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LUMINOSITY–LINE WIDTH RELATIONS AND THE EXTRAGALACTIC DISTANCE SCALE. I. ABSOLUTE CALIBRATION

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ABSTRACT

Multicolor CCD photometry is presented for a sample of 15 spiral and irregular members of the Local, Sculptor, and M81 groups with $M_B \leq -16.0$ and relevant as potential calibrators of the luminosity–line width relations. The sample contains those galaxies for which a ground-based study of Cepheid variables could provide accurate distances and hence an absolute calibration for the relations. Unfortunately, only six of the systems presently have reliable independent distance estimates, but this number is sufficient to provide a reasonable calibration. Distance-independent relations involving line width, color, and mean surface brightness are also discussed. These relations are used to examine the possibility of systematic differences between local galaxies used to calibrate the relations and more distant samples. It is shown that while the "local calibrators" are indistinguishable from a large sample of field galaxies they are bluer in the mean than a large sample of cluster galaxies. In the *B* band a systematic correction of ∼12% in distance is required for cluster samples, but it is argued that the effect in near-infrared passbands is negligible. No other evidence for systematic differences between the photometric/kinematic scaling properties of galaxies is discernible over the range of environments sampled by this investigation. These data imply that the primary source of uncertainty in the extragalactic distance scale now lies with the Galactic calibration of the Cepheid and RR Lyrae variables. The new zero-point calibrations are consistent with previous calibrations of the luminosity–line width relations which lead to high values of H_0.

Subject headings: Cepheids — galaxies: distances and redshifts — radio lines: atomic

1. INTRODUCTION

The luminosity–line width relation (Tully & Fisher 1977; hereafter TF relation) is arguably one of the best understood extragalactic distance indicators applicable over intermediate distances (see Aaronson & Mould 1983). The TF relation has been applied over optical and infrared wavelengths to several hundred galaxies by numerous investigators (see Table 5 in Huchtmeier & Richter 1989). The relation is a tight, empirical correlation between a galaxy's luminosity and its rotationally broadened 21 cm line width, although the theoretical basis for the relation is still rather uncertain. An extensive review of the various methods for estimating extragalactic distances, including the TF relation, can be found in Jacoby et al. (1991).

With the advent of modern CCD detectors it has become possible to obtain total magnitudes for large numbers of galaxies, as well as to obtain accurate and unbiased estimates of galaxy inclinations (e.g., Pierce 1991). These developments have enabled an extensive examination of the TF relation as an estimator of extragalactic distances. This paper is the first in a series which will examine various aspects of the relations and their application to the extragalactic distance scale problem. A preliminary investigation using modern photometric data from CCDs (Pierce & Tully 1988) suggests that the TF relations are a powerful method of estimating the distances to late-type galaxies. However, there have been some concerns about the accuracy and reliability of the TF relations (e.g., Bottinelli et al. 1986; 1987; Sandage 1988; Kraan-Korteweg, Cameron, & Tammann 1988). For now we will say that it appears that the TF relations are applicable over a broad range of environments and there is little room for systematic effects (e.g., Pierce & Tully 1988). In addition, it has been repeatedly demonstrated that previous concerns regarding the effect of Malmquist bias were unwarranted (e.g., Schechter 1980; Pierce & Tully 1988; Tully 1988a). The articles in this series will examine these issues in some detail. The present focus is on the zero-point calibration. Subsequent articles will address (*i*) the local Hubble flow as traced by an unbiased sample of nearby field galaxies, (*ii*) the controversies and misconceptions regarding the Malmquist bias and its role in the TF relations, (*iii*) substructure within the Virgo Cluster and the central role of this cluster in the determination of H_0, and finally (*iv*) the value of the Hubble constant, a critical examination of the internal and external sources of error, and the cosmological implications.

In parallel with the developments in both the application and understanding of the TF relations has been a substantial improvement in the estimated distances for nearby galaxies used to calibrate the relations. These "local calibrators" clearly play a pivotal role in establishing the extragalactic distance scale. Specifically, the application of CCDs to the photometry of Cepheid and RR Lyrae variables in nearby galaxies has expanded the number of systems available to calibrate the TF relations (e.g., Pritchet & van den Bergh 1987, 1988; Freedman, Wilson, & Madore 1991b). In addition, infrared photometry of Cepheids has contributed significantly to the growing confidence in the local distance scale (e.g., Welch

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et al. 1986, 1987). Much of this new information has been used by Freedman (1990) in a recent zero-point calibration of the H-band relation.

The paper presents CCD photometry for a complete sample of late-type galaxies within three of the nearest groups. These data are combined with existing 21 cm line width measurements from the literature in order to examine the absolute calibration of the TF relations. The sample and the data are presented and discussed in § 2. A summary of recent distance determinations for members of these groups is presented in § 3, as well as a discussion of the effect of line-of-sight depth within these nearby groups on the calibration. The TF relations for the nearby groups are presented and discussed in § 3 as well. Section 4 contains a discussion of two *distance-independent* relations which can be used to test for systematic variations in the TF relations. We discuss a small systematic color-correction term for cluster galaxies which is necessary to bring the calibration of all the bandpasses into agreement. Finally, § 5 contains the adopted absolute calibrations, a summary, and some thoughts concerning the application of the TF relations to the extragalactic distance scale problem and to the determination of H_0.

2. THE SAMPLE AND DATA ANALYSIS

B, R_{KC}, and I_{KC} (KC denotes Kron-Cousins, Cousins 1976) CCD images for this sample of nearby galaxies were obtained as part of an ongoing photometric survey of several hundred nearby galaxies (Pierce 1991). Specifically, the sample presented here includes all known spiral and irregular members of the Local, Sculptor, and M81 groups with $M_B \leq -16.0$ subject to the following selection criteria: (*i*) The need for accurate projection corrections for the 21 cm line widths requires that inclinations be limited to greater than 30°. The only members of these groups which did not meet this requirement were the Magellanic Clouds. (*ii*) The assumption that the line widths are due to rotational broadening requires that the sample be restricted to those systems with "normal" morphology. Two additional members of the sample were eliminated on the basis of their peculiar morphology and evidence that they are interacting with M81, namely NGC 3077 and M82. (*iii*) Finally, the need for accurate magnitudes requires that extinction corrections be kept low. UGC 192 (IC 10) of the Local Group was eliminated from the sample due to the fact that its high Galactic extinction ($A_B^b > 3$ mag) leads to uncertain corrected apparent magnitudes.

The images were obtained with the Galileo/IFA 500 × 500 and the NSF-1 800 × 800 CCD cameras of the University of Hawaii in one of four observing configurations. Four optical configurations were used to ensure an adequate field of view such that accurate total magnitudes could be obtained for all the sample members, without resulting to extrapolation via template growth curves. The aperture sizes used range from a "2 inch (5 cm) telescope" with ~12″ pixel^{-1} and a 2°.7 field of view to the University of Hawaii 2.2 m telescope with 0″.6 pixel^{-1} and a 5′ field of view. A few systems, in particular M31 and M33, were imaged with at least two of the configurations such that an internal check was possible to ensure that all observations were on the same photometric system. The photometry of M31 and M33 will be described in particular detail. The instrumental configurations, observational procedures, and photometric calibrations are described more fully by Pierce (1988, 1991).

The images were bias-subtracted and flat-fielded using a combination of both dome and sky flats. Images of "blank fields" were used to monitor the flat-fielding procedure. Photometric calibrations were provided by observations of red-blue pairs of standard stars (Landolt 1983). Single point residuals were typically 0.02 mag rms. The large pixels of the "2 inch telescope" necessitated the use of bright U, B, V, R, I standards taken from the Astronomical Almanac transformed to the Kron-Cousins system. Single point residuals were typically 0.03 mag rms. Total magnitudes for the sample members were obtained using the GASP software written by Mike Cawson (see Davis et al. 1985; Pierce 1988, 1991). We believe that the magnitudes are accurate to ~0.03–0.05 mag.

