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THE DISTANCES AND PROPERTIES OF A SAMPLE OF Sc I GALAXIES

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ABSTRACT

We have obtained H I spectra, optical photometry, and H-band photometry of a subsample of the Sandage-Tammann and Rubin *et al.* lists of distant Sc I galaxies. After eliminating galaxies of face-on or uncertain inclination, our final sample contains 20 galaxies in the velocity range 3000–13,500 km s^{-1}. The infrared Tully-Fisher method is used to derive individual distances to these spiral galaxies. After applying a correction for Malmquist bias, the sample yields a Hubble ratio of 91 ± 3 km s^{-1} Mpc^{-1}. This value is in substantial agreement with an earlier value based on a sample of distant cluster spiral galaxies. This Sc I sample has been reduced in the same way as the cluster sample. Furthermore, the same diameter system has been employed.

The good agreement between the cluster and the Sc I sample strongly argues that environmental effects do not influence the slope of the spiral IR Tully-Fisher relation and that the zero point of the relation is universal. These data also provide further verification of significant infall motion of the Local Group toward Virgo. Indeed, field Sc I galaxies in the south galactic pole yield a higher mean Hubble ratio than those in the north galactic pole.

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

I. INTRODUCTION

The determination of the form of the local (e.g., $v < 10{,}000$ km s^{-1}) velocity-distance relationship is complicated by the presence of systematic deviations from pure Hubble flow. The magnitude and direction of these deviations is uncertain, but their source is probably gravitational in origin. Early work on the infrared Tully-Fisher relation by Aaronson *et al.* (1980) demonstrated that distant clusters yielded a significantly higher Hubble ratio than Virgo. This discrepancy implied a departure from pure expansion motions due to the overdense Virgo Cluster. The infall of the Local Group toward Virgo was later confirmed by Aaronson *et al.* (1982*a*) from a detailed study of the Local Supercluster velocity field. These two studies suggest an infall velocity in the range from 300 to 500 km s^{-1}. It would not be unreasonable to expect that systematic motions of similar amplitude are present in the vicinity of other rich clusters such as Coma or Hercules.

As an additional check on these early results, we thought it important to study a field sample whose redshift is similar to that of the cluster sample of Aaronson *et al.* (1980). One advantage of employing a field sample is that it minimizes any possible environmental modification of the form of the infrared (IR) Tully-Fisher relation (see Giovanelli 1982). One disadvantage, however, is that the Malmquist bias may become important because we are dealing with a magnitude-limited sample. In principle, however, the correction for this bias is straightforward (see Aaronson and Mould 1983).

Our field sample was constructed from the field sample studied by Rubin *et al.* (1976) and Sandage and Tammann (1975). In § II we describe the choice of sample as well as the observing and reduction procedures. In § III we discuss the determination of inclinations and prune the sample down to those spirals whose inclinations are reliable. In § IV we describe the H I content, colors, and line widths of these spirals. Finally in § V we apply the IR Tully-Fisher relation for the purposes of deriving individual distances and Hubble ratios.

II. OBSERVATIONS

Our sample is chosen under the constraints that the galaxies have a probable inclination of greater than 45° and are accessible to Arecibo. Combining the surveys of Rubin *et al.* (1976) and Sandage and Tammann (1975) yielded the candidate

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TABLE 1

THE SAMPLE

Galaxy (1)	Sample (2)	V_{sys} (km s^{-1}) (3)	Flux Integral (Jy km s^{-1}) (4)	ΔV_{50} (km s^{-1}) (5)	ΔV_{20} (km s^{-1}) (6)	H (7)	Ap. Size (arcsec) (8)	Major Axis (9)	Minor Axis (10)
N7819[a]	R	4958	9.2	...	256	12.08	22.5	2.0	1.8
						11.69	34.4	...	...
0008+02	ST	(12722)	...	...	...	12.32	17.5	0.6	0.4
						12.09	22.5	...	...
N173[b]	R	4369	13.0	295	322	11.35	22.5	4.0	3.5
						10.89	34.4	...	...
						10.69	43.7	...	...
N180[b]	ST	5289	9.4	365	398	...	...	2.8	2.3
N182	ST	(5228)	...	...	...	10.69	22.5	2.3	1.8
						10.37	34.4	...	...
						10.27	43.7	...	...
N200	ST	5153	5.3	411	457	11.03	22.5	2.0	1.2
						10.51	34.4	...	...
N257[b]	ST	5270	11.7	394	437	10.86	22.5	2.2	1.6
						10.41	34.4	...	...
						10.25	43.7	...	...
N658[b]	ST	2989	18.0	305	344	10.80	22.5	3.5	1.7
						10.45	34.4	...	...
						10.39	43.7	...	...
N673[b]	ST	5180	11.9	321	355	11.23	22.5	2.3	1.7
						10.69	34.4	...	...
						10.58	43.7	...	...
N706[b]	ST	4993	4.6	287	317	10.90	22.5	2.1	1.7
						10.40	34.4	...	...
						10.24	43.7	...	...
IC 1743	ST	4545	6.1	409	466	10.42	22.5	2.1	0.9
						10.24	34.4	...	...
IC 173	R, ST	(13900)	...	...	...	12.14	17.5	1.1	0.9
						11.91	22.5	...	...
						11.52	34.4	...	...
U1498	ST	4742	2.5	260	345	12.29	17.5	1.0	0.5
						11.89	22.5	...	...
						11.59	34.4	...	...
IC 198	ST	9239	4.6	365	393	11.74	22.5	1.2	0.8
						11.52	34.4	...	...
N840	ST	7273	6.2	446	485	11.28	22.5	2.6	1.4
						10.97	34.4	...	...
						10.90	36.2	...	...
N877	...	3923	19.9	392	438	9.90	48.7	2.3	1.8
						9.59	54.4	...	...
N918[b]	R	1512	15.5	251	270	10.15	70.3	3.6	2.1
						9.81	22.5	...	...
IC 211[b,c]	R, ST	3266	5.2	...	225	12.66	34.4	2.6	2.1
						12.16	43.7	...	...
						12.10	22.5	...	...
U1995	ST	7302	3.7	321	351	12.34	34.4	1.7	0.9
						11.95	22.5	...	...
U2079	R	5647	7.7	239	280	12.56	34.4	1.8	0.8
						12.14	17.5	...	...
0744+28	R	8246	3.0	351	397	11.84	22.5	1.0	0.6
						11.58	34.4	...	...
						11.17	22.5	...	...
U4047	R	4293	5.9	250	332	11.48	34.4	1.8	1.0
						11.14	22.5	...	...
N2942[b]	R	4421	11.1	244	284	12.22	34.4	2.1	1.6
						11.60	22.5	...	...
U5543	R	(13586)	...	...	...	11.87	34.4	1.4	0.8
						11.44	22.5	...	...
1122+23	R	6471	6.1	179	196	12.23	34.4	0.9	0.6
						11.71	22.5	...	...
U6886	R	6980	5.1	360	394	11.49	34.4	1.3	0.9
						11.20	22.5	...	...
N4246	R	3721	13.9	350	376	12.05	34.4	2.4	1.2
						11.36	22.5	...	...
N4475	R	7396	3.1	380	409	12.04	34.4	2.0	1.0
						11.59	22.5	...	...

