A REVISED CEPHEID DISTANCE TO NGC 4258 AND A TEST OF THE DISTANCE SCALE

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ABSTRACT

In a previous paper we reported a Hubble Space Telescope (HST) Cepheid distance to the galaxy NGC 4258 obtained using the calibrations and methods then standard for the Key Project. Here we reevaluate the Cepheid distance using the recently revised Key Project procedures. These revisions alter the zero points and slopes of the Cepheid period-luminosity (P-L) relations derived at the Large Magellanic Cloud (LMC), the calibration of the HST WFPC2 camera, and the treatment of metallicity differences. We also provide herein full information on the Cepheids described in the previous paper. Using the refined Key Project techniques and calibrations, we determine the distance modulus of NGC 4258 to be $29.47 \pm 0.09$ (unique to this determination) $\pm 0.15$ mag (systematic uncertainties in Key Project distances), corresponding to a metric distance of $7.8 \pm 0.3 \pm 0.5$ Mpc and $1.2 \sigma$ from the maser distance of $7.2 \pm 0.5$ Mpc. Additionally, we place weak limits upon the distance to the LMC and upon the effect of metallicity in Cepheid distance determinations.

Subject headings: Cepheids — cosmological parameters — distance scale — galaxies: individual (NGC 4258)

On-line material: machine-readable table

1. INTRODUCTION

Distances to other galaxies obtained by observations of Cepheid variables with the Hubble Space Telescope (HST) lie at the core of the most recent efforts to determine the extragalactic distance scale. The small observed scatter in the relationship between Cepheids’ pulsation periods and luminosities, their large numbers (which allow many independent measures of the distance to a galaxy), and the simplicity of the basic physics underlying their variability all have made them uniquely suitable for this purpose. As a consequence of their integral role in establishing the distance scale, however, any changes in the calibration and application of the Cepheid period-luminosity (P-L) relationship will affect many other secondary methods of distance measurement. Any improvements in techniques for obtaining Cepheid distances are thus extremely valuable, but this also means that any changes in this vital link should be well scrutinized if they are to be adopted.

In a paper describing the final results of the HST Key Project, Freedman et al. (2001) make a number of refinements to the techniques used in earlier papers in the series based upon newly available information. First and foremost, microlensing experiments (e.g., Udalski et al. 1999) and dedicated efforts (K. M. Sebo et al. 2001, in preparation) have greatly enlarged the set of calibrating Large Magellanic Cloud (LMC) Cepheids beyond what had been studied when the initial Key Project P-L relation was determined (Madore & Freedman 1991). The resulting samples have revealed a modest correction to the previously adopted P-L slope for I observations; the V-band slope remains unchanged. In the Key Project methodology, Cepheid magnitudes are corrected for extinction using their observed color excess $E(V-I) = (V-I) - (V-I)_0$, where $(V-I)_0$ is the expected color of an unreddened Cepheid of given period based upon the LMC-calibrated P-L relations. This procedure is sensitive to the reddening, since $A_V = 2.45E(V-I)$. An error in the P-L slope in I thus propagates into a larger, period-dependent error in the true distance modulus; in this case, $\Delta m_0 = -0.24 \log_{10} P - 1$. Because in more distant galaxies only brighter, longer period Cepheids are observable, this generally results in a distance-dependent revision to HST Cepheid distances that in extreme cases can reach $-0.20$ mag. Further details are given in Freedman et al. (2001).

Second, our understanding of charge transfer efficiency and related effects in the WFPC2 CCDs has greatly improved in recent years (e.g., Stetson 1998; Dolphin 2000), motivating revisions in the Hill et al. (1998) photometric zero points used in most earlier Key Project papers. Freedman et al. (2001) adopt the calibration of Stetson (1998), which results in a $-0.02$ mag mean adjustment in $V$ and $-0.04$ mag in $I$ from the Hill “long” zero points. Carrying through the revised procedures for obtaining reddening-corrected distance moduli, they apply a net correction of $-0.07 \pm 0.07$ mag to distances obtained using the Hill “long” zero point (where the error adopted reflects a conservative estimate of systematic differences among recent calibrations).

The third change made in the revised Key Project procedures is the adoption of Cepheid distance moduli adjust-
ed for metallicity effects as standard. The typical metallicity of Cepheids in the LMC with which the $P$-$L$ relation is calibrated differs by $\sim 0.5$ dex from that in many of the fields observed in the course of the Key Project. Metallicity differences may produce measurable differences in the colors and magnitudes of Cepheids in those fields from ones found in the LMC; unfortunately, neither theoretical calculations (e.g., Alibert et al. 1999; Musella 1999) nor observations (see Kennicutt et al. 1998; Sasselov et al. 1997; Kochanek 1997; Nevalainen & Roos 1998) have provided a definitive determination of the magnitude, or even sign, of this effect. Freedman et al. (2001) adopt a correction to Cepheid magnitudes of $-0.2 \pm 0.2$ mag dex$^{-1}$ (based upon current observational results) as standard. In previous Key Project work, distance moduli uncorrected for metallicity effects were primarily used, though results for a correction of $-0.24$ mag dex$^{-1}$ were also given. In their error budget, Freedman et al. (2001) estimate the potential systematic error in a typical Key Project Cepheid distance measurement due to corrections for differences in metallicity from the LMC to be $\pm 0.08$ mag.

Even with these revisions, important uncertainties remain in the Cepheid-calibrated distance scale. Foremost among these is the distance to the LMC, where the Key Project $P$-$L$ relation has been calibrated. A wide variety of measurements of the distance to the LMC have been performed in the past few years. Many of these studies disagree with each other statistically, spanning roughly 0.5 mag in distance modulus. Freedman et al. (2001) adopt 18.50 $\pm 0.10$ mag as the distance modulus of the LMC; the uncertainty in the LMC distance modulus thus leads directly to a systematic uncertainty in the Cepheid distance scale of $\pm 0.10$ mag. After the uncertainties in the LMC distance and metallicity corrections, the next most significant contribution to the Key Project systematic error budget is the difficulty in determining zero points for WFPC2 photometry, which is estimated to lead to a $\pm 0.07$ mag uncertainty in $HST$ Cepheid distance moduli; a variety of other systematic effects could enter at lower levels.

