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HIPPARCOS PARALLAXES AND THE CEPHEID DISTANCE SCALE

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ABSTRACT

Hipparcos parallaxes have recently become available for a sample of Galactic Cepheids, and we have used these new distances to calibrate the Cepheid period-luminosity (PL) relation at six wavelengths (*BVIJHK*). Comparing these calibrations with previously published multiwavelength PL relations we find agreement to within 0.07 ± 0.14 mag, or $4\% \pm 7\%$ in distance. Unfortunately, the current parallax errors for the fundamental pulsators (ranging in signal-to-noise ratio $= \pi/\sigma_\pi$ from 0.3 to 5.3, at best) preclude an unambiguous interpretation of the observed differences, which may arise from a combination of true distance modulus, reddening, and/or metallicity effects. We explore these effects and discuss their implications for the distance to the Large Magellanic Cloud (LMC) and the Cepheid-based extragalactic distance scale. These results suggest a range of LMC moduli between 18.44 ± 0.35 and 18.57 ± 0.11 mag; however, other effects on the Cepheid PL relation (e.g., extinction, metallicity, and statistical errors) are still as significant as any such reassessment of its zero point.

Subject headings: Cepheids — galaxies: distances and redshifts — Magellanic Clouds

1. INTRODUCTION

Feast & Catchpole (1997; hereafter FC97) have recently published the first results on parallaxes to Galactic Cepheids based on measurements from the *Hipparcos* satellite. They list data for the 26 Cepheid parallaxes with the highest signal-to-noise ratios, and after an extensive series of reductions (see their Table 2), they conclude that the best-fit period-luminosity (PL) relation for the visual bandpass is $M_V = -2.81 \log(P) - 1.43$, with a standard error on the *Hipparcos* zero point of ± 0.10 mag, adopting the slope from prior work on LMC Cepheids. The authors go on to apply this V-band solution in determining the distance modulus of the LMC corrected for $E(B-V) = 0.074$ mag. Adding a metallicity correction of $+0.042$ mag and adopting $\langle V \rangle_0 - \log(P)$ from Caldwell & Laney (1991) gives $(m - M_V)_0^{\rm LMC} = 18.70 \pm 0.10$ mag. In this paper we go beyond the V-band PL relation and explore the implications of the *Hipparcos* data for the multiwavelength calibrations of the Cepheid PL relation from the blue (B-band) out into the near-infrared (2.2 μm K-band).

2. COMPARISON WITH V-BAND PERIOD-LUMINOSITY RELATIONS

In Figure 1 we differentially compare four calibrations (*heavy dotted lines*) of the V-band Cepheid PL relation with the FC97 *Hipparcos*-based relation (*solid horizontal lines*). The first two comparisons (in the upper two panels) are with the relations given by Madore & Freedman (1991; hereafter MF91) derived from self-consistent sets of LMC Cepheid data whose stars either had complete *BVRI* observations (labeled "MF91.1" in Fig. 1, containing 32 Cepheids) or complete *BVRIJHK* observations (labeled "MF91.2" in Fig. 1, containing 25 stars)[1] These first two solutions indicate the sensitivity of slopes and zero points to sample selection, which is considerable but within the quoted statistical uncertainties: ± 0.11 and ± 0.20, respectively, for the slopes and ± 0.05 and ± 0.09 mag, respectively, for the zero points. So as to make the subsequent comparisons consistent, the original Sandage & Tammann (1968; hereafter ST68) calibration (labeled "ST68.1" in the lower left-hand panel of Fig. 1) has been placed on the modern Hyades/Pleiades Galactic cluster distance scale by applying a single offset of $+0.13$ mag derived from the average difference between the absolute magnitudes of the Cepheids used in the 1968 calibration updated to that of Feast & Walker (1987; hereafter FW87) in their Table 2. This distance scale corresponds to a Hyades modulus of 3.27 (see Pel 1985) and uses the Pleiades main sequence, at a modulus of 5.57 (van Leeuwen 1983) to correct effectively for the overmetallicity of the Hyades with respect to the older Galactic clusters in which the Cepheid calibrators are found.[2] Finally, the FW87 calibration itself

[1] Tanvir (1997) has suggested that there may be small corrections (ranging from 0.02 to 0.09 mag) to the published I-band magnitudes of these LMC Cepheids arising from the originally sparse sampling and consequent averaging of their light and color curves. For the past 5 years, we have been obtaining new *VI* CCD observations of the LMC calibrators at Las Campanas and now also at Siding Springs Observatories. These new data are designed to address those concerns.