TABLE 1—*Continued*

Galaxy (1)	Sample (2)	V_{sys} (km s^{-1}) (3)	Flux Integral (Jy km s^{-1}) (4)	ΔV_{50} (km s^{-1}) (5)	ΔV_{20} (km s^{-1}) (6)	H (7)	Ap. Size (arcsec) (8)	Major Axis (9)	Minor Axis (10)
U8451	R	5276	5.3	370	392	12.16	34.4	1.8	1.0
						11.57	22.5	...	...
IC 900	R	7073	6.1	353	383	11.75	34.4	1.4	0.9
						11.20	17.5	...	...
U9006	R	7591	4.2	323	405	11.94	17.5	1.3	0.7
U9558	R	13481	2.1	420	460	12.77	22.5	1.1	0.7
						12.43	34.4	...	...
						12.09	22.5	...	...
N5829[b]	R	5685	7.9	172	204	12.31	36.2	2.0	1.6
						11.79	22.5	...	...
U11058	R	4755	4.4	289	323	11.85	36.2	1.6	1.2
						11.21	22.5	...	...
U11555	R	4851	7.2	158	199	12.15	34.4	1.9	0.9
						11.66	22.5	...	...
IC 1401	R	4717	5.9	358	381	11.93	36.2	2.1	0.7
						11.45	22.5	...	...
U12134	R	7389	13.0	410	507	11.98	34.4	1.8	0.7
						11.76	22.5	...	...
2346+05	ST	3812	2.3	147	183	12.98	22.5	...	...
U12810	ST	8113	3.9	437	463	11.79	34.4	1.8	0.7
						11.32	17.5	...	...
N7780	ST	(5125)	...	...	...	11.76	22.5	1.1	0.6
						11.44	34.4	...	...
						11.08	22.5	...	...
N7782	ST	5387	8.9	572	593	10.56	34.4	2.1	1.3
						10.10		...	...

NOTE.—Sources listed in col. (2) are: R, Rubin *et al.* 1976; ST, Sandage and Tammann 1975.
[a] Data from Fisher and Tully 1981.
[b] Correction for partial resolution exceeds 40%.
[c] Profile not available for Fig. 1.

list of 41 Sc I galaxies given in Table 1. Pencil-beam 21 cm observations made with the Arecibo 305 m spherical reflector in 1980 October were greatly aided by prior knowledge of all radial velocities. The H I data were taken and reduced in the manner outlined by Bothun *et al.* (1984; see also Sullivan *et al.* 1981). In particular, we used an autocorrelator configuration that yielded 454 independent channels over a velocity interval of 3700 km s^{-1} (18 MHz). This 18 MHz spectrum consists of two 10 MHz segments offset by 8 MHz from each other. Separate baselines are then fitted to the respective high-frequency and low-frequency ends before the individual segments are combined into one 454 point spectrum (for further details, see Bothun *et al.* 1984).

Infrared photometry for the sample was obtained with the 2.1 m telescope of the Kitt Peak National Observatory (KPNO) over the period 1980 spring–1982 spring. In addition, optical photometry was performed on a limited number of objects using the KPNO 1.3 m telescope in 1982 May. The observations and reduction of these data follow the procedures fully described in Aaronson *et al.* (1982*b*) and Bothun *et al.* (1984).

Tables 1 and 2 list the observational parameters of the program galaxies. In Table 1, column (1) gives the galaxy identifications. Column (2) identifies the galaxy as coming from Sandage and Tammann (1975, ST) or Rubin *et al.* (1976, R) or both. Columns (3)–(6) list the heliocentric H I velocity (or optical velocity for nondetections), the H I flux integral (uncorrected for partial resolution), and the observed 50% and 20% velocity widths. The line widths and their associated errors were calculated in the manner outlined by Aaronson *et al.* (1980). In general, the profile shapes are quite symmetrical and well behaved. Note that our H I data have a much higher signal-to-noise ratio than those of Rubin *et al.* (1976). Column (7) lists the observed H-magnitude, while column (8) gives the corresponding aperture size in arc seconds. Photometric uncertainties in the H-magnitudes are less than 0.03 mag in all cases. Columns (9)–(10) list Nilson (1973, hereafter UGC) major and minor axes. In those cases where the galaxy was not in the UGC, eyeball estimates of the "UGC equivalent" diameter are provided (see Aaronson *et al.* 1980 for details).

The 21 cm profiles are shown in Figure 1. These spectra were smoothed over 3 or 5 channels. Such a procedure introduces only a small (<5 km s^{-1}) bias into the derived line widths. This procedure is identical to that used in the reduction of cluster data, so any biases should effectively cancel. Random errors in line width and systemic velocity for these high signal-to-noise profiles are quite negligible (e.g., less than 10 km s^{-1}). U4047, 0744+28, N200, and N7782, the only galaxies with errors that exceed 10 km s^{-1}, have uncertainties in the widths that are 20–30 km s^{-1}. In three other cases (IC 1743, U1498, U12134), there appears to be artificial noise broadening of the 20% width. For these galaxies, the adopted velocity width is based on the 50% width multiplied by 1.10 (see Aaronson, Mould, and Huchra 1980). Finally, the 21 cm profile of U9006 is of insufficient quality to yield a reliable line width.

Table 2 lists the results of the optical photometry obtained for a limited number of galaxies. Column (1) gives the galaxy

