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A DISTANCE SCALE FROM THE INFRARED MAGNITUDE/H I VELOCITY-WIDTH RELATION. IV. THE MORPHOLOGICAL TYPE DEPENDENCE AND SCATTER IN THE RELATION; THE DISTANCES TO NEARBY GROUPS

MARC AARONSON
Steward Observatory, University of Arizona

AND

JEREMY MOULD
Kitt Peak National Observatory[1]
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ABSTRACT

A newly published catalog of infrared and 21 cm data for 300 galaxies in the Local Supercluster is analyzed in order to investigate empirically several properties of the Tully-Fisher relation. For this sample, we obtain the following results:

1. In the infrared, there is no significant dependence of the Tully-Fisher relation with type. A small type dependence is found in the blue; however, the spread in profile width at fixed magnitude is only about one-third as great as that found earlier by Roberts.

2. The slope of the Tully-Fisher relation is wavelength dependent, increasing in value from the blue to the infrared. The slope of the relation does appear steeper than previously indicated, though, and a small nonlinearity is identified.

3. The scatter in the Tully-Fisher relation is smaller in the infrared, where $\sigma \sim 0.45$ mag, than in the optical.

Distances to a number of nearby groups are calculated using the absolute calibration from Paper I. Good agreement in *relative* distance is found with both the Sandage-Tammann and de Vaucouleurs scales. Current disagreement over the *absolute* distance scale and value of the Hubble constant appears reduced to two issues: the infall velocity toward Virgo, and the distance scale for galaxies in the neighborhood of the Milky Way. While the former now appears to be well under control, the latter will require considerable observational effort before being satisfactorily resolved.

We argue that the two main competing local distance scales provide firm lower and upper limits to the value of the expansion rate. The calibration from Paper I, which falls between these limits, yields $H_0 = 82 \pm 10$ km s^{-1} Mpc^{-1}. The formal error in this estimate is dominated by the adopted uncertainty in zero point of the IR/H I relation.

Subject headings: cosmology — galaxies: clusters of — galaxies: redshifts — galaxies: structure — radio sources: 21 cm radiation

I. INTRODUCTION

The power and accuracy of the infrared magnitude/H I velocity-width relation (or IR Tully-Fisher relation) rests in part on the apparent lack of dependence on morphological type and on the small scatter in the method. Recently, a number of investigators have discussed one or both of these attributes and have reached conflicting conclusions. This has in part been due to the lack of a large sample of galaxies having *both* optical and IR measurements.

Aaronson *et al.* (1982*b*) have recently presented infrared photometry and 21 cm observations for a collection of some 300 nearby galaxies ($V_0 < 3000$ km s^{-1}). These data allow us here to discuss on a much firmer basis issues related to type dependence and scatter; we address these topics in §§ II and III, respectively. Next, we discuss again the absolute calibration of the IR/H I relation in § IV and find that current uncertainty in the nearby distance scale precludes revision of the calibration from Aaronson, Mould, and Huchra (1980, hereafter Paper I). We then present IR Tully-Fisher diagrams and derive distances for a number of nearby groups and compare the results with earlier published work.

II. MORPHOLOGICAL TYPE DEPENDENCE AND THE TULLY-FISHER RELATION

a) *Comparison with Roberts's Sample*

The question of type dependence in the Tully-Fisher method continues to be controversial. The issue is an important one to resolve because a *strong* correlation with type would require accurate calibration in order to

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reliably apply the Tully-Fisher relation as a distance yardstick. Roberts (1978) found such a strong type dependence for blue magnitudes. His conclusions have recently received support from Rubin, Burstein, and Thonnard (1980). Using a sample of 21 Sc galaxies, these authors find the slope of the Tully-Fisher relation for blue magnitudes to be as steep or steeper than that seen in the infrared. They suggest that the slope of the relation is wavelength *independent* for each Hubble type and that previous indications of a smaller slope in the blue were simply an artifact of neglecting the strong type dependence, where the mixing of types having individually steeper slopes led to a shallower slope overall. Opposite conclusions have been reached in earlier papers in this series and also by the recent analysis of de Vaucouleurs *et al.* (1982), although the latter work is perhaps less convincing owing to the large number of "2 σ rejections".

The data of Aaronson *et al.* (1982*b*), which comprise a larger sample than that employed by Roberts (1978), allow a careful examination to be made of type dependence as a function of wavelength in the Tully-Fisher method. We begin with Figure 1*a*, which shows the original type effect seen by Roberts (1978) using data taken directly from his Table 2. A similar diagram using data from Aaronson *et al.* (1982*b*) is shown in Figure 1*b*, which was constructed in a manner identical to that used by Roberts: after binning galaxies by type, absolute magnitudes were calculated from a single Hubble constant (whose value is irrelevant) and the mean velocity width determined in unit magnitude bins. As in Figure 1*a*, only galaxies with high quality types were used in Figure 1*b* (i.e., those on the revised Hubble system having, in addition, a bar parameter). Besides the obvious differences in sample contents, there are some other differences between us and Roberts which should be noted—his inclination cutoff is smaller, his binned types are not quite identical to ours, and his sample contains no redshift cutoff and includes galaxies with redshifts up to 8000 km s^{-1}.

The arrow in Figure 1*b* requires explanation. The use of individual rather than group redshifts can be expected to increase the scatter, especially for nearby galaxies; in the case of M81 the effect is drastic. The arrow indicates where the point containing M81 would lie if this galaxy were placed at its group redshift. [M81 is also the highly deviant point visible in Fig. 2 of Aaronson *et al.* (1982*b*) at $\log \Delta V_{20}{}^c(0) \sim 2.7$ and about two-thirds up the vertical axis.]

For the best determination of the wavelength dependence of morphological type as a second parameter, we should examine the identical set of galaxies in the blue and infrared; we do so using the sample from Aaronson *et al.* (1982*b*) in Figure 2. To construct this figure B_T magnitudes corrected for inclination and galactic absorption have been taken directly from Fisher and Tully (1981); such magnitudes are available for 253 galaxies in the sample. An additional nine galaxies have been added using B_T magnitudes from de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter RC2) corrected for absorption as in Fisher and Tully (1981). Four galaxies in this combined group have uncertain types, and so the final sample in Figure 2 contains 258 galaxies. The galaxy M81 has been assigned its group redshift, but otherwise the figure is constructed in like fashion to Figure 1. Note that now the number of galaxies in each bin is the same in Figures 2*a* and 2*b*.

It is immediately obvious that the type dependence (if any) seen in Figures 1*b* and 2*b* is greatly reduced compared with that in Figures 1*a* and 2*a*. This confirms our previous arguments in earlier papers that type dependence in the Tully-Fisher relation is considerably smaller in the infrared than in the optical. We also emphasize that the Sc galaxies in Figures 1*b* and 2*b* correlate almost perfectly with velocity width, whereas the Sc galaxies in Roberts's sample show essentially no dependence on width. This latter point has received undue emphasis in the discussion by Tammann, Sandage, and Yahil (1980); it is not a valid criticism of the IR Tully-Fisher method.

As expected, Figures 1*b* and 2*b* appear similar, but the type dependence in Figure 1*a* is clearly greater than is apparent in Figure 2*a*. The reasons why Roberts's (1978) sample exhibits a larger type dependence than our own sample are not completely clear. Roberts's sample, as he has discussed, is magnitude-limited in nature, while ours is more nearly volume-limited (see below). It was argued by Mould, Aaronson, and Huchra (1980, hereafter Paper II) that a Malmquist bias could lead to a type dependence, but as discussed below the evidence for this is not compelling. We do note that the data here cover a wider range in magnitude than that used by Roberts. Close examination of Figure 2*a* indicates that most of the "signal" contributing to the type dependence comes from only a narrow magnitude range [which curiously corresponds roughly to the characteristic luminosity L^* in Schecter's (1976) luminosity function]. In this range the type dependence in the blue is nearly as large as found by Roberts. However, the types are seen to come together above and below this particular magnitude interval.

b) *Selection Effects*

Further considerations suggest that the intrinsic type dependence in the Tully-Fisher relation is even smaller than indicated in Figure 2. First, we note that the construction of Figure 2 corresponds to regressing log ΔV on magnitude. De Vaucouleurs *et al.* (1982) have pointed out that this increases the type dependence compared with, for instance, a regression which treats magnitude and log ΔV equally. In fact, de Vaucouleurs *et al.* dismiss Roberts's (1978) results as a regression effect, but this cannot be tested directly because most of his data remain unpublished.

