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A DISTANCE SCALE FROM THE INFRARED MAGNITUDE/H I VELOCITY-WIDTH RELATION.
I. THE CALIBRATION

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ABSTRACT

Large-aperture H (1.6 μm) magnitudes are presented for 12 nearby galaxies and are used to determine the zero point and slope of the infrared magnitude/H I velocity-width relation. By assuming only the Sandage-Tammann distances to M31 and M33, we obtain the following distance moduli to the nearest groups:

Sculptor group:	$m - M = 27.46 \pm 0.2$ mag, $d = 3.1 \pm 0.3$ Mpc;
N2403–M81 group:	$m - M = 27.76 \pm 0.2$ mag, $d = 3.6 \pm 0.3$ Mpc;
M101 group:	$m - M = 29.16 \pm 0.35$ mag, $d = 6.8 \pm 1.1$ Mpc.

Our results are consistent with the relative distance scale constructed by Sandage and Tammann out to the M101 group. Alternatively, if we accept their relative scale on its own merits, the agreement implies that the infrared Tully-Fisher relation is well defined with small scatter over most of the range in observable velocity widths.

The data in this paper should *not* be interpreted as providing stronger support for the Sandage-Tammann absolute distance scale over the one proposed by de Vaucouleurs, because for the galaxies in question, the largest difference between the two scales remains one of zero point. If a zero point based on de Vaucouleurs's distances to M31 and M33 were adopted instead, all other galaxian moduli would decrease by 0.42 mag, or 18% in distance. The uncertainty in the zero point is probably of the order 0.2 mag, but this does not enter into the determination of relative distances in the IR/H I technique.

Subject headings: cosmology — galaxies: photometry — infrared: general — radio sources: 21 cm radiation

I. INTRODUCTION

This paper is the first in a series devoted to the measurement of the distance scale and expansion rate of the universe, using the infrared luminosity/H I velocity-width relation. In a previous paper (Aaronson, Huchra, and Mould 1979, hereafter AHM) we have shown that by using IR photometry at H (1.6 μm) the uncertainties in the technique pioneered by Tully and Fisher (1977) are greatly reduced.

The Hubble constant not only determines the cosmic distance scale via the redshift-distance relation, but also sets important constraints on both the age and eventual fate of the universe. Notwithstanding the enormous effort by astronomers in the last 50 years to measure this quantity, its value remains controversial today. This fact is best exemplified by two recently completed studies. The first is by Sandage and Tammann (1976, hereafter ST7), who find $H_0 = 50 \pm 4$ km s^{-1} Mpc^{-1}; and the second is by de Vaucouleurs (de Vaucouleurs and Bollinger 1979), who obtains $H_0 = 100 \pm 10$ km s^{-1} Mpc^{-1}.

The traditional method of determining extragalactic distances is built upon a sequence of so-called primary indicators (Cepheids, novae), secondary indicators (brightest stars, H II regions), and tertiary indicators

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(luminosity classes, galaxy diameters). The IR/H I technique is an important addition to this serial calibration, because on the one hand its validity can be checked by direct comparison with the distances to the nearest galaxies obtained from primary indicators, while on the other the method can be straightforwardly applied to objects with redshifts at least as high as 10,000 km s^{-1}. The propagation of systematic errors through the usual three-tiered structure, especially in regard to the problematical secondary indicators (Kennicutt 1979), can thus be contained. The IR Tully-Fisher method should, therefore, provide a strong and much-needed backbone to the distance scale.

The purpose of this first paper is to calibrate the relation between luminosity and velocity width. To do this, only two quantities are required: a slope and a zero point. In AHM it was demonstrated that a fourth-power velocity law ($L \propto V^4$) is the dynamical basis of the relation and thereby determines the slope. The true form of this law is recognized empirically in the IR, because at 1.6 μm the old population which dominates the dynamics of spiral galaxies is seen unadulterated by either dust absorption or stellar emission of the young population. So the *relative* distances between galaxies can be found accurately, because the slope of the relation is, as far as we know, universally determined by the fourth-power law. The uncertainty in *absolute* distances then largely reduces to that in the distances to M31, M33, and any additional galaxies which may be included to strengthen the zero point.

In this paper, we first present very large aperture IR measurements (§ II) and a rediscussion of the velocity widths (§ III) for 12 nearby galaxies. The reduction procedures used in this series are described in detail. Then, with a zero point defined by M31 and M33 alone, distances are derived to the Sculptor, N2403–M81, and M101 groups (§ IV) and compared with those given by ST7 and by de Vaucouleurs (1979, hereafter dV4). The results are summarized in § V.

Paper II in the series concerns the distance modulus and redshift of the Virgo cluster and the question of morphological type dependence in the IR/H I relation. In Paper III an estimate of the global value of the Hubble constant is derived from the distance moduli to four clusters in the redshift range 4000–6000 km s^{-1}, and the evidence for Local Group motion relative to Virgo is examined. In later papers we will investigate the noise and possible anisotropy in the Hubble flow as determined both from nearby field galaxies and a more distant field sample, and study the Hubble ratio for a more extensive list of clusters.

II. INFRARED MAGNITUDES

a) *Observations*

In AHM the biggest available aperture size was only ~100″, and so significant growth curve extrapolation was required (3.1 mag in the case of M31!) to obtain magnitudes at the necessary isophotal aperture size. Considerably larger aperture measurements at *H* have now been obtained and are listed in Table 1. Data for 12 nearby galaxies are presented, including M31, M33, two galaxies in the Sculptor group, five in the N2403–M81 group, and three in the M101 group. *These data supersede those given in AHM.*

The measurements were gathered at Kitt Peak over the period 1978 August to 1979 June using the KPNO No. 1 0.9 m (36 inch) and KPNO No. 3 0.4 m (16 inch) telescopes. The entire set of data was measured with the Harvard-Smithsonian InSb detector system; a focal-plane chopper and offset guider were always employed. Both 0.5 and 1 mm InSb detectors were used, the latter effectively doubling the accessible aperture size. The *H* filter had a central wavelength and bandwidth of 1.65 μm and 0.30 μm, respectively, and was always cooled to pumped nitrogen temperature.

On the night of 1978 September 8 multiaperture magnitudes were measured using for the objective a 0.085 m (3.3 inch) f/12 lens on loan from the Kitt Peak optical shop. After removing the secondary and its support structure from the No. 3 0.4 m, the lens (attached to the end of a hollow metal tube) was inserted into the baffle tube in front of the 0.4 m primary. Light was then focused on the focal-plane aperture of the InSb detector by simply sliding the lens along the baffle tube to the appropriate position. This arrangement led to a focal-plane scale of ~204″ mm^{-1} and a maximum aperture size of ~1550″. During the night, both M31 and M33 were visually centered and measured twice.