The photometry of M31 (NGC 224) requires some explanation. In a previous paper (Pierce & Tully 1988) we presented CCD photometry of M31 which differed substantially from that presented here. The discrepancy of these earlier data with material from several sources has also been discussed by Burstein & Raychaudhury (1989). The large angular extent of M31 and M33, the small size of available CCDs, and a limited choice of optical components resulted in a scale of 30″ pixel^{-1} for our earlier data. There were flat-fielding problems which prevented the use of the outer portion of the field of view. These problems and the substantial contamination of the data by field stars, due to the low Galactic latitude of these galaxies, rendered our earlier photometry of these systems rather uncertain. In order to alleviate these concerns we have acquired new photometry of these galaxies through a variety of imaging systems with a substantial range of scales. The larger CCDs now available and greater care in flat-field calibration has significantly improved our photometry of these systems. Independent data for the inner regions of the galaxies (with ~1″.2 pixel^{-1}) have also provided more confidence that the wide-field data are on the same photometric system as the remaining data presented here. Synthetic multiaperture photometry was performed and good agreement ($\Delta B \sim 0.05$ mag) was found for the 2 inch (5 cm) and 24 inch (61 cm) data. In addition, our synthetic multiaperture photometry agrees well ($\Delta B \sim 0.06$ mag) with that given by Longo & de Vaucouleurs (1983) for both M31 and M33. The total B magnitude for M31 from the "2-inch telescope" data agrees well ($\Delta B \sim 0.06$ mag) with that deduced from the photoelectric scans of de Vaucouleurs (1958). Finally, a comparison of simulated B-band aperture photometry of several stars in the "2-inch telescope" field with that given by McClure & Racine (1969) provided yet another independent check of the photometric calibration of M31 and M33 ($\Delta B \sim 0.06$ mag). In summary, there were indeed problems with our earlier photometry of M31 and to a lesser extent that of M33. The data presented here are clearly superior given the numerous internal and external checks now available.

The apparent magnitudes of all the galaxies were corrected for Galactic extinction following Burstein & Heiles (1984), with the extinction in the R, I, and H bands taken to be 61%, 44%, and 10% of that at B. Burstein & Raychaudhury (1989) have pointed out a discrepancy between the value we took from the Nearby Galaxies Catalog (Tully 1988b) for the Galactic extinction for M31 and that given by Burstein & Heiles (1984), with our value being too low. The estimate from DDO photometry by McClure & Racine (1969) is in good agreement with the value by Burstein & Heiles (1984), which we will adopt.

The inclinations of the galaxies were estimated using the technique of ellipse fitting to galaxy isophotes (Pierce 1988, 1991), and the corrections for internal extinction were applied using the model advocated by Tully & Fouqué (1985). This model corrects only to face-on inclinations and consequently does not require an assumption as to the face-on extinction in galaxies. Note, however, that there is some evidence for a lower dust content in low-luminosity systems (e.g., Sandage & Tammann 1981; Issa, MacLaren & Wolfendale 1990; van den Bergh & Pierce 1990). Consequently, our internal extinction estimates for the low-luminosity systems may prove to be too large. Nevertheless, for the time being we will adopt the Tully & Fouqué (1985) approach of a uniform correction for galaxies of all morphological types. The photometric data are presented in Table 1.

A complete review of the current status of 21 cm observations of these nearest galaxies has been carried out. Just as these large galaxies present special problems for the photometry, they are also difficult cases with respect to the radio observations. They are usually bigger than the radio beams and require mapping. Also, there is frequently confusion with Galactic H I near zero velocity. The latter problem can be dealt with effectively only using aperture synthesis techniques because then the slowly varying Galactic component can be subtracted out. Unfortunately, the aperture synthesis observations can lose low spatial-frequency flux associated with the galaxy.

All the line widths for the calibrators have been measured by us, though most of the profiles are taken from the literature. We measure the global line width at 20% of the *peak* intensity. On these high signal-to-noise profiles the measurement errors are usually only a few kilometers per second but external errors surely dominate, and we assign an uncertainty of 10 km s^{-1} in the *best* of individual cases (fortunately, there is at least one high-quality measurement in all cases).

The observed line widths were corrected for the effects of projection and internal turbulence using the prescriptions given by Tully & Fouqué (1985), with the result being referred to as W_R^i. Uncertainty in the inclination corrections to the observed line widths can easily dominate as the source of the dispersion in the TF relations (e.g., Pierce & Tully 1988). Consequently, care in obtaining the most accurate estimate of galaxy inclinations (i.e., the ellipse fitting afforded by CCD surface photometry) has been a key in the effort to have the best data for the TF calibrations. The ellipse-fitting procedure has high precision and is objective and reproducible. We believe the inclination estimates are good to ~3° at an inclination of 45°. Inclination estimates of irregular systems had been subject to considerable uncertainty (e.g., van den Bergh 1988), but deep CCD images have enabled the underlying old-disk population of irregular galaxies to be detected so the inclination of these systems can now be estimated using the ellipse-fitting technique. The measurement and inclination uncertainties lead to a combined uncertainty of ~0.02 in log W_R^i, or 0.17 mag for a typical slope of 8 for the TF relations. This value is similar to that estimated by Bothun & Mould (1987).

3. ADOPTED DISTANCES AND THE LUMINOSITY–LINE-WIDTH RELATIONS

The recent and ongoing success of Cepheid photometry in crowded fields using CCDs has significantly increased both the number and quality of distance estimates for nearby galaxies (e.g., Freedman et al. 1991b; Freedman & Madore 1988, 1990). The application of infrared photometry to Cepheids has also reduced many of the uncertainties associated with the application of Cepheids to the distance scale problem (e.g., Welch et al. 1986, 1987). In addition, the detection and photometry of RR Lyrae variables in Local Group members now provide an independent check of the Cepheid scale using the Population II distance scale (e.g., Pritchet & van den Bergh 1987, 1988). A comparison of planetary nebulae luminosity functions has also produced independent distance estimates for M31 and M81 (Ciardullo et al. 1989; Jacoby et al. 1989; Jacoby, Walker, & Ciardullo 1990). Together, these results are used to estimate distances to six galaxies in the Local, Sculptor, and M81 Groups. Although other techniques have been applied to estimate individual distances to some of these galaxies, most notably the use of carbon stars (e.g., Pritchet et al. 1987), we believe that these alternative methods are presently rather more uncertain than those mentioned above. Consequently, we have chosen not to to consider these additional techniques. All adopted distances assume a distance modulus for the LMC of 18.45 ± 0.15 mag (Welch et al. 1986; Feast & Walker 1987; van den Bergh 1989). The adopted distances for the individual group members can be found in Table 1, and each group will be discussed in turn.

3.1. *The Local Group*

Three members of the Local Group meet the requirements outlined in § 2 for use as calibrators of the TF relations. These are M31 (NGC 224), M33 (NGC 598), and NGC 3109. We have included NGC 3109 as a possible member of the Local Group although its distance of 1.5 Mpc makes it an outlying member at best. As previously mentioned, four members of the Local Group with $M_B \leq -16.0$ which are not suitable "local calibrators" are the LMC, SMC, UGC 192 (IC 10), and the Galaxy.