On the other hand, Burstein *et al.* (1982) argue that for samples which suffer a Malmquist bias (as do both Roberts and their own), one can minimize the bias by treating the distance independent quantity (i.e., log ΔV) as the dependent variable, following the reasoning discussed by Schechter (1980). While this may be a valid

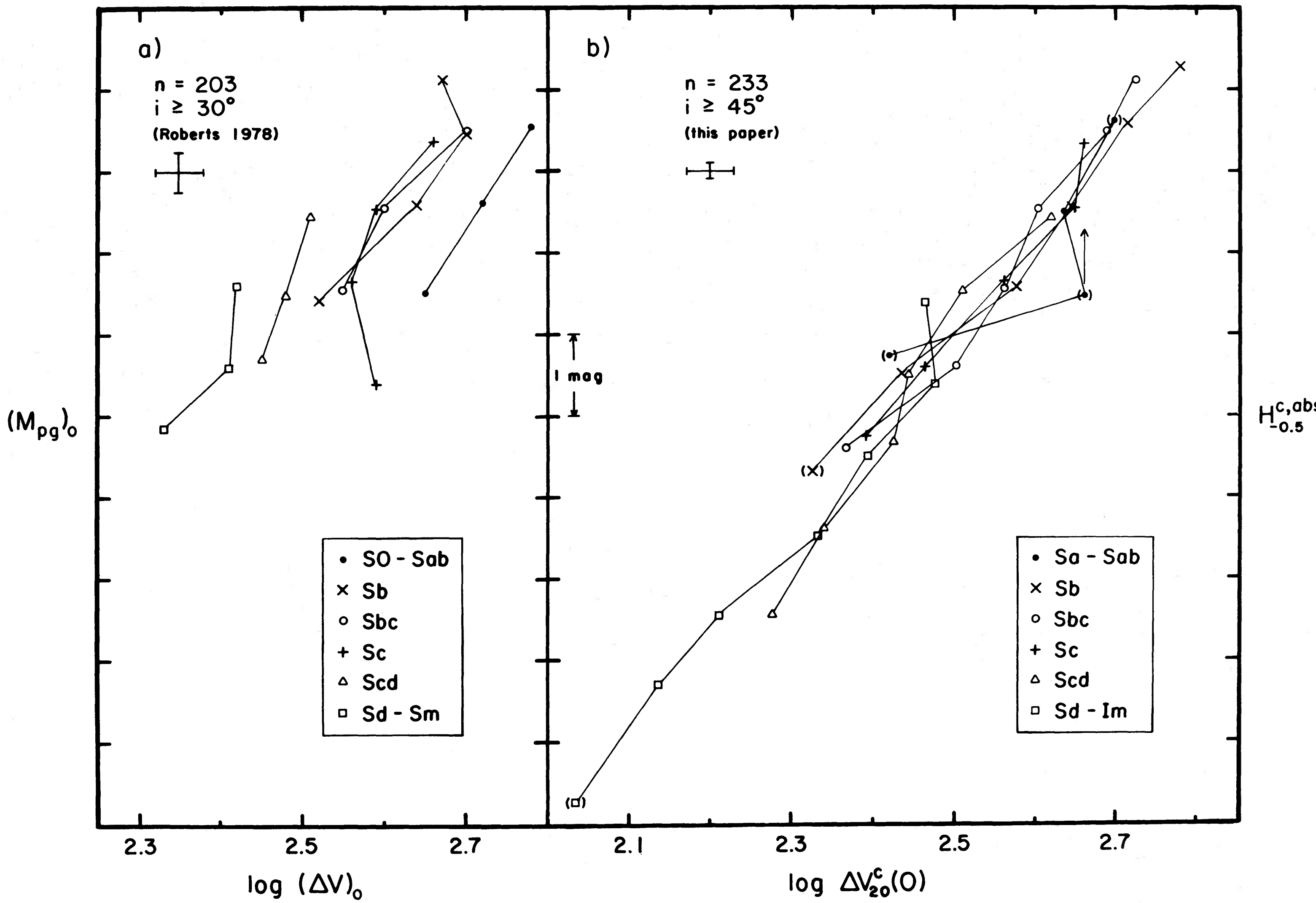

FIG. 1.—An absolute magnitude-velocity width diagram in the blue and infrared binned according to morphological type. Fig. 1*a* reproduces the findings of Roberts (1978), while Fig. 1*b* is constructed from the data in Aaronson *et al.* (1982*b*), restricting the sample only to galaxies with high quality types. A uniform Hubble flow is assumed in both cases. The binning corresponds to regressing log ΔV on magnitude. The point with the arrow attached in Fig. 1*b* is explained in the text. In this and the next two figures, symbols surrounded by parentheses have fewer than three galaxies in the bin, and the error bar shown is the typical uncertainty for an individual measurement.

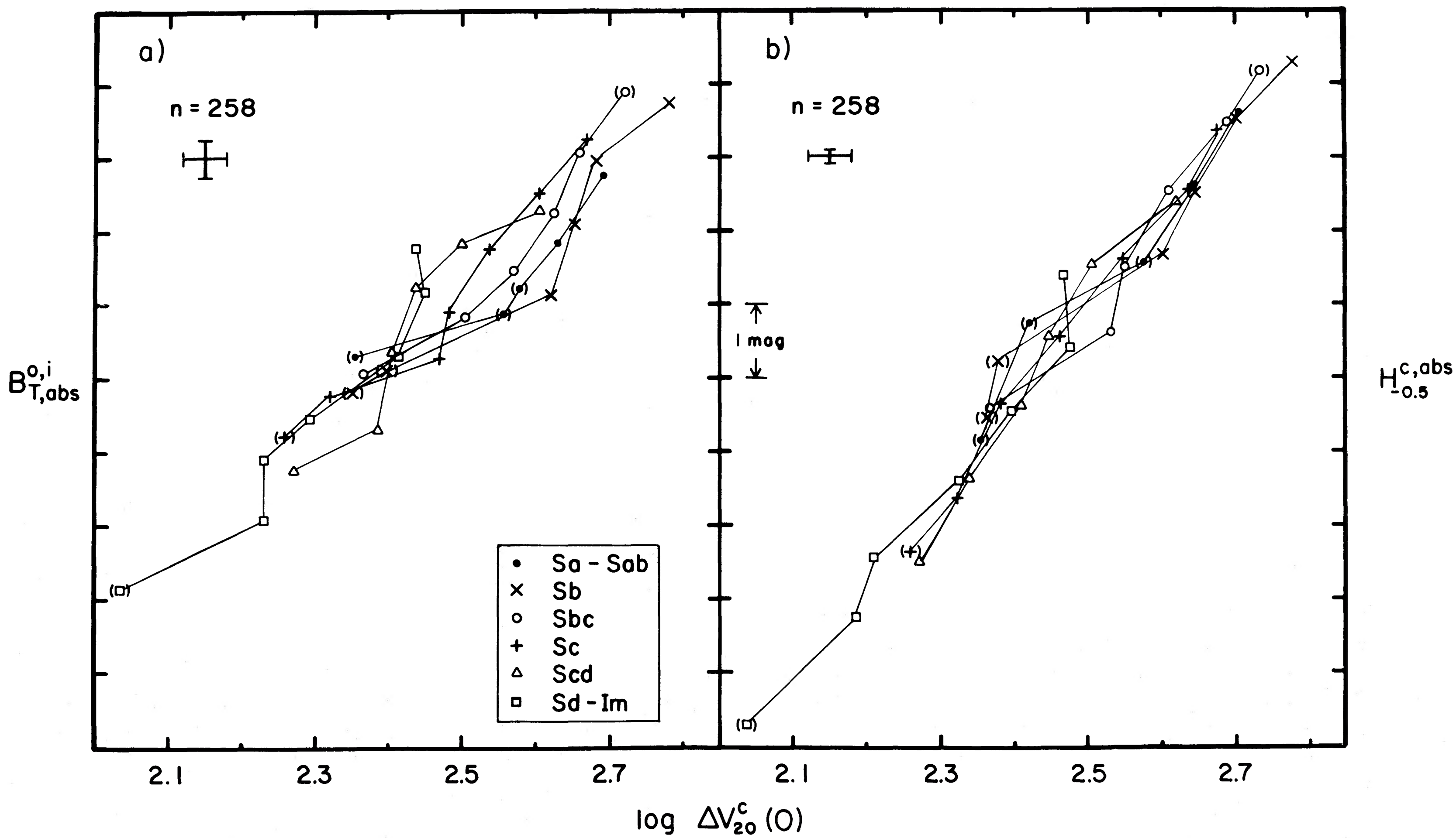

FIG. 2.—The absolute magnitude-velocity width relation in the blue and infrared binned by type, now using all galaxies from Aaronson *et al.* (1982*b*) having both *B* and *H* magnitudes. The bin sizes are identical in Figs. 2*a* and 2*b*. As in Fig. 1, a uniform Hubble flow is assumed, and the binning corresponds to regressing log ΔV on magnitude.

approach for estimating distances, for the purpose of determining intrinsic type dependence in the Tully-Fisher relation we believe their argument is incorrect, but the reasons are subtle and require some explanation.

Schechter (1980) has demonstrated that the velocity width at fixed absolute magnitude is the same for data that are either volume or magnitude limited. Consider then a volume-limited sample of galaxies in the Tully-Fisher plane all having the same morphological type. The distribution of this sample will be characterized by some unknown *bivariate* function $\phi(M, \Delta V)$, and in addition by the measurement errors. Clearly the best slope representation of the sample in a least squares sense is obtained by weighting the fit according to the distribution spread in each coordinate, and not by treating either M or ΔV as independent.

Suppose our sample is instead magnitude limited. It follows as a direct consequence of Schechter's (1980) lemma that the slope obtained by treating either M or ΔV as the independent variable is the same as would be found for the volume limited sample. In other words, the appearance of the distribution in the Tully-Fisher plane is similar for either a volume- or magnitude-limited sample, the latter being merely shifted to larger velocity width and brighter magnitude (the magnitude shift for a Gaussian luminosity function being 1.38 σ^2). Hence, the closest approximation to the true slope in a least squares sense for a magnitude-limited sample is again obtained by weighting the fit with the same distribution spread in M and ΔV found for the volume-limited sample. We have in fact verified this result to ourselves by using Monte Carlo simulations.

Let us now consider the volume-limited case with different morphological types and a different mean luminosity for each type, supposing there is no intrinsic type dependence in the Tully-Fisher relation. If we regress on magnitude for each individual type, the steeper slopes that result will cause an artificial spread in velocity width at fixed magnitude, i.e., a false type dependence. An artificial type dependence will also result if we regress on velocity width, but in the opposite sense. Only the correctly weighted regression will return no type dependence. If an intrinsic type dependence is present in the Tully-Fisher relation, the true form of the relation will still only be returned by a correctly weighted fit.

