THE CARNEGIE HUBBLE PROGRAM

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ABSTRACT

We present an overview of and preliminary results from an ongoing comprehensive program that has a goal of determining the Hubble constant to a systematic accuracy of ±2%. As part of this program, we are currently obtaining 3.6 μm data using the Infrared Array Camera on Spitzer, and the program is designed to include James Webb Space Telescope in the future. We demonstrate that the mid-infrared period–luminosity relation for Cepheids at 3.6 μm is the most accurate means of measuring Cepheid distances to date. At 3.6 μm, it is possible to minimize the known remaining systematic uncertainties in the Cepheid extragalactic distance scale. We discuss the advantages of 3.6 μm observations in minimizing systematic effects in the Cepheid calibration of H0 including the absolute zero point, extinction corrections, and the effects of metallicity on the colors and magnitudes of Cepheids. We undertake three independent tests of the sensitivity of the mid-IR Cepheid Leavitt Law to metallicity, which when combined will allow a robust constraint on the effect. Finally, we provide a new mid-IR Tully–Fisher relation for spiral galaxies.

Key words: distance scale – galaxies: distances and redshifts – stars: variables: Cepheids

Online-only material: color figures

1. INTRODUCTION

1.1. The Need for Higher Accuracy in H0

The determination of cosmological parameters has improved dramatically in the past decade. With measurements from Wilkinson Microwave Anisotropy Probe (WMAP), the Hubble Space Telescope (HST) Key Project, Type Ia supernovae (SNe Ia), and baryon acoustic oscillations, to name just a few examples, a new concordance cosmological model has emerged having an expansion rate H = 0.72, density parameters Ωm = 0.23, and an equation of state parameter w = −1.0, with an uncertainty of ±10% (Freedman & Madore 2010). The “factor-of-two controversy” over the value of the Hubble constant has been resolved (Freedman et al. 2001; Spergel et al. 2007; Riess et al. 2009) and 5%–10% or better precision has now been reached for several fundamental cosmological parameters (Freedman & Madore 2010; Riess et al. 2011; Beutler et al. 2011; Komatsu et al. 2011; Mould 2011), a situation hard to imagine even just a decade ago.

Equally impressive progress is expected given upcoming facilities such as the Large Synoptic Survey Telescope, EUCLID, Global Astrometric Interferometer for Astrophysics (GAIA), and the already active mission Planck. These large missions, combined with a suite of small-to-medium-sized projects planned for the interim, promise an extraordinary opportunity to characterize and understand the processes that govern the origin and evolution of the universe. However, strong physical degeneracies exist amongst the cosmological parameters derived from the angular power spectrum of cosmic microwave background (CMB) anisotropies (from WMAP and Planck, and other CMB experiments). For example, there are well-known degeneracies between the Hubble constant and other cosmological parameters, such as the dark-energy density ΩΛ and w (Hu & Dodelson 2002).

An independent measurement of H0, made to higher accuracy than we have today, will continue to be a critical input for the next generation of cosmology experiments. Uncertainty in H0, if left at the 5% level, will dominate the (coupled) uncertainties in the new higher-precision experiments designed to measure cosmological parameters. As emphasized by Hu (2005), the best complement to current and future CMB measurements for a measure of the dark-energy equation of state at a redshift of about z = 0.5 is a measurement of the Hubble constant that is accurate at the few percent level. The results of Beutler et al. (2011), Komatsu et al. (2011), and Mould (2011) are also interesting in this regard.

1.2. H0 to 2% Accuracy

We are executing a program to recalibrate the extragalactic distance scale and improve our knowledge of the Hubble constant by dealing directly with all of the systematics currently known to be affecting the Cepheid distance scale. We describe here our program using the Spitzer Space Telescope (Werner et al. 2004) and Infrared Array Camera (IRAC; Fazio et al. 2004) as part of a Spitzer Exploration Project (PID 61000: Freedman). The second phase of our program (using more distant galaxies, deeper into the Hubble flow) is designed to be carried out using the James Webb Space Telescope (JWST).

The largest uncertainty in the HST Key Project determination of H0 (Freedman et al. 2001) was the absolute zero point of the Cepheid period–luminosity (PR) relation, which was directly tied to the distance to the Large Magellanic Cloud.
(LMC). Our first requirement is to reduce the uncertainty in the absolute zero point by a factor of two to three, using Spitzer to obtain complete light curve coverage at mid-infrared (IRAC) wavelengths for a well-observed sample of LMC and Galactic Cepheids. From there, we can use Spitzer to extend these mid-infrared measurements to a much larger sample of HST Key Project spiral galaxies in which Cepheids have already been discovered. This single step alone immediately drops the systematic error in the Cepheid distance scale zero point to the (3%) level. As discussed in W. L. Freedman et al. (2012, in preparation) and briefly in Section 6, a preliminary calibration based on our Spitzer data already exceeds the Key Project in accuracy by over a factor of three. As a cross-check, we are also measuring the distance to the maser galaxy, NGC 4258, which is itself an independent calibrator of the distance scale zero point, in addition to the LMC and the Milky Way (Humphreys et al. 2008; Mager et al. 2008; Riess et al. 2011). Our recent results, discussed below, demonstrate that we can reach this required level of accuracy. With the new mid-IR Tully–Fisher (TF) relation for spiral galaxies, we can measure distances into the Hubble flow. Future measurements using JWST will then significantly increase the number of fundamental Cepheid calibrators and bring the uncertainties down to ±2%. We discuss each of these steps in turn, and give an overview of some preliminary results based on our current analysis of Spitzer data.