Unless noted otherwise in Table 1, the photometric uncertainty of the data is less than or equal to 0.03 mag. Most of the observations were repeated on more than 1 night, and some on as many as 4 nights. The limiting noise source in these big-aperture measurements was atmospheric OH emission, which often proved to be highly variable even on otherwise excellent photometric nights. This accounts for the large errors quoted in Table 1 for some of the fainter galaxies. The system of standard stars to which all the data are referred is discussed in Frogel *et al.* (1978); in this system *H* (α Lyr) = 0.0 mag.

After centering the brighter spirals in Table 1 visually, the signal was "peaked up" by scans through the galaxy. For the fainter objects measured on the No. 1 0.9 m, the telescope was computer offset from a nearby field star (typically 3–10′ away). Repeated trials with field stars demonstrated that the 0.9 m could be so offset to a precision of ~1″ over distances less than ~1°. Accurate (~1″) offsets were determined using the KPNO Grant measuring engine and Palomar Observatory Sky Survey (POSS) plates. Two of the objects in Table 1 (N2366 and N4236) do not have well-defined nuclei; the measuring positions selected are given in Table 2 and correspond roughly to the center of the overall luminosity distribution.

b) *Data Reduction*

The data in Table 1 have been corrected for the effect of nonrectangular beam profiles as described in

TABLE 1

INFRARED MAGNITUDES OF NEARBY GALAXIES

Name	Type log D_1 [b]	H(mag) [a]	Aperture (")	log A/D_1	Telescope
N598	SA(s)cd	6.61	212.8	-1.20	KP 16
	2.75	6.06	316.5	-1.03	KP 16
		5.62	409.6	-0.92	KP 16
		4.71	798	-0.63	KP 3
		4.25	1207	-0.45	KP 3
N224	SA(s)b	4.10	101.1	-1.94	KP 16
	3.17	3.44	154.3	-1.76	KP 16
		3.06	212.8	-1.62	KP 16
		2.63	316.5	-1.45	KP 16
		2.56	368	-1.38	KP 3
		2.38	409.6	-1.34	KP 16
		1.89	798	-1.05	KP 3
		1.60	1207	-0.87	KP 3
		1.42	1554	-0.76	KP 3
Sculptor Group:					
N247	SAB(s)d	8.17 ±0.05	212.8	-0.65	KP 16
	2.20	7.63 ±0.06	316.5	-0.48	KP 16
		7.32 ±0.10	409.6	-0.37	KP 16
N253	SAB(s)c	5.11	212.8	-0.72	KP 16
	2.27	4.75	316.5	-0.55	KP 16
		4.56	409.6	-0.44	KP 16
N2403-M81 Group:					
N2366	IB(s)m	11.60 ±0.10	81.2	-0.68	KP 36
	1.81	11.35 ±0.05	102.2	-0.58	KP 36
		10.96 ±0.08	110.6	-0.54	KP 36
		10.44 ±0.08	165.2	-0.37	KP 36
N2403[c]	SAB(s)cd	6.92	212.8	-0.66	KP 16
	2.21	6.92	216.0	-0.65	KP 16
		6.43 ± .05	316.5	-0.49	KP 16
		6.41	318.6	-0.48	KP 16
		6.31	409.6	-0.38	KP 16
		6.25 ± .05	413.1	-0.37	KP 16
IC2574	SAB(s)m	11.63 ±0.06	81.2	-0.89	KP 36
	2.02	11.36 ±0.08	102.2	-0.79	KP 36
		10.95 ±0.05	110.6	-0.75	KP 36
		10.35 ±0.06	165.2	-0.58	KP 36
N3031	SA(s)ab	4.86	212.8	-0.81	KP 16
	2.36	4.88	216.0	-0.80	KP 16
		4.61	312.8	-0.64	KP 16
		4.62	318.6	-0.63	KP 16
		4.42	409.6	-0.53	KP 16
		4.43	413.1	-0.52	KP 16
N4236	SB(s)dm	11.07 ±0.05	81.2	-1.04	KP 36
	2.17	10.74 ±0.05	102.2	-0.94	KP 36
		10.24 ±0.06	110.6	-0.90	KP 36
		9.68	165.2	-0.73	KP 36
		9.10[d]±0.05	318.6	-0.44	KP 16
M101 Group:					
N5204	SA(s)m	10.90 ± .04	51.8	-0.69	KP 36
	1.63	10.25	81.2	-0.50	KP 36
		10.33	82.6	-0.49	KP 36
		10.09	102.2	-0.40	KP 36
N5585	SAB(s)d	10.85	51.8	-0.76	KP 36
	1.70	10.31	81.2	-0.57	KP 36
		10.30	82.6	-0.56	KP 36
		10.09	102.2	-0.47	KP 36
Ho IV	SB(s)m	12.62 ±0.07	51.8	-0.55	KP 36
	1.49	12.15 ±0.07	81.2	-0.36	KP 36

[a] Unless noted otherwise, a nominal error of ±0.03 mag is adopted.

[b] D_1 is in units of 0.1 minutes.

[c] All apertures corrected for presence of two bright field stars having total flux at H = 10.04 mag.

[d] Flux given is probable lower limit due to contamination of reference beam by field stars of unknown magnitude.

TABLE 2

CENTERING POSITIONS FOR TWO DIFFUSE GALAXIES

Galaxy	1950 R.A.	1950 δ
N2366	$07^h23^m38.0^s$	$+69°19'15''$
N4236	12 14 23.8	+69 43 52

Frogel *et al.* (1978). In most cases this correction was less than ~ 0.02 mag, and in the largest instance it was 0.04 mag. The data have also been corrected for extended galaxian flux in the reference beam. For a spherically symmetric galaxy having an approximately linear growth curve, the size of this correction can be parametrized well by the ratio of beam throw to beam diameter. This is illustrated in Figure 1, where the correction is shown for both the type E and type Sb galaxies. The growth curves used to construct Figure 1 were taken from de Vaucouleurs (1977) and are based on B magnitudes. In practice, the corrections for type Sb have been adopted uniformly for all spirals. Both because of the similarity among *infrared* spiral growth curves (AHM) and the smallness of the correction term (see below), no significant error will be introduced by this procedure.

The chopping throw on the 0.9 m ranged between 6 mm and 12 mm in the focal plane, and the photometer was rotated in a direction so as to minimize the contribution either from spatial extent of the galaxy or from foreground stars. On the 0.4 m the chopping throw of 12 mm was fixed in the north-south direction. An appropriate adjustment to the flux correction was made depending on the galaxy inclination and alignment of the position angle relative to the chopping throw. The only corrections applied larger than 0.03 mag were to the 0.4 m measurements of M31 (up to 0.07 mag[4]) and of M33 (up to 0.19 mag). No correction larger than 0.01 mag was required for the 0.085 m measurements.