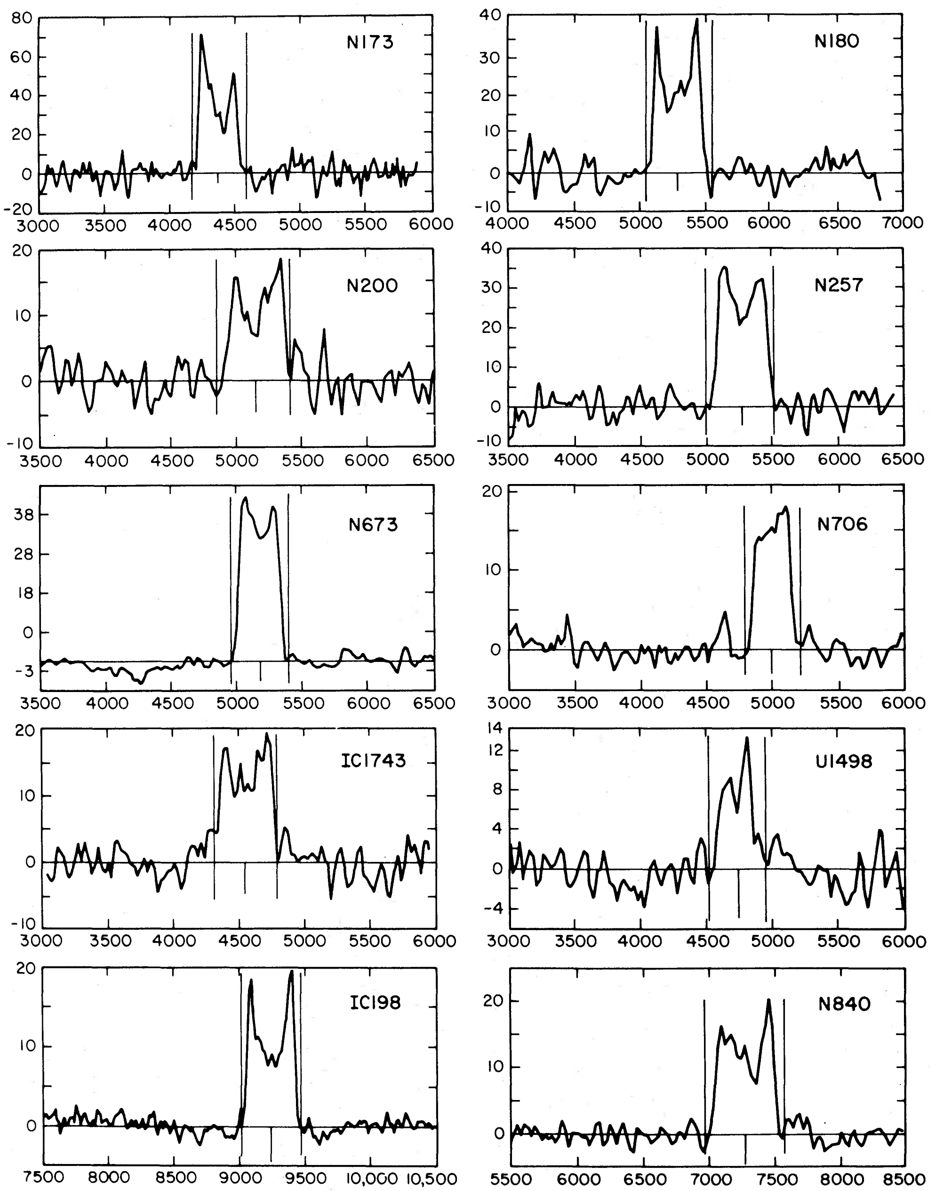

FIG. 1.—The 21 cm spectra of the sample galaxies. Abscissa is velocity in km s^{-1} and ordinate is flux density in mJy. The vertical lines represent the limits used in computing the line integral and velocity width.

ID while columns (2)–(6) give the raw optical magnitudes, colors, and aperture sizes. Errors in the colors are typically less than 0.02 in $B-V$ and $V-R$ and 0.04 in $U-B$. Total magnitudes and colors corrected for the effects of galactic extinction, internal reddening, and redshift can be derived from the raw colors from the procedures outlined by de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter RC2) as modified slightly by Bothun (1981). Finally, column (7) gives the corrected $(B-H)_{-0.5}$ value. $B_{-0.5}$ is obtained from our aperture measurements used in combination with the mean aperture-magnitude relation shown in RC2. This magnitude is then corrected for reddening before subtracting $H_{-0.5}$ to derive the $(B-H)_{-0.5}$ color. We estimate the uncertainty in this color to be approximately 0.2 mag.

We can compare these measurements with others. Peterson (1983, private communication) has done B and V observations of the galaxies tabulated by Rubin *et al.* (1976). Comparison of our photometry with his shows a difference of 0.02 ± 0.02 in $B-V$ and less than 0.1 mag in V; these values are well within the errors. Comparing our H I data for 12 galaxies in common with the sample of Rubin *et al.* (1976) yields a mean difference in systemic velocity of 0 ± 8 km s^{-1}. The mean differences in line widths and flux integral (corrected for partial resolution in the manner outlined by Sullivan *et al.* 1981) are -22 ± 26 km s^{-1} and 1.06 ± 0.30 Jy km s^{-1} respectively. A dispersion of 30% in flux integrals is typical among H I observations (Bothun *et al.* 1984; Sullivan *et al.* 1981).

Finally, we stress that although Sandage and Tammann (1975) and Rubin *et al.* (1976) specify these as Sc I galaxies, both the UGC and RC2 give considerably earlier classifications