As an aside, we can infer the luminosity of the Galaxy by using the TF relations in reverse. We estimate the line width that a distant observer would measure for the Galaxy and infer its luminosity using the calibrations given below. If there is flat rotation in the Galaxy at 220 km s^{-1} (Gunn, Knapp, & Tremaine 1979), then $W_R^i(G) \sim (220/250) W_R^i(\text{M31})$. With the calibration derived in a later section, the absolute magnitudes of our Galaxy are −20.7, −21.7, −22.2, and −23.2 in *B*, *R*, *I*, and *H*, respectively.

The adopted distance to M31 (NGC 224) is taken from four sources: (*i*) the infrared photometry of Cepheid variables by Welch et al. (1986) gives a distance modulus of 24.3 ± 0.1 mag, (*ii*) the CCD photometry of Cepheids in three fields by Freedman & Madore (1990) gives 24.4 ± 0.1 mag, (*iii*) the CCD photometry of RR Lyrae variables by Pritchet & van den Bergh (1987) giving 24.3 ± 0.2 mag, and (*iv*) a comparison of planetary nebulae luminosity functions for M31 (Ciardullo et al. 1989) and the LMC (Jacoby et al. 1990) giving 24.3 ± 0.2 mag. We adopt a distance modulus for M31 of 24.3 ± 0.1 mag.

The distance to M33 (NGC 598) has been the subject of considerable debate, but at least most of this has been laid to rest, thanks to the most recent CCD data. There are three modern distance estimates: (*i*) infrared photometry of Cepheids by Madore et al. (1985) adjusted here for a mean *H*-band extinction of 0.1 mag, giving a distance modulus of 24.4 ± 0.2 mag, (*ii*) CCD photometry of RR Lyraes by Pritchet & van den Bergh (1988) resulting in 24.5 ± 0.2 mag, and (*iii*) the multicolor CCD photometry of Cepheids by Freedman et al. (1991b), which gives 24.5 ± 0.2 mag. We will adopt a distance modulus

TABLE 1

LOCAL CALIBRATION DATA

Galaxy (1)	Group (2)	B_T (3)	R_T (4)	I_T (5)	$H_{-0.5}$ (6)	A_B^i (7)	A_B^b (8)	Incl. (9)	W_{20} (10)	Source (11)	log W_R^i (12)	$M_B^{b,i}$ (13)	$M_R^{b,i}$ (14)	$M_I^{b,i}$ (15)	$M_H^{b,i}$ (16)	μ (17)	Source (18)
NGC 224[a]	Local	4.39	2.92	2.18	0.94	0.61	0.32	78	542	1, 2, 3	2.712	−20.84	−21.95	−22.53	−23.45	24.3	1, 2, 3, 4
NGC 598[a]	Local	6.31	5.43	4.98	4.39	0.16	0.16	54	206	3, 4	2.322	−18.51	−19.26	−19.66	−20.14	24.5	5, 6, 7
NGC 3109[a]	Local	10.57	9.65	9.23	...	0.67	0.13	85	135	3, 5, 6, 7, 8	2.032	−16.13	−16.74	−17.02	...	25.9	8, 9
NGC 55	Sculptor	8.48	7.62	7.20	...	0.67	0.05	87	203	9, 10	2.224	−18.74	−19.32	19.62	...	26.5	10
NGC 247	Sculptor	9.74	8.75	8.32	7.69	0.40	0.06	71	220	5, 11, 12, 13	2.288	−17.22	−18.03	−18.38	−18.86	26.5	10
NGC 253	Sculptor	7.86	6.52	5.93	4.74	0.65	0.04	79	440	5, 14, 15	2.612	−19.33	−20.40	−20.87	−21.83	26.5	10
NGC 300[a]	Sculptor	8.38	7.77	7.36	7.00	0.09	0.05	44	166	9, 16	2.284	−18.26	−18.82	−19.20	−19.51	26.5	11, 12, 13
NGC 7793	Sculptor	9.44	8.63	8.37	7.89	0.12	0.05	48	194	5, 17	2.330	−17.23	−17.97	−18.20	−18.63	26.5	10
NGC 2366	M81	11.64	11.06	11.05	10.83	0.36	0.16	69	118	5, 17, 18	2.000	−16.48	−16.86	−16.78	−16.82	27.6	14
NGC 2403[a]	M81	8.74	7.84	7.39	6.47	0.20	0.14	58	256	19	2.411	−19.10	−19.87	−20.26	−21.06	27.5	15
NGC 2976	M81	10.81	9.74	9.31	...	0.23	0.14	61	160	9, 20	2.166	−17.16	−18.09	−18.45	...	27.6	14
NGC 3031[a]	M81	7.72	6.33	5.70	4.39	0.19	0.17	57	444	21, 22	2.685	−20.34	−21.59	−22.16	−23.35	27.7	15, 16
NGC 4236	M81	10.40	9.59	9.31	9.08	0.45	0.05	73	198	23	2.230	−17.70	−18.32	−18.51	−18.57	27.6	14
UGC 4305	M81	11.61	10.78	10.57	...	0.07	0.09	39	75	5, 18, 24	1.959	−16.15	−16.92	−17.10	...	27.6	14
UGC 5666	M81	11.33	10.49	10.18	10.07	0.36	0.07	69	132	25	2.050	−16.70	−17.37	−17.61	−17.57	27.6	14

[a] Calibrating galaxies for which individual distance estimates are available.

NOTES.—Col. (2): Group assignment.

Cols. (3)–(6): Apparent magnitudes from either photometry presented here or, in the case of the infrared data, from Aaronson et al. 1982, or Freedman 1990 for the *H*-band mag of NGC 300.

Col. (7): Estimated internal extinction assuming $A_R^i = 0.61\ A_B^i$, $A_I^i = 0.44\ A_B^i$, and $A_H^i = 0.10\ A_B^i$, where A_B^i is the internal *B*-band extinction from the model of Tully & Fouqué (1985) using the inclinations from col. (9).

Col. (8): Estimated Galactic extinction assuming $A_R^b = 0.61\ A_B^b$, $A_I^b = 0.44\ A_B^b$, and $A_H^b = 0.10\ A_B^b$, where A_B^b is the value from Burstein & Heiles (1984).

Col. (9): Inclination estimated from fitting ellipses to the isophotes of each galaxy (see text).

Col. (10): Line width of the 21 cm H I line measured at 20% of peak intensity from several sources (col. [11]).

Col. (11): The sources for the line widths given in col. (10): (1) Brinks & Burton 1984; (2) Cram, Roberts, & Whitehurst 1980; (3) Dean & Davies 1975; (4) Reakes & Newton 1978; (5) Fisher & Tully 1981; (6) Huchtmeier, Seiradakis, & Materne 1980; (7) Jobin & Carignan 1990; (8) Reif et al. 1982; (9) Hummel, Dettmar, & Weilebinski 1986; (10) Puche, Carignan, & Wainscoat 1991; (11) Carignan & Puche 1990b; (12) Huchtmeier & Seiradakis 1985; (13) Whiteoak & Gardner 1977; (14) Puche, Carignan, & van Gorkom 1991; (15) Staveley-Smith & Davies 1988; (16) Puche, Carignan, & Bosma 1990; (17) Carignan & Puche 1990a; (18) Tifft & Cocke 1988; (19) Wevers, van der Kruit, & Allen 1986; (20) Tacconi 1990; (21) Appleton, Davies, & Stephenson 1981; (22) Gottesman & Weliachew 1975; (23) Shostak & Rogstad 1973; (24) Cottrell 1976; (25) Seielstad & Wright 1973; (26) Rogstad, Crutcher, & Chu 1979.

Col. (12): The observed line width corrected for projection and internal turbulence according to the procedure given by Tully & Fouqué (1985).