Given the remaining uncertainties, it is worthwhile to test the revised Key Project distance scale using a galaxy with a well-known, primary distance and with a metallicity typical of galaxies observed in the course of the Key Project. To be useful, such a test requires that Cepheids be observed with the same instruments, filters, and parameter measurement techniques as used for objects in the Key Project sample. Such a test has already been applied to the original Key Project distance scale based upon observations of Cepheids in NGC 4258 (Maoz et al. 1999).

The spiral galaxy NGC 4258 (SABbc, $M_B = -20.0$ mag) presents a unique opportunity for such a test because of the precision with which its distance has been measured in a manner independent of the conventional ladder of astronomical distance scales (Freedman 1998). Furthermore, its metallicity and distance are similar to those of typical targets of $HST$ Cepheid programs. The distance to NGC 4258, 7.2 Mpc (corresponding to distance modulus 29.28 mag), has been determined using its apparently simple, Keplerian circumnuclear disk delineated by line-emitting water masers that orbit a supermassive black hole at its center (Miyoshi et al. 1995; Maoz 1995).

This disk was discovered by VLBI observations of water maser emission from the central region of the galaxy (Miyoshi et al. 1995). It is about 16 mas in diameter and $\leq 0.1$ mas in thickness, rotates at speeds of $\approx 10^3$ km s$^{-1}$, and is viewed by us from nearly edge-on. Most remarkably, the rotation curve of the masers is Keplerian to high precision ($\leq 0.5\%$), which provides very strong evidence for a supermassive black hole at the galaxy center (Maoz 1995).

The high angular resolution (0.2 mas) and spectral resolution (0.2 km s$^{-1}$) of VLBA observations (Miyoshi et al. 1995) allow a precise definition of the disk structure and kinematics. Combining the observed rotation velocities with the measured centripetal acceleration in the disk (Greenhill et al. 1995) or with the observed proper motions of the maser sources (Herrnstein et al. 1999) permits independent measurements of the physical size of the disk; comparing these to its observed angular extent yields the distance to the galaxy via simple geometry. These distance measurements are subject to only small uncertainties. The differential systematic error in the maser positions is $\lesssim 0.04$ mas (Miyoshi et al. 1995), translating into a relative distance error smaller than 0.5%. The distance to the masing disk scales with the disk’s inclination as $(\sin i)^{-1}$; since the disk is viewed nearly edge-on, $i = 83^\circ \pm 2^\circ$ (Herrnstein et al. 1999), an error even as high as 4° would introduce a distance error of only 1%. Relativistic corrections due to gravitational redshift and transverse Doppler shift have been taken into account and are much smaller. The disk is slightly warped, but the distance determination is not sensitive to the warp model adopted. The warp contributes, though, to the small uncertainty in the disk inclination mentioned above. The total estimated uncertainty in this distance is $\pm 0.3$ Mpc if the disk is presumed to be circular (which it appears to be to better than 0.5%). If nonzero eccentricities are allowed, the uncertainty increases to $\pm 0.5$ Mpc (we adopt this more conservative value for all further discussions). The direct, geometric methods used are believed to have minimal unknown systematic uncertainties. The two routes to a distance (proper motions and accelerations) yield results in agreement with each other to 1%.

As described in Maoz et al. (1999), we have therefore obtained and analyzed $HST$ observations of NGC 4258 with the intention of testing, and potentially of better determining, the zero point of the Cepheid $P$-$L$ relation. In that work, we used the then standard Key Project methodologies and calibrations and found a $\geq 1.3 \sigma$ discrepancy between the $HST$ Cepheid distance and that obtained from studies of the masering disk. In this paper we perform a similar test after obtaining a Cepheid distance using the revised Key Project procedures, allowing an evaluation of the new techniques. We also provide herein full information (locations, light curves, finding charts, etc.) for the Cepheids described in Maoz et al. (1999). We present the observations, the reduction of the data, and the search for Cepheids in § 2, the resulting derivation of a Cepheid distance in § 3, and the implications in § 4.

### 2. OBSERVATIONS, DATA REDUCTION, AND SEARCHES FOR VARIABLE STARS

We observed a portion of NGC 4258 using the Wide Field Planetary Camera 2 (WFPC2) instrument and the $HST$ on 11 epochs in 1998. The data were acquired with an optimal power-law spacing between them as described in Freedman et al. (1994) and B. F. Madore & W. L. Freedman (2001, in preparation). The F555W and F814W filters were
used for a combined total of one orbit at every epoch, with two frames obtained using each filter to limit the effects of cosmic rays; the exposure time per frame was 500 s. A journal of observations is given in Table 1. To simplify analysis, a fixed orientation was maintained for all epochs. The field observed is superimposed on a ground-based image of NGC 4258 in Figure 1.

2.1. Photometric Reductions

We have obtained photometry from these data with two commonly used software packages: DAOPHOT/ALLFRAME and DoPHOT. For both analyses, the data were first preprocessed via the standard Space Telescope Science Institute pipeline (Holtzman et al. 1995). For the ALLFRAME photometry each frame was also corrected for vignetting and geometrical effects on the effective pixel area as described in Stetson et al. (1998). Photometry was then performed on each of the data frames using the DAOPHOT II/ALLFRAME package (Stetson 1987). ALLFRAME fits a predefined point-spread function (PSF) to all stars on a frame and iteratively determines their magnitudes. The procedures used throughout were similar to those of the Key Project (see Stetson et al. 1998). The photometric zero points of Stetson (1998) were used. Aperture corrections for each frame were derived using a set of bright, isolated stars.

In addition to the Cepheid analysis described below, we also attempted to determine a tip of the red giant branch (TRGB) distance (Lee, Freedman, & Madore 1993) to NGC 4258 using the ALLFRAME photometry for WF2 and WF3. However, our observations were insufficiently deep and contamination by other stellar populations too great to allow any convincing detection of the TRGB.

