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DEEP HUBBLE SPACE TELESCOPE IMAGING OF IC 1613. I. VARIABLE STARS AND DISTANCE¹

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ABSTRACT

We present WFPC2 *VI* photometry of a field in the halo of IC 1613, finding 13 RR Lyrae stars and 11 Cepheids. Our photometry of the red giant branch tip and red clump is used to derive distances to IC 1613, which are consistent with each other and with distances based on the variable stars. We compare these values with similarly measured distances for the Magellanic Clouds, and are able to measure metallicity dependencies of the RR Lyrae and Cepheid distances by requiring consistent relative distance measurements from the four techniques. For metallicities of $[\text{Fe}/\text{H}] = -1.3$ (RR Lyrae stars) and -1.0 (Cepheids), we find a relatively steep slope of 0.34 ± 0.20 mag per dex for the RR Lyrae stars and a shallow slope of -0.07 ± 0.16 mag per dex for the Cepheids, both values within the range of theoretical and empirical results in the literature. We find that a dependence of the red clump absolute magnitude on age, in addition to metallicity, is required to produce self-consistent relative distances between IC 1613 and the Magellanic Clouds. Adopting such a red clump calibration and self-consistent calibrations for the other three distance indicators, we find that the distances to all three objects are in excellent agreement. Our best distance modulus to IC 1613 is $\mu_0 = 24.31 \pm 0.06$, corresponding to a distance of 730 ± 20 kpc. This distance produces an RR Lyrae absolute magnitude of 0.61 ± 0.08 .

Subject headings: Cepheids — galaxies: distances and redshifts — galaxies: individual (IC 1613) — Local Group — stars: variables: other

1. INTRODUCTION

Studies of the stellar populations in nearby galaxies provide a powerful tool for determining the key physical parameters of galaxy evolution, such as the age (star formation history), the chemical composition and enrichment history, the stellar initial mass function, environmental effects, and the dynamical history of the system. Using the *Hubble Space Telescope* (*HST*), it is possible to photometer individual stars down to very faint magnitudes, and to interpret the observable parameters such as the morphology of the color-magnitude diagram (CMD). This approach is a logical stepping stone to understanding galaxy evolution and provides a physical basis for understanding observations of high-redshift galaxies and their implications for cosmological models. Detailed analysis of the intermediate

and old stellar populations of Local Group galaxies should reveal histories in accordance with those implied by studies of galaxies at higher redshift (Tolstoy 1999). With the appropriate data, which currently are obtained primarily using *HST*, this hypothesis can be directly tested.

Here we present new *HST* observations of a field in the halo of IC 1613, a dwarf irregular galaxy in the Local Group. In this paper we concentrate on the variable stars of IC 1613, and in particular their relevance to its distance determination. In a future paper we will reconstruct the star formation history of IC 1613 by analysis of the stellar populations.

The known properties of IC 1613 have recently been summarized by van den Bergh (2000). We here give only a brief summary of relevant properties. Because of its proximity (distance ~ 720 kpc), its high Galactic latitude ($-60^\circ.6$) and thus small Galactic extinction, and its inclination (38° ; Lake & Skillman 1989), IC 1613 provides an excellent opportunity to observe stellar populations in a relatively low metallicity environment. Interestingly, there are few studies of the metallicity in IC 1613. Mateo (1998) gives a

¹ Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. These observations are associated with proposal ID 7496.

value of the mean iron abundance for the old and intermediate-age stellar populations of $[\text{Fe}/\text{H}] = -1.3 \pm 0.2$ (from Lee, Freedman, & Madore 1993, using the RGB color at $M_I = -3.5$; see also Cole et al. 1999) and an oxygen abundance of the interstellar medium of $12 + \log (\text{O}/\text{H}) = 7.8 \pm 0.2$ (Talent 1980). Because of the high Galactic latitude, the reddening to IC 1613 is very low, and here we adopt an extinction of $A_V = 0.08 \pm 0.02$ from Schlegel, Finkbeiner, & Davis (1998).

The distance to IC 1613 was determined from Cepheid variable stars early on by Baade (Sandage 1971) and, based in part on the observations of Cepheids by Freedman (1988), Madore & Freedman (1991) placed IC 1613 at a distance of 765 kpc ($\mu_0 = 24.42 \pm 0.13$). Saha et al. (1992) observed RR Lyrae variable stars and derived a distance of 660 kpc ($\mu_0 = 24.10 \pm 0.27$). Using the observation of the tip of the red giant branch, Lee et al. (1993) derived a distance of 714 kpc ($\mu_0 = 24.27 \pm 0.25$), a value confirmed by the WFPC2 study of an inner field of IC 1613 by Cole et al. (1999). These values are all consistent within the errors, but their differences may be dominated by systematic errors.

Cole et al. (1999) presented an initial study of IC 1613 stellar populations based on 10,700 s of integration in both F555W and F814W, as well as 2600 s in F439W, of a field nearer the center of the Galaxy. They found evidence of a continuous star-forming history, with the presence of all expected components of the CMD (main sequence, red supergiants, blue and red helium burners, asymptotic red giants, red giants, and a red clump), as well as a hint of a blue horizontal branch. From the CMD morphology of the central field, Cole et al. derived an approximate age-metallicity relation for IC 1613, finding it to be similar in form to that of the SMC but ~ 0.3 dex more metal-poor at any given age. Their data, however, were not designed for variable-star study (the primary goal of this paper), so we leave a detailed comparison of their results and the results from these data for a future paper on the stellar populations.

A critical issue in the use of extragalactic stellar distance indicators is their sensitivity to changes in metallicity. This question has received a good deal of attention in the recent literature (e.g., Kennicutt et al. 1998; Sandage, Bell, & Trippico 1999; Caputo, Marconi, & Musella 2000b for discussions of the Cepheid scale; McNamara 1997; Caputo et al. 2000a; and Demarque et al. 2000 for RR Lyrae stars; Lee et al. 1993 and Salaris & Cassisi 1998 for the RGB tip; and Girardi & Salaris 2000 and Udalski 2000 for the red clump). A fundamental point in these discussions is whether offsets due to metallicity are more or less important than uncertainties in the various luminosity zero points. Since the first rung of the variable-star distance ladder is the Magellanic Clouds, which are moderately metal-poor, observations of similar galaxies, such as IC 1613, provide an opportunity to empirically test for the importance of modest variations in metallicity among metal-poor systems. In the present observations, we are able to measure the magnitudes of four independent “standard candles”—RR Lyrae variable stars, Cepheid variable stars, the tip of the red giant branch, and the mean magnitude of the red clump—in a galaxy that has slightly lower metallicity than the Small Magellanic Cloud. By comparing these four distance determinations to those of the Magellanic Clouds, we are able to test for systematic differences associated with each indicator and potential metallicity dependencies.