[2] At the 1997 February 14 meeting of the Royal Astronomical Society in London, F. van Leeuwen and C. S. Hansen Ruiz reported a true distance modulus of 5.29 ± 0.06 mag for the Pleiades cluster, based on *Hipparcos* trigonometric parallaxes. Following the Venice Meeting in 1997 June, the value had changed only slightly to 5.33 ± 0.06 mag (C. Turon 1997, private communication). If adopted, this Pleiades modulus would make the Galactic-cluster–based calibrations approximately 0.3 mag fainter than the FC97 solution plotted in Fig. 1. At this point in time, the Galactic-cluster zero point appears to be in a state of flux, and we will not comment on it further, except to note that the *Hipparcos* calibration will undoubtedly converge on a more accurate zero point than we have access to at this precise moment.

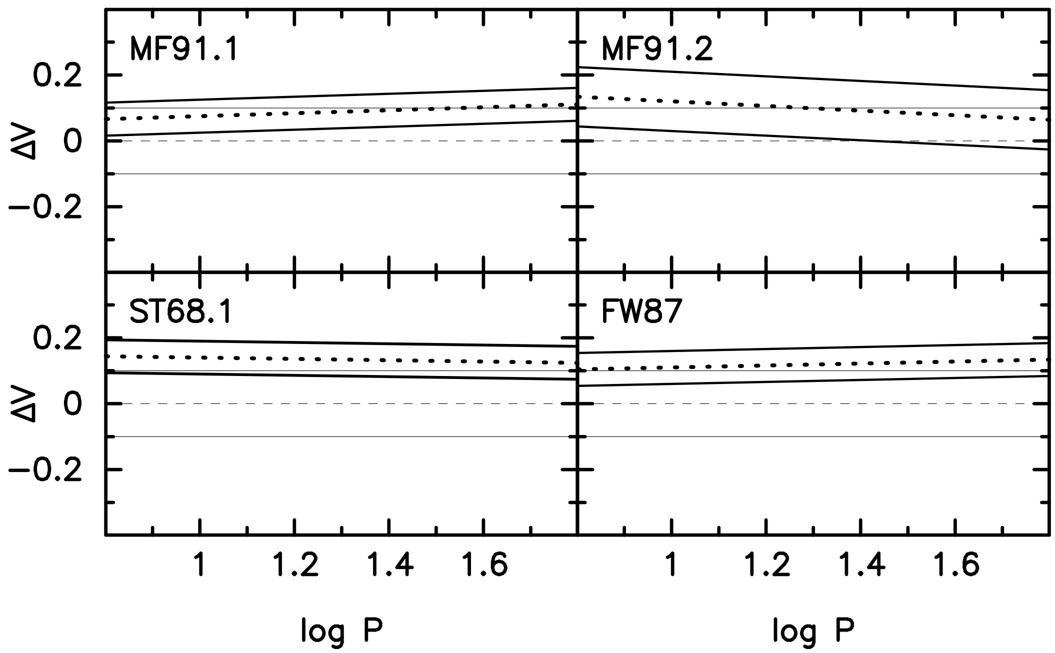

FIG. 1.—Differential comparison of recently published V-band PL relations (*heavy lines*) relative to the *Hipparcos* calibration (*thin lines*). Plotted is the difference $[V - V(Hipparcos)]$ vs. log P, in the sense that if *Hipparcos* is brighter, the difference shown is positive.

is plotted in the lower right-hand panel. In all panels, the dashed horizontal lines represent the fiducial *Hipparcos* calibration flanked by thin parallel lines at ± 0.10 mag.

The error bars of all of the plotted previously published relations overlap with errors quoted for the *Hipparcos* solution (a formal uncertainty was not given by ST68, so we have arbitrarily assigned them an error of ± 0.05 mag). However, the offsets are not randomly distributed, with each of the solutions appearing to be systematically fainter in V than the *Hipparcos* calibration by about 0.1 mag. We discuss the significance and possible implications of this difference in the following sections.