Two relatively recent developments have dramatically changed the landscape regarding a recalibration of the extragalactic distance scale. First, Benedict et al. (2007) used the fine guidance sensors (FGSs) on HST to provide the first high-precision, geometric parallaxes to 10 nearby Galactic Cepheids having periods ranging from 4 to 35 days. Second, Freedman et al. (2008) demonstrated (using Spitzer/SAGE legacy data for the LMC from Meixner et al. 2006) the small dispersion in the mid-infrared PL relations (hereafter referred to as the Leavitt Law) at mid-infrared wavelengths, even for single (not phase-averaged) observations of Cepheids.

2. WHY THE MID-INFRARED?

Mid-infrared observations of Cepheids offer a host of advantages over shorter wavelength data. Most important is the reduced sensitivity of long-wavelength data to line-of-sight interstellar extinction (both Galactic and extragalactic). The interstellar extinction law at mid-infrared wavelengths has now been measured by a number of authors (Rieke & Lebofsky 1985; Indebetouw et al. 2005; Flaherty et al. 2007; Román-Zúñiga et al. 2007; Nishiyama et al. 2009). They find that the shape of the extinction curve varies somewhat between different sight lines, where the observed range of $A_\mu/ A_V = 0.058–0.071$ at 3.6 $\mu$m, and 0.023–0.060 at 4.5 $\mu$m. However, the most important point is that the extinction measured in magnitudes in the mid-IR, as compared with optical V-band data, for example, is reduced by factors of 14–17 at 3.6 $\mu$m, and 16–43 at 4.5 $\mu$m.

In practice then, for $A_V \sim 0.20$ mag, with an uncertainty in the reddening of $10\% (\epsilon E(B-V) = \pm 0.02)$ mag (giving $\epsilon [A_V]$ of $\pm 0.06$ mag), at mid-IR wavelengths this reduces to $A_{3.6,4.5} = 0.01\pm 0.004$ mag; that is, the correction to a V-band distance transforms from 10% to a correction of only 0.5% in distance at 3.6 $\mu$m, and it drops the uncertainty on the distance from 3% in the visual down to a statistically insignificant level of only $\pm 0.2\%$ at 3.6 $\mu$m.

In addition, because stellar surface brightness in the mid-infrared is so insensitive to temperature (being on the Rayleigh–Jeans portion of the spectral energy distribution), the observed, cyclical variation in a Cepheid’s luminosity at 3.6 $\mu$m is almost completely dominated by the comparatively small radial (i.e., surface area) variations. The slope of the PR relation in the mid-IR then becomes virtually equivalent to the period–area relation when the bolometric correction becomes insensitive to temperature (which occurs longward of about 1 $\mu$m for G and K spectral types, typical of Cepheids). The areal variations typically amount to only around 0.3–0.4 mag in total amplitude. (Those over 100 days can have amplitudes of 0.6–0.8 mag.) This is to be compared with observed $B$-band amplitudes that can exceed 2 mag or $I$-band amplitudes that can reach 1 mag. Even just a factor of three decrease in amplitude provides for almost a factor of 10 decrease in the number of randomly phased observations needed to reach the same error on the mean magnitude for a given variable star.

There are yet further advantages to the mid-infrared. The effects of line blanketing, the process by which energy is removed from the optical and UV and is subsequently thermalized and redistributed to the optical/near-infrared (back warming), are expected to be much smaller at mid-infrared wavelengths. Most importantly, because the reddening is so low compared with the optical, 3.6 $\mu$m provides an opportunity for a very clean and direct test for any metallicity effects.

For the HST Key Project determination of the extragalactic distance scale, a list of identified systematic uncertainties sets its finally quoted accuracy at ±10%. The dominant systematics were (1) the zero point of the Leavitt Law, (2) the differential metallicity corrections to the PL zero point, (3) reddening corrections, (4) calibration/instrumental uncertainties, and (5) crowding effects and finally HST point-spread function (PSF) uncertainties and evolution with time/position. In this paper, we discuss the improvements that are coming from Spitzer, and that will eventually come from JWST.

2.1. Model Spectra of Cepheids from 4 to 6 $\mu$m

We show in Figures 1(a) and (b) Kurucz models for solar-metallicity supergiant stars, with effective temperatures and gravities of 4000 K and log($g$) = 0, consistent with those of Cepheids. Note that the IRAC band 1 at 3.6 $\mu$m is devoid of any molecular bands; however, IRAC band 2 at 4.5 $\mu$m overlaps with the broad CO molecular bands in the approximate wavelength range of 4–6 $\mu$m. There are two immediate conclusions from these plots. First, Figure 1(a) illustrates the smooth continuum over the 3.6 $\mu$m band, and as expected, its suitability for distance determinations. Figure 1(b) illustrates that the 4.5 $\mu$m band may not be a suitable distance indicator for Cepheids. We are currently exploring the use of the 4.5 $\mu$m band as a metallicity indicator for Cepheids (Scowcroft et al. 2011).