The DoPHOT photometry was performed using a variant of the DoPHOT package (Schechter, Mateo, & Saha 1993; Saha et al. 1994), which was developed espe-

### Table 1: Journal of Observations

| Epoch | Filter Used | Date     | Julian Date | Exposure Time | File Names |
|-------|-------------|----------|-------------|---------------|------------|
| 1     | F555W       | 1998 Apr 20 | 4901847.600 | 1000          | U4F60101R/2R |
|       | F814W       |           | 4901847.632 | 1000          | U4F60103R/4R |
| 2     | F555W       | 1998 Apr 21 | 4901850.428 | 1000          | U4F60201R/2R |
|       | F814W       |           | 4901850.460 | 1000          | U4F60203R/4R |
| 3     | F555W       | 1998 Apr 23 | 4901854.189 | 1000          | U4F60301R/2R |
|       | F814W       |           | 4901854.221 | 1000          | U4F60303R/4R |
| 4     | F555W       | 1998 Apr 25 | 4901859.086 | 1000          | U4F60401R/2R |
|       | F814W       |           | 4901858.118 | 1000          | U4F60403R/4R |
| 5     | F555W       | 1998 Apr 28 | 4901863.866 | 1000          | U4F60501R/2R |
|       | F814W       |           | 4901863.898 | 1000          | U4F60503R/4R |
| 6     | F555W       | 1998 May 01 | 4901869.241 | 1000          | U4F60601R/2R |
|       | F814W       |           | 4901869.273 | 1000          | U4F60603R/4R |
| 7     | F555W       | 1998 May 05 | 4901878.034 | 1000          | U4F60701R/2R |
|       | F814W       |           | 4901878.066 | 1000          | U4F60703R/4R |
| 8     | F555W       | 1998 May 10 | 4901887.113 | 1000          | U4F60801R/2R |
|       | F814W       |           | 4901887.145 | 1000          | U4F60803R/4R |
| 9     | F555W       | 1998 May 15 | 4901897.864 | 1000          | U4F60901R/2R |
|       | F814W       |           | 4901897.896 | 1000          | U4F60903R/4R |
| 10    | F555W       | 1998 May 22 | 4901912.376 | 1000          | U4F61001R/2R |
|       | F814W       |           | 4901912.408 | 1000          | U4F61003R/4R |
| 11    | F555W       | 1998 May 30 | 4901928.500 | 1000          | U4F61101R/2R |
|       | F814W       |           | 4901928.532 | 1000          | U4F61103R/4R |

*a* For all observations, the WFPC2 camera was used centered on right ascension 13h19m8s95, declination 47d13'26.76 (J2000), with roll angle 325.9943.

*b* Heliocentric; at midpoint of the two exposures.

*c* Total of two exposures.
cially to deal with the photometry of undersampled images such as those obtained with the \textit{HST}. In addition to the data processing mentioned earlier, pairs of cosmic-ray split images were combined prior to performing the photometric reduction with DoPHOT. The algorithm used for this is designed to reject cosmic-ray events; particular care is taken to ensure that the photometry of real objects is preserved. Further discussion of the application of DoPHOT to photometry of \textit{HST} images can be found in Saha et al. (1994), Ferrarese et al. (1996, 1998), and Hill et al. (1998).

The photometric calibration adopted again follows Stetson (1998), as per the revised Key Project procedures of Freedman et al. (2001). The limited number of bright, uncrowded stars prevented us from deriving reliable spatially dependent aperture corrections for DoPHOT. We therefore adopted corrections obtained from observations of an uncrowded field in the Leo I dwarf galaxy. Aperture photometry conducted on the NGC 4258 individual frames, as well as on a deep frame obtained by combining all available epochs, produces results in agreement with the Leo I aperture corrections at the 0.03 mag level, which we therefore adopt as a measure of the uncertainty in the corrections themselves.

2.2. \textbf{Variable Star Searches}

Searches for Cepheid variables using the ALLFRAME photometric measurements were conducted using two different algorithms. One of these selects candidate variables via a modified Welch-Stetson test and performs a nonlinear fit of template Cepheid light curves to their photometry to assess their variability and determine their parameters (for further description see Stetson 1996; Stetson et al. 1998). The other linearly fits template light curves defined on a grid in period and phase to all stars with well-determined photometry; Cepheids are then identified by a set of criteria that are effective at eliminating nonvariables. This algorithm is described in more detail in Newman et al. (1999). Both searches independently yielded similar sets of candidate Cepheid variables and parameter estimates in good agreement. These algorithms in combination yielded 21 potential Cepheid variables.

A search for variable stars was also conducted using DoPHOT magnitude measurements for the \textit{V}- and \textit{I}-band frames independently following the procedure described by Saha & Hoessel (1990). We required that a star be detected at least eight of the 11 epochs in order to be checked for variability. We also excluded all stars in crowded regions by rejecting candidates that had a companion contributing more than 50\% of the total light within a 2 pixel radius. A detailed description of the search procedure can be found in Ferrarese et al. (1996). A star meeting the above constraints was flagged as a variable if $\chi^2 \geq 8$ or $\Lambda \geq 3$, where $\chi^2$ and $\Lambda$ are as used in Saha & Hoessel (1990).

Several spurious variables were detected by this procedure as a consequence of non-Gaussian sources of error and various anomalies in the images (e.g., residual cosmic-ray events) along with the crowding referred to earlier. Each variable star candidate was visually inspected by blinking several of the individual frames against each other. The best period for each variable was selected by phasing the data for all periods between 3 and 60 days in incremental steps of 0.1 days. Although in most cases the adopted period corresponds to a minimum value of the phase dispersion, in a few cases an obvious improvement of the light curve was obtained for a slightly different period. The DoPHOT analysis identified a total of 28 potential Cepheids.

2.3. DoPHOT-ALLFRAME Comparison

All Cepheids found in either data set were on Wide Field chips 2 or 3; we therefore will restrict our discussion to these for the remainder of this paper. On WF2, the agreement of DoPHOT and ALLFRAME results was well within the expected errors in the aperture corrections used; the mean difference between ALLFRAME and DoPHOT magnitudes for 24 bright, isolated stars was 0.026 $\pm$ 0.049 (standard deviation; standard error of the mean 0.009) mag for \textit{V} and 0.015 $\pm$ 0.049 mag for \textit{I}. For WF3, the mean difference for 30 stars was 0.025 $\pm$ 0.027 mag for \textit{V} and 0.088 $\pm$ 0.046 mag for \textit{I}. Mean magnitudes for Cepheids yielded results consistent with these to within 1 $\sigma$, albeit with much larger standard errors as a result of their fainter magnitudes.