3. MULTIWAVELENGTH PERIOD-LUMINOSITY RELATIONS

In Madore & Freedman (1991), we published fiducial PL relations in seven bandpasses, $BVRIJHK$. These were all reached by selecting self-consistent sets of previously published LMC Cepheid data scaled to an LMC true distance modulus of 18.50 mag and applying a single line-of-sight reddening correction using $E(B-V) = 0.10$ mag. $BVRI$ PL relations were calibrated with 32 stars; 25 stars were used for an alternative set of $BVRIJHK$ calibrations. In the following, we compare those multiwavelength PL relations with the *Hipparcos* sample of Galactic Cepheids, individually corrected for foreground reddening and scaled to their geometric parallax distances.

We have collected from the literature multiwavelength ($BVIJHK$) mean magnitudes as have been published for the *Hipparcos*-calibrating Cepheids (notably for the infrared; Wisniewski & Johnson 1968; Welch et al. 1984; Laney & Stobie 1992, and reference therein). These form rather disjointed subsets. After elimination of the suspected overtone pulsators listed by FC97, the total available sample with parallaxes drops from 26 to 20. Of these, only seven have mean magnitudes published at all six wavelengths, while 10 and 13 Cepheids, respectively have either $BVIJK$ or $BVJK$ magnitudes in common. We have analyzed these four groups of stars independently but self-consistently in the following way.

Using the *Hipparcos* parallaxes and Galactic reddenings adopted by FC97 from Fernie, Kamper, & Seager (1993) and scaled to the various wavelengths using the extinction law of Cardelli, Clayton, & Mathis (1989), we derived absolute magnitudes for each of the Cepheids in each of the observed wavelengths. (We note that these corrections for interstellar extinction are not inconsiderable, ranging up to 2 mag in B for several stars). The resulting PL relations are shown in the six panels of Figure 2. Error bars are 1 σ uncertainties from the quoted parallaxes. Note the highly correlated nature of the individual data points about the fiducial lines. We also remind the reader that the computation of distances and their related errors from observed parallaxes is nontrivial (Brown et al. 1997), as distances are not linearly related to parallaxes, and parallax errors can subtly bias samples. A full treatment of this issue is beyond the scope of this paper, but we note that selection biases at least are minimized for stars having the smallest reported errors. As discussed by Brown et al., given the true parallax distribution, the expected biases follow naturally; however, corrections to the observed parallaxes require detailed modeling and assumptions about the true distribution. Fortunately for this application, the Cepheid sample is not parallax selected; the objects were chosen in advance based on their optical variability, periods, and apparent magnitudes.

The differences between these individual (trigonometric) absolute magnitudes and the predicted $BVIJHK$ magnitudes derived from the mean PL relations of MF91 (*solid lines* in Fig. 2) are each plotted in Figure 3 against the corresponding B-band residual. The $(B-V)$ intrinsic color residuals are plotted against the B-band residuals in the