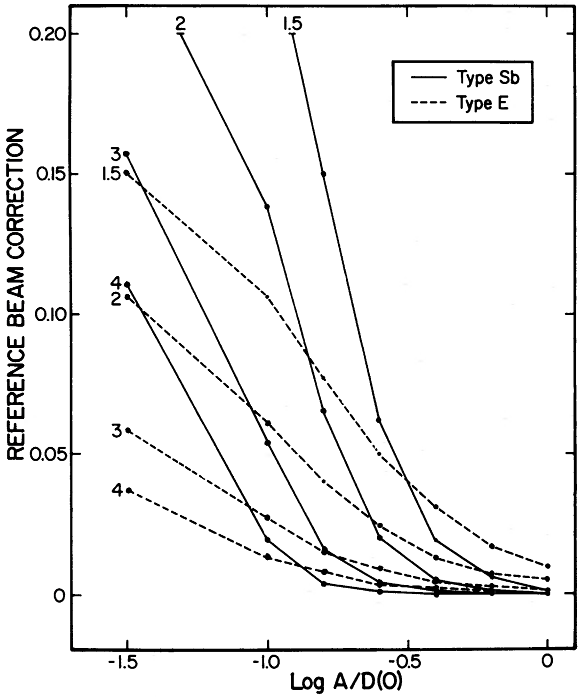

FIG. 1.—The correction for extended galaxian flux (in mag) is plotted against log $A/D(0)$ for 2 morphological types. The curves are parametrized by the ratio of beam throw to beam diameter.

c) Determination of Isophotal Diameters

To correct the H magnitudes to the same isophotal aperture, we adopt the system of de Vaucouleurs, de Vaucouleurs, and Corwin (1976) in the *Second Reference Catalogue of Bright Galaxies* (hereafter RC2). The diameters in this system correspond to an isophote of 25th mag at B, and are based upon a weighting scheme combining eye estimates made using the POSS (primarily from Nilson 1973) and photographic surface photometry. At present, it appears that the RC2 system is our only practical choice; the validity of using both the RC2 and Nilson (1973) diameters is further investigated in Paper III, where both systems are shown to be free of significant systematic errors.

We follow the RC2 procedure for reducing measured diameters to a face-on value, according to $\log D(0) = \log D - 0.235 \log R$, except that a maximum correction of 0.15 dex is adopted. This cutoff is required because for galaxies of sufficient inclination (e.g., $i \gtrsim 82°$), the correction should no longer depend on the axial ratio R. In fact, it can be readily demonstrated that the largest correction allowable for an edge-on exponential disk is 0.15 dex. Our procedure for further correcting the diameter for galactic extinction also differs slightly. In the RC2, the appropriate correction is given by

$$\log D_0 = \log D(0) + A_B G_{25}{}^{-1}\,, \qquad (1)$$

where A_B is the galactic extinction at B in magnitudes, and $G_{25}{}^{-1}$ is the inverse logarithmic gradient of the luminosity profile and is dependent on morphological type. We adopt the RC2 formula for $G_{25}{}^{-1}$, but for A_B we take a cosecant law,

$$A_B = 0.133[\csc(b) - 1]\,, \qquad (2)$$

rather than the somewhat complicated and uncertain equation given in the RC2. The final reduced diameter is referred to as D_1 and is given in Table 1. Note that the diameter extinction term is quite small, being ~ 0 dex at $b = 50°$ and only 0.03–0.04 dex at $b = 15°$.

In the present series of papers the H magnitudes are corrected to an isophotal aperture of $\log A/D_1 = -0.5$ (referred to as $H_{-0.5}$). This choice of aperture size is based on practical considerations; however, we briefly

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[4] As the chopped beam was actually along the bulge rather than the disk of M31, the correction was determined from the type E curve for a galaxy with a log D value of 0.5 less than that of M31 itself.

consider two hypothetical alternatives. First, since the velocity width measures $2V_{\max}$ and is thus determined by the mass interior to some radius $r_{\max}$, we might adopt an aperture size corresponding to $r_{\max}$. For example, if $r_{\max}/D$ was a well-behaved function of morphological type, one could apply a straightforward correction to convert an isophotal magnitude to a "kinematical" magnitude. Unfortunately, because many rotation curves are flat over a large distance, the determination of $r_{\max}$ becomes very ambiguous. Kormendy and Norman (1979) have attempted to define a more consistent radius than $r_{\max}$, which they term r_{rigid}. This quantity measures the point of maximum curvature on the rotation curve where solid-body rotation stops and the curve flattens out; the velocity here is usually near and often equal to $V_{\max}$. In Figure 2 we have plotted the ratio of $r_{\text{rigid}}/r_{D(0)}$ as a function of type using the Kormendy and Norman sample. The expected trend with type is apparent (e.g., Brosche 1973; Huchtmeier 1975), but we consider the scatter much too large to attempt a conversion from isophotal to kinematical magnitude.

A second possibility might be to adopt a larger reference isophote than $\log A/D = -0.5$. To begin with, we note that the outer parts of rotation curves are often sufficiently shallow to indicate that in many instances, the luminous matter eventually becomes decoupled from the mass (see Bosma 1978, p. 151), so that the choice of a reference isophote larger than $\sim \log A/D = 0$ is probably not desirable. Now it was shown in AHM that the shapes of IR growth curves were less dependent on morphological type than in the optical, which will tend to minimize systematic effects introduced by the difference between $H_{-0.5}$ and, say, $H_{0.0}$. A more significant point is seen in Figure 2, where the typical value of $r_{\text{rigid}}/r_{D(0)}$ corresponds to $\sim \frac{1}{3} r_{D(0)}$, or $\log A/D(0) = -0.5$. Since any scatter and/or systematic error in the IR/H I relation might be expected to depend partially on how r_{rigid}/D varies with type, an aperture chosen at $\log A/D = -0.5$ seems as valid as and possibly preferable to one selected at $\log A/D = 0$. One additional interesting fact is that $\frac{1}{3} r_{D(0)}$ is roughly equal to the exponential disk scale length α^{-1} (see Freeman 1970)!

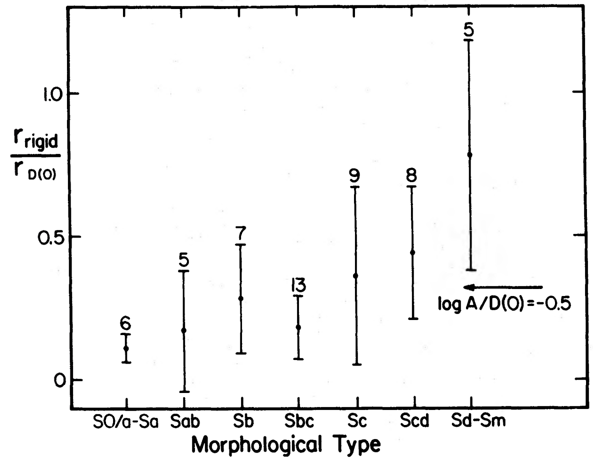

FIG. 2.—The rotation curve parameter r_{rigid} divided by isophotal radius from the RC2 is shown plotted against morphological type. One sigma error bars and the number of galaxies in each bin are also given. The arrow indicates the isophotal aperture to which IR magnitudes in this series of papers are corrected.