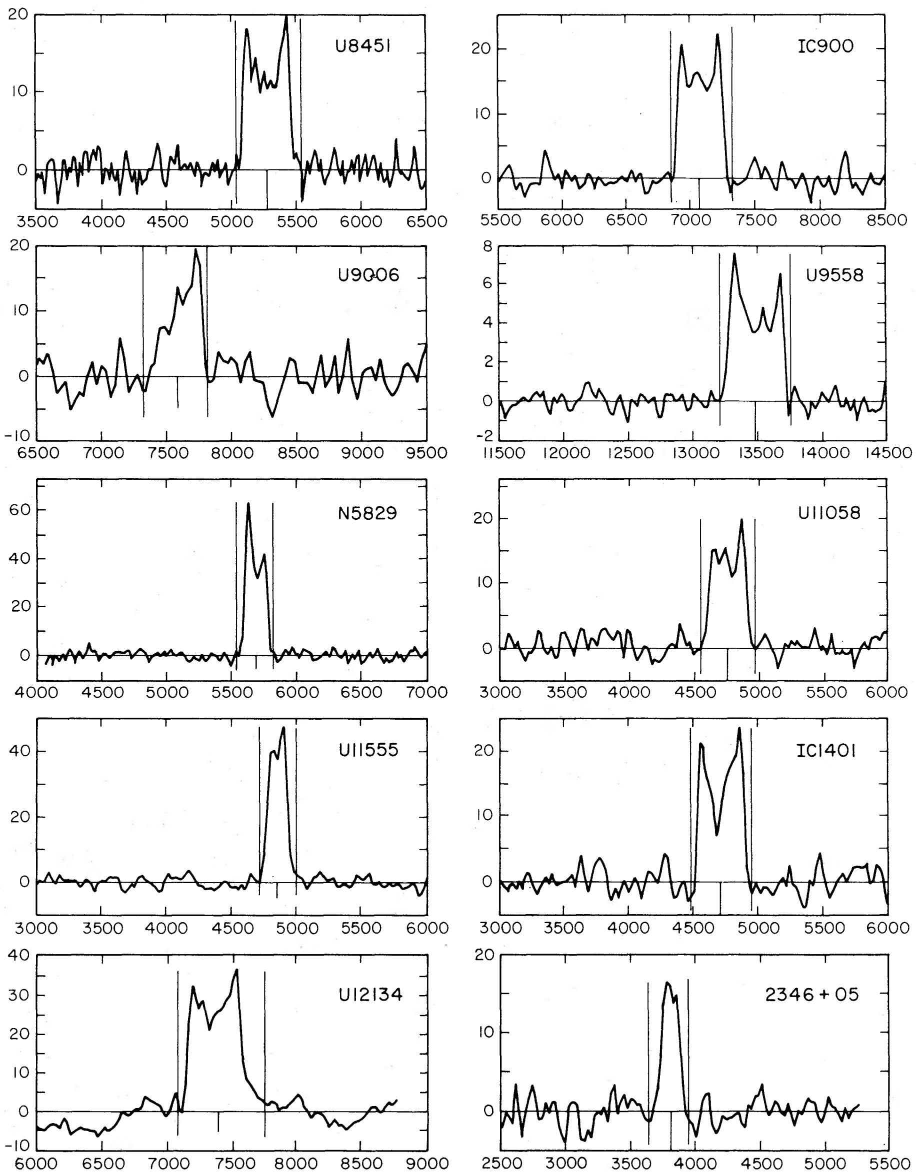

FIG. 1.—*Continued*

for some of them. For instance, N658, N706, and N7782 are all classified as Sb by the RC2. Moreover, the failure to detect N182 and N7780 may also imply that their types are earlier. It is perhaps better to describe the detected galaxies as H I-rich, high surface brightness, disk-dominated systems. Some times the spiral structure is evident, but in other cases the contrast between the arm and interarm regions is lost on the Palomar Observatory Sky Survey (POSS). However, since the IR Tully-Fisher relation is largely independent of morphological type (Aaronson and Mould 1983), the exact classification of these galaxies is irrelevant with respect to the distance scale.

III. INCLINATIONS AND DIAMETERS

A potentially serious problem confronting the present data is the difficulty of deriving reliable inclinations. Since the surface brightness and resolution of the arms are the means for classifying a galaxy as Sc I, our sample does not contain any highly inclined galaxies (e.g., $i > 75°$). In addition, many of the sample galaxies have highly uncertain inclinations. This results from an ill-defined underlying circular disk that yields ambiguous measures of the major and minor axes (e.g., the galaxy has only two arms with no underlying disk visible on the POSS; good examples are U2079 and U11555). Other times, the galaxies have distortions in the outer spiral structure (such as outlying H II regions) that may lead to spurious overestimates of the minor or major axis. Moreover, the central regions of many of these galaxies are overexposed on the POSS, and in some instances the definition of the spiral structure is lost. Perhaps all these characteristics of the sample explain why many are not classified as Sc galaxies in the RC2.