Col. (13)–(16): Absolute magnitudes from the photometry of Pierce (1991) corrected for internal and Galactic extinction (Cols. [7], [8]) assuming the distance moduli given in col. (16).

Col. (17): The adopted distance modulus from the sources given in col. (17) (see text) and assuming a distance modulus for the LMC of 18.45 ± 0.15 mag (e.g., Feast & Walker 1987).

Col. (18): The sources for the adopted distance moduli: (1) Welch et al. 1986; (2) Pritchet & van den Bergh 1987; (3) Ciardullo et al. 1989; (4) Jacoby, Walker, & Ciardullo 1990; (5) Madore et al. 1985; (6) Pritchet & van den Bergh 1988; (7) Freedman et al. 1991b; (8) Demers, Kunkel, & Irwin 1985; (9) Sandage & Carlson 1988; (10) a mean modulus adopted for the Sculptor Group (this paper); (11) Madore et al. 1987; (12) Walker 1988; (13) Freedman et al. 1991a; (14) a mean modulus for the M81 Group (this paper); (15) Freedman & Madore 1988; (16) Jacoby et al. 1989.

for M33 of 24.5 ± 0.1 mag. The distances adopted here for M31 and M33 are essentially the same as those given by van den Bergh (1989).

NGC 3109 has two distance estimates from photographic photometry of Cepheids. Demers, Kunkel, & Irwin (1985) used photographic data to find six Cepheids in this system and derived a distance modulus of 26.0 ± 0.2 mag, assuming that the internal extinction is similar to that for the LMC. No independent extinction estimates for the Cepheids are available. They also used CCD data to check the calibration of their photographic J magnitudes. A more extensive study of the Cepheids in NGC 3109 can be found in Sandage & Carlson (1988). They found 29 variables and obtained a similar distance modulus for NGC 3109 (25.9, with no error estimates given), provided that the LMC has a distance modulus of 18.45 mag and that the extinction of 0.2 mag used by Sandage and Carlson is appropriate. We will adopt a distance modulus of 25.9 ± 0.3 mag and assume that the larger error will reflect the greater uncertainty in the photographic photometry as well as the uncertainty in the internal extinction of NGC 3109. Note that the extinction assumed by both groups is substantially lower than the correction for the total magnitude given by the Tully & Fouqué (1985) model. It is also worth noting that the corrections oppose each other in some sense. That is, a higher extinction for the Cepheids would place NGC 3109 at lower absolute magnitude, while a higher extinction for the galaxy as a whole would give NGC 3109 a higher absolute magnitude.

The importance of NGC 3109 as a calibrator of the TF relations can be seen in Figure 1. This galaxy has the lowest luminosity of any of the calibrators and "anchors" the low-luminosity end of the relation. There is of course a danger in using photographic photometry below $B \sim 21$ mag (e.g., Freedman 1988a). The majority of the Cepheids in NGC 3109 are fainter than this level, even at maximum light. Random-phase I-band CCD magnitudes for the Cepheids in NGC 3109 (e.g., Freedman & Madore 1988) would go a long way toward reducing the remaining uncertainty in the distance of this rather important galaxy.

3.2. *The Sculptor Group*

Five members of the Sculptor Group meet our suitability requirements for use as calibrators for the TF relations. Following de Vaucouleurs & Davoust (1980) we consider NGC 24 and NGC 45 to be background galaxies. The members of this group above our magnitude threshold are NGC 55, NGC 247, NGC 253, NGC 300, and NGC 7793. Unfortunately, there is considerable evidence that the Sculptor Group is significantly extended along the line of sight (e.g., de Vaucouleurs 1979a, b; Puche & Carignan 1988; Sandage & Tammann 1984), possibly spanning as much as 2 mag in distance modulus. Consequently, we would need individual distance determinations for each of the group members in order to use the entire sample as "local calibrators."

Although there is an ongoing effort to obtain individual distance estimates for several Sculptor Group members using Cepheids (e.g., Freedman 1988b), there is presently only one secure distance estimate, namely for NGC 300. The distance to NGC 300 was estimated via photographic photometry of Cepheids by Graham (1982, 1984). He obtained a surprisingly small distance modulus of 26.0 ± 0.2 mag. This result was subsequently brought into question by the infrared photometry of Cepheids by Madore et al. (1987) who obtained 26.3 ± 0.2 mag. Unfortunately, the Cepheids in NGC 300 suffer from severe crowding, which made the IR aperture photometry quite difficult and accurate magnitudes could be obtained for only two stars. The photometry of Graham has been recently reevaluated using CCD photometry by Walker (1988) who found that Graham's photometry contained a scale error at faint magnitudes. The revised photometry resulted in a distance modulus of 26.4 ± 0.2 mag, in closer agreement with the results of Madore et al. (1987). Recent multicolor CCD photometry of the Cepheids identified by Graham by Freedman, Hawley, & Madore (1991a) places NGC 300 at 26.5 ± 0.2 mag. We will adopt the later distance given the uncertainty associated with the infrared and recalibrated photographic results.

Without individual distance estimates, it would appear unwise to use the remaining members of the Sculptor Group as calibrating galaxies for the TF relation, due to the apparently large line-of-sight depth in the group. However, it is worth mentioning that there is general agreement that NGC 253 and NGC 7793 are about a magnitude in distance modulus farther than NGC 300 (see the references given above and those cited within). This would be consistent with the appearance of Figure 1. Here we have adopted the distance of NGC 300 for

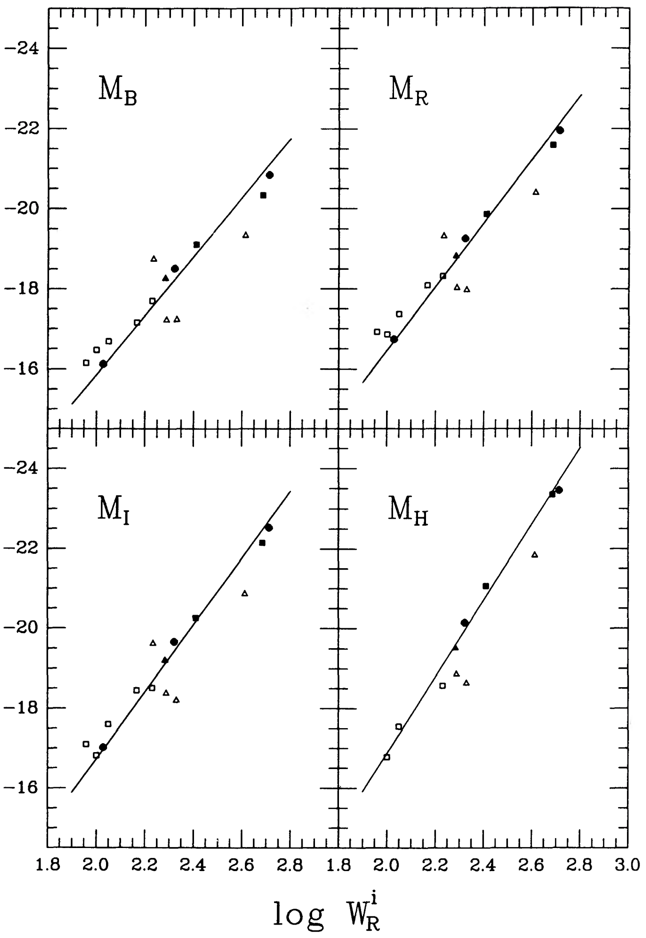

FIG. 1.—The TF relations for the members of the Local (*points*), Sculptor (*triangles*), and M81 (*squares*) groups. The filled symbols represent galaxies with individual distance determinations using Cepheids, RR Lyraes, and/or planetary nebulae. Open symbols represent systems assigned a mean group distance. Note the significant line-of-sight depth for the Sculptor Group. The solid line in each panel is the result of a least-squares fit to similar data for galaxies in the Ursa Major Cluster (Pierce & Tully 1988, 1991) minimizing the residuals in line width. The zero point was established from the six systems with individual distance determinations (i.e., the solid points).

the remaining Sculptor Group members for comparative purposes only. It is also clear from Figure 1 that assuming a common distance for *all* the members of a group such as Sculptor does not significantly improve the calibration of the TF relation and could in fact *decrease* the accuracy of the calibration. We wish to emphasize the need for individual distance estimates in the Sculptor Group. The four additional members would make a substantial contribution to evaluating the dispersion of the TF relations.