We believe that the WF3/\textit{I} results are an aberration closely related to the discrepant distance moduli obtained from ALLFRAME magnitudes on the two chips (q.v. §3). This anomaly is plausibly accounted for by the difficulties of determining aperture corrections in the observed fields, which contain few bright, isolated stars. If we presume that this is the case, the WF3/\textit{I} ALLFRAME photometry may be corrected by bringing it onto the same system as the WF2 and WF3/\textit{V} ALLFRAME magnitudes, i.e., adjusting the WF3/\textit{I} ALLFRAME magnitudes to be 0.022 $\pm$ 0.0035 mag fainter than DoPHOT (the average difference from the other three chip/filter combinations), rather than 0.088 $\pm$ 0.008 mag without any correction. Averaging the ALLFRAME-DoPHOT differences from those three cases may be justified by the fact that errors in aperture corrections, etc., are generally highly correlated between \textit{V} and \textit{I} and from one WF chip to another; and indeed, the ALLFRAME-DoPHOT offsets for WF2/\textit{V} and \textit{I} and WF3/\textit{V} are all quite consistent, agreeing to within 0.01 mag. Therefore, in addition to presenting results for unmodified ALLFRAME photometry, in the next section we also provide distance measurements obtained from ALLFRAME data “corrected” by subtracting 0.066 $\pm$ 0.009 mag from WF3/\textit{I} magnitudes.

3. \textbf{THE CEPHEID P-L RELATIONS}

We have identified and determined light curves, periods, mean magnitudes, and colors for 15 definitive Cepheids in NGC 4258. All of these stars fulfill four criteria: they are identified as variable by all three search techniques, they fit a Cepheid template light curve with reasonable $\chi^2$, they visibly vary in blink comparisons in both \textit{F555W} and \textit{F814W} images, and they have negligible statistical probability of being misidentified nonvariables.

A variety of methods exist for determining the mean magnitudes of Cepheids. In this paper we use the intensity-weighted mean magnitude obtained from a fit to the Cepheid light curve using the templates of Stetson (1996), also known as “template fit” mean magnitudes. This is the preferred method for the Key Project, providing a robust method of determining mean magnitudes analogous to those obtained for more densely sampled data sets (such as the LMC Cepheids used for calibrating the \textit{P-L} relation). We note that adopting other standard magnitude averaging methods changes the NGC 4258 distance modulus obtained
TABLE 2
PARAMETERS OF CEPHEIDS FOUND

| ID   | CHIP | x*  | y*  | $\langle V \rangle^b$ | $\langle I \rangle^b$ | Period (days) | Amplitude$^c$ | $\langle V \rangle^b$ | $\langle I \rangle^b$ | Period (days) |
|------|------|-----|-----|----------------------|----------------------|---------------|---------------|----------------------|----------------------|---------------|
| C1   | 2    | 158.18 | 603.73 | 24.55 ± 0.03 | 23.84 ± 0.03 | 20.5 ± 0.2 | 1.08 | 24.77 | 23.94 | 21.3 |
| C2   | 2    | 102.72 | 455.97 | 24.70 ± 0.03 | 23.84 ± 0.02 | 17.6 ± 0.2 | 0.99 | 24.77 | 23.84 | 17.2 |
| C3   | 2    | 364.28 | 317.39 | 24.86 ± 0.03 | 24.07 ± 0.03 | 17.0 ± 0.1 | 1.14 | 24.86 | 24.07 | 17.0 |
| C4   | 2    | 509.26 | 90.23  | 25.22 ± 0.04 | 24.16 ± 0.03 | 21.4 ± 0.4 | 1.00 | 25.50 | 24.26 | 20.5 |
| C5   | 2    | 405.30 | 604.14 | 25.15 ± 0.03 | 23.33 ± 0.03 | 16.0 ± 0.3 | 0.68 | 25.27 | 24.40 | 14.0 |
| C6   | 2    | 431.21 | 554.94 | 25.59 ± 0.04 | 24.35 ± 0.04 | 15.2 ± 0.3 | 0.74 | 25.68 | 24.42 | 13.9 |
| C7   | 2    | 447.29 | 566.43 | 25.55 ± 0.04 | 24.66 ± 0.05 | 10.4 ± 0.1 | 0.79 | 25.61 | 24.62 | 10.1 |
| C8   | 3    | 627.67 | 365.75 | 25.58 ± 0.04 | 24.65 ± 0.05 | 11.7 ± 0.2 | 0.60 | 25.71 | 24.80 | 11.2 |
| C9   | 3    | 276.75 | 618.19 | 25.10 ± 0.03 | 24.24 ± 0.03 | 15.2 ± 0.3 | 0.95 | 25.12 | 24.36 | 15.2 |
| C10  | 3    | 535.47 | 636.44 | 25.13 ± 0.03 | 24.20 ± 0.04 | 17.3 ± 0.3 | 0.81 | 25.26 | 24.42 | 17.6 |
| C11  | 3    | 566.89 | 659.25 | 24.61 ± 0.03 | 23.53 ± 0.02 | 31.4 ± 0.5 | 0.82 | 24.59 | 23.64 | 30.7 |
| C12  | 3    | 597.51 | 717.16 | 24.57 ± 0.02 | 23.75 ± 0.03 | 18.2 ± 0.2 | 0.93 | 24.60 | 23.85 | 17.6 |
| C13  | 3    | 780.74 | 236.12 | 25.27 ± 0.04 | 24.44 ± 0.04 | 12.3 ± 0.3 | 0.97 | 25.33 | 24.57 | 12.4 |
| C14  | 3    | 495.77 | 645.99 | 25.26 ± 0.03 | 24.19 ± 0.03 | 13.6 ± 0.2 | 0.74 | 25.37 | 24.32 | 13.7 |
| C15  | 3    | 599.59 | 740.72 | 25.44 ± 0.04 | 24.59 ± 0.06 | 13.7 ± 1.3 | 0.82 | 25.57 | 24.73 | 13.0 |

$^a$ In the coordinate system of the first F555W exposure, U4F6010IR.
$^b$ Intensity-weighted mean magnitudes are given for DoPHOT; for ALLFRAME, intensity-weighted means based on the template fits are listed.
$^c$ Peak to peak, in magnitudes, based upon template fit.

by no more than 0.04 mag. We use the Cepheid periods determined in the DoPHOT analysis for all distance modulus calculations, as these yielded smaller scatter about the $P$-$L$ relation for all data sets and averaging methods than alternatives (e.g., periods determined from template fits), likely reflecting the fact that those periods were refined by hand when necessary to improve the Cepheid light curves, rather than being determined solely by an automated algorithm. We have adopted the DoPHOT photometry for all major conclusions reported here, since, as discussed in § 3, ALLFRAME photometry yielded internally discrepant distances from Cepheids on the two WFPC2 chips used; however, as an additional consistency check we also provide ALLFRAME values in much of what follows. We present the locations and characteristics of the Cepheids found in Table 2 and complete DoPHOT photometry for those stars in Table 3. The positions of the Cepheids are shown in Figure 2, and detailed finding charts may be found in Figure 3. DoPHOT light curves for the Cepheids found are depicted in Figure 4.