These results are consistent with those obtained by Marengo et al. (2010) based on time-dependent hydrodynamic models of Cepheids. Their Figure 6, based on a model for the 10 day Cepheid, $\xi$ Gem, shows a broad CO feature at 4.5 (as well as 5.8) $\mu$m, but no features at 3.6 $\mu$m. This behavior is also consistent with the observed [3.6]–[4.5] $\mu$m colors of Cepheids (e.g., Marengo et al. 2010; Monson et al. 2012; V. Scowcroft et al. 2011, in preparation), see also Section 5. Finally, we see the effects of the CO bands at 4.5 $\mu$m in the behavior of the Leavitt Law slopes as a function of wavelength. The slopes approach an asymptotic value of $-3.45$; however, the 4.5 $\mu$m slope is $-$3.45; however, the 4.5 $\mu$m slope is $-$3.45.

$^5$ However, at cooler temperatures the formation of molecules and the appearance of molecular bands, such as CO in the 4.5 $\mu$m region do run contrary to this overall expectation.
Figure 1. Synthetic spectra for supergiants of solar metallicity, spanning the wavelength ranges for the 3.6 and 4.5 μm bands, respectively. These plots were generated by A.M. using the code and line lists from http://wwwuser.oat.ts.astro.it/atmos/Download.html (Kurucz 1993; Sbordone et al. 2004; Sbordone 2005). The spectra are shown at an effective spectral resolution of $R = 600$.

Table 1

| Program                  | Target       | $N_{\text{obs}}$ | Channels |
|--------------------------|--------------|------------------|----------|
| Milky Way                | 37 Cepheids  | 24 phased per Cepheid | [3.6], [4.5] |
| LMC                      | 85 Cepheids  | 24 phased per Cepheid | [3.6], [4.5] |
| SMC                      | 100 Cepheids | 12 phased per Cepheid | [3.6], [4.5] |
| Other Local Group        |              |                  |          |
| IC 10                    | 6 random    | [3.6], [4.5]     |          |
| IC 1613                  | 12 random   | [3.6], [4.5]     |          |
| Leo A                    | 6 random    | [3.6], [4.5]     |          |
| M31, two fields          | 12 random   | [3.6], [4.5]     |          |
| M33                       | 12 random   | [3.6], [4.5]     |          |
| NGC 3109                 | 12 random   | [3.6], [4.5]     |          |
| NGC 6822                 | 12 random   | [3.6], [4.5]     |          |
| Sextans A                | 12 random   | [3.6], [4.5]     |          |
| Sextans B                | 12 random   | [3.6], [4.5]     |          |
| Pegasus Dwarf            | 12 random   | [3.6], [4.5]     |          |
| Wolf–Landmark–Melotte    | 12 random   | [3.6], [4.5]     |          |
| Beyond the Local Group   |              |                  |          |
| GR8                      | 6 random    | [3.6], [4.5]     |          |
| IC 4182                  | 6 random    | [3.6], [4.5]     |          |
| NGC 5253                 | 6 random    | [3.6], [4.5]     |          |
| M81, two fields          | 8 random    | [3.6]            |          |
| NGC 247                  | 10 random   | [3.6]            |          |
| NGC 300, 2 fields        | 5 random    | [3.6]            |          |
| NGC 7793                 | 9 random    | [3.6]            |          |
| NGC 2403, 2 fields       | 5 random    | [3.6]            |          |
| M101                     | 5 random    | [3.6]            |          |
| NGC 4258                 | 12 random   | [3.6]            |          |
| Cen A                    | 8 random    | [3.6]            |          |
| M83                      | 8 random    | [3.6]            |          |
| Tully–Fisher calibrators | 5 galaxies  | 1 per galaxy     | [3.6], [4.5] |
| Tully–Fisher targets     | 398 targets | 1 per target     | [3.6], [4.5] |
| Supernova host galaxies  | 44 targets  | 1 per target     | [3.6], [4.5] |

Notes. Warm Spitzer observations taken in programs P61000–61010, and P70010 (SMC) for the CHP.

clearly discrepant (e.g., Freedman et al. 2008; Marengo et al. 2010; V. Scowcroft et al. 2011, in preparation). This body of evidence suggests that the 4.5 μm band may need to be avoided for distance determinations.

3. THE CARNEGIE HUBBLE PROGRAM (CHP)

We give here a brief overview of the components of the CHP observing program. The galaxies for which we have used Spitzer to obtain observations of Cepheids are given in Table 1, which lists all of the targets by program, the number of observations per Cepheid, how the observations were spaced (phased or random), and the filters used. We also list the numbers of TF calibrators and TF and SNe Ia target galaxies. All of our observations have been made using post-cryogenic or “Warm Spitzer.”