3.3. *The M81 Group*

The M81 group contains seven members suitable for use in calibrating the TF relations. These are M81 (NGC 3031), NGC 2366, NGC 2403, NGC 2976, NGC 4236, UGC 4305 (Holmberg II), and UGC 5666 (IC 2574). As described in § 2, M82 (NGC 3034) and NGC 3077 were excluded from the sample due to their peculiar morphology. Of these seven, only two have individual distance determinations. These are M81 at a distance modulus of 27.6 ± 0.3 mag from the CCD photometry of two Cepheids by Freedman & Madore (1988), and NGC 2403 at a distance modulus of 27.5 ± 0.2 mag, also from Freedman & Madore (1988), though in this case 16 Cepheids were available. In addition, there is a distance estimate for M81 of 27.7 ± 0.2 mag by Jacoby et al. (1989) using the planetary nebulae luminosity function. Given that the Cepheid distance for M81 is based on only two stars, we will adopt distances of 27.7 ± 0.2 and 27.5 ± 0.2 mag for M81 (NGC 3031) and NGC 2403, respectively. Van den Bergh (1989) prefers a modulus of 27.9 ± 0.2 mag for both systems, primarily due to adopting lower values for the extinction. Such an approach would significantly reduce the dispersion of the TF relations. Nevertheless, we will conservatively adopt the estimates given in the previous references.

The M81 group spans over 20° projected on the sky and there is some controversy as to whether there is significant line-of-sight depth (see Tammann & Sandage 1968; de Vaucouleurs 1979b). This issue can be addressed only once accurate individual distance estimates become available. Without further information we will simply adopt a mean distance modulus of 27.6 mag for the remaining members for comparative purposes only. *The absolute calibration of the TF relations will be based on only the six systems with individual distance estimates.*

3.4. *The Combined TF Relations for Nearby Groups*

The TF relations are presented in Figure 1 assuming the distances for the galaxies described above. The well-known increase in slope of the relations toward longer wavelengths (e.g., Pierce & Tully 1988) can be clearly seen. The small dispersion for all but the Sculptor Group members is particularly striking. The large deviations of the members of the Sculptor Group are consistent with previous suggestions of significant line-of-sight depth. We also note that M81 is rather discrepant in the *B* band, consistent with a small morphological type effect (e.g., Pierce & Tully 1988).

The slopes of the lines in Figure 1 were determined by combining the data from the "local calibrators" and a complete sample from the Ursa Major Cluster in a self-consistent and iterative manner. An initial slope estimate for each bandpass was made from a least-squares fit to the Ursa Major data alone minimizing the dispersion in line width. Initial zero points were then established from rms minimization of the "local calibrators" data. A mean distance modulus for the cluster was determined for each bandpass and the two data sets were then combined. A new fit for the slope was performed to the combined data set. Then separate fits to the "local calibrators" and cluster gave a revised distance estimate. At this point, the procedure could be iterated but was found to have already converged. The resulting slopes are in excellent agreement with that determined from a combination of data from the Virgo and Ursa Major Clusters (e.g., Pierce & Tully 1988). However, background contamination in the Virgo Cluster dissuades us from including this sample in the primary calibration of the TF relations. For the Ursa Major data (32 galaxies) we get dispersions of 0.41, 0.37, and 0.39 for the *B*, *R*, and *I* bandpasses, respectively. *H*-band data are available for a sample restricted to the higher surface brightness systems. Fitting to these 18 galaxies we get dispersions of 0.43, 0.35, 0.34, and 0.28 mag for the *B*, *R*, *I*, and *H* bands, respectively. For both these samples there is evidence for a significant line-of-sight depth in the Ursa Major Cluster, implying dispersions which are even smaller, a possibility that will be explored in a later paper.

The data for the "local calibrators" establish the zero point of the TF relations by rms minimization of the scatter in magnitudes given the slope determined above. We find dispersions of 0.34, 0.24, 0.24, and 0.18 mag for the *B*, *R*, *I*, and *H* bandpasses, respectively. Although these dispersions are estimated using only six systems, these values are consistent with estimates for the Ursa Major samples described above after correction for line-of-sight depth (e.g., Pierce & Tully 1991). These values are also comparable with the value expected from errors in deprojected line width and distance estimates alone (e.g., Bothun & Mould 1987; Pierce & Tully 1988). The probability that the actual dispersion of the TF relations is as high as 0.7 mag (e.g., Kraan-Korteweg et al. 1988; Sandage 1988), and that the results obtained here are only a statistical fluke, can be tested via the χ^2 test. For a parent population dispersion of 0.7 mag, the probability of obtaining a dispersion of 0.24 from six randomly chosen data points (5 degrees of freedom) is only 2%. Freedman (1990) has reached a similar conclusion for the *H*-band relation.

The fits illustrated in Figure 1 provide absolute calibrations of the *B*, *R*, *I*, and *H*-band TF relations. However, before giving those fits we must address a small systematic effect.

4. THE DISTANCE-INDEPENDENT RELATIONS

The small dispersion of the TF relations implies a strong coupling between the luminous stellar component and the dark-matter halo within galaxies. The application of the TF relation as a distance indicator relies on the universality of this coupling. If the halo is nonbaryonic the existence of such a tight relation is particularly interesting as the only physical linkage between the two components is gravity. Several mechanisms can be proposed to disturb this linkage over the age of the universe, so an independent test for systematic variations in the TF relations is clearly important.

Two distance-independent relations can be used to test for the systematic variations in the TF relations that might be expected to arise from plausible physical processes operating on galaxies. Figure 2*a* illustrates the relation between the mean *I*-band surface brightness ($\Sigma_I^{b,i}$) within the radius containing 80% of the total *I*-band light (corrected for internal and Galactic extinction), and W_R^i. This relation is relatively insensitive to extinction and star-formation effects but is sensitive to deviations in W_R^i through the effects of stripping or disturbance of the outer H I disk. Figure 2*b* illustrates the relation between