Fig. 2a

Fig. 2b

Fig. 2.—(a) Image of the field covered by WF2 obtained by co-adding all images. The candidate Cepheids found on WF2 are circled and labeled. (b) Same as (a), but WF3 is shown.
### TABLE 3

DoPHOT Photometry of Cepheids Found

| Epoch | C1   | C2   | C3   | C4   | C5   | C6   | C7   | C8   | C9   | C10  | C11  | C12  | C13  | C14  | C15  |
|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| V     |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|       |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|       | 0.01 | 0.01 | 1.12 | 1.07 | 2.07 | 1.08 | 2.08 | 1.09 | 2.09 | 1.10 | 2.10 | 1.11 | 2.11 | 1.12 | 2.12 |
|       | 0.02 | 0.02 | 2.03 | 3.04 | 2.05 | 3.06 | 2.07 | 3.08 | 2.09 | 3.10 | 2.11 | 3.12 | 2.13 | 3.14 | 2.15 |
|       | 0.03 | 0.03 | 3.04 | 4.05 | 3.06 | 4.07 | 3.08 | 4.09 | 3.10 | 4.11 | 3.12 | 4.13 | 3.14 | 4.15 | 3.16 |
|       | 0.04 | 0.04 | 4.05 | 5.06 | 4.07 | 5.08 | 4.09 | 5.10 | 4.11 | 5.12 | 4.13 | 5.14 | 4.15 | 5.16 | 4.17 |
|       | 0.05 | 0.05 | 5.06 | 6.07 | 5.08 | 6.09 | 5.10 | 6.11 | 5.12 | 6.13 | 5.14 | 6.15 | 5.16 | 6.17 | 5.18 |
|       | 0.06 | 0.06 | 6.07 | 7.08 | 6.09 | 7.10 | 6.11 | 7.12 | 6.13 | 7.14 | 6.15 | 7.16 | 6.17 | 7.18 | 6.19 |
|       | 0.07 | 0.07 | 7.08 | 8.09 | 7.10 | 8.11 | 7.12 | 8.13 | 7.14 | 8.15 | 7.16 | 8.17 | 7.18 | 8.19 | 7.20 |
|       | 0.08 | 0.08 | 8.09 | 9.10 | 8.11 | 9.12 | 8.13 | 9.14 | 8.15 | 9.16 | 8.17 | 9.18 | 8.19 | 9.20 | 8.21 |
|       | 0.09 | 0.09 | 9.10 | 10.11 | 9.12 | 10.13 | 9.14 | 10.15 | 9.16 | 10.17 | 9.18 | 10.19 | 9.20 | 10.21 | 9.22 |
|       | 0.10 | 0.10 | 10.11 | 11.12 | 10.13 | 11.14 | 10.15 | 11.16 | 10.17 | 11.18 | 10.19 | 11.20 | 10.21 | 11.22 | 10.23 |
|       | 0.11 | 0.11 | 11.12 | 12.13 | 11.14 | 12.15 | 11.16 | 12.17 | 11.18 | 12.19 | 11.20 | 12.21 | 11.22 | 12.23 | 11.24 |
|       | 0.12 | 0.12 | 12.13 | 13.14 | 12.15 | 13.16 | 12.17 | 13.18 | 12.19 | 13.20 | 12.21 | 13.22 | 12.23 | 13.24 | 12.25 |
|       | 0.13 | 0.13 | 13.14 | 14.15 | 13.16 | 14.17 | 13.18 | 14.19 | 13.20 | 14.21 | 13.22 | 14.23 | 13.24 | 14.25 | 13.26 |
|       | 0.14 | 0.14 | 14.15 | 15.16 | 14.17 | 15.18 | 14.19 | 15.20 | 14.21 | 15.22 | 14.23 | 15.24 | 14.25 | 15.26 | 14.27 |
|       | 0.15 | 0.15 | 15.16 | 16.17 | 15.18 | 16.19 | 15.20 | 16.21 | 15.22 | 16.23 | 15.24 | 16.25 | 15.26 | 16.27 | 15.28 |
|       | 0.16 | 0.16 | 16.17 | 17.18 | 16.19 | 17.20 | 16.21 | 17.22 | 16.23 | 17.24 | 16.25 | 17.26 | 16.27 | 17.28 | 16.29 |
|       | 0.17 | 0.17 | 17.18 | 18.19 | 17.20 | 18.21 | 17.22 | 18.23 | 17.24 | 18.25 | 17.26 | 18.27 | 17.28 | 18.29 | 17.30 |

**Note:** Table 3 is also available in machine-readable form in the electronic edition of the *Astrophysical Journal.*
In accordance with the revised Key Project methodology, we adopt the \( P-L \) relation slopes of Freedman et al. (2001) and only fit for differences in the zero point. Their LMC calibration yields mean absolute magnitudes for Cepheids

\[
\bar{M}_V = -2.760(\pm 0.03)(\log_{10} P - 1) - 4.218(\pm 0.02),
\]

\[
\bar{M}_I = -2.962(\pm 0.02)(\log_{10} P - 1) - 4.904(\pm 0.01),
\]

(1)

where \( \bar{M}_V \) and \( \bar{M}_I \) are the intensity-weighted mean absolute Johnson \( V \) and Kron-Cousins \( I \) magnitudes of the star, respectively, and \( P \) is its period in days. The same relations have been used by Freedman et al. (2001) and Macri et al. (2001). Fitting the observed magnitudes of Cepheids in NGC 4258 with such relations yields a measurement of the apparent distance modulus of the galaxy. We have done this fitting with the standard Key Project processor, which determines overall distance moduli as an unweighted mean of the values for individual stars. From the difference between the absolute magnitudes of LMC Cepheids (for an assumed LMC distance modulus of 18.50 mag) and the observed magnitudes of NGC 4258 Cepheids we then may derive a \( V \) or \( I \) distance modulus to NGC 4258. We present the resulting distance moduli for both ALLFRAME and DoPHOT photometry in Table 4, for both the entire...
sample and the subsets of Cepheids on either chip 2 or chip 3 (which can indicate the presence of catastrophic photometric or other errors). The DoPHOT NGC 4258 P-L relations are plotted in Figure 5, and those from ALLFRAME are plotted in Figure 6.

