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ASTRONOMY
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A New Method of Determining Distances to Galaxies

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Summary. A good correlation between a distance-independent observable, global galaxian H I profile widths, and absolute magnitudes or diameters of galaxies offers a new extragalactic distance tool, as well as potentially being fundamental to an understanding of galactic structure. The relationships are calibrated with members of the Local Group, the M81 group, and the M101 group and have been used to derive distances to the Virgo cluster ($\mu_0 = 30^{\mathrm{m}}.6 \pm 0^{\mathrm{m}}.2$) and the Ursa Major cluster ($\mu_0 = 30^{\mathrm{m}}.5 \pm 0^{\mathrm{m}}.35$). A preliminary estimate of the Hubble constant is $H_0 = 80$ km/s/Mpc.

Key words: galaxies — distances — neutral hydrogen

I. Introduction

We propose that for spiral galaxies there is a good correlation between the global neutral hydrogen line profile width, a distance-independent observable, and the absolute magnitude (or diameter). It is well known that the intrinsic luminosity of a galaxy is correlated with the total mass, which is a derivative of the global profile width and is linearly dependent on distance (cf. Roberts, 1969), and that comparison of the total mass with such parameters as hydrogen mass, luminosity, and neutral hydrogen surface density can be used as a distance tool (cf. Dieter, 1962b; Roberts, 1962; N. Heidmann, 1969; Allen, 1970; Balkowski et al., 1973; Shostak, 1974). Balkowski et al. (1974) noted a correlation between H I profile widths and luminosities among late type spirals and irregulars as did Rogstad and Shostak (1972) and Shostak (1975) for samples of Scd galaxies, although they did not give it a distance application. Mayall (1960) and Brosche (1971) have claimed that the maximum rotation velocity is dependent on morphological type (alternately, Gouguenheim 1969 has related total mass and type). It is our contention that this correlation is primarily an accident of the fact that earlier systems that have been studied are intrinsically larger than later systems. The principal correlation should be with luminosity, with modest, if any, type dependence. This point is important with regard to the internal structure of galaxies, as well as offering a valuable tool for the measurement of extragalactic distances.

The basic difficulty with establishing the relation, and presumably the reason why it has essentially escaped notice, is that if the calibrating systems do not have extremely well known absolute or relative distances, the observational scatter thus introduced renders the relation of little use. We will attempt to demonstrate the effect in two ways: (i) based on nearby systems with well determined distances, and (ii) based on systems in clusters, hence at the same relative distance. A comparison of the two analyses will permit a preliminary determination of the Virgo and Ursa Major cluster distances.

II. Nearby Galaxies

We shall first look for the proposed relation in the nearby "calibrator" galaxies, each with:

(i) a well determined distance;
(ii) accurately known photometric properties;
(iii) an accurately known global hydrogen profile width; and
(iv) a sufficient inclination (exceeding 45° from face-on) so that there is no appreciable error in correcting the hydrogen profile for projection effects.

Criterion (i) restricts the sample to the large members of the Local Group and the members of the M81 group, the sole systems with distances directly related to the cepheid scale [we accept the proposition by Sandage and Tammann (1974a, b), hereafter ST I and II, that the dispersion in distance in this latter group is not large since, in fact, only NGC 2403 has a distance directly determined by cepheids]. The sample can be augmented slightly by accepting the Sandage and

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Table 1. Source of hydrogen profiles

Galaxy \ Source	AHGH	D	D^2	GD	GW	JD	R^2W	SR	V	New	Adopted
M31			535	(565)							535
M33		(205)	202			(190)			194		198
M81					450						450
NGC 2403								265			265
NGC 4236							195	192		175	195
IC 2574							115			117	117
NGC 2366			102							115	115
NGC 5204	126									129	127
NGC 5585	166									166	166
Ho IV	106									100	103

Notes:

1. Entries are H I line profile widths at 20% of maximum intensity, corrected for frequency resolution effects according to:

$\Delta V_c = \Delta V_{20} - \sigma^2/100$ km/s

where ΔV_c is the corrected width, ΔV_{20} the observed width and σ the instrumental frequency resolution, all in kilometers per second