Finally, let us consider a magnitude limited sample with different morphological types. Let us also assume for the moment that the shape of the luminosity function is independent of type, so that the spread in magnitude is also independent of type. The true form of the Tully-Fisher relation is then again only returned by the appropriately weighted fit. However, if the magnitude spread is different for differing types, the intrinsic type dependence will in general not be returned by any regression. We had suggested in Paper II that such an effect might contribute to the type dependence found by Roberts (1978). We can easily test whether the magnitude spread is type dependent by examining the scatter in magnitude as a function of type for our own sample, which we believe is close to being volume limited in nature.[2] The result is that there is no dependence of magnitude scatter on type, and so it does not appear that Malmquist effects alone can introduce much type dependence in the relation.

The question that still remains is how to appropriately weight the regressions. Because our knowledge of the distribution in each coordinate is still limited, the best answer is unclear, but a reasonable choice would seem to be to treat the two variables with equal weight. In any event, we emphasize that the arguments of Burstein *et al.* (1982) are not applicable to the problem of determining the slope and intrinsic type dependence of the Tully-Fisher relation. Treating magnitude as the independent variable guarantees the same width at fixed magnitude for a volume- or magnitude-limited sample, but it does not guarantee the correct slope. The procedure does have the advantage that for determining distances sample selection effects are eliminated; but the disadvantage is that if types are mixed an artificial bias with type is introduced.

c) *Equal Treatment of the Regression Variables*

In Figure 3 we show a third representation of type dependence in the Tully-Fisher relation. Following the above discussion, instead of regressing log ΔV on M, we have performed both regressions and plotted in the figure an average of the bin contents. One other difference enters into Figure 3. Instead of using redshift distances, we use the infall model distances given in column (10) of Table 3 in Aaronson *et al.* (1982*b*). These distances are based on solution 3.1 of Aaronson *et al.* (1982*a*, hereafter AHMST), which yields a total Virgocentric velocity of 331 ± 41 km s^{-1} and perpendicular components of order 100 km s^{-1}. For the remainder of this paper, the term "infall model" refers specifically to this solution. As explained in AHMST the infall model excludes galaxies with galactocentric redshift less than 300 km s^{-1} or lying in a conical shell between 6° and 25° from Virgo. This reduces the sample having both optical and IR data to 217 galaxies.

The most important result of this section is shown in Figure 3*b*, where *we find no significant dependence of the infrared Tully-Fisher relation with type* in our sample. We believe Figure 3 is the best graphical representation of type effect in the Tully-Fisher relation currently available. We emphasize that the appearance of the figure remains essentially unchanged if instead a uniform Hubble flow is assumed. A smaller type dependence is also apparent *in the blue* in Figure 3*a* in comparison with Figures 1*a* and 2*a*. Averaged over luminosity, the spread in width at fixed magnitude visible in Figure 3*a* is perhaps only one-third as large as suggested by Roberts (1978) in the blue. Interestingly, most of the effect seen by Roberts was caused by just the early and

[2] Both the redshift and width residual infall schemes from Aaronson *et al.* (1982*a*) yield results in good agreement, which is only expected for a volume limited sample. Also, there is no correlation in the sample between redshift and velocity width (cf. Roberts 1978).

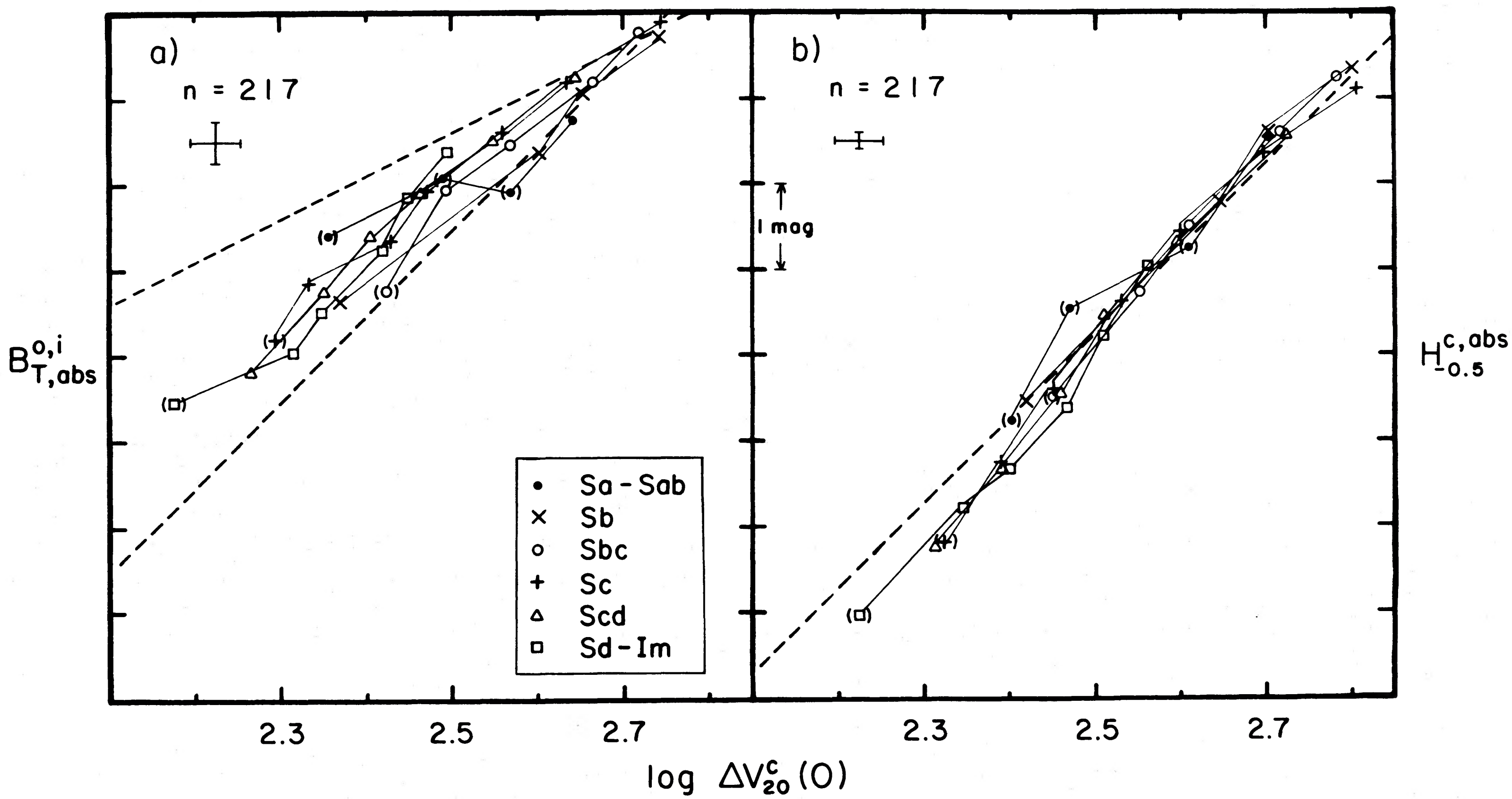

FIG. 3.—Our best representation of type dependence in the Tully-Fisher relation in the blue and infrared. The binning (identical in Fig. 3*a* and 3*b*) corresponds to treating log ΔV and magnitude as equal regression variables. Also, absolute magnitudes are now calculated using the infall model (solution 3.1) from AHMST. The dashed lines in Fig. 3*a* have slopes of 5 and 10; only the steeper slope is shown as a dashed line in Fig. 3*b*.

late types (see Fig. 1*a*), while the dependence found here in both Figures 2*a* and 3*a* appears more evenly distributed with type.

The *B* magnitudes used here do not have the same level of photometric accuracy as the *H* magnitudes, in part because many of the former are transformed from the Zwicky or Harvard systems (see Fisher and Tully 1981), a fact also true for the sample considered by Roberts (1978). To determine whether the results in Figure 3 are affected by this increased uncertainty, we have replotted the data using only a restricted sample of high quality *B* magnitudes. For the infall model, this restricted sample contains just 117 galaxies. Nevertheless, the *B* type dependence for this much reduced sample is essentially identical to that seen in Figure 3*a*, suggesting that use of the larger sample has not biased our results.

Another representation of type dependence in the Tully-Fisher relation is given in Table 1. Here we present the slope and zero point of least squares solutions for both the optical and infrared M-log ΔV relation for various subsets of the data, using now the individual data points. The results have in all cases been determined by treating both M and log ΔV as the dependent variable and averaging the regressions. The zero point was normalized by choosing $H_0 = 80$ km s^{-1} Mpc^{-1}, although obviously any value could be adopted for this purpose, and is referred to log $\Delta V = 2.5$.

In the first part of Table 1 we assumed a uniform Hubble flow. The mean slope we obtain in the blue for the entire sample, $b_B = -8.82$, is very close to the value -8.6 quoted by Roberts (1978). A morphological type dependence of the type found by Roberts (e.g., Fig. 1*a* here) would be reflected in Table 1 as a change in zero point but constancy of slope. Such a type dependence is evident in Table 1 for *B*. It is perhaps not so evident in Figure 3*a* because of the unequal distribution there in bin size. No significant change in *H* zero point with type is apparent in Table 1, but a systematic change of *H* slope with type does appear to be present, a point we discuss further below; this latter effect may also be present at *B*, but not as clearly. These results remain essentially the same when the infall model is adopted, as shown in the second part of Table 1.