In Key Project procedures, the colors of the observed Cepheids (compared to those of a calibration set of such stars in the LMC whose reddening has been assumed) are then used to correct for line of sight of extinction assuming a Cardelli, Clayton, & Mathis (1989) reddening law. This may be done by comparing the distance moduli obtained in the $V$ and $I$ bands; the difference of the two measures the average value of $E(V-I)$. Because the Key Project processor uses only unweighted averages with no rejection, this is equivalent both to applying the extinction correction star by star and then averaging and to fitting the $P$-L relation for a reddening-corrected “Wesenheit” magnitude, $W = P - 2.45(V-I)$ (Madore 1982; Madore & Freedman 1991).

---

**Fig. 3.—Continued**

**F555W (left) and F814W (right) light curves for the candidate Cepheids found, plotted vs. phase of variation. The period (in days) for each Cepheid determined during the DoPHOT analysis is also listed in its label.**
This method yields $E(V-I) = 0.20 \pm 0.04$ mag and an extinction-corrected distance modulus of $\mu_0 = 29.40 \pm 0.06$ mag from DoPHOT photometry for all Cepheids; for the ALLFRAME photometry, the corresponding numbers are $0.19 \pm 0.04$ and $29.53 \pm 0.07$ mag. The true moduli for the subset of Cepheids on either WF2 or WF3 are also listed in Table 4. Note that in the ALLFRAME data set, Cepheids on the two chips yield extinction-corrected distance moduli differing by 0.25 mag, or 1.9σ; the DoPHOT moduli differ by only 0.07 mag (0.5σ). Furthermore, the value for WF2 is quite consistent with that obtained from DoPHOT photometry, both for single chips' samples and overall; this makes the WF3 ALLFRAME results particularly suspect.

The bulk of this discrepancy is eliminated if we perform the WF3/I correction described in §2.3. That adjustment of WF3/I magnitudes by $0.066 \pm 0.009$ mag reduces the overall distance modulus yielded by Cepheids on WF3 by $0.162 \pm 0.021$ mag. Such a correction reduces the ALLFRAME WF2/WF3 discrepancy to 0.09 mag, a 0.7σ difference. As seen in Table 4, this correction would leave ALLFRAME $V$ distance moduli unchanged, alter the WF3 and overall average $I$ moduli to 29.77 mag, and reduce the

### Table 4

NGC 4258 Distance Moduli (No Metallicity Correction)

| Photometry Used          | Subset of Cepheids | $\mu_V$  | $\mu_I$  | $\mu_0$  |
|--------------------------|--------------------|----------|----------|----------|
| DoPHOT ........................ | All                | 29.90 ± 0.07 | 29.69 ± 0.05 | 29.40 ± 0.06 |
|                          | Chip 2             | 29.92 ± 0.13 | 29.72 ± 0.085 | 29.43 ± 0.10 |
|                          | Chip 3             | 29.87 ± 0.10 | 29.67 ± 0.06 | 29.38 ± 0.07 |
| ALLFRAME ................... | All                | 29.99 ± 0.075 | 29.80 ± 0.05 | 29.53 ± 0.07 |
|                          | Chip 2             | 30.03 ± 0.14 | 29.77 ± 0.09 | 29.40 ± 0.10 |
|                          | Chip 3             | 29.97 ± 0.08 | 29.84 ± 0.07 | 29.65 ± 0.09 |
| Corrected ALLFRAME......  | All                | 29.99 ± 0.075 | 29.77 ± 0.05 | 29.44 ± 0.06 |
|                          | Chip 2             | 30.03 ± 0.14 | 29.77 ± 0.09 | 29.40 ± 0.10 |
|                          | Chip 3             | 29.97 ± 0.08 | 29.77 ± 0.07 | 29.48 ± 0.09 |
FIG. 4.—Continued
Fig. 5.—Top: DoPHOT V-band P-L relation for NGC 4258. Cepheids on WF2 are denoted with an open diamond, those on WF3 with a filled circle. The solid line is the best-fit P-L relation with slope as in Freedman et al. (2001). Bottom: Same as top panel, but based on DoPHOT I data.

Fig. 6.—Top: ALLFRAME V-band P-L relation for NGC 4258. Cepheids on WF2 are denoted with an open diamond, those on WF3 with a filled circle. The solid line is the best-fit P-L relation with slope as in Freedman et al. (2001). Bottom: Same as above, but based on ALLFRAME I data. The WF3/I discrepancy of ~0.06 mag cannot readily be seen on this plot.

extinction-corrected distance modulus to 29.48 ± 0.09 mag for WF3, or 29.44 ± 0.065 mag overall (where the errors include the propagated error from the uncertainty in the ALLFRAME-DoPHOT differences, 0.021 mag, added in quadrature). These values are in much better agreement with those obtained from DoPHOT photometry (for which the overall, extinction-corrected distance modulus was $\mu_0 = 29.40 \pm 0.06$ mag). Applying this correction also reduces the scatter in the overall, extinction-corrected ALLFRAME distance modulus from 0.35 to 0.25 mag.

Freedman et al. (2001) find that differences in metallicity have an effect on extinction-corrected Cepheid distances of 0.2 ± 0.2 mag dex$^{-1}$. Using the fits to data on NGC 4258 H II regions from Zaritsky, Kennicutt, & Huchra (1994), we estimate the metallicity in our HST fields to be $12 + \log (O/H) = 8.85 \pm 0.06$, 0.35 dex higher than that adopted for Cepheids in the LMC. This leads to a correction of 0.07 ± 0.07 mag to the distance moduli we have derived. The revised Key Project procedures adopt metallicity-corrected values for the distance modulus as their primary estimate (in contrast to previous practice); we thus do likewise and obtain a final true modulus to NGC 4258 of 29.42 mag. Because the metallicity of NGC 4258 is quite typical of Key Project targets, we treat the uncertainty in the metallicity correction as a systematic uncertainty in the distance scale.