2. DATA AND REDUCTION

2.1. Observations

WFPC2 observations of a field in the halo of IC 1613 were obtained during 1999 22–27 August, as part of program GO-7496, whose purpose is to investigate the stellar populations of dwarf irregular galaxies. The field center ($01^{\text{h}}04^{\text{m}}26^{\text{s}}.7$, $+02^{\circ}03'16''$, J2000) is located $11'.6$ southwest of the center of the galaxy and $6'.7$ southwest of the field studied by Cole et al. (1999). There is no overlap with the field examined by Saha et al. (1992) in the previous IC 1613 RR Lyrae study, which is $14'.6$ to the west, or with the field of Antonello et al. (1999). The data consist of 48 1200 s images: 16 in F555W and 32 in F814W, spread evenly among four dithering pointings. Each orbit consisted of two images in the same filter to aid in cosmic-ray removal. A 25th orbit was used to obtain two F656N (H α) images, which were used for other purposes, but not for the variable-star work that is the topic of this paper.

2.2. Reductions

The data were obtained from the STScI archive using on-the-fly calibration, and thus were pipeline-calibrated using the best available calibration images at the time of retrieval. The images were then reduced using the HSTPHOT package (Dolphin 2000a). The data-quality image (c1f) was used to mask bad and questionable pixels, and the pairs of images from each orbit were combined for cosmic-ray removal, producing eight clean 2400 s images in F555W and 16 images in F814W. A deep image produced by combining all eight F814W images at the first pointing is shown in Figure 1. The sky image (which contains calculated sky values at each pixel and is determined before running photometry for uncrowded images for greater efficiency) was then calculated and hot pixels removed using the HSTPHOT utilities.

Photometry was made using the *multiplot* routine of HSTPHOT, which solves the photometry simultaneously

FIG. 1.—F814W WFPC2 image of IC 1613 field, combined from eight 1200 s exposures.

on multiple images (all 24, in this case) in order to reduce the number of free parameters. The detection threshold was a minimum signal-to-noise ratio (S/N) of 3.5 in both the combined F555W and combined F814W measurements. Charge transfer loss corrections and calibrations were made following Dolphin (2000b). Because of the presence of bright, isolated stars, point-spread function (PSF) solutions and aperture corrections were made for each chip of each image. The color-magnitude diagram is shown in Figure 2, using all stars with the goodness-of-fit parameter $\chi \leq 1.5$, $|\text{object sharpness}| \leq 0.3$ (sharpness of a perfect star is zero), and total S/N of at least 5 in both F555W and F814W. In order to eliminate poor detections, these requirements were also made on the detections at each epoch, with detections failing to meet the χ , sharpness, and S/N criteria eliminated. To verify the accuracy of our photometry, we reduced the data at one pointing independently, using DoPHOT procedures described by Saha et al. (1996). This comparison is shown in detail in Dolphin (2000a), with agreement to within 0.01 mag in both filters.

Before proceeding with the variable-star search, it was necessary to determine the maximum accuracy of the photometry. This was done by comparing the magnitudes of well-measured upper red giant branch stars at each epoch with the combined magnitudes. This comparison, which tests both the reliability of the photometry and that of the aperture corrections, showed a median scatter of 0.015 mag. This value was adopted as the minimum error in the variable-star work, with all smaller photometric uncertainties increased to 0.015 mag. The source of this error is a combination of photometric error from the undersampled images and error in the aperture corrections.

Figure 3 shows the scatter (individual epoch minus combined magnitude) for all stars. The locations of the Cepheids (F555W of ~ 22 – 23) and RR Lyrae stars (F555W of ~ 25)

FIG. 3.—Photometry accuracy for the IC 1613 data. Values given are magnitudes at individual epochs minus mean magnitudes. The locations of the Cepheids (F555W of ~ 22 – 23) and RR Lyrae stars (F555W of ~ 25) are shown by the excess scatter, and the limiting accuracy of 0.015 mag at the bright end is clear.

are shown by the excess scatter, and the limiting accuracy of 0.015 mag at the bright end is clear. Otherwise, the figure is typical for a star-forming dwarf.

2.3. Variable Star Identification

Variable star candidates were identified using a procedure similar to that described by Saha & Hoessel (1990). For a star to be considered a candidate variable, it had to meet four criteria. First, the star had to have good photometry in at least 16 of the 24 epochs, and an rms scatter of at least 0.08 mag. Second, the reduced χ^2 of the photometry, as defined by

$$\chi^2 = \frac{1}{N_{F555W} + N_{F814W}} \times \left[\sum_{i=1}^{N_{F555W}} \frac{(F555W_i - \overline{F555W})^2}{\sigma_i^2} + \sum_{i=1}^{N_{F814W}} \frac{(F814W_i - \overline{F814W})^2}{\sigma_i^2} \right] \quad (1)$$

had to be at least 6.25, where N_{F555W} and N_{F814W} are the number of exposures in the two filters, $F555W_i$ and $F814W_i$ are the magnitudes at each epoch, and $\overline{F555W}$ and $\overline{F814W}$ are the mean magnitudes for each star. The minimum value of 6.25 corresponds to mean deviation of 2.5σ , and was determined empirically for these data. A second χ^2 test was made in order to reduce the ability of single bad points to cause a false detection. The one-third of the points contributing the most to the χ^2 were eliminated, and the reduced χ^2 recalculated from the remaining points. If this value was not at least 0.25, the star was eliminated from the list of candidate variables. Again, the value of 0.25 was determined empirically.

FIG. 2.— $(V-I)$, I color-magnitude diagram (12,983 stars), calculated from mean magnitudes in all epochs. Poorly fitted stars ($\chi > 1.5$ or $|\text{sharpness}| > 0.3$) are not included. Error bars show typical $(V-I)$ uncertainties as a function of I . Absolute magnitudes (on the y-axis on the right) are calculated assuming $I - M_I = 24.36$.

FIG. 4.—CMD of IC 1613 field, showing the periodic variable stars. Filled circles show the Cepheids, diamonds the RR Lyrae stars, and triangles the two possible eclipsing binaries. The detection efficiency was not 100%, and thus there are many stars in the instability strip. Absolute magnitudes (on the y-axis on the right) are calculated assuming $I - M_I = 24.36$.

