Ground-Based Calibration of WFC ALLFRAME Stellar Photometry in M81

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Abstract

The Distance Scale Key Project for the Hubble Space Telescope, which aims to obtain reliable Cepheid distances to a set of galaxies that will be used to calibrate a variety of secondary distance indicators, relies on an accurate calibration of Cepheid magnitudes. The first and nearest of these galaxies is M81, which was observed for 22 epochs with the current aberrated Wide Field Camera, over 1991 to 1992. The ALLFRAME program (based on DAOPHOT-II) was used to obtain the *HST* magnitudes from which 30 Cepheids were identified (Freedman et al 1994). Their mean magnitudes were then calibrated to standard magnitudes via ground-based observations, obtained with the *CFHT* and Palomar 200-inch telescopes (Hughes et al 1994). This was done by establishing secondary standards in each of the WFC fields, in Johnson *V* and Cousins *I*, allowing a direct transformation from ALLFRAME magnitudes to calibrated *V* and F785LP magnitudes, giving mean $V \sim 23$ magnitudes accurate to $\sim \pm 0.1$ mag. The stellar populations in M81 have been analyzed in terms of the luminosity functions and color magnitude diagrams (CMD) derived from these data, from which we identify numerous supergiants, and a CMD morphology similar to M33.

I. ALLFRAME WFC Photometry

The two WFC fields included V30, a known Cepheid (Sandage, personal communication), and the major axis of M81. The Cepheids were identified from 22 F555W epochs. A mean reddening (Freedman et al, 1992) was determined from 6 F785LP epochs. All WFC exposures were acquired during *HST* Cycles 1 and 2, and passed through STScI's calibration pipeline (Lauer 1989; and this volume).

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The photometry was derived from DAOPHOT II (Stetson 1992) and ALLFRAME Stetson (1994, this volume), which takes advantage of the multi-epoch nature of the photometry. ALLFRAME successively fits a point-spread function (PSF) model (with residuals which vary quadratically as a function of chip coordinates) to a list of stars for each epoch WFC frame, and any pixels that deviate from the mean are down-weighted, thereby minimizing the effects of bad pixels and cosmic rays (Stetson 1987).

For the major axis field, one PSF was used for each filter, determined from median images. For the V30 field, the PSFs were modelled on a grid of artificial stars produced by Tiny Tim (J. Krist, STScI) for each chip and filter. Tiny Tim was also used to search for variations in the PSF from epoch to epoch (due to slight changes in focus), but the differences were found to be marginal, so only one grid of stars was produced for each chip and filter, at a mean epoch (1992 Jan 20).