In all cases the slope at *B* is shallower than the slope at *H*. This does not confirm the suggestion of Rubin, Burstein, and Thonnard (1980) that the slope in the Tully-Fisher relation is wavelength independent. The consequences of mixing types in the blue does lead to a shallower slope in the mean than that obtained for individual types, but the effect is small; at *H* this effect in fact goes in the opposite sense. That the slope of the Tully-Fisher relation is wavelength dependent has important implications. For example, Tully, Mould, and Aaronson (1982) show how this result implies a strong

TABLE 1

SLOPE AND ZERO-POINT OF THE TULLY-FISHER RELATION IN THE OPTICAL AND INFRARED

		$B^{0,i}_{T,\mathrm{abs}}$				$H^{c,\mathrm{abs}}_{-0.5}$				
SAMPLE	N	$-b$	$\sigma_{b,B/\log\Delta V}$	$-a$	$\lvert r\rvert$	$-b$	$\sigma_{b,H/\log\Delta V}$	$-a$	$\lvert r\rvert$	NOTES
Uniform Hubble Flow										
Total	262	8.82	0.30	19.20	0.83	12.07	0.28	20.94	0.93	
Sa–Sab	14	6.89	1.27	18.98	0.75	10.90	1.29	21.07	0.91	1
Sb	35	9.68	1.05	18.75	0.87	10.73	0.93	21.04	0.87	
Sbc	41	9.91	1.00	19.13	0.87	11.78	0.92	21.10	0.87	
Sc..............	77	8.81	0.69	19.31	0.88	11.19	0.61	21.01	0.88	
Scd	44	10.93	1.02	19.43	0.90	13.84	0.90	21.05	0.91	
Sd–Im	47	9.90	0.87	19.41	0.89	12.13	0.83	20.84	0.89	
Infall Model										
Total	221	8.24	0.29	18.95	0.85	11.54	0.26	20.68	0.94	
Sa–Sab	9	5.94	1.57	18.91	0.64	9.77	1.19	20.95	0.95	
Sb	31	8.46	0.81	18.61	0.85	9.90	0.67	20.86	0.93	
Sbc	37	9.00	0.88	18.78	0.81	10.93	0.71	20.76	0.92	
Sc..............	69	8.44	0.62	19.08	0.78	11.23	0.53	20.75	0.92	
Scd	37	9.00	0.79	19.12	0.85	12.32	0.72	20.73	0.94	
Sd–Im	34	11.84	1.43	19.35	0.68	13.31	1.39	20.72	0.80	
Clusters										
Virgo	15, 16	8.49	1.03	18.74	0.86	10.27	0.91	20.66	0.94	2, 3
Ursa Major	24	7.14	0.61	18.82	0.91	10.53	0.58	20.59	0.97	4

NOTES.—(1) M81 adjusted to group redshift.
(2) Only 15 galaxies used for Virgo *B* solution, because one galaxy lacked a *B* magnitude.
(3) For zero point, mean cluster redshift of 1019 km s^{-1} adopted.
(4) For zero point, mean redshift for sample in this paper (1012 km s^{-1}) adopted.

correlation between $B-H$ color and the mass of spiral galaxies. This in turn leads to a useful new technique for estimating distances.

The slope at H for the total sample agrees well with the results in Table 1 of AHMST, whether the infall model or uniform flow is adopted here, although it is steeper than the theoretical value of 10 discussed by Aaronson, Huchra, and Mould (1979, hereafter AHM). The systematic dependence of slope with type at H is a manifestation of what appears to be a small nonlinearity in the relation and the fact that different types populate different regions of the Tully-Fisher diagram. This effect is visible in Figure 3*b* (see also Fig. 2 of Aaronson *et al.* 1982*b*) which shows that a single nonlinear relation may apply to the IR data, in which case the constancy of zero point for the linear fits in Table 1 arises from a fortuitous choice of intercept.

As discussed further in the next section, this nonlinearity may be due in part to the increasing influence of noncircular motions in later type galaxies. It may also be partly an artifact of our isophotal diameter choice, which corresponds roughly to one-third the Palomar Observatory Sky Survey diameter. Because the growth curves steepen with advancing type, use of a large isophote would lead to a relation having greater linearity. Similarly, use of the "kinematical diameter" discussed in Paper I would also reduce the curvature. Finally, systematic errors in the isophotal diameters themselves cannot be ruled out as a possible cause of the effect. On the other hand, Burstein (1982) has suggested that one or more of the simple assumptions used by AHM in their discussion of the theoretical aspects underlying the Tully-Fisher relation may be invalid, in which case deviations from a relation with slope 10 would not be surprising. In any event, we emphasize that use of a linear Tully-Fisher relation is adequate for deriving distances (see § IV).[3]

In the last part of Table 1 we give the slope and zero point found from data in the Virgo and Ursa Major clusters. The slopes are again seen to be steeper in the IR than at B, but in both cases they are less steep than the mean slopes found for the total sample of data. This is apparently due to the cluster samples being more heavily weighted with earlier type galaxies.

In regard to the slope of the Tully-Fisher relation at B, the results in Table 1 are not on the face of it consistent with the findings of Rubin, Burstein, and Thonnard (1980) and Burstein *et al.* (1982). From a sample of 21 Sc galaxies (some of whose types are disputed by de Vaucouleurs *et al.* 1982), the latter authors find a steep slope of -14.3. Note, though, that it is not 21 cm velocity widths being considered now but 2 $V_{\max}$ obtained from emission-line optical rotation curves, although de Vaucouleurs *et al.* (1982) find no systematic difference between the two quantities for this Sc sample.

It may be useful to examine Burstein *et al.*'s (1982) data. Treating first B magnitude and then 2 $V_{\max}$ as the dependent variable and averaging the results, we obtain a slope of -10.86 ± 1.28[4] for 21 Sc galaxies. This is considerably less than the Burstein *et al.* value of -14.3 based on $V(R_{25})$ extrapolated from $V_{\max}$ and derived treating only $V(R_{25})$ as the dependent variable. It is marginally less than we find for our own sample of Sc's in the IR (~ 11.2 from Table 1), but greater than what we find at B (~ 8.4–8.8). If following Burstein *et al.* we exclude UGC 2885 from the sample (presumably because of the lower photometric accuracy of this galaxy's B magnitude indicated by Rubin, Ford, and Thonnard 1980), the slope only slightly increases by 0.4. For the Burstein *et al.* sample 2 $V_{\max}$ is highly correlated with redshift; and to see whether this introduces a bias into the result owing to the neglect of infall, we have recalculated their absolute magnitudes following the precepts of Appendix B in AHMST, assuming only an infall velocity of 300 km s^{-1} and no peculiar motion. As it turns out, the slope remains essentially unchanged. Thus, we are not able to fully account for the difference in slope found by Burstein *et al.* (1982) and ourselves. However, the discrepancy is less than a 2 σ effect. As our Sc sample is 3.5 times larger than theirs, we suggest that the steeper slope they obtain may be an artifact of small number statistics, but this point requires further investigation.

Finally, we note that for all cases considered in Table 1 the slopes found at B are considerably steeper than the value -5 proposed by Bottinelli *et al.* (1980) and de Vaucouleurs *et al.* (1982). We discuss this point further in the next section.

To summarize, we have tested for type dependence in the Tully-Fisher relation in the optical and infrared. At B we find a small dependence of velocity width on type at fixed absolute magnitude, but the size of the effect is much less (by about one-third) than was found by Roberts (1978). At H we find no significant spread in either velocity width at fixed absolute magnitude, or absolute magnitude at fixed width. The slope of the relation is seen to increase going from the blue to the infrared for all morphological types. Possible reasons for the larger type dependence at B as compared with H have been discussed by AHM and AHMST, and in Paper II.

III. COMPARISON OF SCATTER IN THE TULLY-FISHER RELATION IN THE OPTICAL AND INFRARED

a) *Results*

The optimal choice of wavelength for application of the Tully-Fisher method to the distance scale problem is clearly dependent on where the scatter is least, a

[3] Curiously, Davies *et al.* (1982) also report evidence for a turnover in the velocity dispersion-luminosity relation for ellipticals at low luminosities. However, the effect they find is *opposite* in sense to that here, e.g., low luminosity ellipticals appear to have smaller velocity dispersions than a linear extrapolation from the high luminosity regime would suggest.

[4] The uncertainty in slope quoted here and elsewhere in the text is that obtained from the regression magnitude as the dependent variable.

TABLE 2

COMPARISON OF SCATTER IN THE TULLY-FISHER RELATION IN THE OPTICAL AND INFRARED

	$B_{T,\mathrm{abs}}^{0,i}$				$H_{-0.5}^{c,\mathrm{abs}}$				
SAMPLE	N	$\sigma_{B/\log \Delta V}$	$\sigma_{\log \Delta V/B}$	$\lvert r \rvert$	N	$\sigma_{H/\log \Delta V}$	$\sigma_{\log \Delta V/H}$	$\lvert r \rvert$	NOTES
All with B magnitudes	262	0.71	0.082	0.83	262	0.66	0.055	0.93	1
All with B magnitudes	221	0.59	0.073	0.85	221	0.52	0.045	0.94	2
High quality B magnitudes	117	0.50	0.067	0.87	117	0.45	0.041	0.95	2
Virgo cluster	15	0.51	0.069	0.86	16	0.45	0.044	0.94	
Ursa Major cluster	24	0.42	0.060	0.91	24	0.40	0.038	0.97	
Infall sample	...	...	...	...	265	0.62	0.052	0.93	1
Infall sample	...	...	...	...	265	0.52	0.045	0.95	2
Total sample	...	...	...	...	306	0.64	0.054	0.93	1

NOTES.—(1) Assumes uniform Hubble flow.
(2) Assumes infall model (see text).

question we examine in this section. In Table 2 we present variances obtained from least squares fits to various samples of our data. In the first row, we treat all galaxies having B magnitudes under the assumption of a uniform Hubble flow. Next we treat all such galaxies using instead the infall model. In both cases the linear correlation at H is greater, and the velocity width variance and in particular the magnitude variance are smaller. As expected, the scatter drops significantly in going from uniform Hubble flow to the infall model.