Finally, a modified Lafler-Kinman algorithm (Lafler & Kinman 1965) was used to test the stars for periodicity. This was implemented by computing Θ for periods between 0.1 and 5.0 days. The Θ parameter is calculated by determining the light curve for a trial period and using the equation

$$\Theta(p) = \frac{\sum_{i=1}^N (m_i - m_{i+1})^2}{\sum_{i=1}^N (m_i - \bar{m})^2}, \quad (2)$$

where N is the number of exposures for a given filter, m_i is the magnitude at epoch i , and $\bar{m}$ is the mean magnitude. If the trial period is incorrect, $m_i - m_{i+1}$ will be the difference between two random points, $\sqrt{2}$ times the rms scatter, producing a Θ of 2. However, if the trial period is correct, the difference between adjacent points will scale as N^{-1} , producing a Θ that scales as N^{-2} . A goodness of periodicity parameter can then be defined as $\Lambda(p) = 2/\Theta(p)$. For this study, the off-period Θ was defined to be the 90th percentile value of Θ over the range of trial periods, giving our goodness of periodicity parameter as $\Lambda(p) = \Theta_{90}/\Theta(p)$.

For the present data set, however, a sufficient number of observations were made in both F555W and F814W for light-curve measurements to be made in both filters. Thus, a combined goodness of periodicity parameter needed to be developed. Given that $\Lambda^{1/2}$ scales as the number of observations in a given filter when at the correct period, a reasonable combined parameter would be

$$\Lambda = 0.25(\sqrt{\Lambda_{F555W}} + \sqrt{\Lambda_{F814W}})^2, \quad (3)$$

where the constant of 0.25 is included to force the off-period Λ to 1. In the general case, a goodness of periodicity for any number of filters can be calculated with

$$\Lambda = \left(\frac{1}{N_{\text{filt}}} \sum_{i=1}^{N_{\text{filt}}} \sqrt{\Lambda_i} \right)^2. \quad (4)$$

For this study, Λ was required to be at least 2.0 for a star to be considered a candidate variable.

We note that because Θ is statistically independent of amplitude (doubling the amplitude would leave Θ unchanged, for example), our determination of Λ does not account for the larger amplitudes of RR Lyrae stars and Cepheid variables in F555W. It is not immediately obvious if or how such an accounting should be made. Nevertheless, we have experimented with other algorithms for the calculation of Λ and Θ , such as

$$\begin{aligned} \Theta(p) = & \left[\sum_{i=1}^{N_{F555W}} (F555W_i - F555W_{i+1})^2 \right. \\ & + \sum_{i=1}^{N_{F814W}} (F814W_i - F814W_{i+1})^2 \left. \right] \\ & \times \left[\sum_{i=1}^{N_{F555W}} (F555W_i - \overline{F555W})^2 \right. \\ & + \sum_{i=1}^{N_{F814W}} (F814W_i - \overline{F814W})^2 \left. \right]^{-1} \end{aligned} \quad (5)$$

and find the selection of variables and their periods to be quite robust, regardless of the choice of algorithm.

Out of the 12,983 total stars, the steps listed above selected 57 variable-star candidates, which were examined interactively. Since this study is primarily concerned with pulsating variables, stars that were variable in only one filter and stars whose F555W and F814W light curves were out of phase were removed from the candidate list, as were false detections, leaving 26 stars in the list. Eleven fall in the instability strip above the horizontal branch, and were classified as Cepheids. Thirteen fall along the horizontal branch, and were classified as RR Lyrae stars. The remaining two are possible eclipsing binaries. Figure 4 shows the IC 1613 CMD, with the variable stars highlighted. It should be emphasized that our detection efficiency was not 100% (and was much lower for stars with periods greater than 0.6 days, the duration of our longest set of consecutive orbits). Thus we cannot rule out the existence of Population II Cepheids, nor are we confident that the “nonvariable” stars falling within the instability strip are not, in fact, variables that were not detected. In addition, while the CMD from combined photometry is largely complete to $I = 27$, the single-epoch S/N of stars below the horizontal branch is such that detection of variables would have been extremely difficult.

Mean magnitudes were calculated for each variable, using a period-weighted average

$$\langle m \rangle = -2.5 \log \sum_{i=1}^N \frac{\phi_{i+1} - \phi_{i-1}}{2} 10^{-0.4m_i}, \quad (6)$$

where ϕ_i is the phase and m_i is the magnitude at each point along the light curve. These values, still in WFPC2 F555W and F814W magnitudes, were then transformed to standard V and I .

3. ANALYSIS

3.1. RR Lyrae Stars

Figure 5 shows the light curves of the 13 RR Lyrae candidates, and Table 1 contains their positions and data. All positions are given relative to the F555W images at the first pointing. The final column in Table 1 lists the quality of the

FIG. 5a

FIG. 5.—Light curves of 13 candidate RR Lyrae stars

TABLE 1
RR LYRAE STARS

ID	Chip	X	Y	$\langle V \rangle$	$\langle V-I \rangle$	Period	Q
V5	WFC2	174.01	582.68	25.222 ± 0.087	0.678 ± 0.097	0.59	3
V8	WFC2	498.73	101.37	24.948 ± 0.039	0.333 ± 0.051	0.50	2
V14	WFC3	368.24	153.10	25.098 ± 0.083	0.345 ± 0.092	0.31	3
V15	WFC3	447.66	154.61	25.077 ± 0.056	0.554 ± 0.067	0.63	3
V16	WFC3	519.91	703.76	25.097 ± 0.068	0.463 ± 0.074	0.34	2
V17	WFC3	559.79	569.96	24.790 ± 0.102	0.410 ± 0.111	0.62	3
V18	WFC3	599.32	495.63	24.971 ± 0.085	0.501 ± 0.090	0.65	4
V19	WFC3	661.68	400.55	25.233 ± 0.152	0.368 ± 0.170	0.43	4
V20	WFC3	770.59	790.22	24.728 ± 0.135	0.287 ± 0.142	0.61	2
V21	WFC4	343.38	584.32	24.987 ± 0.120	0.529 ± 0.132	0.60	4
V22	WFC4	585.38	573.20	25.058 ± 0.091	0.550 ± 0.107	0.58	2
V23	WFC4	610.83	108.18	24.843 ± 0.112	0.406 ± 0.121	0.39	4
V24	WFC4	691.07	215.75	24.890 ± 0.053	0.707 ± 0.094	0.48	2

FIG. 5b

light curve, from 0 to 4 (although all stars with quality values of 0 or 1 have been removed). The criteria that are used to determine the light-curve quality are the uniqueness of the period, the presence or absence of bad points, light curves in phase between the two filters, and the resemblance to a template light curve of the appropriate class of object. We do not attempt to distinguish between fundamental-mode and overtone pulsators in the RR Lyrae stars, given the relatively poor S/N at each epoch (the typical uncertainty in both filters is 0.1 mag). However, we do note that the short periods of variables V14 and V16 make them likely overtone pulsators, and that those of V19 and V23 make them possible overtone pulsators.