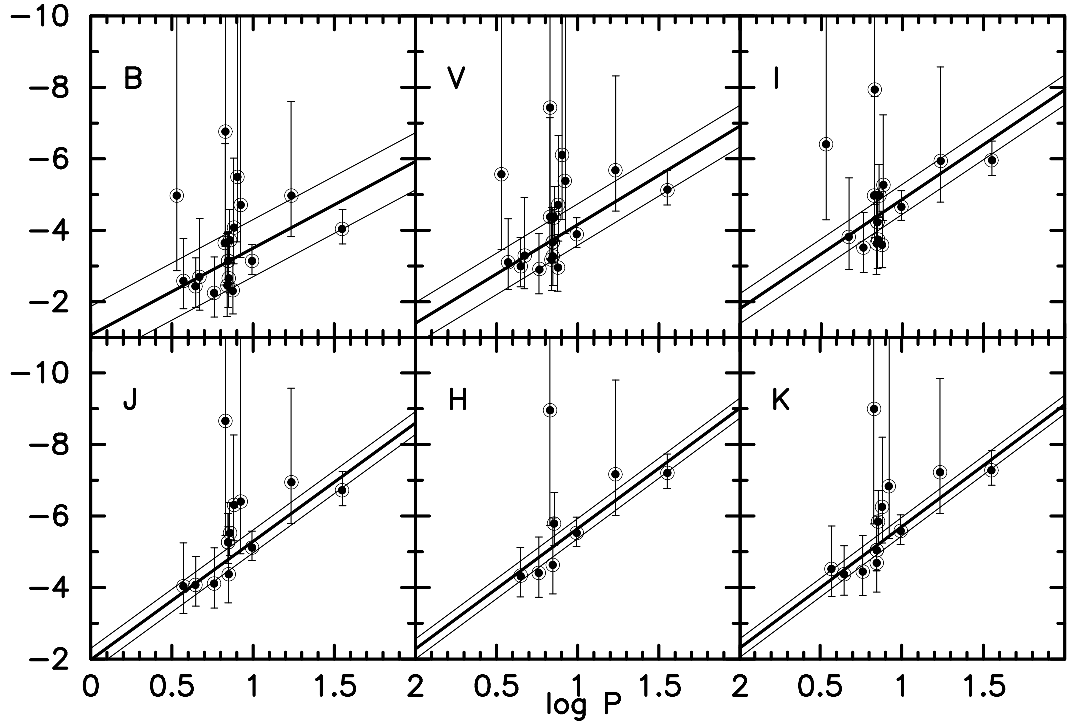

FIG. 2.—Multiwavelength period-luminosity relations for Cepheids with *Hipparcos* parallaxes, plotting all stars that have data available at particular wavelengths, noted in the upper left-hand corner of each panel. In each panel, the solid sloping line is not a fit to the data, but rather it is the published calibration of Madore & Freedman (1991) flanked by thin parallel lines representing the 2 σ limits quoted by them as being the intrinsic width of the instability strip at each wavelength.

upper right-hand panel. The individual residuals at a given wavelength contain random contributions from the parallax uncertainties, reddening errors, and finally the intrinsic (temperature-induced) magnitude residuals that reflect the finite width of the Cepheid instability strip. The observed residuals are, however, extremely large (nearly 5 mag peak to peak) and are almost certainly dominated by the (achromatic) errors in the parallaxes, given the strict unit-slope correlation of the mag-mag residuals and the total lack of any correlation between the magnitude-color residuals (Fig. 3).

Wavelength-dependent offsets between the six mean solutions independently will reflect (1) errors in the adopted true distance to the LMC (which sets all of the zero points in the MF91 multiwavelength PL relation calibrations), (2) reddening errors in the adopted extinction to the LMC sample of calibrating Cepheids, and finally (3) intrinsic differences between the LMC and Galactic Cepheids caused, for example, by metallicity.

Our first solution considers the data set that is the largest (in terms of parallaxes) but also the most restricted in terms of wavelength coverage: it consists of 19 Cepheids observed in B and V. Weighted by the square of the signal-to-noise ratio in the *Hipparcos* parallax, the residuals were summed and averaged at each of the two wavelengths giving mean offsets between the LMC calibration and the Galactic Cepheids. The variance in each mean offset was then calculated from the average of the squares of these same residuals again inversely weighted by the variance in the individually quoted parallaxes. The differences are $\Delta B = +0.23 \pm 0.35$ mag and $\Delta V = +0.16 \pm 0.28$ mag, in the sense that the LMC Cepheid calibration appears to be too faint with respect to the Galactic calibration. (Further restricting the sample to only those 12 stars with $\pi/\sigma_\pi > 2.0$ changes ΔB to $+0.22 \pm 0.24$ mag and ΔV to $+0.15 \pm 0.17$ mag.)

If the (statistically marginal but apparently systematic) differences in the B and V solutions were to be ascribed to reddening alone, then the Galactic data and the LMC calibration can be reconciled by invoking an increase of $\Delta E(B-V) = 0.07$ mag in the adopted mean reddening to the LMC Cepheid sample. This is consistent with a similar suggestion regarding the LMC Cepheid calibration made recently by Böhm-Vitense (1997) based on different data. This reddening solution has the consequence that it would also require the distance modulus of the LMC to be revised downward by -0.06 mag to 18.44 mag; the uncertainty on this offset is at least as large as the uncertainty in the individual moduli (± 0.3 mag), depending on the degree of correlation in those cumulative uncertainties. This particular path, of a reddening solution, cannot be considered definitive. Other possibilities are (1) that the LMC true modulus should be increased by $(0.23 + 0.16)/2 = +0.20$ mag, without any change to the foreground reddening, or (2) that there are differential metallicity corrections amounting to -0.23 and -0.16 mag that need to be applied at the B and V wavelengths, respectively. Of course any suitably contrived linear combination of the above three effects could also be invoked. More constraints on the problem are obviously needed.