In the second column of Table 3, the final values of $H_{-0.5}$ are listed for the 12 galaxies in Table 1. Results for the six objects also found in AHM are all within 0.25 mag of those from that work, and the conclusions of AHM remain unchanged. Three cases in Table 3 are worth special note:

M31.—This is the only galaxy for which significant growth curve extrapolation is still required. Extrapolating a curve based solely on M31 leads to $H_{-0.5} = 0.99$ mag; using a mean Sb growth curve (AHM) leads to 0.89 mag. A value of 0.94 mag is adopted.

N253.—The nucleus of this Sc spiral contains a well-known IR source whose 10 μm emission is $\gtrsim 10$ times that typical for a spiral galaxy (Rieke and Lebofsky 1978). The presence of the nuclear source is also apparent in the near-IR, both from a comparison with the mean H growth curve for Sc galaxies, and from the *JHK* colors. The latter measured with a 410″ beam yield $J - H = 0.80$ mag and $H - K = 0.30$ mag, in contrast to mean Sc colors of $J - H = 0.73$ mag and $H - K = 0.21$ mag (Aaronson 1977). By comparison with the mean Sc growth curve, an adjustment of 0.08 mag was made to the derived value of $H_{-0.5}$ in order to remove the excess emission of the nuclear source.

N4236.—The largest aperture observation is affected to an unknown extent by a number of stars in the (northern) reference beam. This measurement leads to a value of $H_{-0.5} = 9.33$ mag, while extrapolation of the two smaller aperture measurements gives 8.96 mag. A value of 9.09 mag is adopted.

The third column of Table 3 lists values of $H_{-0.5}$ corrected for galactic extinction according to a simple cosecant law and van de Hulst reddening curve No. 15 (Johnson 1966), so that

$$A_H = 0.015[\csc(b) - 1] . \qquad (3)$$

The small size of the extinction at H does not warrant adoption of a more complex reddening dependence.

The amount of internal absorption due to reddening is both poorly determined and controversial (see AHM). Blue magnitude corrections between 0.1 and 1 mag were used by Tully and Fisher (1977), depending on inclination, but it is probable that the true absorption varies widely from galaxy to galaxy even at the same inclination. An important advantage of IR magnitudes is that the effect of absorption is less by a factor of 10; hence, we feel justified at present in making no correction. Similarly, since the redshift term at H is only $K_H \approx 0.35z$ (Frogel *et al.* 1978), correction for this effect will be ignored. Finally, no correction is made here for aperture error due to $(1 + z)^4$ dependence of galaxy surface brightness on

TABLE 3

DATA FOR NEARBY GALAXIES

Name	$H_{-0.5}$ (mag)	$H_{-0.5}{}^{c}$ (mag)	ΔV_{20}[a] (km s^{-1})	ΔV_{50} (km s^{-1})	r_{20}/r_{50}	i[b] (°)	$\Delta V_{20}(0)$ (km s^{-1})
N224	0.94	0.91	540	519	1.04	78	552
N598	4.39	4.38	205	185	1.11	54	253
Sculptor group:							
N247	7.69	7.69	222	193	1.15	75	230
N253	4.74	4.74	430	407	1.06	79	438
N2403–M81 group:							
N2366	10.84	10.82	114	96	1.19	67	124
N2403	6.47	6.45	265	239	1.11	60	306
IC 2574	10.08	10.07	116	89	1.30	67	126
N3031	4.39	4.38	450[c]	408	1.10	58	531
N4236	9.09	9.08	190	173	1.10	75	197
M101 group							
N5204	10.30	10.30	127	114	1.11	55	155
N5585	10.15	10.15	166	151	1.10	52	211
Ho IV	12.49	12.49	103	69[d]	1.50	76	106

[a] Most profile-width sources are given by Tully and Fisher (1977) and Sandage and Tammann (1976). Additional sources used here are as follows: N598, Reakes and Newton (1978); N247, Dean and Davies (1975), Whiteoak and Gardner (1977), and Tully and Fisher (1979); and N253, Huchtmeier (1972), and Whiteoak and Gardner (1977).

[b] The inclination sources are: N224, radio fit of Gottesman and Davies (1970); N598, radio fit of Warner, Wright, and Baldwin (1973); N2403 and N4236, radio fits of Shostak (1973); N3031, radio fit of Gottesman and Weliachew (1975); N247 and N253, Danver (1942); and N2366, IC 2574, N5204, N5585, and Ho IV, eq. (4), this paper.

[c] Sandage and Tammann (1976) quote a lower value of 439 km s^{-1}, based on both the profiles of Gottesman and Weliachew (1975) and of Rots (1974). However, when adjustment is made for continuum level as noted by Rots (1974), the latter profile width gives 450 km s^{-1}, in agreement with the former.

[d] A hump is present on the high-quality profile of Allen *et al.* (1978) just at the 50% level. Above the hump, $r_{20}/r_{50} \approx 1.64$; below the hump, $r_{20}/r_{50} \approx 1.40$. A value of 1.50 is adopted.

redshift, although the effect will be accounted for in later papers concerning much higher redshift objects. Based on the above discussion, we consider a nominal error of ±0.10 mag appropriate for the quantity $H_{-0.5}{}^{c}$.

III. VELOCITY WIDTHS

At least two published velocity widths are available for all of the galaxies in Table 1, and the agreement among observers is generally within 15 km s^{-1}. Most of the sources are listed both in Tully and Fisher (1977) and/or ST7 and will not be repeated here. Additional sources are given at the bottom of Table 3.

Unfortunately no consistent definition of velocity width has been adopted in the literature. However, virtually all profile widths have one of two characteristic shapes: (1) a rectangular structure with two horns at the edges, typical of high-luminosity galaxies; or (2) a Gaussian-like structure with a single central peak, typical of both lower luminosity and face-on galaxies. The best fractional height of the peak to choose for measuring the width is not obvious. The often used level of 20% is presumably more indicative of $V_{\max}$; but the 20% level is difficult to determine when the signal-to-noise ratio is poor and is sensitive to changes in turbulent broadening, as shown by the synthetic models of Roberts (1978). A level of 50% is almost unaffected by turbulent broadening (Roberts 1978) and is easier to determine with a low signal-to-noise ratio, but may not be as physically meaningful as the 20% level for Gaussian-like profiles having shallow sloping sides.

In the present set of papers we adopt the following working definition of velocity width:

i) For rectangular profiles with two horns, the mean height of the horns is taken as the peak of the profile, and the width at 20% (50%) of this height is measured. The effects of noise, telescope pointing errors, and frequency resolution on the amplitude of the horns is thereby lessened.

ii) For Gaussian profiles with a single peak, the width at 20% (50%) of this peak is employed.

All of the published profiles for the galaxies in Table 1 have been examined to check for consistency with the above defintion; our adopted values for the widths at the 20% level, ΔV_{20}, are listed in Table 3. Although the 20% width will be used for the remainder of this paper, also listed in Table 3 for future reference are the widths at the 50% level, ΔV_{50}, and the ratio $r_{20/50} = \Delta V_{20}/\Delta V_{50}$. No correction to the velocity widths has been made for turbulent broadening or instrumental frequency resolution, as these effects are typically less than ~2 km s^{-1}. Similarly, no correction for relativistic Doppler effect on the velocity widths has been applied, although such a correction will be used in subsequent papers for objects at much larger redshift.