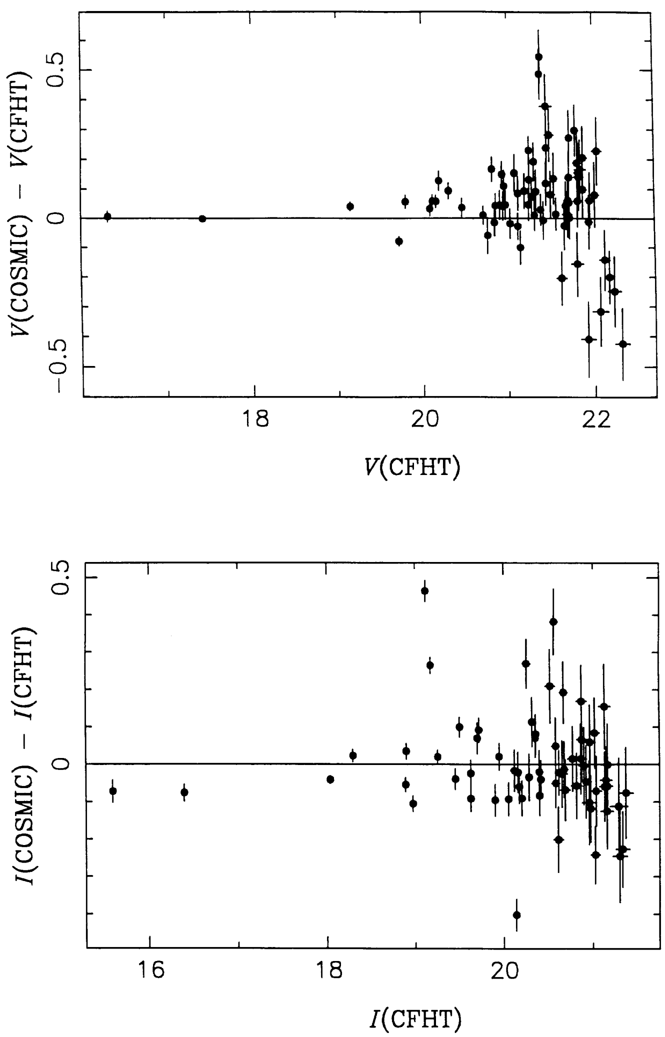

Figure 1: The difference in *V* and *I* magnitudes derived from independent exposures, for stars in the overlap region between the Palomar 5m (COSMIC) V30 field taken on 1992 June 8, and the *CFHT* field taken on 1988 Jan 20.

Table 1: Calibration of WFC Photometry

Chip	N	V – F555W$_{ALF}$	F785LP – F785LP$_{ALF}$
		—V30 field—	
1	8	3.40 ± 0.03	2.38 ± 0.17
2	11	3.62 ± 0.05	2.69 ± 0.12
3	15	3.64 ± 0.03	2.73 ± 0.04
4	15	3.51 ± 0.04	2.81 ± 0.05
		—Major axis field (June 8)—	
1	6	3.39 ± 0.03	2.76 ± 0.22
2	3	3.57 ± 0.07	2.74 ± 0.18
3	2	3.50 ± 0.10	2.42 ± 0.33
4	5	3.50 ± 0.08	2.64 ± 0.09
		—Major axis field (June 9)—	
1	6	3.51 ± 0.07	2.80 ± 0.14
2	3	3.63 ± 0.14	2.84 ± 0.15
3	2	3.61 ± 0.14	2.53 ± 0.35
4	5	3.64 ± 0.05	2.80 ± 0.07

Table 2: Calibration of Mean WFC Photometry

Chip	N	V – F555W$_{ALF}$		F785LP – F785LP$_{ALF}$	
		Ground-based	FW92	Ground-based	FW92
1	18	3.44 ± 0.03	(3.51)	2.61 ± 0.11	(2.70)
2	17	3.61 ± 0.04	(3.68)	2.73 ± 0.08	(2.73)
3	19	3.62 ± 0.03	(3.66)	2.69 ± 0.05	(2.59)
4	25	3.53 ± 0.04	(3.57)	2.78 ± 0.04	(2.61)

II. Calibration of WFC Photometry

Calibration of WFC photometry onto a standard system is by no means straightforward, as spherical aberration causes variations in the shape of the PSF across each chip (Faber & Westphal 1992, hereafter FW92). Also, none of the WFC flatfields are entirely flat (Phillips et al 1993), and there exists a time variation of detector sensitivity due to contamination of up to 0.15 mag in F555W (Ritchie & MacKenty 1993). To account for these effects, we established a set of 65 secondary standards in the two M81 fields, obtained from ground-based photometry of the brighter stars. V and I photometry from the *CFHT* of half the V30 field was verified to ±0.02 mag by independent observations on the Palomar 1.5m and the KPNO 4m. The Palomar 5m COSMIC camera was used to image both fields on 1991 June 8 and the major axis field on June 9. Although not perfectly photometric, the accuracy of the *V* and Gunn *I* photometry can be gauged by the scatter in the overlap region with the *CFHT* exposures, see Figure 1. The mean COSMIC–*CFHT* photometry for the 8 secondary standards in common was +0.05 ±0.03 mag in *V*, and −0.01 ±0.03 mag in *I*. The color term in converting F555W to *V* is minimal (~ 0.02 mag) over the color range of the Cepheids (0.60 to 1.65 in F555W–F785LP), but as F785LP to *I* is large (~ 0.14 mag), we converted the secondary standards' *I* to F785LP (Harris et al 1991).