Multiplying the uncertainties in $\langle V \rangle$ by 4 divided by the light-curve quality, and taking an average weighted by σ^{-2} , the best $\langle V \rangle$ for the sample of 13 RR Lyrae stars is 25.00 ± 0.03 mag. Eliminating the two possible outliers fainter than $V = 25.2$, the weighted average is 24.98 ± 0.03 . Similarly eliminating the two possible outliers brighter than $V = 24.8$, the weighted average becomes 25.02 ± 0.03 . Given the very small shift in the mean magnitude after

eliminating the lowest and highest points, it seems reasonable to adopt the value of $\langle V \rangle = 25.00$ for the mean RR Lyrae magnitude, while adding the ± 0.02 shift in quadrature to the 0.03 mag uncertainty, producing a final uncertainty of 0.04 mag. This mean V magnitude is consistent with the value of $\langle g \rangle = 24.90 \pm 0.10$ obtained by Saha et al. (1992), which corresponds to a mean V magnitude of 24.94 ± 0.10 (Saha & Hoessel 1987). An extinction A_V of 0.08 mag is adopted from Schlegel et al. (1998) (assuming $A_V/A_B = 3.1/4.1$), with the uncertainty estimated to be ± 0.02 mag, producing an extinction-corrected mean V magnitude of $\langle V \rangle_0 = 24.92 \pm 0.04$.

Once the mean V magnitude is established, obtaining a distance estimate requires a value for the absolute magnitude. This is generally done by adopting a value for the mean RR Lyrae metallicity and a preferred M_V versus $[\text{Fe}/\text{H}]$ relation. We can measure the mean RR Lyrae metallicity via the red giant branch, whose tip spans the color range $1.45 < (V - I) < 1.62$. Assuming that RR Lyrae stars are only produced in populations older than 10 Gyr, we find an allowable metallicity range of $-1.5 < [\text{Fe}/$

FIG. 5c

H] < -1.1 (with $[\text{Fe}/\text{H}] = -1.5$ and $t = 15$ Gyr falling along the blue edge of our RGB, and $[\text{Fe}/\text{H}] = -1.1$ and $t = 10$ Gyr falling along the red edge), based on isochrones interpolated from those of Girardi et al. (2000). Thus we find a value of $[\text{Fe}/\text{H}] = -1.3 \pm 0.2$ for the RR Lyrae metallicity. For comparison, metallicity calculations using the Da Costa & Armandroff (1990) $(V - I)_{M_I = -3.0}$ and Lee et al. (1993) $(V - I)_{M_I = -3.5}$ calibration produce the identical metallicity ($[\text{Fe}/\text{H}] = -1.3 \pm 0.2$), after conversion to the Carretta & Gratton (1997) metallicity scale.

The range of resulting absolute magnitudes is rather large, however, producing significant uncertainty in the RR Lyrae distance. Theoretical models of Girardi et al. (2000) predict an absolute magnitude of $M_V = 0.60 \pm 0.03$, those of Demarque et al. (2000) produce an absolute magnitude of $M_V = 0.62 \pm 0.05$, and those of Caputo et al. (2000a) produce an absolute magnitude of $M_V = 0.57 \pm 0.12$. Carretta et al. (2000) find a relation based on LMC distances and *Hipparcos* parallax measurements of subdwarfs that produces an absolute magnitude of $M_V = 0.59 \pm 0.07$. Other theoretical models produce brighter RR Lyrae stars,

with Caloi, D'Antona, & Mazzitelli (1997) and Cassisi et al. (1999) finding $M_V \approx 0.55$ for the zero-age horizontal branch (ZAHB), the mean RR Lyrae magnitude being about 0.1 mag brighter. Observational determinations based on *Hipparcos* show a larger spread in values, such as those of Fernley et al. (1998), which produces an absolute magnitude of $M_V = 0.73 \pm 0.14$, and Gratton et al. (1997), which produces an absolute magnitude of $M_V = 0.45 \pm 0.04$. We therefore conservatively adopt a value of $M_V = 0.60 \pm 0.15$, which produces an distance modulus of 24.32 ± 0.16 . We will return to the issue of the RR Lyrae zero point later, using independent distance measurements to derive the absolute magnitude of RR Lyrae stars in IC 1613.

3.2. Cepheids

Although the observations were designed primarily to detect RR Lyrae stars, 11 short-period Cepheids were also discovered. Figure 6 shows their light curves, and Table 2 lists their positions and data. As with Table 1, the quality rating ranges from 0 to 4, with 4 being the cleanest light curve and best-defined period. The Cepheids were also clas-

FIG. 5d

FIG. 5e

sified into fundamental-mode and overtone pulsators, with all but V13 classified based on their light curves. As shown by Mantegazza & Poretti (1992), overtone pulsators have a Fourier spectrum with a weaker second order than that of fundamental pulsators, meaning that their light curves will be more sinusoidal. Ten of the eleven Cepheids were thus

classified, and the period-luminosity relation in Figure 7 shows this discrimination to be successful, with all overtone pulsators falling well above the mean period-luminosity relation. The period of V13 was poorly constrained because of the poor sampling of epochs, and thus it could not be similarly classified. However, its position on the period-

FIG. 6a

FIG. 6.—Light curves of 11 candidate Cepheids

luminosity relation was clearly in the space occupied by overtone pulsators, allowing its classification based on period and magnitude.

The presence of five fundamental-mode Cepheids allows

for a second distance measurement from these data. One can do this following Madore & Freedman (1991), determining the reddening-free magnitude $W = 2.43I - 1.43V$ (assuming $A_V/A_I = 1.7$) for the five Cepheids and calcu-

TABLE 2

CEPHEIDS

ID	Chip	<i>X</i>	<i>Y</i>	$\langle V \rangle$	$\langle I \rangle$	Period	Mode	<i>Q</i>
V1	WFC1	290.70	582.93	22.103 ± 0.064	21.650 ± 0.049	1.67 ± 0.17	OT	2
V2	WFC2	120.54	360.19	22.584 ± 0.059	21.990 ± 0.024	1.31 ± 0.05	OT	4
V3	WFC2	133.33	429.22	21.802 ± 0.120	21.211 ± 0.060	3.31 ± 0.06	FM	4
V4	WFC2	146.33	595.41	22.606 ± 0.074	22.040 ± 0.051	1.09 ± 0.08	OT	3
V6	WFC2	387.65	282.16	21.548 ± 0.162	21.083 ± 0.090	3.03 ± 0.05	FM	4
V7	WFC2	482.48	424.66	23.006 ± 0.093	22.455 ± 0.065	1.34 ± 0.06	FM	4
V9	WFC2	505.88	94.89	22.675 ± 0.110	22.095 ± 0.076	1.75 ± 0.06	FM	4
V10	WFC2	552.35	83.57	23.144 ± 0.150	22.627 ± 0.071	1.05 ± 0.03	FM	3
V13	WFC3	366.95	129.45	21.403 ± 0.045	20.760 ± 0.030	2.82 ± 1.20	OT	3
V25	WFC4	716.29	460.78	22.565 ± 0.147	22.206 ± 0.051	0.95 ± 0.05	OT	4
V26	WFC4	717.22	589.95	22.769 ± 0.050	22.211 ± 0.032	1.00 ± 0.07	OT	3