The velocity widths must be corrected for inclination to an edge-on value, according to $\Delta V(0)$

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$= \Delta V/\sin i$. In the present series of papers, the following priority scheme for determining inclinations is adopted:

i) First-priority inclinations are those determined from multiparametered fits to detailed high-resolution radio synthesis maps.

ii) Second priority is given to inclinations from the study of Danver (1942), which were determined by rectification of the spiral arm structure.

iii) Third priority is given to inclinations calculated from the axial ratio b/a, according to

$$i = (\cos^{-1} \sqrt{[1.042b^2/a^2 - 0.042]}) + 3° . \quad (4)$$

Equation 4 is the Hubble (1926) formula $\cos^2 i = (q^2 - q_0{}^2)/(1 - q_0{}^2)$, with $q = b/a$ and $q_0 = 0.2$, plus a small correction term explained below. Inclinations calculated from equation (4) are adjusted, where appropriate, according to the opening of the spiral arm structure. Axial ratios are taken from the RC2, or if necessary transformed to that system.

Our reasons for considering radio fitting to be the best measure of sin i are twofold. First, the method is the only one which actually measures the inclination of the rotating gas. Second, the method is based on quantitative analysis of kinematic structure. Basically, the procedure is to force consistency of rotation curves measured at different position angles by iterating the inclination angle and several other kinematic parameters. Such fits generally produce a well-determined value for sin i over most of the visible disk (e.g., Bosma 1978). While the presence of warping can introduce ambiguity into the process on the order of $\sim 5°$, such warps appear to occur well beyond r_{rigid}, and in all but one case illustrated by Bosma (1978), also beyond $r_{\max}$.

A comparison of inclinations calculated with axial ratios from the RC2 with inclinations determined from radio fits indicates the existence of a small but significant systematic difference, in the sense that axial ratios predict an inclination too face-on, as shown by Figure 3. A similar effect has been discussed by Tully and Fisher (1977) and seems best explained by opening of the spiral arms along the minor axis. The same result appears when Danver's (1942) inclinations are compared with those from axial ratios, although with considerably more scatter. A comparison of 117 spirals galaxies having $i(\text{Danver}) \geq 45°$ yields $i(\text{Danver}) - i(\text{Axial}) = 2° \pm 6°$. The effect does not appear to be a result of possible morphological type dependence of the parameter q_0, since, if the prescription suggested by Heidmann, Heidmann, and de Vaucouleurs (1972) is followed (e.g., $q_0 \approx 0.1$ for Sb–Sd spirals), the size of the discrepancy is increased even further. To account for the effect, we employ a correction of $+3°$ to inclinations calculated from RC2 axial ratios (see eq. [4]).

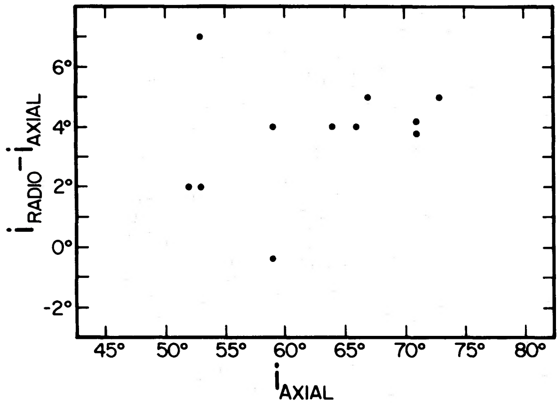

FIG. 3.—The difference between inclination determined from radio synthesis fits (i_{radio}) and from axial ratios (i_{axial}) is plotted against i_{axial}. Some sources for i_{radio} are given in Table 3; additional sources are Bosma (1978) and van Albada and Shane (1975).

Our adopted inclinations and corrected velocity widths are given in the final two columns of Table 3.

IV. DISTANCES TO NEARBY GROUPS

a) The Selection Criteria

Three selection criteria are followed in this series. The first one is required in order to minimize errors in the velocity widths:

i) Only galaxies with inclinations greater than 45° are accepted.

In AHM it was shown that the basis of a $L \propto V^4$ power law could be derived from the virial theorem plus three assumptions: (1) the constancy of mass profiles and rotation curves as a function of some dimensionless scale length, (2) the constancy of central mass surface density, and (3) the constancy of mass-to-light ratio M/L. In the spirit of these assumptions, two additional criteria are adopted:

ii) Galaxies without a well-defined nucleus and clear disk structure and/or possessing other obvious morphological peculiarities are excluded or given low weight.

iii) Galaxies having point-source H I emission, such as some of the S0 galaxies detected by Krumm and Salpeter (1979), are not accepted.

Recognition of point-source objects, which as far as is known occur only in early-type galaxies, does not necessarily require spatial radio mapping. Those detected by Krumm and Salpeter (1979) have a clear signature in that $\Delta V < 100 \text{ km s}^{-1}$, more than 300 km s^{-1} different from what would be expected if the H I were truly extended.

The assumptions discussed above imply that (S0 galaxies aside) increased scatter in the IR/H I relation is most likely to be found among low–surface-brightness dwarf galaxies, for it is precisely such objects which often lack a nucleus and well-defined disk structure. Some evidence for this will in fact be seen in what follows. An equivalent selection rule perhaps encompassing our second (and also third) criterion might thus be to adopt a velocity-width cutoff; the results below suggest that a cutoff of $\sim 200 \text{ km s}^{-1}$ (after correction for inclination effect) may be appropriate. However, we do not feel at present that such a stringent criterion is warranted.

b) The Slope of the Relation

Stated simply, the constants *a* and *b* must be found in the equation:

$$H_{-0.5}{}^{\mathrm{abs}} = a + b[\log \Delta V_{20}(0) - 2.5]\,. \qquad (5)$$

Theoretically we expect $b = -10$. AHM suggested that this slope was seen in the IR but not in the blue, because M/L_B varies markedly in spirals of differing mass, but M/L_H is more nearly constant. This suggestion appears to be confirmed by Faber and Gallagher (1979). Using a large sample of field galaxy rotation curves, these authors find a significant correlation of M/L_B with morphological type (and consequently mass), but almost no correlation between M/L_K and type. Since $H - K$ is virtually independent of type (Aaronson 1977), this result is equally valid for M/L_H.

In Table 4 we have summarized all currently available empirical IR determinations of the slope *b*. Several effects might cause deviation from the predicted value of 10. On the one hand, a small but finite dependence of M/L_H with mass due to the young population in dwarf galaxies would lead to a smaller slope. In addition, because the cluster samples are magnitude limited, a bias is present which acts to produce a shallower slope. Numerical experiments have been performed which suggest that this bias introduces an error of only ~2%. On the other hand, the result of using $H_{-0.5}$ instead of $H_{0.0}$ is to steepen the slope, owing to the form of growth curve dependence on morphological type.