In order to better gauge the reliability of the inclinations

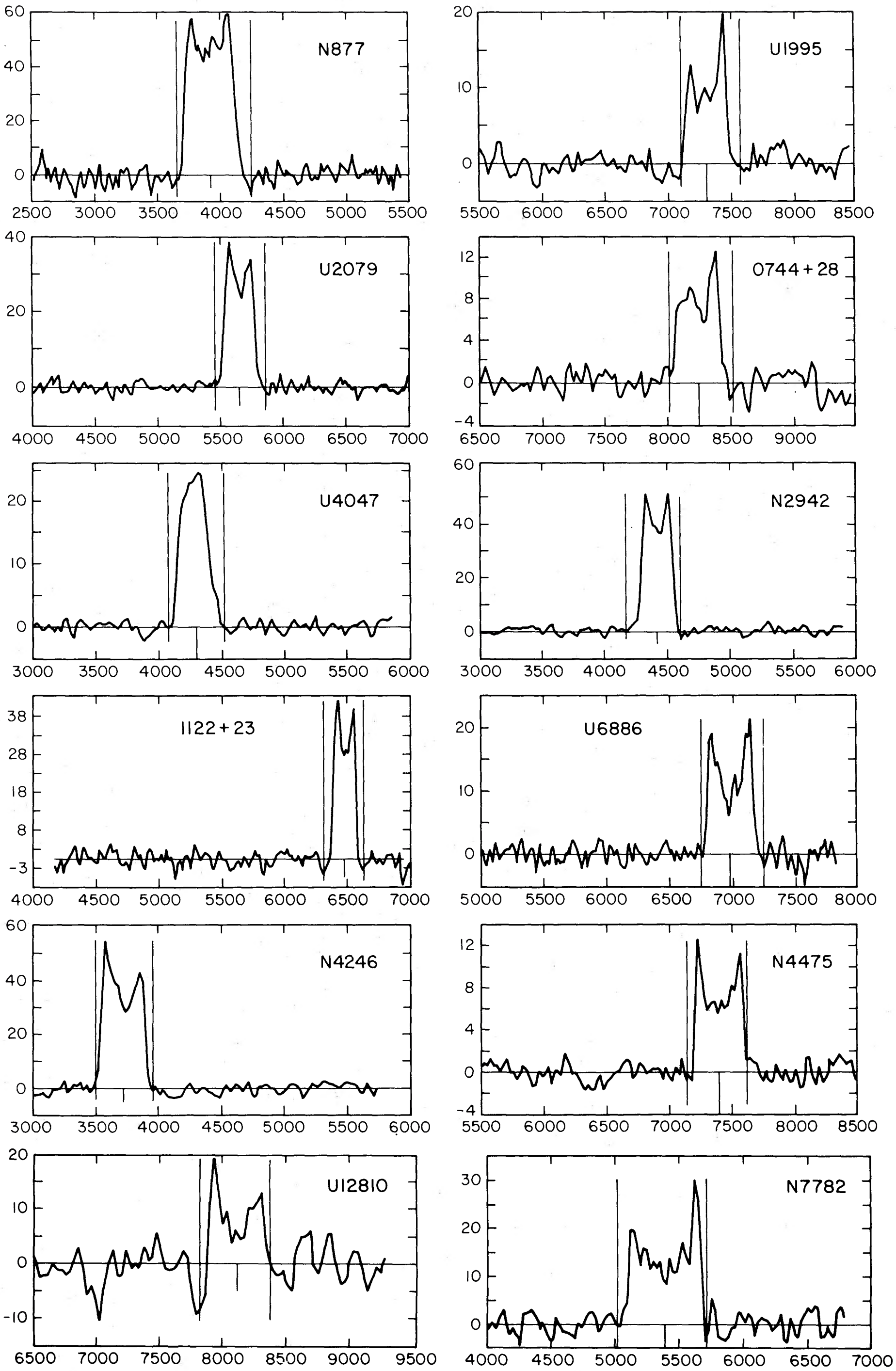

FIG. 1.—*Continued*

TABLE 2

Optical Photometry

Galaxy (1)	V (2)	Ap (3)	$B-V$ (4)	$U-B$ (5)	$V-R$ (6)	$(B-H)$ (7)
N173	13.19	58.6	0.83	0.22	0.75	...
	12.83	82.5	0.72	0.13	0.78	...
N182	13.42	35.6	1.05	0.42	0.86	...
	13.07	58.6	0.93	0.47	0.88	...
N200	13.42	35.6	0.77	0.16	0.84	3.5
	12.96	58.6	0.83	0.09	0.78	...
N257	13.49	35.6	0.79	0.23	0.86	3.6
	12.98	58.6	0.75	0.12	0.83	...
N658	13.37	35.6	0.69	0.12	0.79	3.3
	12.99	58.6	0.71	0.00	0.84	...
	12.85	82.5	0.67	−0.09	0.81	...
N673	13.67	35.6	0.71	−0.01	0.85	3.4
	13.05	58.6	0.67	−0.07	0.80	...
N706	13.28	35.6	0.71	0.03	0.81	3.4
	12.76	58.6	0.69	0.01	0.82	...
IC 1743	13.98	23.4	0.88	0.19	0.99	3.8
	13.61	35.6	0.81	0.12	0.95	...
U1498	15.04	17.7	0.68	0.02	0.84	3.2
	14.76	23.4	0.71	0.05	0.84	...
IC 198	14.77	23.4	0.76	0.11	0.84	3.6
N840	14.06	35.6	1.02	0.37	0.89	3.8
	13.78	58.6	0.88	0.29	0.89	...
IC 211	14.51	35.6	0.51	−0.19	0.66	2.8
	13.98	58.6	0.56	−0.14	0.66	...
U2079	15.44	23.4	0.68	0.05	0.87	3.0
	13.84	35.6	0.68	0.08	0.78	...
N2942	14.36	35.6	0.74	0.11	0.76	3.1
	13.73	58.6	0.65	0.08	0.70	...
	13.29	82.5	0.68	0.09	0.70	...
U5543	14.31	35.6	0.92	0.07	0.76	3.4
	14.04	58.6	0.73	0.11	0.78	...
1122+23	14.82	23.4	0.74	0.14	0.74	3.2
	14.34	35.6	0.68	0.09	0.76	...
U6886	14.08	35.6	0.80	0.24	0.86	3.6
	13.66	58.6	0.76	0.13	0.79	...
N4246	13.46	58.6	0.69	0.15	0.77	3.1
	13.16	82.5	0.65	0.11	0.75	...
N4475	14.03	58.6	0.72	0.17	0.78	3.3
U8451	13.95	58.6	0.74	0.19	0.78	3.1
	13.73	82.5	0.76	0.13	0.80	...
IC 900	13.38	58.6	0.64	0.05	0.72	3.1
	13.23	82.5	0.66	0.04	0.69	...
U9558	14.89	35.6	0.75	0.12	0.81	3.2
N5829	14.50	35.6	0.63	0.00	0.71	3.3
	13.89	58.6	0.58	0.00	0.71	...
	13.58	82.5	0.53	−0.05	0.67	...
U11058	14.04	35.6	0.81	0.19	0.82	3.4
	13.24	58.6	0.70	0.16	0.76	...
U11555	14.32	35.6	0.67	0.07	0.82	3.1
	14.02	58.6	0.56	0.03	0.83	...
U12134	14.58	35.6	0.78	0.17	0.81	3.1
	14.20	58.6	0.69	0.11	0.74	...
	14.02	82.5	0.68	0.13	0.80	...
U12810	14.96	23.4	0.78	0.22	0.89	3.5
	14.33	35.6	0.83	0.10	0.84	...
N7782	13.79	23.4	1.02	0.52	0.98	3.9
	13.26	35.6	1.03	0.42	0.92	...
	12.77	58.6	0.96	0.31	0.90	...
	12.54	82.5	0.88	0.29	0.93	...
N7819	13.96	58.6	0.65	0.04	0.79	3.2
	13.68	82.5	0.70	0.02	0.73	...

from the Sky Survey prints and have remeasured the inclinations and compared our results to others. This comparison is shown in Table 3 (note that six galaxies from Table 1 have been dropped as they were either nondetections, had no IR measures, or were very obviously face-on). Inclinations have been calculated from the axial ratio using the procedure outlined in Aaronson, Mould, and Huchra (1980). Table 3 lists the inclination obtained by using the axial ratio listed in the RC2 (or transformed to that system) as well as the inclinations derived by Sandage and Tammann (1975, designated ST). In addition, two of the authors (G. D. B. and J. P. H.) made independent measures of the axial ratios from the POSS blowups. The final adopted inclination shown in column (6) is a straight mean of the various estimates.

The sample galaxies have been divided into three quality bins regarding the inclination. Class A galaxies are those whose inclinations we judge to be reliable (these tend to be the most edge-on cases). Class B galaxies have adopted inclinations that are marginally acceptable. Class C galaxies are ones whose nominal inclinations are highly uncertain and generally include

TABLE 3

Table of Inclinations

Galaxy (1)	RC2 (2)	ST (3)	J. P. H. (4)	G. D. B. (5)	I (6)	Class (7)
N7819	35	...	...	30	<40	C
N173	40	45	54	50	47	C
N182	41	...	...	40	40	C
N200	61	68	71	74	68	B
N257	46	55	59	53	53	B
N658	61	66	65	65	64	B
N673	41	47	44	48	45	B
N706	43	53	40	38	43	C
IC 1743	68	68	68	68	68	A
U1498	62	65	58	65	63	A
IC 198	59	66	67	58	62	B
N840	58	70	70	68	66	B
N877	43	...	...	40	42	C
N918	55	55	...	55	55	A
IC 211	41	53	...	40	41	C
U1995	62	62	63	61	62	A
U2079	66	...	72	71	69	C
0744+28	52	...	54	49	52	B
U4047	54	...	...	60	57	C
N2942	39	...	55	49	47	C
1122+23	0	...	25	0	<40	C
U6886	48	...	56	53	52	B
N4246	59	...	68	64	64	B
N4475	60	...	64	65	63	A
U8451	61	...	66	61	62	B
U9006	60	...	...	62	61	B
IC 900	52	...	53	53	53	A
U9558	60	...	60	60	60	A
N5829	31	...	...	...	<40	C
U11058	41	...	53	51	48	C
U11555	59	...	...	67	63	C
IC 1401	70	...	77	73	73	A
U12134	73	...	73	73	73	A
U12810	69	76	75	74	73	A
N7782	59	53	67	67	61	A

derived from axial ratios, we have made 9 times blowups less inclined or optically disturbed galaxies, or both. In the derivation of Hubble ratios, we use the adopted inclinations listed in column (6) of Table 3 and consider only class A and B galaxies, none of which have inclinations less than 45°.