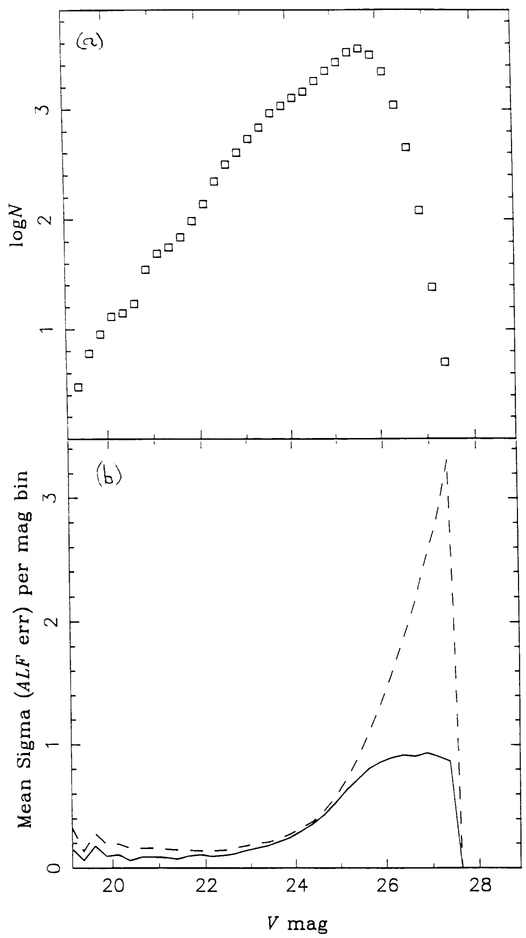

Figure 2: (a) Calibrated *V* luminosity function of stars that were recovered in all 22 F555W epochs in all chips and in both M81 fields, and which had rms dispersions about their mean of less than 3 standard deviations (as these are likely to have been severely contaminated by cosmic ray hits). (b) The solid line is the mean rms dispersion about the mean of the 22 epoch magnitudes of the stars in (a), for each of 50 magnitude bins. The dashed line is the mean single-epoch uncertainty given by ALLFRAME in the same magnitude bins. The uncertainties in the calibration from the secondary standards are included.

We tried various methods to account for the differences in zero points between the photometric sets (COSMIC and *CFHT* for V30, and two nights of COSMIC for the major axis) seen in Table 1, by correcting for the differences between the empirical and Tiny Tim PSFs, and fitting surfaces to the flat field corrections (Phillips et al

1993), but none systematically reduced the field-to-field differences. Therefore, we combined the three sets, to give a mean offset between the standard and ALLFRAME photometry given in Table 2, which are comparable to what we can derive from FW92 (the figures in parentheses).

III. Stellar Populations

When the V–F555W$_{ALF}$ corrections in Table 2 are applied to the ALLFRAME photometry, we derive the luminosity function (LF) in Figure 2a. The recovery rate of simulated stars showed the completeness limit of the M81 WFC fields to be $V = 25$ mag, corresponding to the position of the LF turnover. The uncertainties in these magnitudes are shown in Figure 2b, which plots the mean rms dispersion and mean ALLFRAME uncertainties from the 22 F555W epochs. Close agreement is seen down to V ≤ 25, beyond which the ALLFRAME uncertainties and rms dispersions start to lose meaning, as they are for magnitudes clearly beyond the limit of WFC. The slope of the LF of blue stars ($V - I < 0.24$ mag) is ~ 0.57 mag^{-1}, similar to other nearby late-type galaxies (Freedman 1985).