Originally, we obtained 3.6 and 4.5 μm measurements of 37 Galactic Cepheids (Monson et al. 2012). Each Cepheid was observed 24 times over the course of its cycle, and the
observations were scheduled to give uniform sampling of the light curves. All of these Cepheids are close enough to be future GAIA satellite targets, which will provide accurate parallaxes for a larger sample of Milky Way Cepheids. We have been awarded further Spitzer time to observe a larger sample of Galactic Cepheids, in anticipation of the launch of GAIA, which would bring the number of Milky Way targets in line with our LMC and Small Magellanic Cloud (SMC) samples. Ultimately, this larger sample of Cepheids will provide a robust zero point for the calibration of \( H_0 \). We have also obtained twenty-four 3.6 and 4.5 \( \mu \)m measurements of 85 well-observed Cepheids in the LMC (V. Scowcroft et al. 2011, in preparation). As an adjunct program, we have also obtained 12 epochs of 3.6 and 4.5 \( \mu \)m measurements for a sample of 100 SMC Cepheids, useful for calibration of the metallicity effects for Cepheids.

In Figure 2, we show 3.6 and 4.5 \( \mu \)m example light curves for two Galactic Cepheids from Monson et al. (2012), two LMC Cepheids from V. Scowcroft et al. (2011, in preparation), and two Cepheids from Scowcroft et al. (2011). These Cepheids have a range of periods from 5 to 66 days. The very small scatter in these light curves indicates the high quality of the Spitzer photometry.

Moving out in distance, we have obtained 12 epochs of 3.6 \( \mu \)m data for several galaxies within the Local Group and beyond containing known Cepheids (see Table 1). Critical for an independent zero-point calibration of the Leavitt Law, we have observed Cepheids in the maser galaxy NGC 4258 (at 7.2 Mpc). Finally, we have obtained 3.6 \( \mu \)m photometry for several hundred galaxies located in clusters with measured TF distances, which can then be calibrated with Cepheids (Section 3.5). Over 50 galaxies with SNe Ia distances measured by Contreras et al. (2010) have also been observed as part of this program, which will allow an independent determination of \( H_0 \) with this calibration well into the far-field Hubble flow. We now describe the individual aspects of the CHP in more detail.

### 3.1. The Galactic Cepheid Calibration

To date, as part of the CHP to set the absolute zero point and slope of the Leavitt Law relation in the mid-IR, we have obtained high-precision, uniformly sampled, 3.6 and 4.5 \( \mu \)m light curves for the Galactic Cepheid parallax sample (Monson et al. 2012). All of the light curves have comparable quality to what is shown in Figure 2. We also have equivalent data for an order-of-magnitude larger sample of LMC Cepheids (V. Scowcroft et al. 2011, in preparation), discussed further below. The former calibrates the absolute zero point; the latter determines the slope. In addition to the 10 Milky Way Cepheids with HST trigonometric parallaxes from the FGS (Benedit et al. 2007), we have observed 27 other Cepheids within 4 kpc of the Sun (Monson et al. 2012) that are close enough for astrometric parallaxes for GAIA. The currently available sample of HST/FGS Galactic Cepheids yields a zero-point calibration of the Cepheid PL relation good to \( \pm 2\% \). An independent check of this calibration and a 50% statistical improvement will come with the Spitzer observations of nearby Cepheids once GAIA has obtained geometric parallaxes for them. Seventeen of the Cepheids in our sample are also known to be members of Galactic open clusters or associations (Turner 2010), for which GAIA again will provide a more accurate calibration.

### 3.2. The Distance to the LMC

Distance measurements to the LMC have played a critical role in the calibration of the extragalactic distance scale (e.g., Freedman et al. 2001; Riess et al. 2005; Sandage et al. 2006). Because of its proximity, a number of different methods have been used to estimate the distance to the LMC. The range in quoted distances is almost certainly dominated by systematic errors. As tabulated in Gibson (2000) and in Freedman et al. (2001), most of the values for the LMC distance modulus have tended to fall between 18.1 and 18.7 mag (i.e., 42.55 kpc); more recent values have tended to cluster around a distance modulus of 18.5 mag (see Alves 2004; Schaefer 2008), which is the value adopted by the Key Project.

In the LMC, there are 92 Cepheids for which there are published optical (BVRI) and near-infrared (JHK) light curves and time-averaged photometry (Madore & Freedman 1991; Persson et al. 2004). These stars were chosen to be unconfused in the \( K \) band, distributed across the face of the LMC, and having periods ranging from 3 to 100 days. Approximately two dozen near-IR phase points were obtained at each (JHK) wavelength for each star. We have now obtained time-averaged IRAC photometry for 85 of these LMC Cepheids (selected to have periods in excess of 6 days), consisting of two dozen observations at both 3.6 and 4.5 \( \mu \)m (V. Scowcroft et al. 2011, in preparation). These observations were scheduled evenly based on the known period for each Cepheid so that they would be uniformly spaced when phase-folded into a light curve, the success of which can be seen in Figure 2.

Long-period Cepheids are intrinsically the brightest and are therefore the first (and sometimes the only) Cepheids detected in the most distant galaxies. The extragalactic distance scale therefore rests heavily on the long-period Cepheid calibration; however, the Galactic HST parallax sample contains only one long-period Cepheid, l Car at \( P = 35 \) days. The final set of LMC Cepheids observed for the CHP is almost an order of magnitude larger in size than the currently available total set of Galactic calibrators, and is therefore being used to define the slope and width of the long-period (\( P \geq 10 \) days) end of the Leavitt Law.