In the present series of papers we adopt a slope $b = -10$. Given the various considerations, we believe this to be the most reasonable approach. The results in Table 4 suggest an uncertainty in this value of ~ ±0.5. Of course, whether this range reflects a *real* variation of slope with environment is presently unclear. We do note that the slope determined from our "loosest" cluster, the N2403–M81 group, agrees very well with that obtained from Virgo, the richest cluster in the sample. A further point is that small variations in slope *b* have little effect on the final results (e.g., eq. [5]). For example, the total range in zero point (using ST7 distances) corresponding to a variation of *b* from 9 to 11 is only 0.15 mag. Similarly, if group or cluster velocity widths are distributed evenly about a $\log \Delta V_{20}(0)$ value of 2.5, systematic errors due to possible slope variation will largely cancel.

TABLE 4

SLOPE OF THE INFRARED/H I RELATION

Sample	N	$-b$	σ_b
Ursa Major (AHM)	16	9.4	±0.6
N2403–M81 (this paper)	5	10.0	±0.8
Virgo (Paper II)	18	10.2	±0.7
Mean of distant clusters (Paper III)	...	11.0	±1.0

c) Comparison of Distance Moduli

Distances to the nearest groups from the IR/H I technique can be derived by using only one Local Group galaxy to calibrate the zero point, *a*. To minimize the uncertainty, we employ two Local Group members for this purpose, M31 and M33. The results are given in Table 5, using distances both from ST7 and de Vaucouleurs (1978*b*). G. de Vaucouleurs (1978*a*) has summarized recent determinations of the Hyades modulus and concludes that the best available value is 3.29 mag. We concur with this result and have increased the ST7 distance moduli by 0.26 mag accordingly. It is unfortunate that the mean Sandage-Tammann and de Vaucouleurs zero points in Table 5 differ by 0.42 mag, or 18% in distance. We cannot independently choose between the alternatives because in both cases the relative moduli of M31 and M33 are consistent within the intrinsic dispersion in the relation of ~0.35 mag (AHM and Paper II).

The calibration of primary distance indicators adopted by Sandage and Tammann and by de Vaucouleurs differs in at least two major ways. First, Sandage and Tammann rely solely upon Cepheids, whereas de Vaucouleurs additionally introduces novae and RR Lyrae stars. Second, Sandage and Tammann assume a simple cosecant reddening law (based on stellar and galactic colors and magnitudes) with an absorption-free polar cap; while de Vaucouleurs uses a longitude-dependent law (based on galaxy counts) with an absorption of some 0.2 mag in *B* at the poles. Further comparison is outside the scope of this paper, but we opt for the Sandage-Tammann distances as our fiducial zero point because of the impressive consensus

TABLE 5

CALIBRATION OF THE ZERO POINT (in mag)

Name	Distance Modulus[a]	$H_{-0.5}{}^{\mathrm{abs}}$	a_{ST7}	$dV2$[b] Distance Modulus	$H_{-0.5}{}^{\mathrm{abs}}$	a_{dV2}
N224	24.38	−23.47	−21.05	24.07	−23.16	−20.74
N598	24.82	−20.44	−21.40	24.30	−19.92	−20.88
Mean	...	...	−21.23	...	...	−20.81
	...	...	±0.18	...	...	±0.07

[a] Distance from Sandage and Tammann (1976, ST7), increased by 0.26 mag for adopted Hyades modulus of 3.29 mag.

[b] Distance from de Vaucouleurs (1978*b*).

of polar cap reddening determinations (Sandage and Visvanathan 1978; see also Burstein and Heiles 1978). We retain the de Vaucouleurs zero point for reference; in our judgment the uncertainty in the adopted zero point is ±0.2 mag. As discussed previously, this does not enter into determination of relative distance moduli. Finally, we note that the mean difference in distance modulus determined from the primary indicators of the two scales is 0.57 mag (based on a total of six Local Group galaxies from Sandage and Tammann 1974*a*, ST7, and de Vaucouleurs 1978*b*), or 23% in distance. The value of 0.31 mag quoted by de Vaucouleurs (1978*b*) does not account for adjustment of the Sandage-Tammann distances by 0.26 mag to a Hyades modulus of 3.29 mag, a point *not* in contention by the latter authors (see ST7).

The distances to the remaining galaxies in Table 3 can now be derived. With the Sandage-Tammann zero point, we have

$$H_{-0.5}{}^{\text{abs}} = -21.23 - 10.0[\log \Delta V_{20}(0) - 2.5]\,. \tag{6}$$

The results are presented in Table 6. Both unweighted and weighted solutions are offered for the distance moduli to the N2403–M81 and M101 groups. The latter were determined simply by adopting a weight of 0.5 for objects with $\Delta V_{20}(0) < 200$ km s^{-1}. For reasons discussed both in § IV*a* and below, we believe the weighted solutions, though not significantly different, are to be preferred. In addition, an error of ±0.2 mag is probably more appropriate for the N2403–M81 and especially Sculptor distance moduli, rather than the smaller formal errors listed in the Table.

Also given in Table 6 for comparison are distance moduli determined by Sandage and Tammann (ST7) and by de Vaucouleurs (dV4). The latter have been increased by 0.57 mag following the above discussion. The results for each group will be briefly examined in turn.

The Sculptor Group.—The galaxies in this group are sufficiently close for observations of primary distance indicators, and such work is currently in progress, although not yet published. G. de Vaucouleurs (dV4) has suggested that the Sculptor group is the nearest beyond the Local Group, a proposition in agreement with the present results. Our distance modulus to Sculptor, $m - M = 27.46 \pm 0.2$ mag, agrees well with de Vaucouleurs's redetermined zero point ("re-zeroed") value of $m - M = 27.57 \pm 0.3$ mag. For further comparison, Lewis and Robinson (1973) derive a modulus of 27.65 ± 0.3 mag (adjusted to a Hyades modulus of 3.29 mag) based on the mean of a number of secondary indicators. Sandage and Tammann (1975) give a value of 27.97 ± 0.3 mag derived from their luminosity class and H II region calibration. However, this is in part based on N45, a probable background member. Also, Sandage (1979) has indicated he now considers N247 and N300 (another Sculptor member) to be closer than the N2403–M81 group.