FIG. 6b

lating the reddening-free absolute magnitude $M_W = -3.049 \log P - 2.40$ using the Madore & Freedman (1991) calibration. Applying this technique to the IC 1613 fundamental Cepheids and using a weighted average of the uncertainties gives a reddening-corrected distance modulus of $\mu_0 = 24.50 \pm 0.11$ and a mean extinction, A_V , of 0.16 ± 0.11 mag. The V and I period-luminosity relations are shown in Figure 7, with the Cepheids found by Freedman (1988) plotted as well. As can be seen in the figure, the present data are consistent with and provide an extension to the longer period data of Freedman (1988).

However, the EROS Collaboration result (Bauer et al. 1999) of a steepening in the period-luminosity relation for periods shorter than 2 days implies that three of our five fundamental-mode Cepheids should be eliminated from this calculation. (This break is shown by the dashed line in Fig. 7.) Thus, the reddening-corrected distance modulus becomes $\mu_0 = 24.55 \pm 0.18$ for the two remaining fundamental-mode Cepheids. The large uncertainty is the result of using the reddening-free distance, which multiplies

V uncertainties by 2.43 and I by 1.43 and adds them in quadrature. Given the low extinction to IC 1613 and the presence of a good extinction estimate of $A_V = 0.08 \pm 0.02$, the uncertainty can be lowered by correcting the individual V and I distance moduli for extinction and combining them.

Finally, it should be noted that the I photometry of V3 do not adequately sample the full range of the light curve, since the earliest epoch was at a phase of 0.2 after the peak. Thus the phase-averaged $\langle I \rangle$ magnitude is biased toward fainter magnitudes. Because this was not a problem in the V photometry, the procedure of Labhardt, Sandage, & Tammann (1997) was used to calculate the correct mean $\langle I \rangle$, brightening the value from 21.21 to 21.15. The data for V6 have a similar problem, but a similar correction is impossible because neither the V nor I photometry span the entire range of magnitudes. However, because the V light curve omits as much of the trough as the I light curve omits of the peak, these errors should largely cancel when averaging the V and I distances obtained for V6.

FIG. 6c

Table 3 shows the mean V and I magnitudes corrected for extinction values $A_V = 0.08 \pm 0.02$ and $A_I = 0.05 \pm 0.02$. Absolute magnitudes M_V and M_I are calculated using Madore & Freedman (1991), with their rms scatter adopted as the uncertainties. Given the smaller intrinsic scatter in the I period-luminosity relation, the distance for each of the Cepheids is weighted twice as much in I as in V . Averaging the values for the two stars gives a best Cepheid distance from these data of $\mu_0 = 24.45 \pm 0.15$ mag, consistent with the value of $\mu_0 = 24.42 \pm 0.13$ determined by Madore & Freedman (1991) from the Cepheid calibration used here, as well as with previous measurements of Sandage (1971), McAlary, Madore, & Davis (1984), and Freedman (1988). The values in Figure 7 are for this dis-

tance and the adopted extinction, with the dashed line showing the expected V relation for $P < 2$ days based on the EROS result. Because of their larger sample size, we adopt the Madore & Freedman (1991) value in our discussion, after converting it to our adopted extinction of $A_V = 0.08$ for the sake of comparison with other distance measurements. This decreases their distance to $\mu_0 = 24.40 \pm 0.13$. We discuss possible metallicity effects on the Cepheid distance scale below.

3.3. Other Distance Measurements

Although variable stars provide excellent distance indicators, there remain questions about the zero-point calibrations at the 20% level, as well as uncertainties regarding

TABLE 3
CEPHEID DISTANCES

ID	$\langle V \rangle_0$	$\langle I \rangle_0$	Period	M_V	M_I	μ_0
V3.....	21.80 ± 0.12	21.15 ± 0.06	3.31 ± 0.06	-2.83 ± 0.27	-3.40 ± 0.18	24.58 ± 0.21
V6.....	21.55 ± 0.16	21.08 ± 0.09	3.03 ± 0.05	-2.73 ± 0.27	-3.28 ± 0.18	24.33 ± 0.21

FIG. 6d

their dependencies on the metallicity of the parent population of stars. These issues are discussed in the following section. IC 1613 also provides us with additional distance benchmarks, which provide further constraints for studying this problem.

FIG. 7.—Cepheid period-luminosity relation. Filled circles show fundamental pulsators, open circles show overtone pulsators, and crosses show the Cepheids found by Freedman (1988). All but one of the Cepheids were classified by light-curve shape. The solid lines show mean P-L relations from Madore & Freedman (1991), with a distance modulus of 24.45 and extinction of $A_V = 0.08$. The dashed line shows the break at $P = 2$ days, based on Bauer et al. (1999).

The red giant branch (RGB) tip (Lee et al. 1993) and red clump (Paczynski & Stanek 1998; Udalski 2000) provide two possible standard candles. The RGB tip in I is especially attractive, given its insensitivity to age and metallicity in theoretical models (e.g., Girardi et al. 2000). From the CMD in Figure 2 and an edge-detection algorithm, we measure an RGB tip at $I = 20.40 \pm 0.09$. However, this value is something of an upper limit to the RGB tip magnitude, since the small number of stars present in the upper RGB makes it plausible that the theoretical RGB extends above the position of these stars. With an upper RGB luminosity function of roughly seven stars per 0.1 mag, our 68% confidence limit for the true RGB tip is 0.03 mag above the brightest star, increasing our uncertainty in the RGB tip measurement to 0.10 mag.

We can derive a more accurate RGB tip by using the denser field studied by Cole et al. (1999), which contains significantly more red giants. Reducing those data with HSTPHOT and applying the Dolphin (2000b) CTE correction and calibration, we find the RGB tip at $I = 20.35 \pm 0.07$, consistent with that determined for the present data (where the 0.07 mag uncertainty is a result of possible red giant branch/asymptotic giant branch confusion near the tip). The luminosity function for the upper RGB is shown in Figure 8. Applying our adopted extinction correction of $A_I = 0.05 \pm 0.02$ produces an extinction-corrected RGB tip magnitude of $I_0 = 20.30 \pm 0.07$. We find the photometry of Cole et al. to be nearly 0.1 mag brighter, and note that we adopt the HSTPHOT-based photometry for the inner field, since it is more consistent with the photometry for the outer field (which was consistent with DoPHOT reductions of the same data), and because of the availability of an HSTPHOT-based calibration and CTE correction (Dolphin 2000b).