In Figure 3, we show the Leavitt Law at 3.6 \( \mu \)m for 82 Cepheids in the LMC as observed by V. Scowcroft et al. (2011, in preparation), with 6 days \( < P \) \( < 60 \) days. Cepheids with \( \log P > 1.8 \) are shown, but have been excluded from the fits. The dispersion in the 3.6 \( \mu \)m relation amounts to only \( \pm 0.106 \) mag or \( \pm 5\% \) in distance for a single Cepheid. For comparison, we also show the V-band data from Madore & Freedman (1991) for LMC Cepheids. The dispersion in this case is more than a factor of two greater, amounting to \( \pm 0.252 \) mag. Comparison with the dispersion seen the near-infrared is quite favorable, with the \( H \)- and \( K_s \)-band dispersions being \( \pm 0.116 \) mag and \( \pm 0.108 \) mag, respectively (Persson et al. 2004).

These data demonstrate the power of Spitzer to provide a quantitatively significant improvement in the calibration of the Hubble constant based upon a Cepheid distance scale. As discussed above, at 3.6 \( \mu \m \) compared with optical wavelengths, the effects of reddening are significantly lower, the expected effects of metallicity are lower (see Section 4), and the dispersion in the Leavitt Law is about \( \pm 0.1 \) mag, giving distances good to \( \pm 5\% \) for a single Cepheid. Accordingly, for a sample of 82 Cepheids, the distance to the LMC can be determined to a level of statistical precision better than \( \pm 1\% \). The systematic accuracy is \( \pm 2\% \); this lower limit being set by small numbers of Cepheids in the Galactic calibration. With the addition of parallaxes from

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6 See the extensive compilation of 275 distance estimates to the LMC currently available from the NASA/IPAC Extragalactic Database (NED): http://nedwww.ipac.caltech.edu/cgi-bin/nDistance?name=lmc.
Figure 2. Light and color curves for a selection of Cepheids in the Milky Way (top row), LMC (middle row), and SMC (bottom row). Cepheids with periods longer than 12 days are observed at regularly spaced intervals of $P/24$ (or $P/12$ for the SMC). Short-period ($P < 12$ days) Cepheids such as V Cen are observed every $12 \pm 4$ days. These plots illustrate the high-quality, well-sampled light curves that can be obtained over a large range of periods utilizing the outstanding scheduling efficiency of Spitzer.
3.3. Cepheid Distances to Local Group Galaxies

We are currently obtaining high-precision, mid-IR Cepheid distances to all Local Group galaxies known to contain Classical Cepheids. Several of these are calibrators for the TF relation, while others also can act as a basis for testing for metallicity effects on the Cepheid PL relation (see below). The Local Group targets are listed in Table 1. All of these galaxies and their Cepheids have been observed at optical wavelengths and many of them have already been followed up in one or more near-infrared bands (e.g., Gieren et al. 2008, and references therein for the Araucaria Project on near-infrared observations of Cepheids in southern hemisphere galaxies).

We have analyzed publicly available archival data on two Local Group galaxies, NGC 6822 (at 500 kpc; Madore et al. 2009) and IC 1613 (at 700 kpc; Freedman et al. 2009). In each of these galaxies, we were able to recover and measure the brightest Cepheids that were uncrowded. Analysis of all 12 epochs of data for IC 1613 is currently underway (Scowcroft et al. 2011). The NGC 6822 PL relations in all four IRAC bands are shown in the left panel of Figure 4. These archival exposures were not optimized for measuring faint stars, but they clearly show that Cepheids can be seen out to the edge of the Local Group, and beyond. The exposure time per pixel for NGC 6822 was only 240 s, and yet Cepheids with periods from 10 to 100 days were easily measured. The right panel of Figure 4 demonstrates the ability of IRAC observations to cut through the intervening extinction. In this instance, the apparent $B$ modulus is affected by 1.1 mag of extinction, while the uncorrected 3.6 $\mu$m apparent modulus is within 0.08 mag of the true modulus.

3.4. Beyond the Local Group

As summarized in Table 1, we have obtained 3.6 $\mu$m imaging data for a number of nearby galaxies with known Cepheids beyond the Local Group. The primary challenge for these more distant galaxies will be the effects of crowding, or overlapping of images. We are exploring a number of methods to mitigate the effects of crowding on the photometry. These galaxies will serve the dual roles of calibrators of secondary distance methods and probes of the expansion rate inside 8 Mpc or so. Beyond this distance, the higher resolution and higher sensitivity of JWST will be required for accurate measurements of Cepheid distances at 3.6 $\mu$m. The goal of attaining a measurement of $H_0$ to a (statistical and systematic) level of $\pm 2\%$ will require direct Cepheid distances to the larger sample of more distant galaxies. Most of the galaxies with Cepheid distances measured as part

Figure 3. Phase-averaged 3.6 $\mu$m (red circles) and $V$-band (blue squares) Leavitt Law relations for the LMC. The 3.6 $\mu$m data are from V. Scowcroft et al. (2011, in preparation), the $V$ band from Madore & Freedman (1991). Note the small dispersion of $\pm 0.108$ mag at 3.6 $\mu$m, which is more than a factor of two less than for the $V$ band. The dashed lines represent weighted least-squares fits to the PL relations for Cepheids in the period range 6–60 days. The solid lines denote $2\sigma$ ridge lines.

(A color version of this figure is available in the online journal.)