An alternative possibility is that some of the wavelength-dependent effects seen in the comparison of the Galactic (high-metallicity) data with the LMC (lower metallicity) data could be caused by chemical composition differences between the two samples. Taken at face value, the depen-

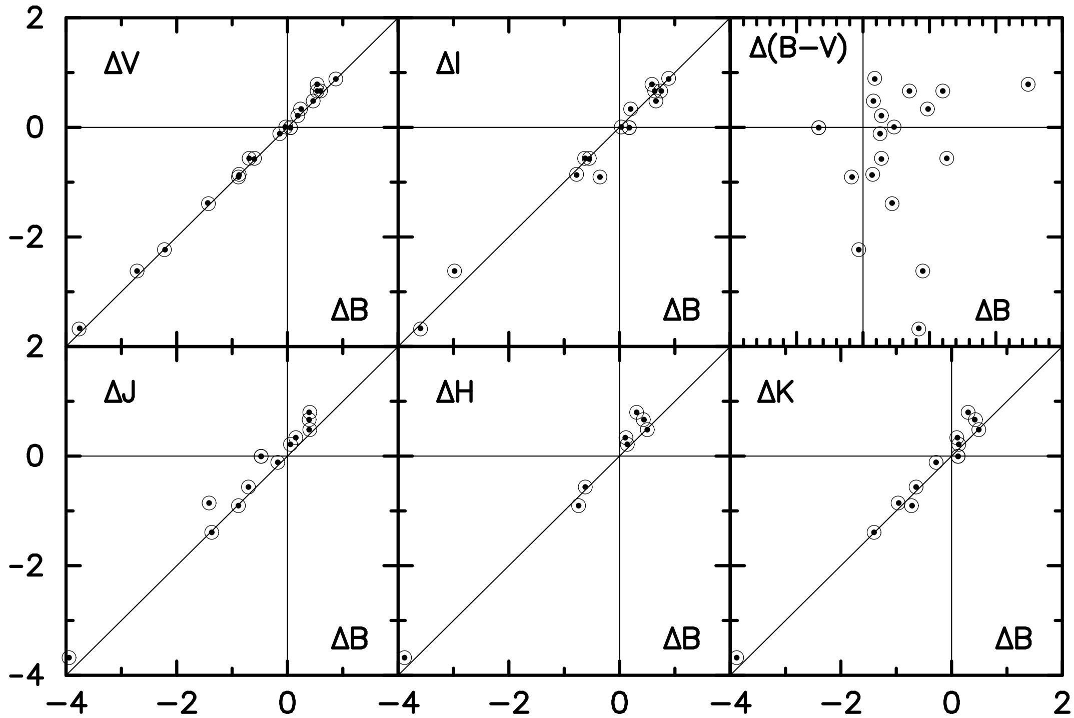

FIG. 3.—*B*-band residuals from the multiwavelength period-luminosity relations sequentially plotted as functions of residuals from each of the other five PL relations and (*upper right-hand panel*) against the $(B-V)$ color residuals. The total lack of correlation in the latter instance is unexpected except in the limit at which the residuals are dominated by distance errors in the derived parallaxes. This latter situation is apparently the case given the strong (unit-slope) correlations of the residuals in each of the other panels, regardless of wavelength.

dence of the apparent V modulus on metallicity would be very large, $\Delta V/\Delta[\mathrm{Fe/H}] = 0.16/0.15 = 1.1$ (± 1.9) mag dex^{-1}, assuming that the full offset in V noted in the above comparison is caused by metallicity and adopting a metallicity underabundance of 1.4 times between the LMC and the Solar neighborhood (see, e.g., FW87). However, we note that this effect is basically indistinguishable from reddening in its form (as evidenced by our first set of solutions) and

