.

![Figure 1. Plot of spectroscopic [Fe/H] metallicities as a function of period for 22 LMC Cepheids observed by Romaniello et al. (2008). No trend is seen in the data.](image)

Viewed in isolation, the scatter at any given wavelength is large and the slope of any given correlation has a low significance. However, the run of slopes as a function of wavelength is clearly monotonic. This would not reasonably be the case if each of the measured slopes was statistically insignificant and randomly distributed around zero. This raises the possibility that the relative slopes may not be as poorly determined as is suggested by the significance of the individual fits alone.

We also note that the scatter is highly correlated across the various wavelengths. This correlated scatter is not unexpected. In addition to any systematic shift of a Cepheid’s luminosity due to metallicity, there will be other sources of correlated noise. Intrinsic temperature (color) differences amongst Cepheids at a fixed period will also manifest themselves in a similar way. Differential reddening will scatter Cepheids around the mean (apparent) PL relation. The amplitudes of both of these effects are known to be decreasing functions of wavelength, and although there is no reason to expect either of them (and certainly not the line-of-sight extinction) to be functions of the star’s metallicity, they will both contribute significantly to any measured residual deviation of a given star from the mean PL relation. The back-to-front geometry of the LMC also contributes correlated scatter. While we cannot unambiguously disentangle and individually subtract out the effects of reddening, temperature, and geometry, we can take out their averaged and combined contribution to this sample of stars in order to enhance the signal-to-noise against which any residual metallicity effect can be viewed.

In order to re-evaluate the formal error (but not the absolute values) of the individual slopes at each wavelength, we have undertaken to decorrelate the noise in each of the metallicity–residual plots by applying the following filter: First, we choose the $H$-band data as fiducial. It has essentially zero slope, but still measurable scatter. We then multiplicatively scale the $H$-band residuals and subtract them star-by-star from each of the other wavelength residual plots, choosing the scale factor that minimizes the scatter at each particular wavelength. Because metallicity is independent of period for this sample (see above), and because the $H$-band data themselves show no trend with metallicity, there can be no effect of this scaled subtraction on the slopes of the other relations. New regressions show this to be the case, but the true significance of these same slopes now becomes more clear (see Figure 3).

In Figure 4 we plot the sensitivity of the PL relation to metallicity (i.e., the slopes from Figure 2) as a function of wavelength, but using the error bars derived from the

### Table 1

| Bandpass | Slope (mag dex$^{-1}$) | $\sigma$ (mag dex$^{-1}$) | $R^2$ |
|----------|------------------------|---------------------------|-------|
| $B$      | +0.59                  | ±0.49                     | 0.37  |
| $V$      | +0.50                  | ±0.31                     | 0.27  |
| $J$      | +0.14                  | ±0.07                     | 0.12  |
| $H$      | +0.05                  | ±0.02                     | Fiducial |
| $K$      | +0.02                  | ±0.03                     | 0.10  |
| 3.6      | −0.39                  | ±0.16                     | 0.77  |
| 4.5      | −0.25                  | ±0.18                     | 0.77  |
| 5.8      | −0.39                  | ±0.17                     | 0.85  |
| 8.0      | −0.38                  | ±0.16                     | 0.88  |
noise-decorrelated data (which are given in Table 1). A significant monotonic decline in sensitivity with metallicity is seen. The effect is in the sense that at optical ($BV$) wavelengths, there is a positive ($\sim+0.5$ mag dex$^{-1}$) effect. There are too few Cepheids with $U$-band data to obtain a statistically significant result, but the overall trend at $U$ is consistent with a greater sensitivity to metallicity at shorter wavelengths, albeit with greater uncertainty. There appears to be little sensitivity to metallicity at 1–2 $\mu$m ($JHK$), and then the effect reverses sign with $\sim−0.3$ mag dex$^{-1}$ at mid-infrared wavelengths. These results are consistent with those noted by Romaniello et al. (2008); that is, opposite in sign to most of the existing empirical calibrations of the metallicity effect.

We do not know the reason for this difference. We note simply that the current test offers the advantage of high-resolution spectroscopic [Fe/H] abundances for individual Cepheids, rather than a measure of the average [O/H] abundance for H II regions at the same azimuthal distance from the centers of the host galaxies as the Cepheids. It is also a test based on Cepheids alone, rather than a combination of TRGB and Cepheid distance scales. In any case, this test provides a completely independent means to place empirical limits on the sensitivity of the Cepheid Leavitt Law to metallicity.

For the HST Key Project (Freedman et al. 2001), a metallicity correction of $−0.2 ± 0.2$ mag dex$^{-1}$ was adopted, based on the empirical results of Kennicutt et al. (1998) and later Sakai et al. (2004). If instead we adopt the result from this paper, where the data suggest that the reddening-free $W$ magnitude is not affected by metallicity, then as noted by Freedman et al. (their Section 8.7) the Hubble constant is increased by 4% from 72 to 75 km s$^{-1}$ Mpc$^{-1}$.