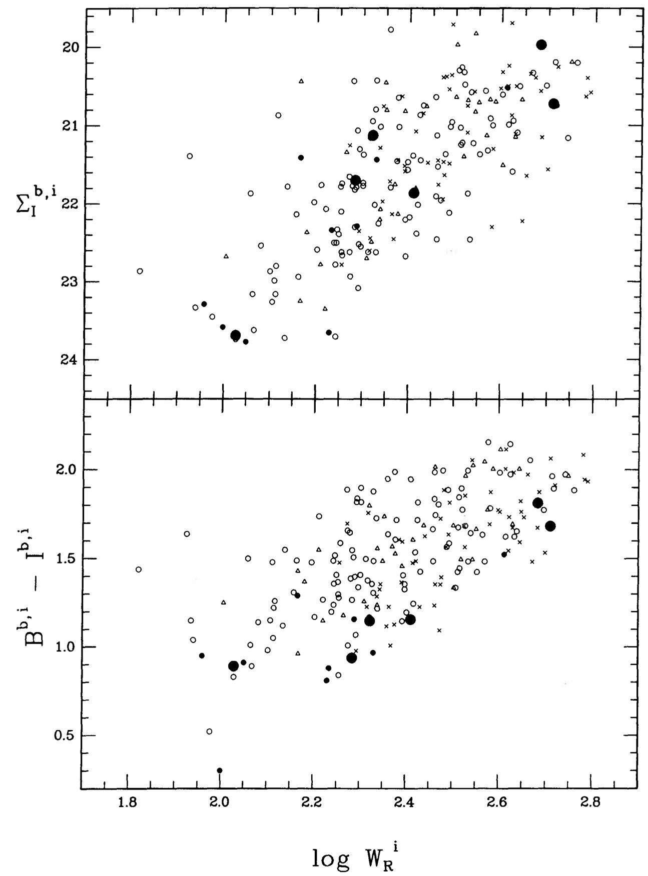

FIG. 2.—Two distance-independent relations. (*a*) The mean *I*-band surface brightness ($\Sigma_I^{b,i}$) vs. line width (W_R^i), and (*b*) the mean $B^{b,i} - I^{b,i}$ color vs. line width (W_R^i). The solid points are the 15 systems suitable for use as "local calibrators," the larger symbols being those six galaxies actually used to calibrate the TF relations. The open circles are members of the Virgo Cluster, the open triangles are members of the Ursa Major Cluster, and the crosses are members of a complete sample of field spirals. The top diagram is insensitive to the effects of star formation and extinction corrections but is sensitive to dynamical processes which affect the line widths (stripping, interactions, etc.). The bottom diagram is sensitive to extinction corrections and to the recent ($\sim$1 Gyr) star-formation history of a particular galaxy. Note that the field sample and the six "local calibrators" are significantly bluer at a given W_R^i than are the cluster galaxies.

mean $B^{b,i} - I^{b,i}$ color (corrected for internal and Galactic extinction) and W_R^i. This relation is sensitive to variations in the recent ($\sim$1 Gyr) star-formation rate as well as to assumptions about internal extinction. The large solid points represent the six "local calibrators" with individual distance estimates, the remaining solid points being those systems suitable for use as "local calibrators." The open circles represent members of the Virgo Cluster, the open triangles represent members of the Ursa Major Cluster, and the crosses represent members of a volume-limited sample of field galaxies. The crossing time of the low-density Ursa Major Cluster is long, so this sample *might* be expected to be equivalent in evolutionary terms to a field sample.

It is immediately obvious from Figure 2 that *the local systems are found along the blue limit of the color–line width relation*, though the mean *I*-band surface brightness ($\Sigma_I^{b,i}$) for the different samples are indistinguishable. An additional surprise is that the Ursa Major systems are indistinguishable from the Virgo systems, despite the significantly different crossing times for the two clusters. On the other hand, the sample of field galaxies is significantly bluer at a given W_R^i than are typical cluster members and is indistinguishable from the "local calibrators." This systematic difference in the mean color of field and cluster spirals was first noted by Holmberg (1958). The majority of plausible physical mechanisms which could result in systematic variations in the TF relations should produce deviations in one of these diagrams. For example, if stripping of the H I envelope within clusters is proposed in order to produce systematically smaller values of W_R^i, the effect should be obvious in Figure 2*a*. The *I*-band light is dominated by the light from evolved stars of 5–10 Gyr in age. Consequently, it would be reasonable to assume that stripping of the *outer* H I envelope would have little effect on the *I*-band surface brightness. As can be seen from the figure, there is no evidence for any systematic difference between the "local calibrators," the field, or *these* cluster samples.[2] We take this as strong evidence against systematic variations in W_R^i within the currently explored range of environments. However, there are clearly *extreme* environments, such as the cores of dense clusters, where stripping could be significant, and caution is necessary.

On the other hand, a significant problem is raised by the systematic blueness of the "local calibrators" compared with the cluster galaxies in Figure 2*b*. *If the problem is ignored, then the calibrations from the fits shown in Figure 1 will result in systematically different distance estimates in the different passbands and different environments.* The residuals in color are not correlated with inclination so the problem is not with *internal* absorption corrections. The calibrators tend to be at lower Galactic latitudes than the other samples so an explanation could be *over* correction for Galactic absorption. However, with *no* correction the observed effect is reduced only by 40%. Hence, systematic deviations in the absorption correction cannot be the dominant factor. The dispersion in $B^{b,i} - I^{b,i}$ at a given W_R^i must be due to real variations in the mix of stellar populations.

It will be argued that the "local calibrators" have *B*-band magnitudes that are brighter than the mean but have normal *I*- and *H*-band magnitudes. In a comparison of the six "local calibrators" with good distances and 32 members of the Ursa Major Cluster (18 with *H* magnitudes), the following results are noted: (*i*) the calibrators have $B^{b,i} - I^{b,i}$ colors that are bluer by a highly significant 0.25 mag at a given W_R^i compared with the Ursa Major galaxies, (*ii*) the calibrators have $R^{b,i} - I^{b,i}$ colors that are bluer by a marginally significant 0.06 mag, (*iii*) the calibrators have $I^{b,i} - H^{b,i}$ colors that are *insignificantly* different (0.03 mag) from the Ursa Major galaxies, and (*iv*) if ΔI from the mean $I^{b,i}$ versus log W_R^i diagram is plotted against $\Delta(B-I)$ from the mean $B^{b,i} - I^{b,i}$ versus log W_R^i diagram the result is a *scatter* diagram for the Ursa Major sample.

Points (*iii*) and (*iv*) support the thesis that the unusually blue objects at a given log W_R^i are this way because of *excess blue light* and that their near-infrared fluxes are normal. There is the intriguing possibility that galaxies in low-density environments have identifiably different (bluer) stellar populations than those

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[2] These data can be used to place a quantitative limit on any systematic variations in W_R^i with environment. The rms dispersion in log W_R^i at a particular $\Sigma_I^{b,i}$ is 0.1. With 15 "local calibrators" (assuming all are representative of the same environment), this reduces to a mean uncertainty of 0.02 in log W_R^i, corresponding to 0.16 mag in the TF relations given a typical slope of 8. This is equivalent to 8% in distance.

in moderately dense environments. This problem will be reexamined in a later paper. For the moment, we conclude: (*i*) the systematic blueness of the "local calibrators" means that, unless corrected, there *will be* a systematic zero-point offset between the *B*-band and *I*- or *H*-band distance estimates for cluster galaxies with *average* colors, and (*ii*) the evidence supports the proposition that the *infrared fluxes of the calibrators are typical.*

Our recourse, subject to reevaluation, is to make a *correction to the B-band calibration* (and a slight one to the *R* band) so that all bands give consistent distances to cluster galaxies. These corrections are just the above identified mean color offsets: 0.25 mag to *B* (12% in distance) and 0.06 mag to *R* (3% in distance). A similar zero-point offset for the *B* band was noticed by Pierce & Tully (1988).

In Figure 3, the six "local calibrators" are superposed on the sample of Ursa Major Cluster galaxies. For the *B*, *R*, and *I* bands the cluster magnitudes assume the distance modulus of 30.95 determined *naturally* by the *I*-band fit and consistent with the *R*- and *B*-band fits after color correction. In the case of the sample with *H*-band data, the best fit requires a distance modulus of 30.89. The systematic offset in the *B* band between the "local calibrators" and the cluster sample can be clearly seen. Our current preferred distance to the Ursa Major Cluster is 15.4 ± 1.2 Mpc, the same as our earlier estimate (Pierce & Tully 1988).