The absolute magnitude at the RGB tip can be estimated

either empirically (Lee et al. 1993) or theoretically (Girardi et al. 2000). Empirical calibrations rest on the globular cluster distance scale, which itself depends on an assumed RR Lyrae absolute magnitude calibration, and thus cannot be used to make an *independent* distance measurement for our study. Theoretical techniques, on the other hand, are subject to uncertainties in the input physics (Castellani & degl'Innocenti 1999) and the transformation from physical parameters (luminosity and temperature) to observed magnitudes and colors. In order to produce an independent distance measurement and to account for the uncertainties, we thus adopt an absolute magnitude calculated from interpolated isochrones from Girardi et al. (2000), while conservatively adding the difference between this value and that calculated from the Lee et al. (1993) calibration to our uncertainties. Fitting the isochrones to our red giant branch for ages from 2 to 15 Gyr, we measure a mean metallicity of $[\text{Fe}/\text{H}] = -1.15 \pm 0.2$ and an absolute magnitude of $M_I = -4.02 \pm 0.02$. For comparison, the calibration given by Lee et al. (1993), using the equivalent metallicity on the Zinn & West (1984) scale ($[\text{Fe}/\text{H}] = -1.37$ from the conversion given by Carretta & Gratton 1997), produces an absolute magnitude of $M_I = -4.06 \pm 0.04$, consistent but 0.04 mag brighter. We thus arrive at an RGB tip absolute magnitude of $M_I = -4.02 \pm 0.05$ and a distance modulus of $\mu_0 = 24.32 \pm 0.09$.

We note that the RGB tip calibration of Salaris & Cassisi (1998) provides a significantly more luminous tip, at $M_I = -4.25 \pm 0.02$, which would increase the IC 1613 distance modulus to $\mu_0 = 24.55 \pm 0.07$. We are unable to reconcile this value with the red clump distance (below), regardless of the star formation history assumed for IC 1613. Because the red clump is the only one of the four distance indicators calibrated directly by *Hipparcos*, we choose to adopt the calibration above of $M_I = -4.02 \pm 0.05$, with the RGB tip distance modulus of $\mu_0 = 24.32 \pm 0.09$.

Another independent measurement of the distance is pro-

vided by the mean I magnitude of the red clump (RC). Although $M_I(\text{RC})$ varies significantly with both age and metallicity (e.g., Girardi et al. 1998 and Girardi & Salaris 2000 for theoretical work; Sarajedini 1999 for empirical work), Girardi & Salaris (2001) have demonstrated that it can be adequately modeled and used as an accurate distance indicator that provides distances consistent with other, more tested, distance measurements.

The measurement of the red clump mean magnitude is relatively easy, aided by the separation of the two features in the CMD. Figure 9 shows the I luminosity function for stars with $0.8 \leq (V - I) \leq 0.95$ and $22 \leq I \leq 25.5$, with the best-fit polynomial (RGB) plus Gaussian (red clump) shown. The peak of the Gaussian falls at $I = 23.90 \pm 0.01$ (uncertainties derived using bootstrap tests and a variety of bin sizes), which corresponds to an extinction-corrected value of $I_0 = 23.85 \pm 0.02$. For comparison, our HSTPHOT-reduced photometry of the inner field (the field studied by Cole et al. 1999) produces a slightly brighter red clump magnitude of $I = 23.86 \pm 0.01$. The difference of 0.04 mag is statistically significant; the most likely explanation is the presence of a larger fraction of young ($t \lesssim 1$ Gyr) stars in the inner field.

Determination of the red clump absolute magnitude, however, is significantly more difficult. Udalski (2000) provides an empirical calibration of $M_I(\text{RC})$ versus metallicity, but this calibration would have to be extrapolated by nearly a dex in metallicity for application to IC 1613 and is based on the assumption that there is no age-metallicity relation in the Galactic disk. Neither of those problems can be easily solved analytically, so we instead employ the Girardi et al. (2000) theoretical isochrones as an accurate relative absolute magnitude indicator, with which we can compare the local disk clump with that of IC 1613 (a method very similar to method 2 of Girardi & Salaris 2000). We produced a synthetic CMD for the local Galactic disk based on the age-metallicity relation and star ages given in Table 3 of

FIG. 8.— I -band luminosity function along the RGB. Our measured tip of the RGB is at $I = 20.35 \pm 0.07$, and is marked by the vertical line at that position.

FIG. 9.— I -band luminosity function for stars with $0.8 \leq V - I \leq 0.95$ and $22 \leq I \leq 25.5$. The line is the best fit, using a quadratic polynomial to fit the RGB and a Gaussian to fit the red clump.

Rocha-Pinto et al. (2000), and a set of 15 synthetic CMDs for IC 1613 based on a range of possible age-metallicity relations and star formation histories consistent with the results of Cole et al. (1999). Applying the usual Gaussian clump plus quadratic RGB fit to the synthetic CMDs, we measure a difference of $\delta M_I = -0.22 \pm 0.08$ mag between the IC 1613 red clump and the Galactic disk red clump, the IC 1613 clump being brighter. Combined with the *Hipparcos*-based local red clump calibration of $M_I = -0.23 \pm 0.02$ (Stanek & Garnavich 1998), we derive a semi-empirical IC 1613 red clump absolute magnitude of $M_I = -0.45 \pm 0.09$ and a red clump distance modulus of $\mu_0 = 24.30 \pm 0.09$.

Thus, two additional independent distances can be obtained using the RGB tip and the red clump. The RGB tip distance is corrected for age and metallicity relatively easily, but difficulty in observational determination of the tip magnitude and uncertainty in the calibration create additional error. In contrast, the red clump position is easily measured with high precision, but the systematics from age and metallicity dependencies are not as well constrained.

4. DISCUSSION

4.1. Relative IC 1613–SMC–LMC Distances

With the availability of four independent distance measurements to IC 1613, we can attempt to determine relative distances between IC 1613 and the Magellanic Clouds. Since the zero point subtracts out when measuring relative distances, this allows us, for the time being, to ignore the uncertainties in the calibrations. Table 4 and Figure 10 show these comparison values.