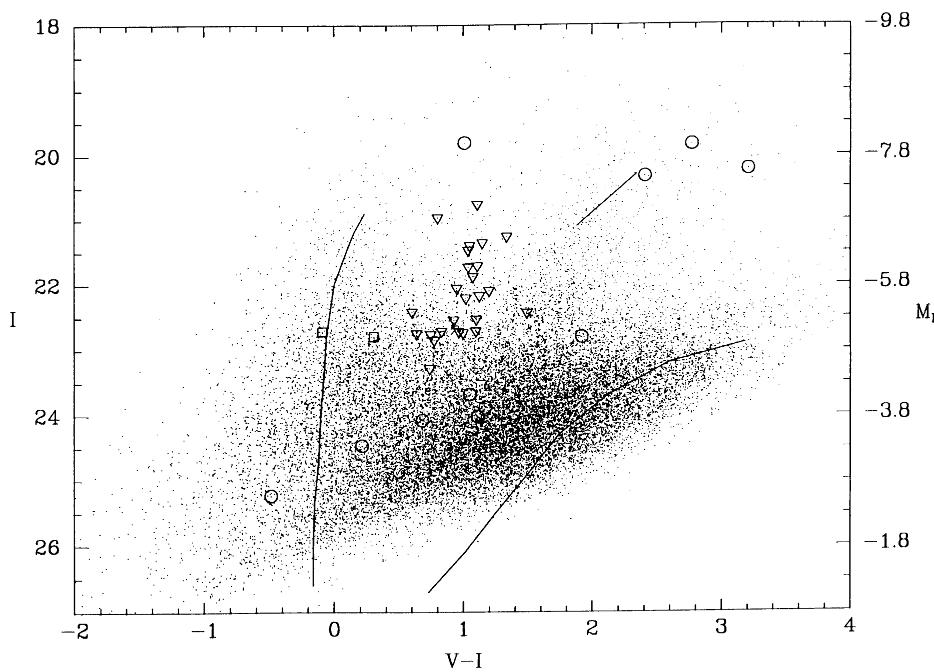

Figure 3: I vs. $V - I$ color magnitude diagram for all 26,082 stars detected in V and I in M81. Lines represent main sequence, red giant and red supergiant loci from Shapley III in the LMC (Reid et al 1987). Open triangles are Cepheids (see Freedman et al 1994). Open squares are eclipsing variables, and open circles are long-period variable candidates. The absolute magnitude scale is shown on the right, based on a distance modulus of 27.80 mag to M81.

Features in the combined CMD for both fields (Figure 3) are aligned with loci derived from the upper main sequence, red supergiants, and red disk giants of Shapley Constellation III in the LMC (Reid, Mould & Thompson 1987). The CMDs of the M81 fields are also very similar to that measured for the disk of M33 (Wilson, Freedman, & Madore 1990). This similarity is not surprising, as the three galaxies contain an abundance of HII regions and young star forming regions, which dominate the CMD in this luminosity range.

As expected, the Cepheids (triangles) occupy the instability strip in the CMD. Two eclipsing binaries (squares) are located in the blue plume. Four long-period variable (LPV) candidates (circles) with $V - I > 1.5$ mag are likely red supergiant LPVs. To measure their periods (100 to 900 days), further (red) exposures of these fields are being taken in *HST* cycles 3 and 4 to extend the baseline. The blue faint LPV candidates may be R CrB variables, and the one bright LPV candidate with $V - I \sim 1.0$ mag may be a long period Cepheid. Although giants are probably detected (especially in our stacked images), they lie too close to the magnitude limit of our data to be reliably measured.

Conclusions

The mean V magnitudes of the 30 Cepheids found in M81 ranged from 21.6 to 23.8 (and their periods ranged from 10 to 55 days), corresponding to single epoch magnitude uncertainties (Figure 2b) of 0.1 to 0.3 mag, respectively. The uncertainties in the mean V magnitudes should therefore be in the range 0.02 to 0.06 mag (but will depend on their position and environment, and how well their light curve is sampled). But the aim is to get a distance for M81, and the accuracy in the zero point of a line of best fit to the $P - L$ relation of all 30 Cepheids is 0.06 mag, but the uncertainties due to reddening, ALLFRAME photometry, calibration, and Cepheid metallicity give a total error of 0.2 mag, equivalent to a total error of 10 percent in the distance to M81.

The bright stellar populations observed in M81 are similar to those in M33 and the star formation regions of the LMC.

References

Faber, S. & Westphal 1992 WFPC SV Report (FW92)
Freedman W. L. 1985, ApJ, 299, 74
Freedman W.L., et al 1992, ApJ, 396, 80
Freedman W.L. et al 1994, ApJ, in press.
Harris H.C., Baum W.A., Hunter D.A., Kreidl T.J. 1991, AJ, 101, 677
Hughes S.M.G. et al 1994, ApJ, in press.
Lauer T.R. 1989, PASP, 101, 445
Phillips D. et al 1993, submitted to AJ
Reid N., Mould J., & Thompson I. 1987, ApJ, 323, 433
Ritchie C.E., & MacKenty J.W. 1993, *WFPC Instrument Science Report* 93-02, STScI.
Stetson P.B. 1987, PASP, 99, 101
Stetson P.B. 1992, in *3rd ESO/ST-ECF Data Analysis Workshop*, ESO Conference and Workshop proceedings No.38, eds. P.J.Grosbol and R.H.Warmels, p187.
Wilson, C. D., Freedman, W. L., and Madore, B. F., 1990, AJ, 99, 149