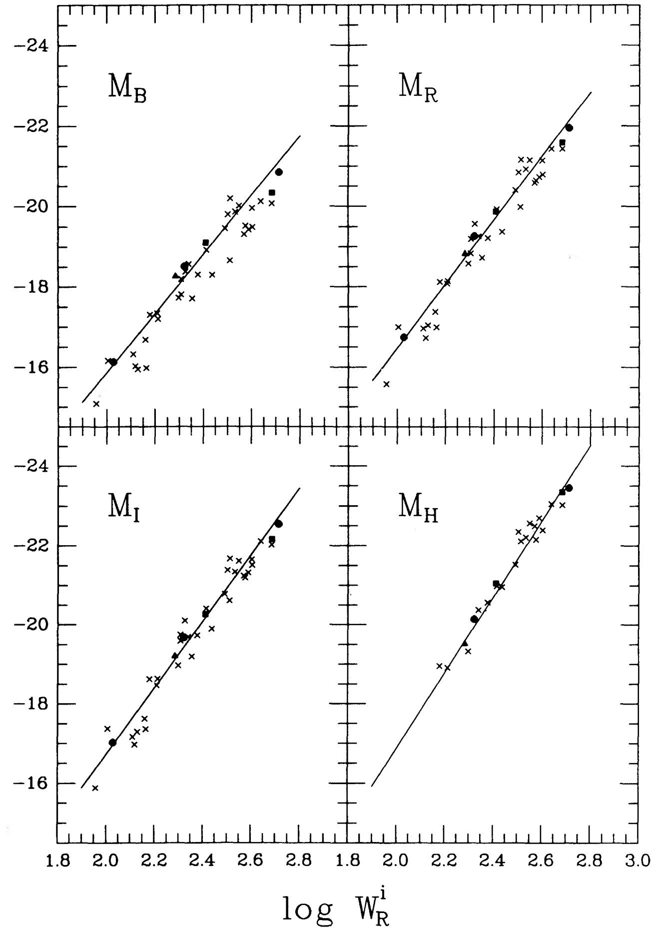

FIG. 3.—The TF relations for the "local calibrators" with individual distance estimates (*solid points*) superposed on the Ursa Major Cluster data (*crosses*). The Ursa Major absolute magnitudes assume $(m - M)_{UMaj} = 30.95$ for *B*, *R*, and *I*, and 30.89 for *H*. The straight lines are the calibration equations given at the beginning of § 5, except that the *B* and *R* bands have not received the 0.25 and 0.06 mag *color-corrections*, respectively, due to the systematically bluer colors of the "local calibrators." Note the discrepancy between the "local calibrators" and the Ursa Major data for the *B* bandpass.

In summary, these data provide significant limits on any systematic variations in the TF relations which could influence the determination of extragalactic distances. There is no evidence for systematic variations in the longer wavelength TF relations above ~10% in distance, provided of course that environments particularly hostile to gas-rich galaxies, such as the cores of rich clusters, are avoided. As a result, the TF relations appear capable of producing excellent estimates of extragalactic distances and there is little room for systematic errors in the results, particularly in the case of the *R*, *I*, and *H* bands. Consequently, the application of the TF relations to the extragalactic distance scale problem should enable the determination of H_0 to ~10%.

5. ABSOLUTE CALIBRATION AND SUMMARY

We obtain the following absolute calibrations from the fits shown in Figure 1 and 3:

$$M_B^{b,i} = -7.48(\log W_R^i - 2.50) - 19.55 + \Delta_B \pm 0.14 ,$$
$$M_R^{b,i} = -8.23(\log W_R^i - 2.50) - 20.46 + \Delta_R \pm 0.10 ,$$
$$M_I^{b,i} = -8.72(\log W_R^i - 2.50) - 20.94 \pm 0.10 ,$$
$$M_H^{b,i} = -9.50(\log W_R^i - 2.50) - 21.67 \pm 0.08 .$$

The correction factors $\Delta_B = 0.25$ and $\Delta_R = 0.06$ are required for statistically consistent distances between the different bands to clusters such as Virgo and Ursa Major. These correction factors are ~0 for galaxies outside of clusters. The error in zero points in the above calibrations do not reflect the uncertainty in the distance to the LMC nor that in the color-correction terms. These solutions are specific to the Tully & Fouqué (1985) prescriptions for line-width and extinction correction.

The fact that the *B*-band calibration depends on environment is very unsatisfactory. It is of course possible to formulate the correction in terms of the $B^{b,i} - I^{b,i}$ or $B^{b,i} - H^{b,i}$ colors but then in this case *the B-band relation offers nothing.* Bottinelli, Gouguenheim, & de Vaucouleurs (1983) have argued that the *B* band is comparable with the *H* band in accuracy because of the shallower slope of the *B* band TF relation. However, it must now be acknowledged that there is a significant environmental effect that diminishes the interest in the *B* band, resulting in discrepancies in the estimated distances of cluster and "field" galaxies of ~12%. The addition of new "local calibrators" from *any* field sample is unlikely to change the situation (e.g., Fig. 2*b*). This calibration problem can *partially* explain the larger distance to the Virgo Cluster obtained by Fouqué et al. (1990) who exclusively used *B* band photometry.

Too summarize, the *B*, *R*, and *I* results are derived from multicolor CCD photometry of a complete sample of nearby galaxies suitable as "local calibrators" for the luminosity–line-width or TF relations combined with existing 21 cm line-width measurements. The *H*-band result is our treatment of published data (Aaronson, Mould, & Huchra 1980; Aaronson et al. 1982). The dispersions of longer wavelength relations are typically 0.2–0.3 mag depending on how much is made of the depth effects in the Ursa Major Cluster. An examination of *distance-independent* relations implies no significant difference between the properties of "local calibrators" and either field or cluster samples for the redder bandpasses, but there is evidence that the "local calibrators" are 0.25 mag bluer in the mean than are typical cluster members. A color correction *must* be applied to the "field calibration" to ensure the consistency of distance estimates between B, R, I, and H bands for cluster galaxies of average color. The correction is 12% in B-band distances and 3% in R-band distances. We anticipate that the systematic uncertainties in these calibrations are $\leq 7\%$ ($\sim 4\%$ in the calibration fits and $\leq 6\%$ in the color-correction term).

With six calibrating galaxies the absolute calibration of the TF relations is limited as much by the uncertainty in the distance to the LMC through the Galactic calibration of the Cepheid and RR Lyrae variables. This uncertainty is said to be about 0.15 mag, or 7% in distance (e.g., Feast & Walker 1987). As a result, the absolute calibration of the luminosity–line-width relations is now established to within 10% in distance. There are already a sufficient number of "local calibrators" for the TF relations to establish the absolute calibration to a precision of 5% in the near-infrared if the majority of galaxies are indeed similar in these bands. *Consequently, further substantial improvements in the absolute calibration of the TF relations are likely to be made only through an improvement in distances at the Galactic scale.* Subsequent papers in this series will make use of the absolute calibration given here to examine the Hubble flow in the nearby field and to determine the distance of the Virgo Cluster. Together these results will be used to determine the value of H_0.