Figure 4. Left panel: random-phase Leavitt Law relations for Cepheids in NGC 6822 observed as part of the SINGS Legacy program in all four IRAC bands. Right panel: multiwavelength fit of a Galactic extinction curve to apparent Cepheid distance moduli to NGC 6822. The data are from Madore et al. (2009). The shape of the curve is fixed; its amplitude is set by the line-of-sight extinction; and the intercept gives the true distance modulus. The two near-infrared data points fall off of the main fit for currently unknown reasons. The mid-IR apparent distance moduli appear close to the true modulus even before any extinction correction is applied.
of the Key Project, as well as the increasing samples of SNe Ia (e.g., Riess et al. 2011) will require JWST observations.

3.5. The Mid-IR Tully–Fisher Relation and the Far-field Hubble Flow

There are 10–20 galaxies in each of the clusters calibrated as part of the HST Key Project sample, based on the survey of Giovanelli et al. (1997), that can be used to determine $H_0$ using the Spitzer-calibrated mid-IR TF relation. The galaxies in these clusters probe 9000 km s$^{-1}$ (or 120 Mpc) into the Hubble flow. We have further supplemented this cluster sample with field objects selected from the Flat Galaxy Catalog (Karachentsev et al. 1993) for which there are published H$^0$-line profiles. This sample extends the TF reach to around 18,000 km s$^{-1}$ (or 240 Mpc). The two samples will allow us to average over any residual perturbations to the Hubble flow even at high redshift, and guard against possible environmental (field versus cluster) effects. We have also obtained 3.6 $\mu$m data for nine galaxies that may ultimately have water maser distances independently determined for them (Braatz & Gugliucci 2008). Finally, we are observing a sample of disk galaxies drawn from The Carnegie (Low-$z$) Supernova Program (Contreras et al. 2010) that have had SN Ia events measured in them, allowing us to make a direct cross-calibration and tie-in of TF with the SN distance scale. Analysis of these data is currently underway (M. Seibert et al. 2012, in preparation). A more direct tie-in between galaxies beyond the resolution/confusion limit of Spitzer, having both Cepheids and Type Ia SN events, must await the combined sensitivity and resolution of JWST.

In addition to Cepheids, Spitzer also offers advantages for the TF relation in the mid-IR where once again the effects of extinction are minimized. In addition, the contribution of old stars as tracers of mass can be maximized. Of the 23 nearby galaxies that can be used to calibrate the TF relation, having distances determined by HST, 17 of these have new 3.6 $\mu$m AB magnitudes (M. Seibert et al. 2012, in preparation). In Figure 5, we show the $B$, $V$, $I$, and 3.6 $\mu$m sample of 17 calibrating galaxies for which there are data for all four wavelengths. The $B$-, $V$-, and $I$-band magnitudes have been corrected for inclination-induced extinction effects and their 20% line widths have been corrected to edge-on (Sakai et al. 2000); no extinction correction has been applied to the 3.6 $\mu$m data. The 1$\sigma$ scatter in these relations is $\pm$0.43, 0.37, 0.32, and 0.31 mag for the $B$, $V$, $I$, and 3.6 $\mu$m data, respectively; the outer lines follow the mean regressions at $\pm2\sigma$. Each of these galaxies entered the calibration with its own independently determined Cepheid-calibrated distance from Freedman et al. (2001). In Figure 6, we show example TF 3.6 $\mu$m relations for 4 out of 24 clusters of galaxies for which we have 3.6 $\mu$m data. These data will provide an independent estimate of the value of $H_0$ (M. Seibert et al. 2012, in preparation).

4. TESTS FOR METALLICITY SENSITIVITY OF THE MID-IR PL RELATIONS

A remaining systematic effect in the determination of $H_0$ is the sensitivity of the Cepheid PL relation to metallicity. We undertake three independent tests of the sensitivity of the Cepheid Leavitt Law to metallicity, any one of which could, in principle, calibrate the effect if it is measurable in the mid-IR, and all three of which combined, will robustly constrain the effect. The significant advantage of the mid-IR is that the relative insensitivity to extinction allows a more precise test of metallicity alone.

The first test involves the LMC alone (Freedman & Madore 2011). Romaniello et al. (2008) present evidence that the LMC Cepheids themselves have a spread of metallicity amounting to 0.5 dex in [Fe/H]. The mid-IR PL relations are predicted to have a residual dispersion of less than $\pm0.08$ mag after time-averaged magnitudes are obtained and geometrical effects due to the three-dimensional extent and orientation of the LMC are removed. Any metallicity effect must be buried within that small dispersion, along with any other second- and third-order effects,
i.e., variations of radius and temperature across the instability strip at fixed period, the presence or absence of (physical) red companions, plane-thickness variations in the LMC (over and above global tilt corrections), and residual differential extinction effects.