Another possible source of systematic error involves galaxy diameters. The diameter system used to determine the $H_{-0.5}$ magnitudes of the galaxies under consideration here is identical to the system described in detail by Aaronson *et al.* (1980). In essence, this system transforms UGC diameters to the RC2 scale. Therefore, any systematic errors in the UGC scale will lead to systematic errors in the determination of $H_{-0.5}$ and the Hubble ratio. Presently, we are unsure if such systematic effects are contaminating our results. In order to clarify the situation, we have acquired B and R CCD frames of approximately 200 cluster spirals and will report on possible diameter errors in a future paper. Of course, what really matters in the practical application of the Tully-Fisher relation is an accurate match of the IR aperture size to the radius at which the rotation curve flattens out. Variations in the ratio of these two quantities, caused by differences in the forms of the rotation curve and differences in mass density (surface brightness profiles), is a major source of scatter in the observed IR magnitude–line width relation.

In addition, Romanishin *et al.* (1982) find there is a noticeable displacement in the IR Tully-Fisher relation for a sample of low surface brightness spirals relative to normal spirals. In order to correct for this observed displacement, those authors postulate that a correction to the $H_{-0.5}$ magnitudes is required for galaxies of low surface brightness. Since our sample contains mostly high surface brightness spirals, might a similar correction, but of opposite sign, be required? Again, the CCD data will allow a more quantitative assessment of the dependence of $H_{-0.5}$ magnitude on surface brightness. For the purposes of the present paper, any such correction is unwarranted as these spirals occupy the same region of the IR Tully-Fisher relation as the cluster spirals of similar luminosity, i.e., a displacement is *not* observed. The Romanishin *et al.* (1982) correction is most likely a manifestation of the result noted by Bothun, Balick, and Skillman (1982). That is, for certain kinds of late-type spirals, an aperture size corresponding to $\log A/D = -0.5$ is simply too small as the rotation curve keeps rising at this radius. As noted by Romanishin *et al.* (1982), observations through larger apertures are required to properly locate these spirals on the IR Tully-Fisher relation.

IV. GENERAL PROPERTIES OF THIS SAMPLE

Table 4 summarizes the mean global properties of the disk-dominated galaxies that comprise the present sample. Distance-dependent quantities have been calculated by using a uniform flow model with a Hubble ratio of 100 km s^{-1} Mpc^{-1}. One result of immediate interest is that the mean $\log M_H/L_B$ value (~ -0.38) for our sample of *luminous*, high surface brightness disk galaxies is similar to (if not higher than) that obtained for late spirals of much lower absolute magnitude (e.g., M33 type galaxies; cf. Fisher and Tully 1981). In fact, one galaxy, U12134, has the largest H I content ($\sim 3 \times 10^{10}\ M_\odot$) we have determined yet among the 500 or so H I detections obtained at Arecibo. With the increased sensitivity now available at Arecibo, galaxies such as these can be detected out to redshifts of approximately 0.06.

TABLE 4

MEAN PROPERTIES OF THIS SAMPLE

Property	Value	N
$(B-V)_0^{T}$ [a]	0.61 ± 0.02[b]	29
$(U-B)_0^T$	0.00 ± 0.02	29
$(B-H)_{-0.5}$	3.3 ± 0.05	27
$V_{20}(0)$ (km s^{-1})	467 ± 20	20
Log $M_{\rm H}$[c,d] ($M_\odot$)	9.8 ± 0.04	32
$H^c_{\rm abs\,-0.5}$ [c]	-22.8 ± 0.15	20
Log $M_{\rm H}/L_B$ $(M_\odot)/(L_\odot)$ ...	-0.38 ± 0.04	27

[a] We assume $A_b = 0$ at the poles.
[b] Error quoted is error in the mean.
[c] $H_0 = 100$.
[d] Includes correction for partial resolution.

Another intriguing global parameter of our sample galaxies is their $(B-H)_{-0.5}$ color (see Table 2 for individual entries). Tully, Mould, and Aaronson (1982) and Wyse (1982) have recently discovered a color-magnitude relation for spiral galaxies. The galaxies in the present sample have observed $(B-H)_{-0.5}$ colors that are consistent with those predicted from the line width–color relation given by Tully, Mould, and Aaronson (1982). However, these galaxies are remarkable in that their H I content is extraordinarily high for either their $(B-H)_{-0.5}$ color or their line width. In particular, the mean $\log M_H/L_{H_{-0.5}}$ (hydrogen mass normalized to infrared *not* blue luminosity) value of the spirals with measured $(B-H)_{-0.5}$ colors is -0.50 ± 0.06 compared with a value of -0.90 ± 0.05 for galaxies of similar color in the Local Supercluster sample (which also includes only H I detections) of Aaronson *et al.* (1982*b*; see Bothun 1984 for details). Furthermore, our late-type high-luminosity galaxies are significantly redder (by ~ 1 mag) than morphologically similar, but lower luminosity Sc galaxies (cf. Tully, Mould, and Aaronson 1982).

The observation that these "bulgeless" galaxies are red in $(B-H)_{-0.5}$ and yet have high H I content and current star formation (best manifested by the strength of the arms) is an important one. If our sample galaxies are not anomalously dusty, then their $(B-H)_{-0.5}$ color suggests a high ratio of old to new stars or a very metal rich giant population, or both conditions. Alternatively, their red colors may be due to the influence of a high concentration of red supergiants following a very recent burst of star formation. However, both observational (Aaronson 1977) and theoretical evidence (Renzini 1981) mitigate against this circumstance.

If the star formation rate (SFR) in the disks of these luminous galaxies is governed by an exponential decline, it is difficult to understand their present-day high H I content, compared with earlier galaxies of similar luminosity. However, if the disk SFR has been quasi-constant over a Hubble time, then perhaps these galaxies started out with a very large reservoir (mass) of H I and the universe is not yet sufficiently old for this reservoir to have been depleted through star formation. Alternatively, continuous star formation in the disk could be interrupted by periods of quiescence. Indeed, Schommer and Bothun (1983) have discussed the properties of a sample of small B/D, H I rich, but very red (mean $B-V \approx 0.78$; mean $(B-H)_{-0.5} \approx 3.6$) spirals in terms of their possible relation to the more actively star-forming spirals of this paper. Those authors offer the suggestion that Sc I galaxies can "hide" in a dormant stage where they would appear as smooth-armed, small B/D spirals that have high H I content and large line widths.