In the third line of Table 2 we consider only those galaxies with high quality B data, again using the infall model. The scatter at B is seen to drop considerably compared to that in line 2, but the scatter at H has also dropped by a proportionately equal amount, indicating that in both cases the decrease in scatter is merely a sample selection effect. The scatter at B for this restricted sample is still seen to be greater than that at H. We conclude that the additional uncertainty in B magnitudes for the full sample contributes little to the scatter.

In the next two lines in Table 2 we consider the scatter in the Virgo and Ursa Major cluster relations, and again find less scatter at H than at B. The magnitude scatter we obtain for these two clusters (0.45 and 0.40 mag) is probably the best gauge of the scatter in the IR Tully-Fisher relation because first, no allowance in the infall model has been made for group velocity dispersion; and second, there are no doubt real deviations from the infall model itself. Except perhaps for the luminosities of first-ranked cluster ellipticals, no other distance indicator based on the global properties of galaxies has been convincingly demonstrated to have comparably small scatter. Note further that if allowance is made for uncertainty in the observational quantities (see Aaronson *et al.* 1982*b*), and for depth effect of the clusters, the intrinsic scatter in the relation may be as low as $\sigma \sim 0.2$–0.3 mag. In the final three lines of Table 2 we give the scatter at H for the entire infall sample, assuming both uniform flow and the infall model, and for the complete sample of 306 galaxies assuming uniform flow (see Fig. 2 in Aaronson *et al.* 1982*b*). Again, we see the expected decrease in scatter in going from uniform flow to the infall model.

It cannot be argued that the use of an incorrect galactic extinction law has resulted in the increased B scatter. Consider the Virgo and Ursa Major clusters. The galaxies there are at sufficiently high latitude and close enough together on the sky such that none of the various reddening laws discussed in the literature can have much effect on the results. Nor can it be argued that the use of incorrect internal absorption has caused the larger B scatter. Consider again the Ursa Major cluster. It was demonstrated in AHM that the internal absorption correction advocated by Sandage and Tammann (1976) led to 50% more scatter than that used by Tully and Fisher (1977), the latter being similar to what was used here. We have also examined the Ursa Major relation using corrected B_T's adopted directly from the RC2. Although the sample is then reduced from 24 to only 9 galaxies, we again find less scatter at H than at B and significantly better correlation ($\lvert r \rvert = 0.90$ versus 0.67).

In summary, for all cases we have investigated, the scatter in the Tully-Fisher relation is smaller in the infrared than in the optical. Reasons for expecting this to be so have been discussed at length in earlier papers. However, the scatter at B in Table 2 is close to that found at H, suggesting that the internal absorption corrections used by Fisher and Tully (1981) are probably fairly reliable.

b) Comparison with Bottinelli et al.

Bottinelli *et al.* (1980) claim that the scatter in the Tully-Fisher relation calculated from B magnitudes is smaller, by 50%, than that obtained from H magnitudes. The basic premise underlying their argument is that the errors are dominated by uncertainty in log ΔV, for which Bottinelli *et al.* adopt a nominal value of 0.06 dex. Bottinelli *et al.* then argue that since the scatter in magnitude is governed by the slope in the relation, and since $b = -5$ at B and -10 at H, the scatter from this source along is $\sigma_B = 0.3$ mag and $\sigma_H = 0.6$ mag.

(They suggest additional errors contribute a total scatter of $\sigma_B = 0.4$ mag.)

We believe there are a number of problems with Bottinelli *et al.*'s (1980) line of argument which are useful to examine in view of the completely opposite conclusions reached by ourselves above. First, the H I data in their sample are of considerably lower quality than in our own, both because they use profiles of much lower signal-to-noise ratio, and because they have a much smaller inclination cutoff (only 20°). It is not surprising then that the errors in their line widths so thoroughly dominate their uncertainties.

The nominal error in log ΔV we adopt for our data, 0.03 dex, is only half of their quoted nominal error. We believe this is a realistic estimate for the present data set. In particular, the H I errors can hardly be larger for the following reason: We have shown above that the magnitude scatter in the Virgo and Ursa Major clusters, where 21 cm errors are typical for the sample as a whole, is only 0.45 and 0.40 mag, respectively; while the magnitude scatter for all galaxies in the infall solution is 0.52 mag. The intrinsic depth of the clusters in the first case, and deviations from the smooth infall model in the second case, then place an upper limit on our velocity width errors of about 0.04 dex.

Another problem with Bottinelli *et al.*'s analysis is that the slope ratio b_H/b_B is not 2 as they report, but in the range 1.3–1.4, as indicated in Table 1. Hence, the increase in magnitude scatter due to this slope change is much less than they estimate. Furthermore, their value of $b_B = -5$ is not only well below what we find, but also smaller than obtained by several other investigators in the blue (cf. Tully and Fisher 1977; Sandage and Tammann 1976). [Bottinelli *et al.* do not list directly their slopes, although de Vaucouleurs *et al.* (1982) do quote regressions for one sample which leads to a mean slope $b_B \approx -6.2$.]

Part of the disagreement in slope may be due to Bottinelli *et al.*'s (1980) attempt to correct the line widths for the effects of noncircular motions, as the size of the correction is expected to be a systematic function of width, but it is difficult to check this directly because only sketchy details of what is in any event a questionable procedure are given. However, this cannot be the entire explanation. Examination of Figure 3*a* here shows that in order to achieve a slope of -5, the required velocity dispersion for late-type galaxies is some 90 km s^{-1} if the correction is applied linearly, as in the approach of Bottinelli *et al.*, or some 170 km s^{-1} if the correction is applied in quadrature, the proper correction probably lying somewhere in between. These values are of course not realistic: Estimates of H I turbulence generally range from only 10–20 km s^{-1}, and perhaps another 20 km s^{-1} might be contributed by additional noncircular effects such as streaming motions along spiral arms, tidal disturbances, kinematical disruptions arising from star formation bursts, etc. (see Roberts 1978; Mihalas and Binney 1981). These latter effects will vary considerably from galaxy to galaxy, reducing the utility of any correction attempted.

Noncircular motions may play some role in explaining the apparent nonlinearity in the IR Tully-Fisher relation, but again somewhat large values (40–120 km s^{-1}) are required to achieve a slope of -10. In any event, a velocity dispersion correction will have little effect on the ratio of slopes in the blue and infrared, which is the key to the Bottinelli *et al.* argument.

IV. DISTANCES TO NEARBY GROUPS AND H_0

a) Reexamination of the Absolute Calibration

We now have enough additional nearby galaxies available to make reexamination of the calibration from Paper I a worthwhile exercise. As is well known, there are two competing distance scales in the astronomical literature, one by Sandage and Tammann and one by de Vaucouleurs. We begin with the Sandage-Tammann scale, for which there are at present 16 calibrators we can use to determine the zero point of the IR Tully-Fisher relation, i.e., the constant a in the equation $H_{-0.5}^{c,\mathrm{abs}} = a - 10[\log\ \Delta V_{20}{}^c(0) - 2.5]$. The calibrating galaxies and distance moduli in magnitude are NGC 224: 24.32; NGC 598: 24.76; NGC 247: 27.5; NGC 253 and 7793: 28.1; five galaxies in the NGC 2403/M81 group: 27.76; three galaxies in the M101 group: 29.4; and three galaxies in the CVn I group: 28.88. Distances for all but the CVn I group are taken directly from Table 2 of Sandage and Tammann (1981, hereafter RSA). For the CVn I group we assume our calibrators NGC 4244, 4258, and 4826 lie at the mean of the distances to IC 4182, NGC 4214, and NGC 4395 found by Sandage and Tammann (1982), increased by 0.2 mag for consistency with the larger Hyades modulus used with the RSA distances. Note that all of the above distances are based on primary or secondary indicators, primarily Cepheids and the brightest blue and red supergiants.

In Figure 4 we plot absolute H magnitude against velocity width for the 16 calibrators, which are seen to lie along a well-defined Tully-Fisher relation. The resulting zero point is $a = -21.39 \pm 0.11$ mag. The 1 σ magnitude deviation about the mean line in Figure 4, $\sigma = 0.42$ mag, is close to the expected scatter in the Tully-Fisher relation (see Table 2). However, depth effects may contribute considerably to this scatter.

While 16 galaxies is certainly a respectable number for a distance scale calibration, we do not consider the problem adequately solved, as illustrated by Figure 5. Here we present an alternative calibration using 13 of the previous 16 spirals (the CVn I group is now dropped) and the nearby distance scale of de Vaucouleurs. The calibrating galaxies and distances are NGC 224: 24.07; NGC 598: 24.30; NGC 2366: 27.14; NGC 2403: 27.09; NGC 3031: 27.7; NGC 4236: 27.65; IC 2974: 27.72; the three M101 galaxies: 28.5; and the three Sculptor galaxies: 27.0. The M31 and M33 moduli are taken from the abstract of de Vaucouleurs (1978*a*), while the remaining moduli are from Table 7 of de Vaucouleurs (1978*b*). These moduli lead to a zero point of $a = -20.74 \pm 0.10$ mag, leading to distances 0.65 mag smaller than found from the Sandage-Tammann scale.