In Figure 7, we show the deviations of individual \( \text{JHK} \), 3.6 and 4.5 \( \mu \)m LMC Cepheid magnitudes from the \( P \text{R} \) relation as a function of spectroscopic \([\text{Fe}/\text{H}]\) metal abundances from Romaniello et al. (2008). \([\text{Fe}/\text{H}]\) values range from approximately \(-0.6\) to \(-0.1\) dex. This plot is an updated version of Figure 2 from Freedman & Madore (2011), now based on time-averaged magnitudes, rather than the two (random-phase) observations available previously. The slopes are very shallow for all of the near- and mid-IR wavelengths; a crossover occurs at the \( K \) band where the slope is nearly flat. Formally, the 3.6 \( \mu \)m slope is \(-0.09 \pm 0.29\) mag dex\(^{-1}\). We have also added data to this plot for three Galactic Cepheids for which there are both 3.6 \( \mu \)m data from Monson et al. (2012) and \([\text{Fe}/\text{H}]\) measurements from Romaniello et al. The Galactic Cepheid \( \beta \) Car has a higher \([\text{Fe}/\text{H}]\) abundance than any of the LMC Cepheids with \([\text{Fe}/\text{H}] = 0.0\). Yet there is again no indication in this (small) sample for a significant metallicity effect. The slope is close to flat also for the Galaxy.

The second test involves both M31 and M33. Each galaxy supports a modest metallicity gradient as measured from spectroscopic studies of their \( \text{H} \)\( \alpha \) regions. Given the insensitivity to reddening in the mid-IR, a change in the apparent zero point of the mid-IR PL relations as a function of radius will provide a much stronger test for metallicity than can be achieved at optical wavelengths alone where the combined effects of reddening and metallicity are difficult to disentangle. We have observed Cepheids in M31 and M33, covering the full range of metallicity that each of these galaxies presents, sampled in at least four radially distinct positions.

Finally, all targeted Local Group galaxies have independently determined tip of the red giant branch (TRGB) distances. By comparing the TRGB distances with the mid-IR Cepheid distances, one can test for a correlation of those differences with metallicity (e.g., Lee et al. 1993; Sakai et al. 2004). Cepheids and TRGB stars are decoupled in their systematics, metallicities, history of star formation, and location in each of the galaxies. They are of equally high precision as distance indicators, and the moduli independently derived from them can be compared. We have observed Cepheids in Sextans A and Sextans B, NGC 3109 and Wolf–Lundmark–Melotte, IC 1613 and NGC 6822 for this test, obtaining 12 phase points per object in order to bring the uncertainty in their individual mean mid-IR magnitudes down to better than \( \pm 0.04\) mag.

We again emphasize that the strength of these tests resides in the fact that the mid-IR Cepheid moduli require extremely small corrections for extinction, unlike the same tests performed at optical wavelengths where extinction corrections are far larger than the sought-after metallicity effect. If a metallicity effect

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**Figure 6.** Example 3.6 \( \mu \)m Tully–Fisher relations for four clusters of galaxies (Antlia, A262, Cancer, and Ursa Major) from M. Seibert et al. (2012, in preparation). The dispersions in these relations are shown in the lower right. (A color version of this figure is available in the online journal.)

**Figure 7.** Deviations of individual \( \text{JHK} \), 3.6 and 4.5 \( \mu \)m LMC Cepheid magnitudes from their respective period–luminosity relations plotted as a function of individual spectroscopic \([\text{Fe}/\text{H}]\) metal abundances from Romaniello et al. (2008). This is an updated and augmented version of a plot that first appeared in Freedman & Madore (2011); here we only focus on the near-infrared (\( \text{JHK} \)) and mid-IR (3.6 and 4.5 \( \mu \)m) relations. The mid-IR LMC data are now based on time-averaged IRAC data (V. Scowcroft et al. 2011, in preparation). Fits to the data are shown as thick solid lines; the thin solid lines are flat. For the 3.6 \( \mu \)m correlation only, we show the corresponding deviations (labeled solid squares) for three Galactic (high-metallicity) Cepheids that are common to the CHP and Romaniello samples. These data support the conclusion that metallicity effects at near- and mid-IR wavelengths are small compared to the optical and ultraviolet.
exists at mid-infrared wavelengths, we can calibrate and correct for it.

5. CEPHEID MID-IR COLORS: CO ABSORPTION AT 4.5 μm

As noted above, the Rayleigh–Jeans portion of the spectral energy distribution for Cepheids is emitted at mid-IR wavelengths where there is very little or no sensitivity to temperature. The slope of the tail of the distribution is constant, independent of the temperature of the star. Thus, if a Cepheid approximates a blackbody, the expectation would be that colors based on the IRAC filters (at 3.5, 4.5, 5.8, or 8.0 μm) would be relatively constant as a function of phase and/or period. However, as seen previously in Figure 1, for the 4.5 μm band, the presence of broad CO molecular absorption bands between about 4 and 6 μm affects the 4.5 (and 5.8) μm IRAC filters. The 3.6 μm band lies outside of the CO feature. The models of Marengo et al. (2010) show that these deep CO absorption bands occur in all supergiants of the temperature and gravity of Cepheids, and they also vary during the Cepheid pulsational cycle. The color variation seen through the cycle results from the fact that the CO absorption is sensitive to temperature and varies both within a single Cepheid’s pulsation cycle and between Cepheids of different mean temperatures.