2. *References*

AHGH: Allen, van der Hulst, Goss and Huchtmeier (1975)
D: Dieter (1962a)
D^2: Dean and Davies (1975)
GD: Gottesman and Davies (1970)
GW: Gottesman and Weliachew (1975)
JD: de Jager and Davies (1971)
R^2W: Rogstad, Rougoor and Whiteoak (1967)
SR: Shostak and Rogstad (1973)
V: Volders (1959)
New: Our observations with 91-m and 43-m telescopes at NRAO. Profiles given in the appendix

Table 2. Nearby galaxies

	(1) Type	(2) Lc	(3) Δ	(4) m_{pg}	(5) A_B	(6) A_ξ	(7) $M_{pg}(o)$	(8) a	(9) b	(10) A	(11) ξ	(12) ΔV	(13) $\Delta V(o)$
Local Group													
M31	SAb	I–II	0.710 Mpc	$4^{\text{m}}33$	0.44	$0^{\text{m}}60$	$-20^{\text{m}}96$	197	92	41 kpc	78°	535 km/s	546 km/s
M33	SAcd	II–III	0.817	6.19	0.12	0.17	−18.66	83	53	20	55	198	242
M81 Group													
M81	SAab	I–II	3.25	7.85	0.07	0.23	−20.01	35	14.4	33	58	450	530
NGC 2403	SXcd	III	3.25	8.80	0.24	0.17	−19.17	29	15	27	60	265	306
NGC 4236	SBdm	IV	3.25	10.05	0.02	–	−17.53	26	8.7	25	75	195	202
IC 2574	SXm	IV–V	3.25	10.91	0.04	–	−16.69	16	8.0	15	68	117	126
NGC 2366	IBm	IV–V	3.25	11.41	0.19	–	−16.34	10.0	5.3	9.5	63	115	129
M101 Group													
NGC 5585	SXd	IV	7.24	11.25	0	–	−18.05	8.7	5.7	18	51	166	214
NGC 5204	SAm	IV	7.24	11.62	0	–	−17.68	8.0	4.2	17	57	127	151
Ho IV	IBm	IV–V	7.24	12.95	0	–	−16.35	6.5	2.7	14	70	103	110

Tammann (1974c, hereafter ST III) distance to the M101 group, but these secondary calibrators will be identified.

Criteria (ii) and (iii) are not restrictive since all the galaxies classed Sb and later that will interest us have homogeneous photometric data (Holmberg, 1958) and have been studied in H I (references in Table 1). The Sc pec galaxy NGC 2976 in the M81 group is excluded because it is badly confused with Galactic H I emission. Criterion (iv) particularly excludes the large irregulars in the Local Group and, very unfortunately, M101.

The data have been accumulated in Tables 1 and 2. The former gives references for published global line profiles and our estimate of the full width at the 20% of maximum intensity level. The global profiles attributed to us are found in the appendix. In the final column is the adopted profile width, ΔV (typical accuracy ± 10 km/s rms). In Table 2, by column are: (1) types after de Vaucouleurs and de Vaucouleurs (1964, hereafter RCBG), (2) luminosity classes (van den Bergh, 1960a); (3) distances [M31 from van den Bergh (1971),

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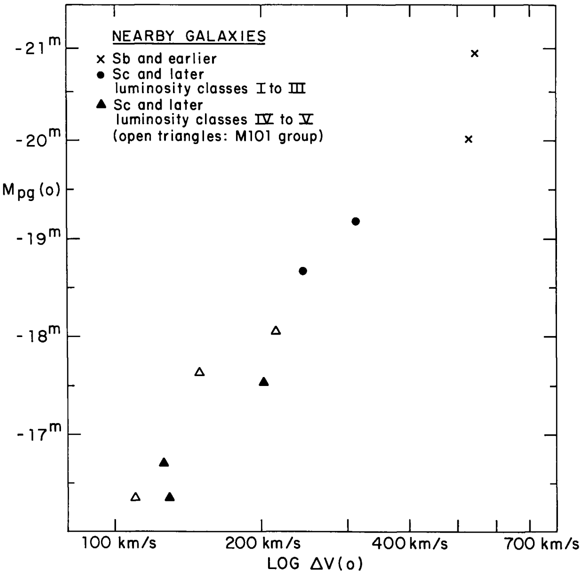