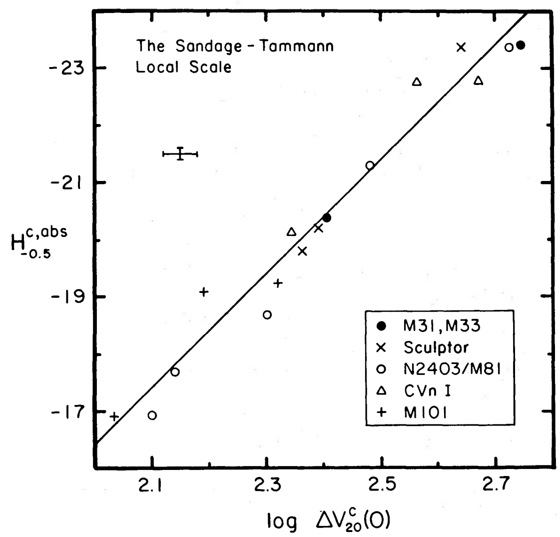

FIG. 4.—Absolute calibration of the IR/H I relation using the nearby distance scale of Sandage and Tammann.

The 1 σ magnitude deviation in Figure 5 is now only 0.36 mag.

Which scale is "correct"? On the one hand, the rather convincing evidence for an absorption-free polar cap from Burstein and Heiles (1982) implies the de Vaucouleurs distances are too small. On the other hand, two recent developments provide equally convincing evidence that the Sandage-Tammann distances are too large. Both of these are related to the brightest M supergiants, which appear to be passable standard candles. First, Humphreys (1980) has clearly demonstrated that the brightest supergiants in M33 (both blue and red) are significantly reddened by internal absorption in M33 itself, on average by ~0.5 mag, with considerable star-to-star variation. This effect has not been heretofore accounted for in applications using brightest supergiants, and it seems likely that such reddening would also be important in regard to Cepheids (see also Hanes 1982). Of course, any correction for internal reddening decreases true distance modulus. It is also worth noting that Humphrey's (1980) modulus to M33 agrees excellently with the modulus obtained from the infrared Tully-Fisher relation, using M31 solely as a calibrator.

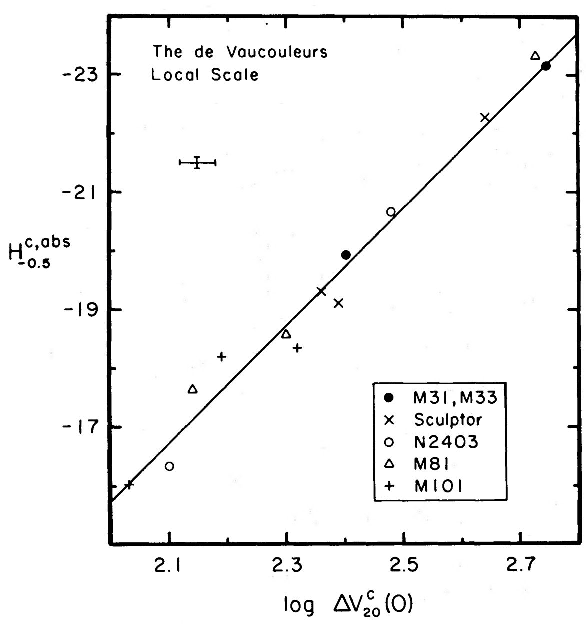

FIG. 5.—Absolute calibration of the IR/H I relation using the nearby distance scale of de Vaucouleurs. The zero point here differs by 0.65 mag from that in Fig. 4.

The second important development concerns M101, a galaxy which has played a fundamental role in the distance scale (see Paper II). Humphreys and Strom (1982) have identified candidate M supergiants in this spiral which indicate (on the old Hyades modulus) a distance modulus of 28.9 mag, and their application of a conservative internal reddening correction results in a true modulus of 28.6 mag. This is 0.7 mag closer than the Sandage-Tammann (1974) distance and provides strong support for the arguments made in Paper II and recently by several other authors (e.g., Capaccioli and Fasano 1980; Lawrie and Kwitter 1982) that their M101 distance is too large. The argument of Tammann (1979) that such a close distance is not permitted because the blue supergiants become underluminous compared with those in the Milky Way is rendered irrelevant if these stars suffer comparable internal reddening as those in M33, which seems very likely. Spectroscopic confirmation that the objects found by Humphreys and Strom are in reality supergiants would be an important step in resolving the current distance scale controversy.

For the present, we retain the Paper I zero-point calibration, for which $a = -21.23$ mag. Even though the origin of this zero point is based on just the two calibrators M31 and M33, we nevertheless regard it as a reasonable compromise between the two competing scales.

Sandage and Humphreys (1980) have reported that a grossly warped optical plane is present in M33. These authors point out that such a warping could affect calibration of the Tully-Fisher relation, and this logic is extended further by Tammann, Sandage, and Yahil (1980), who argue that for some (edge-on) spirals a meaningful inclination value cannot be defined. It thus seems important to examine the evidence and potential effects of warping on the Tully-Fisher method.

Large scale warping of H I in the outer plane of galaxies appears to be a somewhat common occurrence (Sancisi 1981). However, the effect on measured velocity widths should be small because in general warps do not appear until well beyond the location at which the rotation curve flattens out (see Fig. 2 of Paper I). According to Sandage and Humphreys (1980), though, the warp in M33 extends considerably inward. They argue that the inclination and position angle change from $i \sim 40°$ and P.A. $\sim 50°$ at a radial distance of $r \sim 2$ kpc (10′) to $i \sim 70°$ and P.A. $\sim 15°$ at $r \sim 6$ kpc (30′). Their conclusions rest on fitting logarithmic spiral functions to M33's ill-defined arms, which as Sandage and Humphreys discuss is not necessarily the correct procedure. The extreme warping proposed for M33 must be quite rare, otherwise there would be common instances of edge-on galaxies in which a similar effect would be easily visible. However, we are hard-pressed to think of many such examples.

Even if M33 were so severely warped the effect on the maximum rotational velocity would appear to be small. This can be seen, for instance, from the M33 rotation curve shown in Figure 7 of Newton (1980). Adjusting this curve according to the prescription of Sandage and Humphreys (1980) leaves $V_{\rm rot}$(max) virtually unchanged. However, we believe considerable evidence exists which suggests that the inner H I disk of M33 is not warped at all, implying an absence of warping in the spiral arms as well. In the last decade, 21 cm synthesis maps of M33 have been published with every increasing resolution and sensitivity (Warner, Wright, and Baldwin 1973; Rogstad, Wright, and Lockhart 1976; Reakes and Newton 1978; Newton 1980). In none of these cases is there evidence cited for systematic warping in the inner disk. For instance, Rogstad, Wright, and Lockhart (1976) employ a "ring-fitting" model; their Figure 11 shows a major-axis position angle change $\lesssim 2°$ from $r = 2$ to 6 kpc, and not the more than 30° change claimed by Sandage and Humphreys (1980). Also, Kaufman (1981) explicitly calculates the M33 velocity field using the radio data and various possible tilt parameters. Her Figure 5 also provides strong evidence against any large position angle change. Furthermore, it is difficult to understand how the residual velocity fields found in the different H I studies can appear so well behaved if such large warping has really been neglected. For instance, consider the appearance of Plate 7 in Newton (1980), a particularly important study in this regard because spiral structure in the H I is for the first time clearly seen. There is little evidence in this plate for any large-scale systematic residuals which might be expected to arise from warping of the inner disk. Finally, no significant systematic change in axial ratio with radius is apparent in the *B* surface photometry of de Vaucouleurs (1959). This last result could be influenced by the presence of spiral arm structure itself, and it would clearly be of interest to obtain structural parameters from the old disk of M33 using deep red plates instead.

Hence, it does not seem that inner warping in the disk of M33 has been convincingly demonstrated. In any event, it appears that the existence of galaxy warps has minimal effect in application of the Tully-Fisher relation, either in M33 or elsewhere.

b) Group Distances

In Table 3 we summarize distance moduli to a number of nearby groups. Following the above discussion, these were obtained using the absolute calibration of Paper I (eq. [6] there). Included in Table 3 are distances to 10 of the 14 nearby groups listed by de Vaucouleurs (1975). We have not used distances from the infall model because many nearby groups of interest would then be excluded. The two methods do, however, give consistent distances, as shown below. The group assignments in Table 3 are taken directly from column (12) of Table 3 in Aaronson *et al.* (1982*b*).

The results in § III above suggest that an improvement in the Paper I calibration which incorporates the apparent nonlinearity in the relation might be possible. However, given the continuing uncertain state of the local distance scale (i.e., out to M101) discussed earlier, and the need for a larger sample to pin down the nonlinearity more precisely, we forego for the present this potential improvement. Furthermore, the curvature is so small that use of a linear relation is an adequate approximation, as evidenced by the fact that a nonlinear relation was tried by AHMST but had little effect on their infall results. It might also be argued that the Paper I calibration, which assumes a slope in the relation of 10, is not consistent with the result in Table 2, where a steeper slope (~ 11.5) is indicated. However, as was demonstrated in Paper I, because of interplay between the slope and zero point it makes little difference which slope is actually adopted for deriving groups distances, as long as the sample is not dominated by galaxies with extremely large or small widths. Another way to see this is to compare distances from the Paper I calibration with those obtained from the infall model, which uses a slope of 12.12 (see Table 1 of AHMST). Excluding the NGC 24/45 pair (see below), the mean difference in distance modulus for the two methods based on 19 groups is -0.07 ± 0.06 mag, where we have derived infall model distances from column (11) of Table 3 in Aaronson 1982*b*, normalizing to the Virgo distance from Table 3 here.

In Figure 6 we present infrared Tully-Fisher diagrams from the richer clusters and groups. We discuss below the results for groups of particular interest.

South Polar.—Although once considered an entity at a single distance, it is becoming increasingly clear that the South Polar or Sculptor group is broken up into a number of subgroups strung out considerably in space (Graham 1981; RSA). Our own results lend support to this view, as we place the NGC 24/45 pair considerably behind NGC 247, 253, and 7793 (Fig. 6*a*).