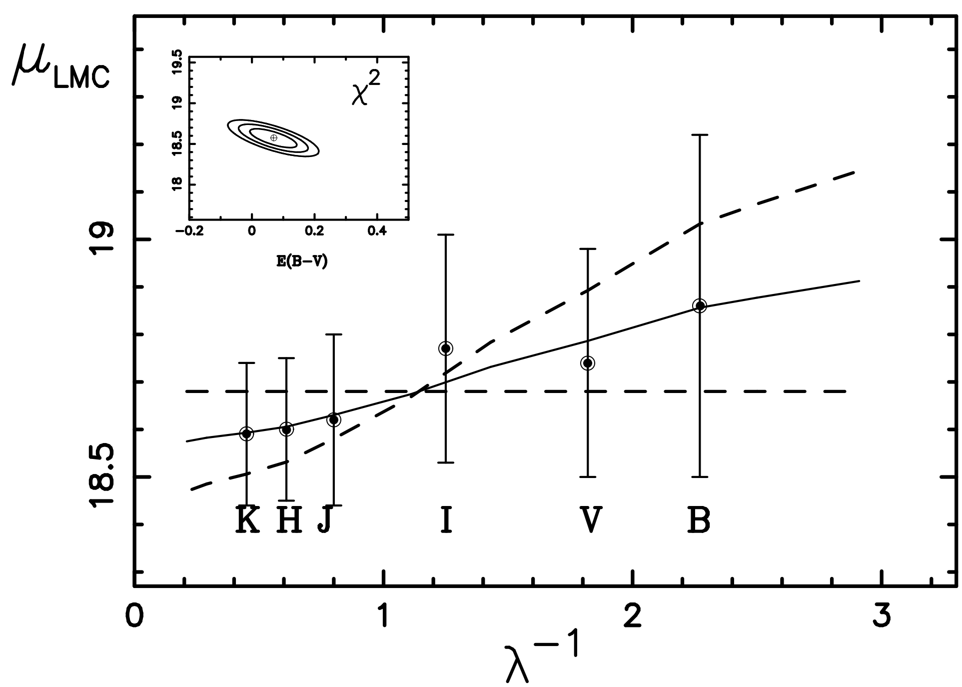

FIG. 4.—Apparent modulus plots for LMC Cepheids observed at *BVIJHK* scaled to the *Hipparcos* zero point and using the published multiwavelength PL solutions of Madore & Freedman (1991). The solid line is a weighted χ^2 fit of a reddening line to the data; the broken line indicates the 1 σ limits on that solution. Inset (*top left-hand corner*) shows the χ^2 surface, indicating the minimization solution for the modulus and reddening as well as the interdependence of their associated errors.

TABLE 1

MULTIWAVELENGTH MODULI FOR LMC CEPHEIDS

Number of Stars	$\mu_B \pm \sigma$ (mag)	$\mu_V \pm \sigma$ (mag)	$\mu_I \pm \sigma$ (mag)	$\mu_J \pm \sigma$ (mag)	$\mu_H \pm \sigma$ (mag)	$\mu_K \pm \sigma$ (mag)
19..........	18.73 ± 0.35	18.66 ± 0.28	...	...	...	...
13..........	18.71 ± 0.36	18.64 ± 0.24	...	18.44 ± 0.23	...	18.54 ± 0.13
10..........	18.74 ± 0.36	18.67 ± 0.24	18.71 ± 0.20	18.44 ± 0.24	...	18.57 ± 0.14
7...........	18.86 ± 0.36	18.74 ± 0.24	18.77 ± 0.24	18.62 ± 0.18	18.60 ± 0.15	18.59 ± 0.15

that the offset (whatever its origin) when treated as reddening leads to a true distance modulus for the LMC that is unchanged from previous assumptions at 18.50 mag. Given this apparent degeneracy between reddening and metallicity and the current large uncertainties in the parallaxes, assessing the dependence on metallicity from these data alone will remain problematic.

Moving to the infrared to obtain added leverage on the solution has numerous well-known advantages, as first articulated in McGonegal et al. (1982), such as that reddening effects are known to decrease with wavelength in a well-defined and calibrated manner, and that, simultaneously, metallicity effects are also expected to decrease in amplitude with increased wavelength.

Our second solution is based on 13 Cepheids each having *BVHK* data in common. This four-color solution gives a derived reddening increase for the LMC Cepheid sample of $+0.04 \pm 0.08$ mag, with no formal offset in the derived 18.50 ± 0.13 mag true modulus for the LMC. Our next approximation employs 10 Cepheids each now having *BVIJK* mean magnitudes. Here the formal solution for the true modulus for the LMC is 18.53 ± 0.14 mag, with a corresponding increase in the mean reddening of $+0.06 \pm 0.07$ mag. Finally, we have analyzed a sample of seven Galactic Cepheids, each having *BVIJHK* photometry, to obtain one last solution: $\Delta E(B-V) = 0.07 \pm 0.07$ mag with $(m - M)_{\rm LMC} = 18.57 \pm 0.11$ mag. The fit to this final set of observations is shown in Figure 4; the χ^2-weighted residual fitting surface is shown as an inset. The individual apparent moduli discussed here and their errors are summarized in Table 1.