For RR Lyrae stars, we adopt an absolute magnitude of $M_V = 0.60$ at $[\text{Fe}/\text{H}] = -1.3$. We conservatively adopt a metallicity dependence of 0.25 ± 0.10 mag per dex, which is consistent with both the steep scale ($dM_V/d[\text{Fe}/\text{H}] \sim 0.3$; e.g., Sandage & Cacciari 1990) and the shallow scale ($dM_V/d[\text{Fe}/\text{H}] \sim 0.2$; e.g., Carretta et al. 2000), producing absolute magnitudes of $M_V = 0.58 \pm 0.01$ at $[\text{Fe}/\text{H}] = -1.4$ (NGC 121 in the SMC) and $M_V = 0.45 \pm 0.06$ at $[\text{Fe}/\text{H}] = -1.9$ (the clusters used for the LMC measurement). The resulting relative distances are shown in the first

row of Table 4; we note that absolute distances would also need to include the zero-point error of ± 0.15 mag.

The Cepheid distance scale is based on the Madore & Freedman (1991) calibration, which assumes an LMC distance modulus of 18.50. This calibration does not include any metallicity dependence, a potential source of error, given the significant metallicity range covered by these three objects (from $[\text{Fe}/\text{H}] \simeq -1.0$ for IC 1613 to $[\text{Fe}/\text{H}] \simeq -0.4$ for the LMC). Because literature values for the dependence are more varied than are those for the RR Lyrae dependence, we do not attempt to make a correction here; instead, the values in the second row of Table 4 assume no metallicity dependence.

The third and fourth rows of Table 4 similarly give RGB tip and red clump distances to the three objects. We adopt the Girardi et al. (2000) models to provide the absolute magnitudes of the RGB tips, and the Girardi & Salaris semiempirical calibrations of the Magellanic Cloud red clump absolute magnitudes.

We note that both the relative IC 1613–SMC distances and the relative IC 1613–LMC distances are consistent between the four measurement methods. Using a weighted average of the four (by σ^{-2}) relative IC 1613–SMC distance measurements, we find a value of 5.44 ± 0.05 , corresponding to a linear distance ratio of $d_{\text{IC 1613}}/d_{\text{SMC}} = 12.2 \pm 0.3$. Because of the possible metallicity dependence in the Cepheids and the large metallicity difference between IC 1613 and the LMC, we average only the RR Lyrae, RGB tip, and red clump relative distances, finding a relative IC 1613–LMC distance of 5.83 ± 0.06 (a linear distance ratio of $d_{\text{IC 1613}}/d_{\text{LMC}} = 14.7 \pm 0.4$).

4.2. Metallicity Dependencies of Distance Indicators

Although the uncertainties are significant, we also wish to use the metallicity baseline in this comparison to examine the effects of metallicity on the RR Lyrae and Cepheid distance measurements. We first note that since the four relative IC 1613–LMC distance measurements are all consistent, our data are consistent with the metallicity dependencies adopted in the previous section: $dM_V/d[\text{Fe}/\text{H}] = 0.25$ for RR Lyrae stars and $dM_V/d[\text{Fe}/\text{H}] = dM_I/d[\text{Fe}/\text{H}] = 0$ for Cepheids.

TABLE 4
IC 1613, SMC, AND LMC DISTANCE MODULI

Method	IC 1613	SMC	IC 1613–SMC	LMC	IC 1613–LMC
RR Lyrae	24.32 ± 0.05^a	18.88 ± 0.07^b	5.44 ± 0.09	18.49 ± 0.07^c	5.83 ± 0.09
Cepheid	24.40 ± 0.13^d	18.91 ± 0.04^e	5.49 ± 0.14	18.50 ± 0.00^f	5.90 ± 0.13
RGB tip	24.32 ± 0.07^g	18.90 ± 0.04^h	5.42 ± 0.08	18.57 ± 0.09^i	5.82 ± 0.11
Red clump	24.30 ± 0.09	18.85 ± 0.06^j	5.45 ± 0.11	18.46 ± 0.11^k	5.84 ± 0.14

^a Adopting $M_V(\text{RR Lyrae}) = 0.60$. For this and all other distances in this table, calibration uncertainties are assumed to be zero because we are only interested in measuring relative distances.

^b From Walker & Mack 1988 for NGC 121 ($[\text{Fe}/\text{H}] = -1.4$), adopting $M_V(\text{RR Lyrae}) = 0.58 \pm 0.02$.

^c From Walker 1992 for clusters with mean $[\text{Fe}/\text{H}] = -1.9$, adopting $M_V(\text{RR Lyrae}) = 0.45 \pm 0.06$.

^d From Madore & Freedman 1991, adjusting to our extinction of $A_V = 0.08$.

^e Laney & Stobie 1994, adopting an LMC distance modulus of 18.50.

^f LMC distance modulus of 18.50 is assumed in calibration of IC 1613 and SMC distances.

^g Adopting $M_I(\text{TRGB}) = -4.02$.

^h From Cioni et al. 2000, adopting $M_I(\text{TRGB}) = -4.02$ and $A_I = 0.07$ based on Schlegel et al. 1998.

ⁱ From Sakai, Zaritsky, & Kennicutt 2000, adopting $M_I(\text{TRGB}) = -4.03$ calculated from the Girardi et al. 2000 models.

^j From Girardi & Salaris 2000.

^k From Girardi & Salaris 2000, adopting the mean of their two possible values.

FIG. 10.—Distance modulus differences between IC 1613 and the Magellanic Clouds, using four distance measurements. The top panel shows the IC 1613–SMC differences, and the bottom panel the IC 1613–LMC differences. We note that all four distance measurement techniques produce consistent distance ratios.

We first address the issue of the RR Lyrae metallicity dependence. Combining the red clump and RGB tip distances (which have both been corrected for population effects) to determine relative distances to the three objects, we derive reddening-corrected absolute magnitudes of $M_V(\text{IC 1613}) = 0.61 \pm 0.08$, $M_V(\text{SMC}) = 0.58 \pm 0.08$, and $M_V(\text{LMC}) = 0.41 \pm 0.10$. Fitting these values to a straight line (and adopting the metallicities from the previous section) with a least- χ^2 algorithm, we find a metallicity dependence of $dM_V/d[\text{Fe}/\text{H}] = 0.34 \pm 0.20$ mag per dex for the RR Lyrae absolute magnitude, a large value but consistent with more robust estimates of the metallicity dependency of the RR Lyrae absolute magnitudes (e.g., Sandage et al. 1999; McNamara 1997; Layden et al. 1996; Carney, Storm, & Jones 1992; Sandage & Cacciari 1990; Liu & Janes 1990). Since our measured value has a large uncertainty, we continue to use the adopted dependence of $dM_V/d[\text{Fe}/\text{H}] = 0.25 \pm 0.10$ mag per dex.