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REFERENCES

Aaronson, M., Huchra, J. P., Mould, J. R., Schechter, P. L., & Tully, R. B. 1982, ApJ, 258, 64
Aaronson, M., Mould, J. R., & Huchra, J. 1980, ApJ, 237, 655
Aaronson, M., & Mould, J. R. 1983, ApJ, 265, 1
Appleton, P. N., Davies, R. D., & Stephenson, R. J. 1981, MNRAS, 195, 327
Bothun, G., & Mould, J. R. 1987, ApJ, 313, 629
Bottinelli, L., Fouqué, P., Gouguenheim, L., Paturel, G., & Teerikorpi, P. 1987, A&A, 181, 1
Bottinelli, L., Gouguenheim, L., & de Vaucouleurs, G. 1983, A&A, 118, 4
Bottinelli, L., Gouguenheim, L., Paturel, G., & Teerikorpi, P. 1986, A&A, 156, 157
Brinks, E., & Burton, W. B. 1984, A&A, 141, 195
Burstein, D., & Raychaudhury, S. 1989, ApJ, 343, 18
Burstein, D., & Heiles, C. 1984, ApJS, 54, 33
Carignan, C., & Puche, D. 1990a, AJ, 100, 394
———. 1990b, AJ, 100, 641
Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D. 1989, ApJ, 339, 53
Cottrell, G. A. 1976, MNRAS, 177, 463
Cousins, A. W. J. 1976, MNRAS, 81, 25
Cram, T. R., Roberts, M. S., & Whitehurst, R. N. 1980, A&AS, 40, 215
Davis, L. E., Cawson, M., Davies, R. L., & Illingworth, G. 1985, AJ, 90, 169
Dean, J. F., & Davies, R. D. 1975, MNRAS, 170, 503
Demers, S., Kunkle, W. E., & Irwin, M. J. 1985, AJ, 90, 1967
de Vaucouleurs, G. 1958, ApJ, 128, 465
———. 1979a, ApJ, 227, 380
———. 1979b, ApJ, 227, 729
de Vaucouleurs, G., & Davoust, E. 1980, ApJ, 239, 783
Feast, M. W., & Walker, A. R. 1987, ARA&A, 25, 345
Fisher, J. R., & Tully, R. B. 1981, ApJS, 47, 139
Fouqué, P., Bottinelli, L., Gouguenheim, L., & Paturel, G. 1990, ApJ, 349, 1
Freedman, W. L. 1988a, ApJ, 326, 691
Freedman, W. L. 1988b, in The Extragalactic Distance Scale, ed. S. van den Bergh & C. J. Pritchet (Provo: Brigham Young Univ. Press), 24
Freedman, W. L. 1990, ApJ, 355, L35
Freedman, W. L., Hawley, S., & Madore, B. F. 1991a, ApJ, submitted
Freedman, W. L., & Madore, B. F. 1988, ApJ, 332, L63
———. 1990, ApJ, 365, 186
Freedman, W. L., Wilson, C., & Madore, B. F. 1991b, ApJ, 372, 455
Gottesman, S. T., & Weliachew, L. 1975, ApJ, 195, 23
Graham, J. A. 1982, ApJ, 252, 474
———. 1984, AJ, 89, 1332
Gunn, J. E., Knapp, G. R., & Tremaine, S. D. 1979, AJ, 84, 1181
Holmberg, E. 1958, Medd. Lunds Astron. Obs., Ser. 2, No. 136
Huchtmeier, W. K., & Richter, O.-G. 1989, A General Catalogue of H I Observations of Galaxies (New York: Springer)
Huchtmeier, W. K., & Seiradakis, J. H. 1985, A&A, 143, 216
Huchtmeier, W. K., Seiradakis, J. H., & Materne, J. 1980, A&A, 91, 341
Hummel, E., Dettmar, R. J., & Weilebinski, R. 1986, A&A, 166, 97
Issa, M. R., MacLaren, I., & Wolfendale, A. W. 1990, A&A, 236, 237
Jacoby, G. H., Branch, D., Ciardullo, R., Davies, R. L., Harris, W. E., Pierce, M. J., Pritchet, C. J., Tonry, J. L., & Welch, D. L. 1991, PASP, submitted
Jacoby, G. H., Ciardullo, R., Ford, H. C., & Booth, J. 1989, ApJ, 344, 704
Jacoby, G. H., Walker, A. R., & Ciardullo, R. 1990, ApJ, 365, 471
Jobin, M., & Carignan, C. 1990, AJ, 100, 648
Kraan-Korteweg, R. C., Cameron, L. M., & Tammann, G. A. 1988, ApJ, 331, 620
Landolt, A. 1983, AJ, 88, 439
Longo, G., & de Vaucouleurs, A. 1983, University of Texas Monographs in Astronomy, No. 3 (Austin: Univ. of Texas Press)
Madore, B. F., McAlary, C. W., McLaren, R. A., Welch, D. L., Neugebauer, G., & Matthews, K. 1985, ApJ, 294, 560
Madore, B. F., Welch, D. L., McAlary, C. W., & McLaren, R. A. 1987, ApJ, 320, 26
McClure, R. D., & Racine, R. 1969, AJ, 74, 1000
Pierce, M. J. 1988, Ph.D. thesis, University of Hawaii
———. 1991, in preparation
Pierce, M. J., & Tully, R. B. 1988, ApJ, 330, 579
———. 1991, in preparation
Pritchet, C. J., Richer, H. B., Schade, D., Crabtree, D., & Yee, H. K. C. 1987, ApJ, 323, 79
Pritchet, C. J., & van den Bergh, S. 1987, ApJ, 316, 517
———. 1988, in The Extragalactic Distance Scale (ASP Conf. Pub. Ser.), ed. S. van den Bergh & C. J. Pritchet (Provo: Brigham Young Univ. Press), 59
Puche, D., & Carignan, C. 1988, AJ, 95, 1025
Puche, D., Carignan, C., & Bosma, A. 1990, AJ, 100, 1468
Puche, D., Carignan, C., & van Gorkom, J. 1991, AJ, 101, 456
Puche, D., Carignan, C., & Wainscoat, R. J. 1991, AJ, 101, 447
Reakes, M. L., & Newton, K. 1978, MNRAS, 185, 277
Reif, K., Mebold, U., Goss, W. M., van Woerden, H., & Siegman, B. 1982, A&AS, 50, 451
Rogstad, D. G., Crutcher, R. M., & Chu, K. 1979, ApJ, 229, 509
Sandage, A. 1988, ApJ, 331, 605
Sandage, A., & Carlson, G. 1988, AJ, 96, 1599
Sandage, A., & Tammann, G. A. 1981, A Revised Shapley-Ames Catalog of Bright Galaxies (Washington, DC: Carnegie Institution)
———. 1984, Nature, 307, 326
Schechter, P. L. 1980, AJ, 85, 801
Seielstad, G. A., & Wright, M. C. H. 1973, ApJ, 184, 343
Shostak, G. S., & Rogstad, D. H. 1973, A&A, 24, 405
Staveley-Smith, L., & Davies, R. D. 1988, MNRAS, 231, 833
Tacconi, L. 1990, unpublished Westerbork observation
Tammann, G. A., & Sandage, A. 1968, ApJ, 151, 825
Tifft, W. G., & Cocke, W. J. 1988, ApJS, 67, 1
Tully, R. B. 1988a, Nature, 334, 209
———. 1988b, Nearby Galaxies Catalog (Cambridge: Cambridge Univ. Press)
Tully, R. B., & Fisher, J. R. 1977, A&A, 54, 661
Tully, R. B., & Fouqué, P. 1985, 58, 661
van den Bergh, S. 1988, PASP, 100, 344
———. 1989, A&A, Rev., 1, 111
van den Bergh, S., & Pierce, M. J. 1990, ApJ, 364, 444
Walker, A. R. 1988, PASP, 100, 949
Wevers, B. M. H. R., van der Kruit, P. C., & Allen, R. J. 1986, A&AS, 66, 505
Welch, D. L., McAlary, C. W., McLaren, R. A., & Madore, B. F. 1986, ApJ, 305, 583
Welch, D. L., McLaren, R. A., Madore, B. F., & McAlary, C. W. 1987, ApJ, 321, 162
Whiteoak, J. B., & Gardner, F. F. 1977, Australian J. Phys., 30, 187