Finally, if we now adopt the metallicity correction of $\Delta V = 0.04$ mag advocated by FC97 and assume that the effects at *JHK* are negligible (and eliminate *B* and *I* from the solution given that metallicity corrections for these filters are not well defined at this time), we find for this four-color solution, $\Delta E(B-V) = 0.06 \pm 0.11$ mag with $(m - M)_{\rm LMC} = 18.57 \pm 0.11$ mag. This is virtually indistinguishable from the full *BVIJHK* solution given above.

4. DISCUSSION AND CONCLUSIONS

We have used the *Hipparcos* parallaxes of nearby Galactic Cepheids to explore corrections to the multiwavelength period-luminosity relations for LMC Cepheids. The latter are based on an LMC data set scaled to a true distance modulus of 18.50 mag and an adopted foreground reddening of $E(B-V) = 0.10$ mag. Although the current uncertainties in the parallaxes are large and still depend upon the specific subsets of the Cepheids chosen for the comparison, the agreement is good, indicating that, to within ± 0.14 mag (or 7% in distance), the previously adopted zero point is substantially correct. Based on different subsamples of data having either *BV*, *BVJK*, *BVIJK*, or *BVIJHK* photometry, LMC moduli ranging from 18.44 to 18.57 mag are derived. These results, summarized in Table 2, differ from the FC97 value of 18.70 mag, which is based solely on the reddening-corrected *V* photometry of Caldwell & Laney (1991), externally adjusted for metallicity. The *Hipparcos* data alone do not allow us to discriminate between metallicity effects and the physically distinct possibility of added reddening to the LMC.

To alleviate the ambiguity posed by the need to solve for both reddening and metallicity effects on the Cepheid distances simultaneously, we are currently deriving OB star reddenings along the individual lines of sight to several dozen LMC Cepheids. This will allow us to decouple the reddening determinations from metallicity effects and go beyond the use of a single mean (foreground plus internal) reddening for the LMC calibrating Cepheid sample. Preliminary reductions indicate that the variance from field to field is large [ranging from $E(B-V) = 0.00$ up to 0.40 mag] while still indicating that an average value of $\langle E(B-V)\rangle = 0.10$ mag is appropriate for the LMC calibrating Cepheids. Details will be presented in Madore, Freedman, & Pevunova (1998).

We close by noting that at least three other very recent determinations of the true modulus to the LMC fall on either side of the value 18.50 mag adopted by MF91 in setting a zero point for the Cepheid distance scale. Both Reid (1997) and Gratton et al. (1997) derive large LMC moduli (18.65 ± 0.10 and 18.63 ± 0.06 mag, respectively) using *Hipparcos*-based calibrations of the Galactic globular cluster and RR Lyrae distance scale. On the other hand, Gould & Uza (1998) have reanalyzed the SN 1987A "light echo" and derive an upper limit of $\mu_{\rm LMC} < 18.37 \pm 0.04$ mag for the LMC true distance modulus; although they note that if the ring is slightly elliptical ($b/a \sim 0.95$), this upper limit increases to $< 18.44 \pm 0.05$ mag. A value of 18.56 ± 0.05 mag has been derived by Panagia et al. (1997) from the same data. Until these differences are fully understood and resolved and given the remaining uncertainties in the *Hipparcos* Cepheid-parallax data, we prefer to adopt a true distance modulus of 18.50 mag for the LMC, but now

TABLE 2

MULTIWAVELENGTH REDDENING SOLUTIONS

Filters	Number of Stars	$E(B-V) \pm \sigma$ (mag)	$\mu_{\rm LMC} \pm \sigma$ (mag)
BV............	19	0.17 ± ...	18.44 ± 0.35
BVJK.........	13	0.14 ± 0.08	18.50 ± 0.13
BVIJK........	10	0.16 ± 0.07	18.53 ± 0.14
BVIJHK......	7	0.17 ± 0.07	18.57 ± 0.11
$V_c JHK$........	8	0.16 ± 0.11	18.57 ± 0.11

bounded by an uncertainty of ± 0.15 mag, defined to encompass the above range of recently published values fully. This value is consistent with other estimated distances to the LMC based on a wide variety of methods (for a comprehensive modern review, see Westerlund 1997). Viewed in that perspective, the *Hipparcos* data confirm the Cepheid distance scale at better than the $\pm 10\%$ level (95% confidence).

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