3.1. Uncertainties

We present an error budget for our measurement of the distance to NGC 4258 in Table 5. In addition to the random errors determined in the course of fitting P-L relations, uncertainties in the aperture corrections used are also random between different Cepheid target galaxies. From studies of globular clusters and Key Project galaxies, we expect these to be approximately 0.05 mag or less in both V and I and highly correlated between the two bands; the combined uncertainty due to the aperture corrections in the reddening-corrected distance modulus would then still be 0.05 mag. Differences between ALLFRAME and DoPHOT photometry of bright stars are much smaller than this in all cases save WF3/I. Since it appears that the difference between the overall DoPHOT and uncorrected ALLFRAME distance primarily reflects a correctable error in the WF3/I ALLFRAME photometry alone, we estimate that photometric errors in the DoPHOT results that are unique to our study of NGC 4258 may constitute 0.05 mag. Adding all potential sources in quadrature, the total random uncertainty in our determination of a Cepheid distance to NGC 4258 ($R_{	ext{tot}}$ in Table 5) is 0.09 mag.

This measurement is also subject to a number of potential sources of systematic error that affect Key Project distance
determinations similarly, as described in Table 5; their possible contributions have been estimated to total ± 0.15 mag (Ferrarese et al. 2000; Freedman et al. 2001). For those potential systematic errors that affect all Cepheid distances obtained in the same manner as ours uniformly, we have adopted the uncertainty estimates of the Key Project (Freedman et al. 2001); more detailed descriptions may be found therein.

We thus obtain a Cepheid distance modulus to NGC 4258 of 29.47 ± 0.09 (unique to this determination) ± 0.15 mag (systematic uncertainties in Key Project distances), corresponding to a metric distance of 7.8 ± 0.3 ± 0.5 Mpc. When treated in the same way, the uncorrected ALLFRAME results yield a distance modulus of 29.60 ± 0.10 mag, corresponding to a metric distance of 8.3 ± 0.4 Mpc, while the corrected ALLFRAME results yield a distance modulus of 29.51 ± 0.09 mag, corresponding to a metric distance of 8.0 ± 0.3 Mpc. The distance to NGC 4258 derived from observations of Cepheids using the revised Key Project methodologies is thus not significantly greater than the maser distance of 7.2 ± 0.5 Mpc (Herrnstein et al. 1999).

4. IMPLICATIONS

In assessing the validity of the calibration of the Cepheid distance scale using NGC 4258, we must consider how significant the difference we have found is. First of all, we may examine whether the differences are consistent within the random and systematic error budgets of the two processes, i.e., whether previously considered sources of error are sufficient to account for what we have found. The Cepheid and maser distances differ by 0.9 σ if we add in quadrature our measurement uncertainty of 0.3 Mpc, the Key Project systematic error estimate of 0.5 Mpc, and the maser distance error estimate of 0.5 Mpc; potential systematic errors in either technique do not appear to have been underestimated. In performing a test of the validity of the revised Key Project distance scale, however, we must consider what sort of a discrepancy we can measure. All HST Cepheid distances following the revised techniques will share the systematic errors that affect our results. Thus, we should consider only the random errors unique to this measurement and those errors affecting the maser distance in determining whether a recalibration would be an improvement. In that case, we find a 1.2 σ difference, as opposed to a 1.6 σ difference if the results of Maoz et al. (1999) were evaluated with the same error budget. Put differently, if we were to presume that the maser distance to NGC 4258 is correct and recalibrate the distance scale based upon our Cepheid observations of NGC 4258, all revised Key Project distances would have to be reduced by 0.19 mag, increasing the resulting measurements of the Hubble constant by 10%; the total systematic error budget for the new calibration would be 0.16 mag (8%), slightly greater than that resulting from the current, LMC-based methods. Modest changes in calibration or methodology would be sufficient to bring the Cepheid and maser distances into substantially better agreement; for instance, the LMC distance need only be reduced by a few hundredths of a magnitude, well within the Key Project estimate of its uncertainty, to bring the difference below 1 σ.

We can similarly use our measurement of the distance to NGC 4258 to test other calibrations of the Cepheid P-L relation. In particular, we have applied the Milky Way–based calibration of Feast (1999), which corresponds to

$$M_V = -2.81(\pm 0.06) \log_{10}(P - 1) - 4.26(\pm 0.05),$$

$$M_I = -3.07(\log_{10}(P - 1) - 4.89,$$

following the conventions of equation (1). Note that the slopes adopted in deriving these relations are substantially different from those used by Freedman et al. (2001). Although the Cepheids in Feast’s calibration are not at uniform distance, making their use to calibrate the P-L relation somewhat more complicated, they are independent of any assumptions about the LMC distance and of very similar metallicity to the fields we have studied. Using these relations leads to a Cepheid distance modulus for NGC 4258 of 29.51 ± 0.06 (random) mag, 0.23 mag greater than the maser result; a metallicity correction of −0.2 mag dex−1 increases this by only 0.01 mag. This is a total discrepancy of 1.3 σ if we consider all possible errors and assume a systematic uncertainty of 0.05 mag in Feast’s calibration, 1.2 σ for 0.1 mag, or 1 σ for 0.15 mag uncertainty. If, as above, we compare the discrepancy to what we can measure, we find that the maser and Cepheid distances are 1.5 σ apart; the calibration of Feast (1999) might be improved by referencing it to NGC 4258.

Some authors (e.g., Gibson 2000) have used the results of Maoz et al. (1999) to estimate the distance to the LMC, based upon the assumption that the maser distance to NGC

| Parameters | Source | Error |
|------------|--------|-------|
| $S_1$      | Systematic errors in LMC P-L calibration  | ± 0.10 |
| $S_2$      | A. LMC true modulus                     | ± 0.01 |
| $S_3$      | B. LMC P-L zero point                    | ± 0.02 |
| $S_4$      | A and B added in quadrature              | ± 0.10 |
| $S_5$      | Systematic errors in WFPC2 zero points   | ± 0.07 |
| $S_6$      | Average metallicity correction           | ± 0.08 |
| $S_7$      | Systematic errors unique to NGC 4258 photometry | ± 0.05 |
| $S_8$      | Dependence of NGC 4258 distance modulus on magnitude averaging method | ± 0.04 |
| $R_1$      | Random error in the NGC 4258 extinction-corrected distance modulus | ± 0.07 |
| $R_{tot}$  | C. NGC 4258 P-L fit ($V$)                | ± 0.05 |
| $S_{tot}$  | D. NGC 4258 P-L fit ($I$)                | ± 0.06 |
| $S_{tot}$  | C and D partially correlated             | ± 0.09 |
| $S_{tot}$  | Systematic errors in Key Project techniques ($S_1$, $S_2$, and $S_3$ added in quadrature) | ± 0.15 |
NGC 4258 is correct and that any differences between the Cepheid distance to that galaxy and the maser distance are due to an error in the distance to the LMC assumed in calibrating \( P-L \) relations. Such a procedure is subject to many sources of uncertainty; the random uncertainty in the resulting LMC distance will correspond to the sum in quadrature of the random uncertainties in the maser and Cepheid distances to NGC 4258. Furthermore, the uncertainty due to potential systematic errors in that procedure includes contributions from all possible systematics in the maser and Key Project error budgets, save the distance to the LMC itself. If we nevertheless proceed in this manner, we determine an LMC distance modulus of \( 18.31 \pm 0.11 \) (random) \( \pm 0.17 \) (systematic).