Fig. 1. Absolute magnitude – global profile width relation for nearby galaxies with previously well-determined distances. Crosses are M31 and M81, dots are M33 and NGC 2403, filled triangles are smaller systems in the M81 group and open triangles are smaller systems in the M101 group

others from ST I and ST III]; (4) photographic magnitudes (Holmberg, 1958); (5) magnitude corrections due to galactic extinction according to the precepts in ST I [based on Sandage (1973), except that the source for M31 and M33 is McClure and Racine (1969), and for NGC 2403 is Tammann and Sandage (1968)]; (6) magnitude corrections due to galactic absorption as a function of inclination according to the precepts used by Sandage and Tammann (1974d, hereafter ST IV)

$$A_{\xi}=0^{\mathrm{m}}\!.28\,(a/b-1)$$

(where the axial ratios are from the RCBG, not from Columns 8 and 9) applied to luminosity classes I to III but no correction made to classes IV to V or to irregulars regardless of class (the same correction has been applied to the two earlier systems M31 and M81 as to the Sc types—see discussion below); (7) absolute magnitudes; (8) Holmberg (1958) major axis diameter, a; (9) Holmberg minor axis diameter, b; (10) absolute major axis diameter; (11) inclination, ξ, taken from source of radio profile [from Balkowski (1973) for IC 2574, NGC 5204, NGC 5585 and from ratio of axes after Holmberg (1958), for Ho IV]; (12) full width at 20% of maximum intensity of the global H I profile (forward from Table 1); and (13) H I profile width adjusted to an edge-on orientation by:

$$\Delta V(o)=\Delta V/\sin\xi\,.$$

Corrections to edge-on inclination were always less than 30%, hence, the uncertainty should be less than 5% and more typically 2–3% (assuming inclinations are known to ±5°). Therefore, the accuracy of $\Delta V(o)$ ranges from ±4% at the high luminosity end of Figure 1 to ±10% at the low luminosity end. In the following relationships we take these uncertainties, though not negligible, to be dominated by those in magnitudes and diameters.

We have precisely followed the magnitude corrections presented in ST I and ST IV even though we are not in total agreement with them, particularly regarding the complete lack of corrections for luminosity classes IV to V (e.g., Fisher and Tully, 1975). However, (a) we agree with them that, ultimately, the question of what corrections to make is not well determined, and (b) in view of the results we are going to present for the distance to the Virgo cluster, we want our determination to be as clearly comparable as possible. It could well be argued that the two Sb systems should have received a larger A_{ξ} correction (following Holmberg, 1958). Doing so would modestly affect (steepen) the shape of our relation but not the measurement of the distance to the Virgo cluster because both the nearby and Virgo samples have two Sb systems, at similar locations on our diagrams and with similar inclinations.

In explicitly following the corrections to magnitudes given in ST IV we do introduce an inconsistency between the inclination implied in the quantity A_{ξ} and the value of ξ used to correct ΔV. For the *present* discussion we want to remain on the ST IV magnitude scale, but for the projection correction to ΔV the best inclination is needed.

In Figure 1, corrected global profiles $\Delta V(o)$ are plotted against corrected absolute magnitudes, $M_{\mathrm{pg}}(o)$, for the local sample. With different symbols we distinguish Sb's, Sc I to III's and S or Ir IV to V's as well as the three members of the M101 group. It is difficult to give a realistic estimate of the scatter with so few points, but if the vertical scatter is $\pm 0^{\mathrm{m}}\!.3$, this translates as ±15% in distance. It is noted that with the distance assumed to the M101 group (ST III) these points are consistent with the rest, although a best fit might suggest a distance modulus smaller by $0^{\mathrm{m}}\!.2$.