In Figure 2, we showed 3.6 and 4.5 μm light curves, in addition to [3.6]−[4.5] μm color curves for two Cepheids in each of the Milky Way, LMC and SMC. In general, we find that the [3.6]−[4.5] μm color curves for most of the longer-period (P > 10 days) Cepheids in the LMC and the Galaxy display a significant cyclical variability. To our knowledge, this effect has never been observed previously since light curves for Cepheids at 4.5 μm have never been obtained before (previous observations have been one or two epochs only). However, V Cen and HV12452, with P = 5.5 and 8.7 days, respectively, show little variability and have colors of zero. The light curves for the SMC, which has a lower metallicity than the Galaxy and the LMC, show very little effect at any period. As we have discussed, this variability occurs as a result of the presence of the CO bandhead falling within the 4.5 μm filter. The CO feature strengthens when the stellar atmosphere is more expanded and therefore cooler. As seen in V. Scowcroft et al. (2011, in preparation) the amplitude of the color variability also increases with increasing period. No cyclical CO variability is seen for Cepheids with periods less than about 10 days (the hottest Cepheids). A detailed discussion of the 4.5 μm CO feature in our Cepheid sample is presented in Scowcroft et al. (2011).

6. REDUCING THE UNCERTAINTY IN H₀

At the end of the Key Project, the overall systematic uncertainty in the value of the Hubble constant was found to be 10% (Freedman et al. 2001). Three of the largest sources of systematic uncertainty listed included (1) 5% involving the distance to the LMC, setting the zero point of the Cepheid PL relation, (2) 3.5% due to the uncertainties involved in making the photometric tie-in between ground-based telescopes and the HST photometric system(s), and (3) ±4% uncertainty due to the difference in metallicity between the LMC and the higher-metallicity spiral galaxies in the Key Project sample.

All three of these major systematics are directly addressed by the use of Spitzer. The mid-infrared data, which now include Galactic zero-point calibrators, and rich sampling of long-period LMC Cepheids defining the slope and width of the mid-IR PL relation, have been made through the identical 3.6 μm filter, using the same instrument (IRAC), on the same, stable platform (“Warm Spitzer”). In doing so, the photometric tie-in uncertainties have, by design, been eliminated. Similarly, the shape, width, and zero-point calibration of the Cepheid PL relation are also now well measured using a combination of HST parallaxes and Spitzer observations. Moreover, the Milky Way Galaxy has a metallicity comparable to those of the bulk of the HST Key Project sample of spiral galaxies, thereby reducing the uncertainty previously incurred in using the (lower-metallicity) LMC as the zero-point calibration.

Figure 8 shows the 3.6 μm Leavitt Law for the five Galactic Cepheids from Monson et al. (2012) with log P > 0.8 and with measured HST parallaxes from Benedict et al. (2007). These are I Car, ζ Gem, β Dor, W Sgr, and X Sgr. Shown also are 82 LMC Cepheids from V. Scowcroft et al. (2011, in preparation), with 0.8 < log P < 1.8. A new calibration of H₀ based on these data is presented in (W. L. Freedman et al. 2012, in preparation). The data are plotted to minimize the variance in the combined sample. Error bars are smaller than the plotted symbols. To maximize the overlap in the period range of the Milky Way and LMC Cepheid samples, and to avoid uncertainties caused by a possible difference in the slope of the Leavitt Law at short periods, as well as to avoid overtone pulsators, only the five Milky Way Cepheids with log P > 0.8 are included in the fit. The Galactic calibrators (large symbols) fit within the scatter of the LMC Cepheid Leavitt relation (small symbols), with a slope that is consistent, to within the uncertainties, with that for the LMC. The Galactic Cepheids set the zero point of the relation; the larger sample of LMC Cepheids is used to set the slope.

7. SUMMARY

A fundamental recalibration of the extragalactic distance scale is underway using 3.6 μm observations of Cepheid variables to determine distances within the Milky Way, throughout the Local Group, and into the nearby and then more distant Hubble flow. This program is explicitly designed to address directly all of the known local systematic uncertainties currently impacting the optically based Cepheid distance scale. As discussed in detail in W. L. Freedman et al. (2012, in preparation), these new
data already result in a decrease of the systematic uncertainty to ±3%, a factor of three over the Hubble Key Project. Given the history of large systematic errors plaguing attempts to measure an accurate value of the Hubble constant, this small uncertainty may seem optimistic. However, this formal uncertainty reflects the fact that the largest systematic uncertainties (absolute zero point, the metallicity difference of the LMC compared with the more distant spiral galaxies containing Cepheids, reddening) have all been mitigated with Spitzer mid-IR photometry.

The major recent breakthroughs are the IRAC and Spitzer observations of Cepheids at 3.6 μm, combined with the determinations of direct high-precision geometric parallaxes to Galactic Cepheids (Benedict et al. 2007). These data provide a solid zero point (from the parallaxes) and a very high precision distance indicator (using the mid-infrared Leavitt Law slope and scatter defined by LMC Cepheids). The mid-IR data are almost completely insensitive to each of the previously known systematic uncertainties that ultimately limited the previous determination of H₀ using Cepheids to a 10% uncertainty.

The limiting factor then becomes the small number of Galactic Cepheids that have absolute parallaxes sampling the finite width of the PL relation. We have therefore identified the next tier of Cepheids that will be parallax targets for GAIA. As part of the CHP, the mid-IR data are now already in hand for these calibrators, and awaiting parallax measurements. At that point, the systematic error on the Galactic zero point will have been retired to ±1% allowing the total uncertainty on the Hubble constant to drop to <±2%.

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