The comparable distance obtained for N253 (even without the 0.08 mag correction discussed in § II*c*) is

TABLE 6

COMPARISON OF DISTANCE SCALES

Galaxy	$m - M^{a}$ (mag)	Weight	$m - M^{b}$ (mag)	Method[c]	$m - M^{d}$ (mag)	Method[c]
Sculptor group						
N247	27.53	1	...	...	...	...
N253	27.39	1	...	...	...	...
Mean	27.46 ± 0.07	...	...	...	27.57 ± 0.3:	4, 5, 6, 7
M81 group						
N2366	27.98	$\frac{1}{2}$	...	...	27.71	2, 4
N2403	27.54	1	27.82	1	27.66	1, 2, 4
I2574	27.30	$\frac{1}{2}$	...	...	28.29:	4
N3031	27.86	1	...	...	...	...
N4236	28.25	$\frac{1}{2}$	...	...	28.22:	2, 4
Unweighted mean	27.79 ± 0.17	...	27.82 ± 0.2	1	27.67 ± 0.2 to N2366, 2403 pair	...
Weighted mean	27.76 ± 0.15	...	...	...	28.27 ± 0.3: to M81 Mean: 27.97	...
M101 group						
N5204	28.43	$\frac{1}{2}$	29.74	2, 3	...	...
N5585	29.62	1	29.71	2, 3, 4	...	...
Ho IV	28.98	$\frac{1}{2}$	29.64	2, 3	...	...
Unweighted mean	29.01 ± 0.34	...	29.56 ± 0.3	...	29.07 ± 0.3:	2, 4
Weighted mean	29.16 ± 0.35	...	...	...	...	...

[a] From this paper.

[b] Distances from Sandage and Tammann (1976, ST7), increased by 0.26 mag for adopted Hyades modulus of 3.29 mag.

[c] The distance methods used are: (1) Cepheids, (2) H II regions, (3) luminosity class, (4) brightest stars, (5) star counts, (6) brightest 4 galaxies, and (7) largest 4 galaxies.

[d] Distances from de Vaucouleurs (1979, dV4), "re-zeroed" by 0.57 mag (see text).

noteworthy in view of the anomalous nuclear IR source and suggests that the IR/H I technique is relatively insensitive to similar sources which may also be present in some more distant galaxies.

The N2403–M81 Group.—The Sandage and Tammann distance to this group, $m - M = 27.82 \pm 0.2$ mag, is based entirely upon Cepheids measured in N2403. Our own measurement to N2403, $m - M = 27.54$ mag, and to the group as a whole, $m - M = 27.76 \pm 0.2$ mag, agrees satisfactorily with the ST7 distance, which in turn agrees well with the mean "re-zeroed" de Vaucouleurs modulus of $m - M = 27.97 \pm 0.3$ mag. Sandage and Tammann (1974*a*) have argued that the members of the group are all at the same distance. As the separation of N4236 from N2366 is some 28°, a spatial extent of ~1.8 Mpc is implied, a somewhat large but not totally unreasonable value. G. de Vaucouleurs (dV4) has proposed that the group in reality breaks up into two subgroups—a near one composed of N2366 and N2403 at $m - M = 27.67$ mag ("re-zeroed"), and a far one composed of the remaining galaxies at $m - M = 28.27$ mag ("re-zeroed"). The results in Table 6 do not provide much support for this conjecture, although our distance to N2403 is 0.32 mag closer than to that of M81 itself. While there is some suggestion of increased scatter among the low-luminosity dwarfs, clearly, such scatter might be entirely due to depth effects. On the other hand, neither N2366 or N4236 have well-defined nuclei, and in fact by far the most luminous optical point in N2366 is the bright H II region Mk 71 which lies on the edge of the galaxy. (An IR aperture was centered on this point, but considerably less flux was detected than with a comparable aperture centered on the nuclear region.) Thus, one or both of these objects might properly be rejected by the second selection criterion discussed in § IV*a*. We prefer instead to adopt the weighting scheme shown in Table 6.

The M101 Group.—Our mean distance to this group of $m - M = 29.16 \pm 0.35$ mag is intermediate between the Sandage and Tammann value of 29.56 ± 0.3 mag and the de Vaucouleurs "re-zeroed" value of 29.07 ± 0.3 mag. However, our distance is not very well determined because of the large scatter of the data. Also, since all three objects lie near the low end of the range in $\log \Delta V_{20}(0)$, our distance is more sensitive than usual to the adopted slope b (§ IV*b*).

The earlier voiced suspicion that larger dispersion is more likely at the low-luminosity end of the IR/H I relation may be reflected here. Depth effects alone do not appear to account for the full scatter: If the group is constructed as given by Sandage and Tammann (1974*b*), then the most outlying member from M101 itself is N5204, which lies 6°2 away. The implied spatial separation is then ~1 Mpc, or only 0.35 mag in modulus. Curiously, the M101 dwarfs exhibit a wide range in the ratio of hydrogen mass to total mass, from 0.04 to 0.25 (Sandage and Tammann 1974*b*), but how this might affect the IR/H I technique is not immediately clear.

V. SUMMARY

In Table 7 we compare three determinations of the zero point of the IR/H I relation. The first is that obtained earlier for just M31 and M33. The second is an unweighted mean obtained from all 12 galaxies by adopting the Sandage-Tammann distances to the N2403–M81 and M101 groups, and de Vaucouleurs's ("re-zeroed") distance to the Sculptor group, as given in Table 6. In doing so we are, of course, assuming that the consistency of the "re-zeroed" de Vaucouleurs mean distance to the N2403–M81 group also extends to the closer Sculptor group. The third zero point is a weighted mean from all 12 galaxies, following the same weighting scheme as in Table 6. We note that all three zero points agree well.

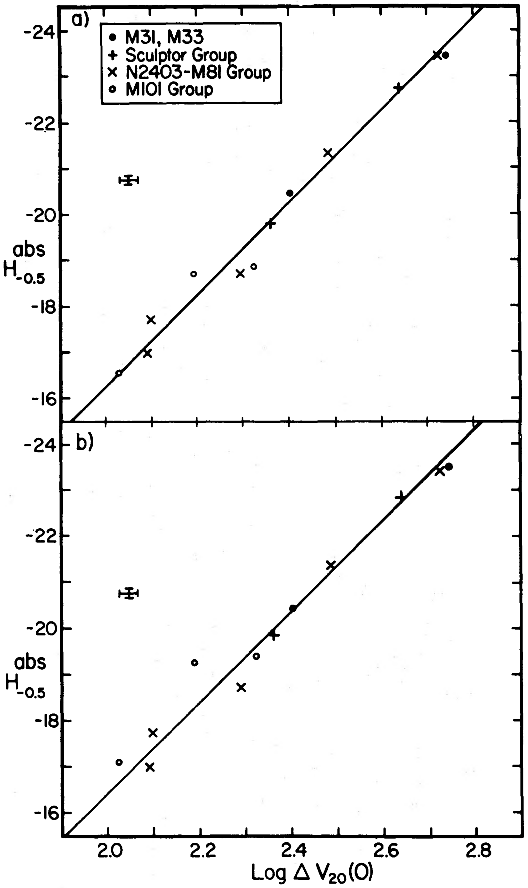

FIG. 4.—The absolute magnitude at H, referred to the $\log A/D_1 = -0.5$ isophote, is shown plotted against the logarithm of the velocity width for 12 nearby galaxies. (*a*) The zero point is determined by the Sandage-Tammann distance to M31 and M33 alone, and the remaining absolute H magnitudes were found by using our mean derived (unweighted) group distances from Table 6. The equation of the line is $H_{-0.5}{}^{\text{abs}} = -21.23 - 10.0\,[\log \Delta V_{20}(0) - 2.5]$. (*b*) The zero point is determined from the mean (unweighted) distances of all 12 galaxies, by using the Sandage-Tammann distances to the N2403–M81 and M101 groups and the ("re-zeroed") de Vaucouleurs distance to the Sculptor group. The equation of the line is $H_{-0.5}{}^{\text{abs}} = -21.40 - 10\,[\log \Delta V_{20}(0) - 2.5]$. Nominal errors of ±0.10 mag and ±0.02 dex are also shown, and the symbol key in (*b*) is the same as in (*a*).