The NGC 24/45 pair is the only group in Table 3 for which a significant difference exists between distance obtained from the Paper I calibration and from the infall model, in that with the former method the pair is placed 1.4 mag farther in modulus. The reasons for this are not clear. Curiously, the calibration of Paper I leads to a small Hubble ratio for the NGC 24/45 pair, similar to the low Hubble ratios found for the nearest groups.[5] Considerations of photographic resolution (see the RSA) appear to lend support to the distance

[5] It seems generally agreed among all authors that the velocity dispersion about uniform Hubble flow is small in the immediate neighborhood of the Milky Way, a conclusion largely based upon distances to the nearby groups Sculptor, NGC 2403–M81, and M101. As Tully (1982) has emphasized, this result is not inconsistent with the possibility of large Local Group peculiar velocity and/or infall toward Virgo; nearby galaxies simply partake of the same motion. Tully (1982) has in fact proposed an interesting model which condenses the Local Supercluster into a small number of galaxy clouds undergoing mass motion toward Virgo.

TABLE 3

DISTANCE MODULI TO NEARBY GROUPS

Name	Alternate[a]	N	m-M (mag)	σ_μ[b] (mag)
NGC 24/25 Pair	...	2	29.86	0.26
NGC 134	dV39	2	31.00	0.07
South Polar	dV1, HG13	3	27.64	0.19
NGC 701/755 Pair	...	2	31.23	0.09
NGC 1023	dV7, HG67	5	29.98	0.24
Eridanus	dV31, HG30+HG32	8	31.12	0.14
Fornax	dV53, HG17	7	30.88	0.23
NGC 2336	HG92	3	32.24	0.07
NGC 2403-M81	dV2, HG85+HG86	5	27.88	0.14
NGC 2841	dV6, HG71+HG74	3	30.96	0.30
NGC 3079/U5459 Pair	...	2	31.27	0.08
NGC 3184	dV12	3	30.65	0.18
Leo Triplet	dV9	3	29.84	0.25
Leo	dV11+dV49, HG56	5	31.32	0.23
NGC 3521	...	3	30.94	0.54
Ursa Major	dV17+dV32+dV34, HG60	24	31.15	0.08
Coma I	dV13, HG60	6	30.42	0.32
Virgo	dV18+dV19, HG41	16	31.08	0.11
Virgo South	dV26, HG41	7	30.88	0.22
CVn I	dV3, HG60	3	28.45	0.31
NGC 5033	HG68	3	31.24	0.26
M51	dV5	2	29.69	0.28
M101	dV5, HG75	3	29.01	0.33
NGC 5371	HG69	3	32.29	0.17
NGC 5364	HG55	2	31.10	0.40
NGC 5676	dV37, HG73	3	32.60	0.16
NGC 5566	dV29+dV50, HG49+HG50	9	31.71	0.15
NGC 5866	dV30, HG78	2	30.48	0.23
NGC 6070	...	3	32.32	0.01
Grus	dV27, HG12+HG15	8	31.20	0.27
NGC 7320/7331 Pair	...	2	30.55	0.52
NGC 7537/7541 Pair	...	2	32.34	0.15

[a] Sources are dV: de Vaucouleurs 1975; HG: Huchra and Geller 1982.

[b] Quoted errors reflect the scatter in the data only. To these an additional zero point error should be added, which we estimate (perhaps optimistically) as ~0.2 mag.

for the pair given in Table 3, rather than the closer infall model distance.

Fornax.—Revisions in the data have led to a decrease of ~0.1 mag in distance modulus compared with the result of Aaronson *et al.* (1981). Combining this with a 0.1 mag increase for the Grus group removes the small discrepancy in infall velocity found for the two clusters by Aaronson *et al.*

NGC 2403–M81.—These galaxies, which may break up into two subgroups, form a well-defined relation. We have added to Figure 6*e* the possible member NGC 1560 (see de Vaucouleurs 1975).

Leo.—This appears to be one of the more confusing regions in the sky. Sandage and Tammann (1975) and Huchra and Geller (1982) consider Leo to be a single group, while de Vaucouleurs (1975) and Tully (1982) break Leo into three units—a foreground group consisting largely of the Leo Triplet (NGC 3623, 3627, and 3628), and two background groups. Our own data are more consistent with the latter view (see Fig. 6*f*). Note, however, that our Leo distance is not based on any of the conventional group members, but on a number of outlying galaxies.

NGC 3521.—This may not be a true group, as the individual galaxy distance moduli correlate almost precisely with redshift, accounting for the large magnitude scatter in Table 3.

Ursa Major.—Our data are richest for this cluster, and the Tully-Fisher relation is very well defined with small scatter (Fig. 6*g*). Remarkably enough, some of this scatter appears due to the loosely bound nature of the cluster, a point illustrated in Figure 7*a*. Here we have plotted distance modulus against redshift, and find a significant correlation ($r = 0.67$). The solid line shows the mean least squares fit to the data, and has a slope $b = 5.54 \pm 0.81$, while the dashed line shows the canonical slope of 5 based upon uniform Hubble flow. Although small, the deviation of the two lines is in the sense expected for a collection of galaxies slightly retarded from uniform expansion by their mutual gravitational attraction. In principle, one might calculate the density parameter Ω from these regressions as is done for the Supercluster

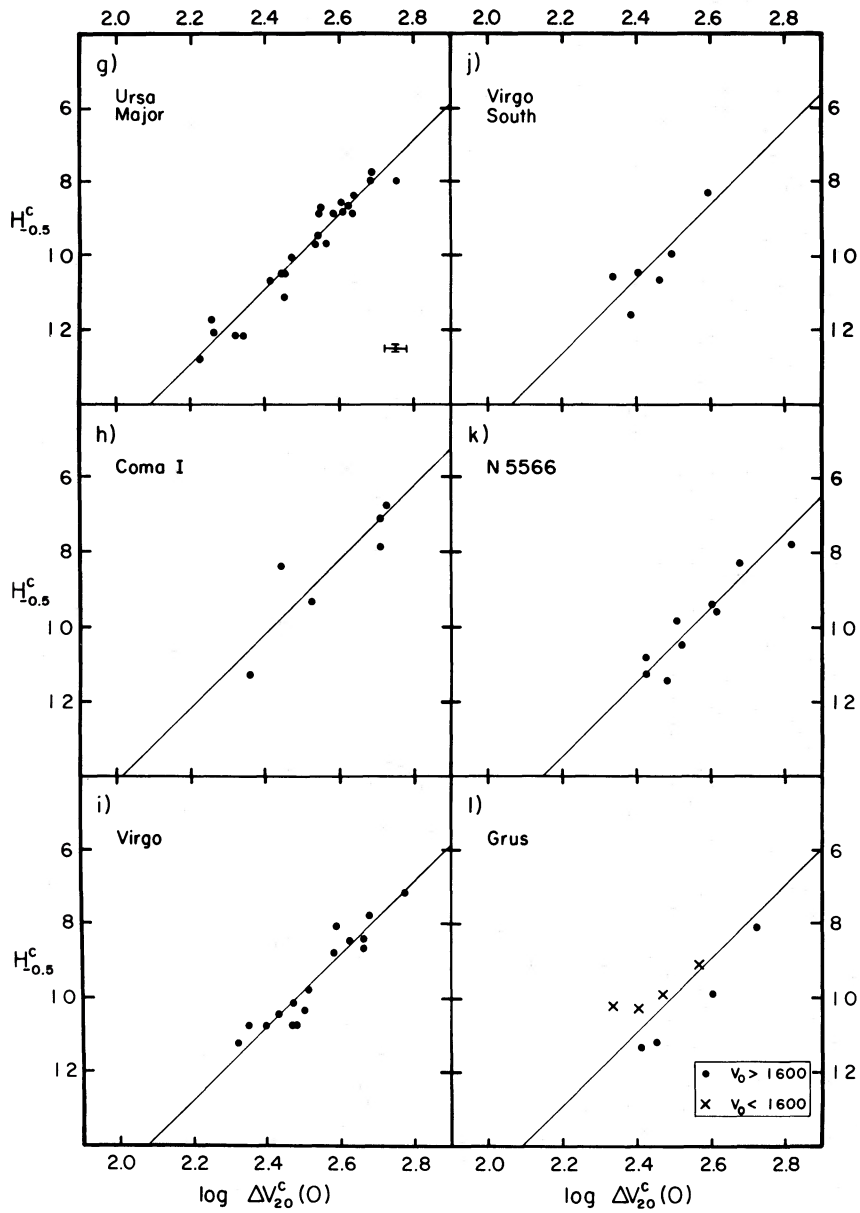

FIG. 6.—Infrared Tully-Fisher diagrams for selected nearby groups (see text for discussion). All solid lines have a slope of 10.

as a whole, but the result would be of low weight owing to the scatter and the small number of galaxies.

Coma I.—The galaxies in this group exhibit more scatter about the Tully-Fisher relation than any of the other groups in Figure 6. Interestingly, of the groups in Table 3 Coma I lies closest to the Virgo cluster itself. As discussed in AHMST, redshifts for galaxies near Virgo are not expected to be particularly well correlated with distance, and it may be that Coma I is not a group in the true sense.

Virgo.—Revisions of the data lead to a distance modulus $\sim$0.1 mag greater than found in Paper II.

Virgo South.—Galaxies in the so-called Southern Extension are often assumed to lie at the same distance as Virgo, and within the errors our sparse data support this view. However redshift is not expected to be well correlated with distance in this region (see de Vaucouleurs 1975 for an attempt at detailed mapping of the area).

M51.—Our distance to this group is based on the two outlying galaxies NGC 5073 and 5055.