For the Cepheids, we adopt recent metallicities of $[\text{Fe}/\text{H}] \simeq -1.0$ for IC 1613 (based on an isochrone fit to these data), $[\text{Fe}/\text{H}] \simeq -0.8$ for the SMC (based on the cluster age-metallicity relation given by Olszewski, Suntzeff, & Mateo 1996), and $[\text{Fe}/\text{H}] \simeq -0.4$ for the LMC (also based on the cluster age-metallicity relation given by Olszewski et

al. 1996). Following our procedure from the RR Lyrae dependence measurement, we compare the Cepheid distances to those from the other distances (this time using the RR Lyrae, red clump, and RGB tip distances to measure the “true” distances). From the data in Table 4, we measure Cepheid – “true” distances of 0.08 ± 0.14 for IC 1613, 0.03 ± 0.06 for the SMC, and 0.01 ± 0.05 for the LMC. A least- χ^2 fit to these points produces a metallicity dependence of -0.07 ± 0.16 mag per dex in the Cepheid distances, consistent with zero or with the small metallicity dependencies determined empirically by Kennicutt et al. (1998) and theoretically by Sandage et al. (1999) and Alibert et al. (1999). Despite the large uncertainty, these data appear to rule out extreme values of the metallicity dependence, such as those of Caputo et al. (2000b), Beaulieu et al. (1997), and Gould (1994). We adopt a conservative correction of -0.1 ± 0.2 mag per dex, and correct the IC 1613 Cepheid distance (taken from Madore & Freedman 1991) to $\mu_0 = 24.34 \pm 0.18$. This value is still based on an assumed LMC distance modulus of 18.50, and adding 0.1 mag of uncertainty to that value produces our best IC 1613 Cepheid distance of $\mu_0 = 24.34 \pm 0.20$.

4.3. The Distance to IC 1613 and RR Lyrae Calibration

After applying the corrections above, we have four distance measurements to IC 1613, summarized in Table 5. Taking a weighted average (again weighting by σ^{-2}), we measure the IC 1613 distance modulus to be $\mu_0 = 24.31 \pm 0.06$, corresponding to a distance of 730 ± 20 kpc. Although we have, in a sense, required the four distance measurements to be consistent in the previous section and thus have the possibility of circularity, we note that the RR Lyrae, RGB tip, and red clump distances are taken from § 3.3 (the RR Lyrae metallicity dependence measured above does not factor into the IC 1613 distance). In addition, our weighted average of the distance measurements is 24.31 ± 0.06 , whether or not the Cepheid distance is included (because of its high uncertainty). For completeness, we note that, had we used the Burstein & Heiles (1982) extinction maps instead of the Schlegel et al. (1998) maps, we would have used extinctions of $A_V = 0.02$ and $A_I = 0.01$, and arrived at a distance modulus of $\mu_0 = 24.36 \pm 0.06$.

We note that, given the accurate RGB tip and red clump measurements, we are able to work “backward” to determine the RR Lyrae absolute magnitude. Removing the RR Lyrae distance from the weighted average, we arrive at an IC 1613 distance of $\mu_0 = 24.31 \pm 0.07$. Combining this with our reddening-corrected mean magnitude of $V_0 = 24.92 \pm 0.04$, we calculate the absolute magnitude of IC 1613 RR Lyrae stars to be 0.61 ± 0.08 .

5. SUMMARY

We have presented photometry, variable-star analysis, and a series of distance measurements of a WFPC2 field in

TABLE 5
IC 1613 DISTANCE MODULI

Method	This Work	Primary Source of Error	Best Value
RR Lyrae	24.32 ± 0.16	M_V vs. $[\text{Fe}/\text{H}]$ calibration	24.32 ± 0.16
Cepheid	24.45 ± 0.15	Small number (2)	24.34 ± 0.20
RGB Tip	24.32 ± 0.09	Measurement	24.32 ± 0.09
Red Clump	24.30 ± 0.09	Age effects	24.30 ± 0.09
Combined:			24.31 ± 0.06

the halo of IC 1613. We found 13 RR Lyrae stars and a mean extinction-corrected magnitude of $\langle V \rangle_0(\text{RR Lyrae}) = 24.92 \pm 0.04$. The presence of these stars confirms the existence of an old horizontal branch, consistent with the ground-based results of Saha et al. (1992). We also found 11 short-period Cepheids, two of which were fundamental-mode with sufficiently long periods to determine a distance. Finally, we applied RGB tip and red clump distance measurements to IC 1613, determining distances for each. The summary of our values is given in Table 5, along with the primary sources of error in those four measurements.

We assume that the RGB tip distance is the most robust of the four, given that the dependencies on age and metallicity are very small and have been calibrated. However, the small field of view of WFPC2 limits our ability to accurately measure the position of the tip, limiting the accuracy of our measurement to $\mu_0(\text{RGB}) = 24.32 \pm 0.09$. The red clump distance, on the other hand, has significant calibration uncertainty based on the age dependence, but its position can be accurately measured in these data. Adding the population dependencies into our uncertainties, we find a red clump distance of $\mu_0(\text{RC}) = 24.30 \pm 0.09$.

Our sample of Cepheids was insufficient to produce an accurate distance measurement, but we were able to confirm that our two ~ 3 day fundamental-mode Cepheids were consistent with the Cepheid distance obtained by Madore & Freedman (1991). We were also able to estimate, via comparisons with LMC and SMC distances, a metallicity dependence of -0.07 ± 0.16 mag per dex. Applying a conservative estimate of the metallicity dependence (-0.1 ± 0.2 mag per dex) and an extinction of $A_V = 0.08$ from Schlegel et al. (1998) to the Madore & Freedman

(1991) values produces a corrected IC 1613 Cepheid distance modulus of $\mu_0(\text{Cepheid}) = 24.34 \pm 0.20$. Combining this with our other distance measurements with a weighted average, we arrive at our best IC 1613 distance modulus of $\mu_0 = 24.31 \pm 0.06$, corresponding to a distance of 730 ± 20 kpc.

A similar treatment was given to the RR Lyrae stars, producing a metallicity dependence of 0.34 ± 0.20 mag per dex in the V absolute magnitude, consistent with literature values. Given the wide variety of RR Lyrae absolute magnitudes in the literature, we also found it useful to measure the IC 1613 RR Lyrae absolute magnitude, given our observed mean V magnitude and the distances calculated through other measurements. We calculated a mean M_V of 0.61 ± 0.08 at $[\text{Fe}/\text{H}] \simeq -1.3$, a value consistent with both the “faint” calibration of Fernley et al. (1998) and the “bright” calibration of Gratton et al. (1997).

We note that when each distance measurement is properly calibrated and corrected for population effects, the RR Lyrae, Cepheid, RGB tip, and red clump distance techniques produce consistent relative distances between IC 1613 and the Magellanic Clouds. We find a relative IC 1613–SMC distance modulus of 5.44 ± 0.05 and a relative IC 1613–LMC distance modulus of 5.83 ± 0.06 . We also note that all four distance indicators produce consistent distances to IC 1613.

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