TABLE 7

COMPARISON OF SANDAGE-TAMMANN ZERO POINTS

Galaxy	a (mag)	Weight
M31	−21.05	1
M33	−21.40	1
Sculptor group ($[m - M] = 27.57$ mag)[a]		
N247	−21.27	1
N253	−21.42	1
N2403–M81 group ($[m - M]_{\rm ST} = 27.82$ mag)		
N2366	−21.07	$\frac{1}{2}$
N2403	−21.51	1
I2574	−21.75	$\frac{1}{2}$
N3031	−21.19	1
N4326	−20.80	$\frac{1}{2}$
M101 group ($[m - M]_{\rm ST} = 29.56$ mag)		
N5204	−22.36	$\frac{1}{2}$
N5585	−21.17	1
Ho IV	−21.81	$\frac{1}{2}$
Mean M31+M33	−21.23 ± 0.18	...
Total sample:		
Unweighted	−21.40 ± 0.12	...
Weighted	−21.36 ± 0.10	...

[a] G. de Vaucouleurs (1979) distance "re-zeroed" by 0.57 mag (see text).

The relation between $H_{-0.5}^{\rm abs}$ and $\log \Delta V_{20}(0)$ is shown plotted in Figure 4 for the 12 galaxies in Table 3. In Figure 4*a* we have used our mean unweighted distances from Table 6 to calculate the $H_{-0.5}^{\rm abs}$ values; and in Figure 4*b* we have used de Vaucouleurs's ("re-zeroed") distance for Sculptor, and the Sandage-Tammann distances for the other galaxies, in order to calculate $H_{-0.5}^{\rm abs}$. We conclude from Tables 6 and 7 and Figure 4 that our results are consistent with the relative distance scale constructed by Sandage and Tammann out to the M101 group. If the relative Sandage-Tammann scale is accepted as correct, the agreement implies that the IR Tully-Fisher relation is well defined with small scatter over most of the range in observable velocity widths. The data in this paper should *not* be interpreted as providing stronger support for the Sandage-Tammann absolute distance scale over the one proposed by de Vaucouleurs, because, for the galaxies in question, the largest difference between the two scales remains one of zero point.

In Papers II and III we shall adopt equation (6) here as the final calibration, even though it is based on just M31 and M33 alone. If all 12 galaxies are used, any resulting distance increases by only 6% (Table 7). However, we believe that uncertainties in the distances to even the nearest groups do not warrant the latter approach.

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REFERENCES

Aaronson, M. 1977, Ph.D. thesis, Harvard University.
Aaronson, M., Huchra, J., and Mould, J. 1979, *Ap. J.*, **229**, 1 (AHM).
Allen, R. J., van der Hulst, J. M., Goss, N. M., and Huchtmeier, N. 1978, *Astr. Ap.*, **64**, 359.
Bosma, A. 1978, Ph.D. thesis, University of Groningen.
Brosche, P. 1973, *Astr. Ap.*, **23**, 259.
Burstein, D., and Heiles, C. 1978, *Ap. J.*, **225**, 40.
Danver, C. G. 1942, *Ann. Obs. Lund*, No. 10.
de Vaucouleurs, G. 1977, *Ap. J. Suppl.*, **33**, 211.
———. 1978*a*, *Ap. J.*, **223**, 351.
———. 1978*b*, *Ap. J.*, **223**, 730.
———. 1979, *Ap. J.*, **224**, 710 (dV4).
de Vaucouleurs, G., and Bollinger, G. 1979, *Ap. J.*, **233**, 433.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G. 1976, *Second Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press) (RC2).
Dean, J. F., and Davies, R. D. 1975, *M.N.R.A.S.*, **170**, 503.
Faber, S. M., and Gallagher, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 135.
Freeman, K. C. 1970, *Ap. J.*, **160**, 811.
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Gottesman, S. T., and Davies, R. D. 1970, *M.N.R.A.S.*, **149**, 763.
Gottesman, S. T., and Weliachew, L. 1975, *Ap. J.*, **195**, 23.
Heidmann, J., Heidmann, N., and de Vaucouleurs, G. 1972, *M.N.R.A.S.*, **75**, 85.
Hubble, E. 1926, *Ap. J.*, **64**, 321.
Huchtmeier, W. 1972, *Astr. Ap.*, **17**, 207.
———. 1975, *Astr. Ap.*, **45**, 259.
Johnson, H. L. 1966, in *Stars and Stellar Systems*, Vol. **7**, *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 167.
Kennicutt, R. C. 1979, *Ap. J.*, **228**, 696.
Kormendy, J., and Norman, C. A. 1979, *Ap. J.*, **233**, 539.
Krumm, N., and Salpeter, E. E. 1979, *Ap. J.*, **228**, 64.
Lewis, B. M., and Robinson, B. J. 1973, *Astr. Ap.*, **23**, 295.
Nilson, P. N. 1973, *Uppsala General Catalogue of Galaxies*, *Uppsala Astr. Obs. Ann.*, Vol. **6**.
Reakes, M. N., and Newton, K. 1978, *M.N.R.A.S.*, **185**, 277.
Rieke, G. H., and Lebofsky, M. J. 1978, *Ap. J.* (*Letters*), **220**, L38.
Roberts, M. S. 1978, *A.J.*, **83**, 1026.
Rots, A. H. 1974, Ph.D. thesis, University of Groningen.
Sandage, A. 1979, private communication.
Sandage, A., and Tammann, G. A. 1974*a*, *Ap. J.*, **191**, 603.
———. 1974*b*, *Ap. J.*, **194**, 223.
———. 1975, *Ap. J.*, **196**, 313.
———. 1976, *Ap. J.*, **210**, 7 (ST7).
Sandage, A., and Visvanathan, N. 1978, *Ap. J.*, **223**, 707.
Shostak, G. S. 1973, *Astr. Ap.*, **24**, 411.
Tully, R. B., and Fisher, J. R. 1977, *Astr. Ap.*, **54**, 661.
———. 1979, private communication.
van Albada, G. D., and Shane, W. W. 1975, *Astr. Ap.*, **42**, 433.
Warner, P. J., Wright, M. C. H., and Baldwin, J. E. 1973, *M.N.R.A.S.*, **163**, 163.
Whiteoak, J. B., and Gardner, F. F. 1977, *Australian J. Phys.*, **30**, 187.

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