Thus, the H I and line width properties of these spirals imply that mass or mass density cannot be the only important parameter behind the Hubble sequence. There do exist galaxies without bulges that nevertheless have large line widths, large masses, and active star formation. This is important in the context of the possible correlation between morphological type and maximum rotational velocity. For instance, Rubin *et al.* (1982) have presented a study of the rotational properties of Sb galaxies and assert that any magnitude–line width relation depends strongly on Hubble type. In contrast, Aaronson and Mould (1983) do not see any strong Hubble type dependence in their data. The reasons for this discrepancy are not apparent but probably ultimately involve inherent differences between the two samples. With regard to this controversy, we note that the mean corrected line width of our sample is 467 ± 20 km s^{-1}, which is virtually identical to the value of 463 ± 21 km s^{-1} obtained for the Sb sample of Rubin *et al.* (1982). However, this value is significantly larger than the value of 359 ± 20 km s^{-1} obtained for the Sc sample of Burstein *et al.* (1982). Interestingly, two galaxies (IC 1401, U12810) originally classified as Sc I by Rubin *et al.* (1976) and Sandage and Tammann (1975) now appear as Sb in Rubin *et al.* (1982).

V. INDIVIDUAL DISTANCES AND HUBBLE RATIOS

The application of the IR Tully-Fisher relation in the derivation of galaxian distances has been fully discussed by Aaronson, Huchra, and Mould (1979). Examples of this application can be found in Aaronson and Mould (1983) and references therein. In this section, we use the relation to derive distances and Hubble ratios to our sample using the slope and zero point of Aaronson, Mould, and Huchra (1980). The calibrating relationship that is used is based *only* on the Sandage-Tammann (1975) distances to M31 and M33 and is blindly applied to all galaxies irrespective of their environment. If the slope or zero point, or both, of this relation are environment dependent, then application of this relation to the cluster data will produce biased values. It is precisely this bias that we are testing for in the present sample.

Figure 2 demonstrates that this sample does form an IR magnitude–line width relation. Only galaxies of class A and B (see Table 3) appear in this figure. For the purposes of this figure, absolute magnitudes were calculated using a uniform Hubble flow. The actual value of the Hubble ratio is, of course, irrelevant. Over a somewhat limited range in magnitude (3 mag), the data are fitted fairly well by a line of slope 10. The scatter about this line is 0.33 mag. The actual fit was accomplished by finding the slope 10 line which best minimized the residuals.

Table 5 summaries the distance derived using the IR Tully-Fisher relation. Again, the galaxies listed in column (1) include only objects of inclination class A and B. As discussed by Aaronson, Mould, and Huchra (1980), low-inclination galaxies (i.e., class C) yield systematically lower Hubble ratios because of the tendency to underestimate the proper inclination for face-on galaxies owing in part to the opening of the spiral arms along the minor axis. Also, we have excluded one galaxy (N918) with $v < 3000$ km s^{-1} in order to eliminate any

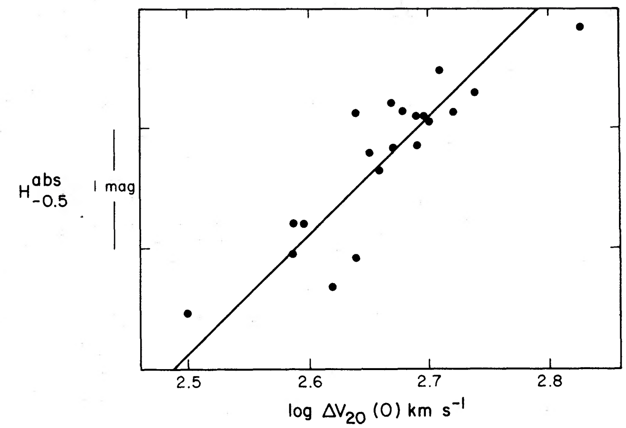

FIG. 2.—Infrared magnitude/H I velocity width relation for the sample of 20 galaxies listed in Table 5. Absolute magnitudes were calculated assuming a uniform Hubble flow. Solid line has a slope of 10. The total range in absolute magnitudes is 3 mag. The two points that lie conspicuously below the line are N4246 and U8451. N4246 lies near the Virgo Supercluster, while U8451 is in the Coma Supercluster. Possible perturbations from these mass concentrations may then be responsible for the 2 σ displacement of these points from the mean relation.

perturbing effects of the Local Supercluster. H-magnitudes, corrected for foreground reddening and surface brightness dimming according to equation (7) of Aaronson *et al.* (1980) and referred to an isophotal diameter of log $A/D = -0.5$, are listed in column (2). Velocity widths corrected for inclination and redshift according to equation (1) in Aaronson *et al.* (1980) are listed in column (3). Absolute H-magnitudes are calculated from equation (6) in Aaronson, Mould, and Huchra (1980). The resulting distance moduli and distances are given in columns (4) and (5). The galactocentric redshift in column (6) [calculated from 300(sin L)(cos b)] is then used to derive the Hubble ratio in column (7).

The distances and Hubble ratios that result from the present sample are expected to be biased because of its magnitude-limited nature. This is the familiar Malmquist effect. Since the distribution in magnitude at fixed velocity width is roughly Gaussian, it is possible to correct for this bias in a straightforward manner (Aaronson and Mould 1983). We have done so in the final two columns of Table 5 by adding $1.38\sigma^2$ to $H_{-0.5}{}^c$ and recalculating the distance moduli and Hubble ratios.

Aaronson and Mould (1983) found that the scatter in the IR Tully-Fisher relation was approximately 0.45 mag (see Fig. 1 of Aaronson *et al.* 1982*b*). This in turn leads to a correction of 0.28 mag in distance modulus. There are two reasons why it is likely that a scatter of 0.45 mag is too large. First, the sample is not purely magnitude limited. Second, the intrinsic scatter in the relation is certainly less than the observed scatter, and properly it is the former quantity that should be used. Unfortunately, the value of the intrinsic scatter in the IR Tully-Fisher relation is an elusive quantity. Hence, we are quite uncertain what value of σ properly should be used. For instance, the formal scatter in Figure 2 is considerably less and has a value of 0.33 mag, which leads to a correction of 0.15 mag in distance modulus. In the final two columns of Table 5 we list the corrected Hubble ratios that arise using the two estimates for the scatter. In the following discussion, we use the corrected