Similarly, we may use the maser and Cepheid distances to NGC 4258 to place limits on the effect of metallicity on Cepheid luminosities. In that case, we should consider all random and systematic uncertainties in the maser or Cepheid distances save those due to metallicity effects; they total 0.21 mag. Thus, the Cepheid distance becomes 1 \( \sigma \) discrepant from the maser distance if there is a total metallicity correction of 0.09 mag to the uncorrected Cepheid distance, and 2 \( \sigma \) discrepant with a correction of 0.30 mag. As the metallicity of NGC 4258 is 0.35 \( \pm 0.06 \) dex greater than that of the LMC, we thus can limit the effect of metallicity on Cepheid mean magnitudes to \(-0.26 \text{mag} \text{dex}^{-1}\) at 1 \( \sigma \), or \(-0.9 \text{mag} \text{dex}^{-1}\) at 2 \( \sigma \).

NGC 4258 has provided the most stringent geometrical test of the revised Key Project distance scale so far. The 0.26 mag discrepancy between the maser distance and the Cepheid distance to NGC 4258 obtained with the original Key Project methods diminishes to 0.19 mag when the revisions of Freedman et al. (2001) are applied. This provides one piece of evidence that the changes made to the Key Project distance scale are, in fact, improvements. A stronger test of the \( HST \) Cepheid distance scale based on the maser distance to NGC 4258 would require a substanti-3ially larger sample of Cepheids (which should reduce the uncertainties in determining the \( VI \) \( P-L \) relations and the reddening) and better determination of aperture corrections; these issues can be addressed simultaneously by searching for Cepheids with \( HST \) in a field that contains more stars and has undergone more recent star formation, preferably with the higher resolution that will be afforded by the Advanced Camera for Surveys. It would be reasonable to expect that observations of a region richer in Cepheids might yield as many as 3 times the number of Cepheids (giving a distance modulus uncertainty of 0.04 mag) and aperture corrections accurate to \( \pm 0.04 \) mag; better agreement between \texttt{ALLFRAME} and \texttt{DoPHOT} analyses might also occur with improved data. Reductions of uncertainties in the maser distance (e.g., via improved constraints on the eccentricity of the circumnuclear disk) would also be greatly beneficial for its use to calibrate the extragalactic distance scale. Successful maser distances to other galaxies, establishing a Hubble relation, would more firmly establish this novel and promising technique. The data available at present are sufficient only to test calibrations of the extragalactic distance scale, but that alone is of great value. With improvements in both Cepheid and maser analyses, NGC 4258 has great potential for establishing a new primary step in the distance ladder, reducing the potential systematic errors in measurements of the Hubble constant to perhaps as little as 5\%, and bypassing controversies over the distance to the LMC and the effect of metallicity on the colors and magnitudes of Cepheids entirely.

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REFERENCES

Alibert, Y., Baraffe, I., Hauschildt, P., & Allard, F. 1999, A&A, 344, 551
Cardelli, J. C., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Dolphin, A. E. 2000, PASP, 112, 1397
Feast, M. 1999, PASP, 111, 775
Ferrarese, L., et al. 1996, ApJ, 464, 568
---. 1998, ApJ, 464, 568
---. 2000, ApJ, 529, 745
Freedman, W. L. 1998, Relativistic Astrophysics and Cosmology, ed. A. V. Olinto, D. N. Schramm, & J. A. Frieman (Singapore: World Scientific)
Freedman, W. L., et al. 1994, ApJ, 427, 628
---. 2001, ApJ, submitted
Gibson, B. K. 2000, preprint (astro-ph/9910547)
Greenhill, L. J., Henkel, C., Becker, R., Wilson, T. L., & Wouterloot, J. G. A. 1995, A&A, 304, 21
Herrnstein, J. R., et al. 1999, Nature, 400, 539
Hill, R. J., et al. 1998, ApJ, 496, 648
Holzman, J. A., et al. 1995, PASP, 107, 1065
Kennicutt, R. C., Jr., et al. 1998, ApJ, 498, 181
Kochanek, C. S. 1997, ApJ, 491, 13
Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, ApJ, 417, L553
Macri, L., et al. 2001, ApJ, 549, 721
Madore, B. F. 1982, ApJ, 253, 575
Madore, B. F., & Freedman, W. L. 1991, PASP, 103, 933
Maoz, E. 1995, ApJ, 494, L181
Maoz, E., et al. 1999, Nature, 401, 351
Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, Nature, 373, 127
Musella, I. 1999, in ASP Conf. Ser. 167, Harmonizing Distance Scales in a Post-\textit{Hipparcos} Era, ed. D. Egret & A. Heck (San Francisco: ASP), 288
Nevalainen, J., & Roos, M. 1998, A&A, 339, 7
Newman, J. A., et al. 1999, ApJ, 523, 506
Saha, A., & Hoessel, J. G. 1990, AJ, 99, 97
Saha, A., Labhardt, L., Schwengeler, H., Macchetto, F. D., Panagia, N., Sandage, A., & Tammann, G. A. 1994, ApJ, 425, 14
Sasselov, D. D., et al. 1997, A&A, 324, 471
Schechter, P. L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342
Stetson, P. B. 1987, PASP, 99, 191
---. 1996, PASP, 108, 851
---. 1998, PASP, 110, 1448
Stetson, P. B., et al. 1998, ApJ, 508, 491
Udalski, A., et al. 1999, Acta Astron., 49, 223
Zaritsky, D., Kennicutt, R. C., Jr., & Huitch, J. P. 1994, ApJ, 420, 87