2.2. Deviations from the Hubble Flow

If metallicity is affecting the magnitudes and colors, and therefore the derived distances to Cepheids, this effect should add (correlated) scatter into the Hubble diagram. That is, galaxies of higher metallicity should preferentially scatter in one direction away from the ridgeline in a plot of distance versus velocity when calibrated by low(er) metallicity Cepheids. The test is very straightforward: As a function of the metallicity of the host galaxy we are looking for a correlation of metallicity with distance modulus deviations in the Hubble diagram.

We have used the reddening-corrected $VI$ Cepheid distance data as published in Table 3 of the Key Project summary.
Figure 3. Same data as in Figure 2 but now with the residuals decorrelated using the $H$-band data as fiducial. The slopes are preserved from the fits to the data in Figure 2. The significance of these slopes is now greatly enhanced.

Figure 4. Sensitivity of Cepheid magnitudes to metallicity as a function of wavelength. The slopes derived from the plots in Figure 1 are shown as a function of bandpass (expressed as the inverse wavelength). The error bars are from the noise-decorrelated data. The line is a unweighted fit (excluding the low-significance $U$-band data point to the far right) designed simply to emphasize the trend.

paper (Freedman et al. 2001, uncorrected for metallicity); and we updated the flow-corrected velocities using the WEB tool provided by NASA/IPAC Extragalactic Database (adopting a Hubble constant of 73 km s$^{-1}$ Mpc$^{-1}$), which provides corrections for perturbations caused by Virgo, the Great Attractor, and the Shapley Supercluster. For the three galaxies in the Virgo Cluster we used a single velocity appropriate to the cluster as a whole (957 km s$^{-1}$). Likewise for the two galaxies in the Fornax Cluster we use a corrected recession velocity of 1306 km s$^{-1}$.

Figure 5 shows the correlation of deviations in the Hubble diagram (read off as deviations in distance modulus) plotted as a function of the H II region [O/H] abundances, measured at the same radial distance as the Cepheids. There is a considerable amount of residual scatter, presumably due to random errors in the Cepheid distances combined with additional peculiar velocities of the parent galaxies over and above the cluster-induced flows. A formal regression gives the following solution: 

$$\delta\mu_o(\text{Cepheid–Hubble flow}) = -0.17(\pm0.31)([O/H] - 8.80) - 0.21(\pm0.10 \text{ mag})$$

indicating a mild dependence on metallicity (with the opposite sign from the dependence found in the earlier tests in this paper, and opposite in sign to the effect reported by Romaniello et al. 2008), but with extremely weak statistical significance. We conclude that the peculiar velocities of these nearby Cepheid galaxies are sufficiently large, and that the sample of galaxies with Cepheid distances is sufficiently small, that this test cannot currently provide a robust test of the metallicity effect.
Figure 5. Distance modulus deviations of individual galaxies around a pure Hubble flow, corrected for bulk motions induced by Virgo, the Great Attractor, and the Shapley Constellation, plotted as a function of the host galaxy metallicity. The sense of the residuals is that positive residuals indicate that measured distances are greater than distances predicted for a quiet flow. The trend with metallicity is such that high-metallicity Cepheids are measured to be too close when using a low-metallicity PL relation.

3. DISCUSSION AND CONCLUSIONS

Spectroscopic [Fe/H] measurements for LMC Cepheids from Romaniello et al. (2008), combined with multi-wavelength Leavitt relations, provide empirical evidence for a systematic and wavelength-dependent change in the luminosities of Cepheids with atmospheric metallicity. The changes are largest at the bluest wavelengths (amounting to about +0.5 mag dex$^{-1}$ in the $B$ and $V$ bands) and monotonically decrease with increasing wavelength. The correlation goes flat at about 2 $\mu$m after which the effect reverses in sign and reaches about $-0.3$ mag dex$^{-1}$ across the mid-IR. This trend is consistent with a purely atmospheric effect where line blanketing is known to be greater at blue wavelengths with the subsequent redistribution of energy resulting in a slight (energy-balancing) increase in the effective temperature at longer wavelengths, in this case apparently for wavelengths beyond 2 $\mu$m.

This test is distinct from other previous tests for the metallicity sensitivity of the Leavitt Law to date in that it uses direct measurements of the Cepheid metallicities on a star-by-star basis, without recourse to (intermediary) H II region abundances for instance, or external comparisons (with Population II TRGB distances, for example). Consistent with the results from Romaniello et al. (2008), the sign of the effect in this calibration is different from the aforementioned external tests and calibrations. $R$- and $I$-band data for this set of Cepheids would be of interest in further calibrating this relationship.

A test of the metallicity sensitivity of the Leavitt Law using deviations from the pure Hubble flow reveals a very weak signal in general statistical agreement with other independent tests, but of very low significance.

Taken on balance we draw the following practical conclusion. Dealing with metallicity effects on Cepheid distances is best accomplished by minimizing their impact from the outset by moving the calibrations away from the optical to longer wavelengths. Based on the results from this test, the crossover point in the wavelength sensitivity of the metallicity correction is at near-infrared $H$ or $K$-band wavelengths. In any case near- or mid-infrared data are to be preferred over optical observations for the additional fact that they significantly reduce the impact of all (foreground Milky Way or host-galaxy) line-of-sight extinction. For the immediate future, moving to the infrared seems to be the best practical solution to a complicated problem that is still controversial as to its magnitude and sign at optical wavelengths.

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