TABLE 5

DISTANCES AND HUBBLE RATIOS

GALAXY[a] (1)	$H_{-0.5}$[c] (2)	$\Delta V(0)$ (km s^{-1}) (3)	$m-M$ (4)	r (Mpc) (5)	V_0 (km s^{-1}) (6)	V_0/R[b] $\sigma=0$ (7)	$\sigma=0.33$ (8)	$\sigma=0.45$ (9)
N200	10.51	485	33.59	52.3	5290	101	95	89
N257	10.34	538	33.88	59.9	5418	91	85	82
N658	10.24	379	32.26	28.3	3115	110	102	96
N673	10.51	494	33.67	54.3	5295	98	91	86
IC 1743	10.19	477	33.21	43.7	4662	106	99	93
U1498	12.00	316	33.23	44.2	4835	110	102	96
IC 198	11.68	432	34.26	71.2	9334	131	122	116
N840	10.83	518	34.21	69.4	7357	106	100	93
U1995	12.05	388	34.17	68.2	7243	106	100	93
0744+28	11.43	490	34.56	81.8	8185	100	94	88
U6886	11.35	488	34.47	78.3	6853	88	82	77
N4246	11.12	413	33.51	50.4	3610	72	67	63
N4475	11.55	448	34.29	72.2	7382	102	96	90
U8451	11.68	436	34.31	72.7	5324	73	68	64
IC 900	11.39	469	34.33	73.4	7025	96	90	84
U9558	12.51	509	35.80	144.6	13529	94	89	83
IC 1401	11.49	392	33.64	53.8	4922	91	85	80
U12134	11.77	460	34.63	84.3	7617	90	84	81
U12810	11.38	471	34.34	73.9	8271	112	105	99
N7782	9.91	666	34.38	75.0	5569	74	69	66

[a] NGP galaxies are: 0744+28, U6886, N4246, N4475, U8451, IC 900, U9558. The rest are SGP.

[b] Col. (7) gives Hubble ratio assuming no Malmquist correction. Col. (8) gives correction using $\sigma = 0.33$ ($1.38\sigma^2 = 0.15$ mag). Col. (9) gives correction using $\sigma = 0.45$ ($1.38\sigma^2 = 0.28$ mag).

Hubble ratios listed in column (8) of Table 5 as they represent some middle ground between two possible extremes.

The mean corrected Hubble ratio and its scatter (i.e., per point scatter) for the 20 spirals in Table 5 is 91 ± 14 km s^{-1} Mpc^{-1}. This result is in good agreement with that found for four distant clusters by Aaronson *et al.* (1980) and with the 10 cluster sample of Aaronson *et al.* (1984). There has been some controversy over the role of the environment in determining the H I properties of spiral galaxies. Certainly there do seem to be detectable differences in gas content and galaxy type in very dense regions (e.g., Coma) (see Dressler 1980; Bothun, Schommer, and Sullivan 1982), but, in general, the sample galaxies from which Aaronson *et al.* (1980, 1984) derive their conclusions do not come from regions nearly this dense. The agreement in Hubble ratios between the cluster samples and this fairly isolated sample shows that environmental effects do not appear to be important in the practical application of the IR Tully-Fisher relation. In other words, *the zero point of the relation is universal.*

This result does not support the statements of Giovanelli (1982) regarding the dependence of M/L on the local density of galaxies. The cluster sample of Aaronson *et al.* (1984) has a range in projected density similar to that of the Perseus Supercluster sample of Giovanelli (1982). In this cluster sample, we have searched for a dependence of M/L_B and, more importantly, M/L_H on surface density and have failed to find any trend. There is hence no indication that the M/L_H ratios of our cluster spirals are different in any way from either the present field sample or the sample of local calibrators. However, there does appear to be a dependence of M/L_H on luminosity which is most noticeable at the low-luminosity end ($H_{-0.5} < -20.5$) (Romanishin *et al.* 1982; Aaronson and Mould 1983; Bothun 1984). The mean luminosities of the galaxies in both the present sample and the cluster sample are well above this value.

The mean Hubble ratio for our distant field sample is significantly greater than that for Virgo, for which the same zero point a Hubble ratio of 60 is seen (Aaronson and Mould 1983). Thus, the field sample presented here provides yet further evidence for the existence of a significant infall velocity toward Virgo. The amount of infall can be estimated from the Virgo distance (16.2 Mpc: Aaronson and Mould 1983), times the mean Hubble ratio of the present sample (91) minus the Virgo redshift (1019 km s^{-1}) which yields 455 ± 50 km s^{-1}. This value is higher than the infall velocity found by Aaronson *et al.* (1982*a*) based on a study of galaxies in the Local Supercluster. This may in part be a consequence of the high mean luminosity of the present sample coupled with intrinsic curvature in the IR Tully-Fisher relation (see Aaronson and Mould 1983). However, curvature is not seen in the sample of local calibrators, and hence any attempt to correct for the effect would not modify the present result. Better consistency with Aaronson *et al.* (1982*a*) would be achieved by using the more extreme Malmquist correction (Table 5, col. [9]).

Moreover, the galaxies in the north galactic pole (NGP) yield a mean Hubble ratio of 83 ± 4 which is lower than the ratio for those in the south galactic pole (SGP), 95 ± 4; this is a marginally ($2.2\,\sigma$) significant difference. The infall of the Local Group is once again revealed in this asymmetry. The amount of infall implied is 458 ± 75 km s^{-1}, in good agreement with the above. However, this method of determining the infall velocity is very uncertain owing to the poorly defined mean redshifts of the NGP and SGP samples.

Several recent infall studies, heavily weighted by galaxies outside the Local Supercluster, have suggested an infall velocity in the range 400–500 km s^{-1} (Aaronson *et al.* 1980; Tonry and Davis 1981; Hart and Davis 1982). These results could be reconciled with the smaller infall of Aaronson *et al.* (1982*a*) if the Local Supercluster itself is participating in bulk motion. The present results give some support to this, but our sample is small and the proper correction for the Malmquist effect is uncertain. A smaller value (i.e., approximately 350 km s^{-1}) for the total Virgocentric motion cannot be convincingly ruled out.

Finally, we would like to emphasize that application of the IR Tully-Fisher relation to the Sandage-Tammann sample of Sc I galaxies yields a Hubble ratio and infall velocity significantly larger than the reported value (Sandage and Tammann 1975). The reasons for this discrepancy remain unclear.

VI. SUMMARY

We have used a sample of distant Sc I galaxies as probes into the Hubble flow. Our basic result is twofold. (1) These disk-dominated, high surface brightness galaxies are extraordinary in many of their properties. Although morphologically similar to less luminous examples, these galaxies are significantly redder, though not significantly more poor in gas. This suggests that at least some galaxies can manage to put a substantial old population in a disk instead of in a bulge, and yet continue to have present-day star formation. Possibly this behavior can be understood in terms of stochastic star formation operating even in luminous galaxies. (2) Application of the IR Tully-Fisher method to this sample yields a Hubble ratio which is similar to the value obtained over the same velocity range but in a much different environment. This demonstrates that the environment has had a negligible effect on the form of the Tully-Fisher relation in most practical applications. Moreover, the galaxies in the south galactic cap give a systematically higher value than the galaxies in the north galactic cap, a result independent of the Malmquist correction. Overall, our sample yields a most probable range of values for the distant Hubble ratio of 85–97 km s^{-1} Mpc^{-1} and an infall toward Virgo of 350–500 km s^{-1}. More precise values are beyond the limits of the present data.

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