NGC 5566.—This is another confusing region which may be broken up into two subgroups, although the galaxies considered all together form a well-defined Tully-Fisher relation (Fig. 6*k*).

Grus.—The conclusion of Aaronson *et al.* (1981) that this is not a group in the true sense has been strengthened further by revisions in the data. Distance

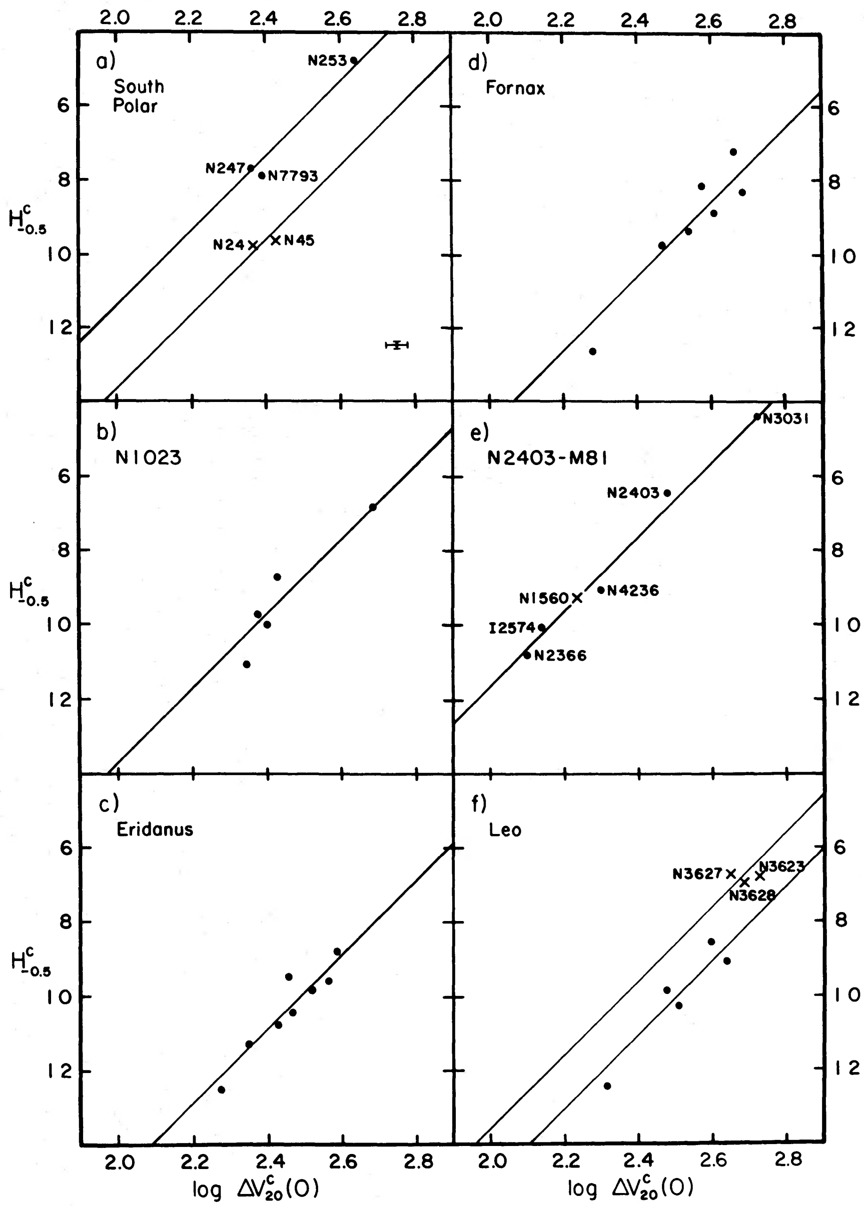

FIG. 6.—*continued*

modulus has been plotted against redshift in Figure 7*b*, and an almost perfect correlation is seen. The deviation of the least squares fit with slope $b = 6.52 \pm 0.70$ from a slope of 5 is again in the expected sense.

In Figure 8 we compare the results in Table 3 with distances to the same groups given by Sandage and Tammann (1975) and by de Vaucouleurs (1975, Table A1). Distances from these sources are based largely on tertiary indicators, i.e., H II regions sizes and luminosity classes. In Figure 8*a* we have supplemented the comparison with additional results based on only one galaxy; as might be expected, these points exhibit rather greater scatter. The significance of Figure 8 is that it demonstrates the good agreement in relative distance scale found by ourselves, Sandage and Tammann, and de Vaucouleurs; a similar good agreement was also found in Paper I. The systematic deviation in Figure 8*b* is simply an artifact of our having adopted the local Sandage-Tammann distance scale in our derivation of the Paper I calibration. Indeed, at small distances the agreement with the Sandage-Tammann moduli is excellent (Fig. 8*a*). At larger distances the small deviation from the slope of one apparent in Figure 8*a* would seem to have as its source the systematic errors in the Sandage-Tammann H II region diameters discovered by Kennicutt (1979).

c) *The Hubble Constant*

We calculate here in a straightforward manner the value of H_0 by adjusting the observed Virgo velocity-distance ratio for infall. First, adoption of the Sandage-Tammann zero-point scale yields a Virgo modulus of 31.24 ± 0.16 mag, where we have included in this error estimate the formal zero point uncertainty determined from scatter of the calibrators. Correction of the Virgo redshift (1019 ± 51 km s^{-1}—see Paper II) for a Local Group infall of 331 ± 41 km s^{-1} (AHMST) then leads to a Hubble constant $H_0 = 76 \pm 7$ km s^{-1} Mpc^{-1}. If instead the de Vaucouleurs zero-point is adopted, the result is $H_0 = 103 \pm 9$ km s^{-1} Mpc^{-1}. Finally, if we adopt the calibration from Paper I, the implied value for H_0 is then 82 ± 10 km s^{-1} Mpc^{-1}, a value we regard as our best current estimate of the expansion rate. Note that the error in this last result is dominated by an adopted uncertainty of 0.2 mag in zero point. Our preferred Hubble constant and the group distances from Table 3 can be scaled in a simple manner, if necessary, when current questions about the local distance scale are resolved.[6]

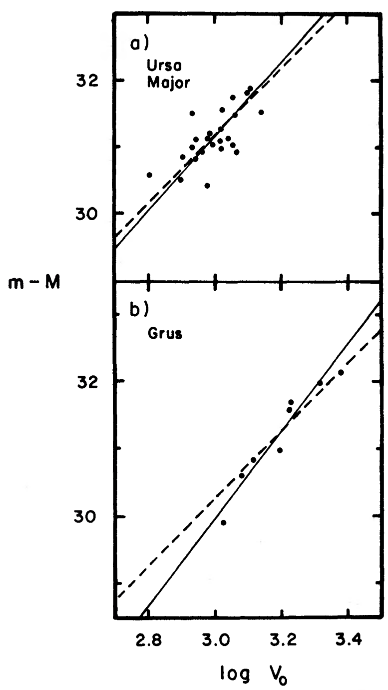

FIG. 7.—Distance modulus obtained from the calibration in Paper I plotted against redshift for spirals in the Ursa Major and Grus clouds. The solid lines are the mean least squares fits to the data, while the dashed lines have a slope of 5.

[6] An expansion rate ~15% larger was obtained by Aaronson *et al.* (1980), owing primarily to their measurements of an infall velocity ~150 km s^{-1} greater than that found by AHMST. The discrepancy may in part be a result of systematic diameter errors for galaxies in two of the four distant groupings studied by Aaronson *et al.* (Z74–23 and the Perseus Supercluster). This point will be addressed further in a future paper.

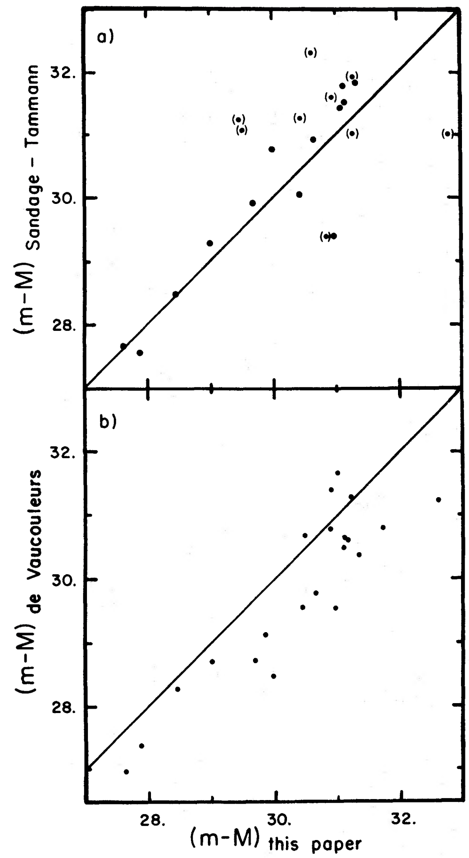

FIG. 8.—A comparison of group distance moduli derived in this paper with those given by Sandage and Tammann (1974) and by de Vaucouleurs (1975). Points surrounded by parentheses in Fig. 8*a* represent distances based on only one galaxy. The solid lines both have unit slope.

We conclude that current uncertainties and disagreements in the absolute distance scale and the value of H_0 can be reduced to two quantities: (a) the infall velocity toward Virgo; and (b) the distance scale in the neighborhood of the Milky Way, where the few available distances form the calibration basis for all global indicators. The former of these appears to be now well under control (AHMST), while it seems that considerable work by the astronomical community will be required before the latter is resolved.

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MARC AARONSON: Steward Observatory, University of Arizona, Tucson, AZ 85721

JEREMY MOULD: Robinson Laboratory, California Institute of Technology, Pasadena, CA 91125