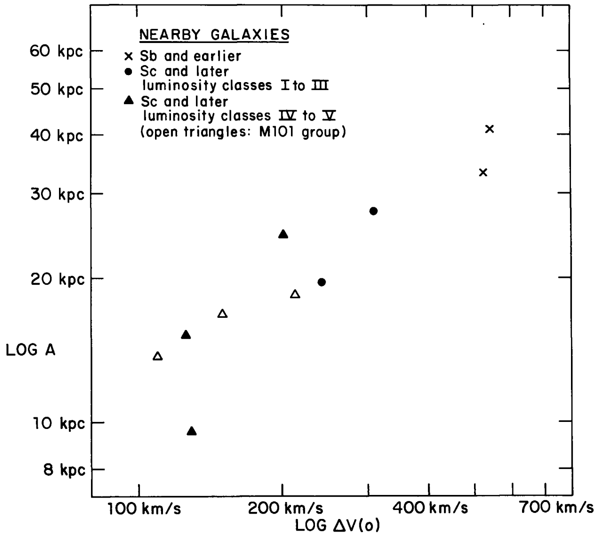

Fig. 2. Absolute Holmberg diameter – global profile width relation for the same nearby galaxies as in Figure 1

Table 3. Virgo cluster galaxies studied by Holmberg

NGC	Type	Lc	$m_{\rm pg}$	A_ξ	$m_{\rm pg}(o)$	a	b	ξ	ΔV	$\Delta V(o)$
4178	SBdm	II:	$11^{\rm m}.75$	$0^{\rm m}.47$	$11^{\rm m}.28$	$7'.3$	$3'.1$	77°	285	293
4192	SXab	I–II:	10.89	0.62	10.27	11.6	3.2	78	455	465
4206	SAbc	–	12.69	1.05	11.64	6.6	1.6	78	294	301
4501[c]	SAb	I	10.07	0.23	9.84	9.4	5.5	64	532	592
4532[c]	IBm[b]	III:	12.17	–	12.17	4.0	2.6	65	265[d]	(294)
4535[c]	SXc	I:	10.38	0.13	10.25	9.9	8.9	42[a]	292	(436)
4651[c]	SAc	II:	11.21	0.13	11.08	6.1	4.5	59	377	440
4654	SXcd	II	11.03	0.21	10.82	7.0	4.9	55	302	368

[a] Inclination outside bounds of requirement (iv)

[b] Morphological type outside bounds of requirement (iii)

[c] Also observed by Huchtmeier et al. (1976)

[d] Broad wing on profile

An alternate relationship is shown in Figure 2 where $\Delta V(o)$ is plotted against absolute diameter, A_H. We have not made corrections to diameters as a function of galactic latitude (Heidmann et al., 1971) because, although probably necessary, the amplitude of the effect is very uncertain. We have also not corrected for inclination effects on the diameter (following Tully, 1972).

Ameliorations to Figures 1 and 2 in the future will center on (a) refining the magnitude and diameter correction factors, and (b) making precision distance measurements to further systems, for example, the members of the Sculptor group.

III. Virgo Cluster

It might be hoped that the form of the relation and the intrinsic scatter could be established by studying a sufficient number of galaxies within a single group. The Virgo cluster is the richest nearby group and was covered in detail by Holmberg (1958) making available quality magnitudes and diameters. We look for candidates meeting the following requirements:

(i) galaxies studied photometrically by Holmberg (1958),
(ii) galaxies within 6° of the center of the cluster (i.e., *not* in the southern extension),
(iii) galaxies of types Sb$^+$, Sc$^-$, Sc$^+$ in Holmberg (1958),
(iv) galaxies more edge-on than 45° (but less than 85° to avoid severe type and absorption uncertainties), and
(v) galaxies sufficiently isolated so that the H I profiles will not be confused.

Table 4. Virgo cluster galaxies lacking photometric data

Name	Type	Lc	a	b	ξ	ΔV	$\Delta V(o)$
UGC 7513	Sc	–	$5'.0$	$1'.0$	90°	284 km/s	284 km/s
NGC 4498	SBd	–	5.0	2.7	60	185	214
NGC 4758	S ...	–	4.4	1.5	74	205	213
IC 769	SAbc	–	3.8	2.7	60	280	323
IC 3522	I. m	V	2.0	1.1	58	130	153

Unfortunately, these requirements in their ensemble turn out to be rather restrictive and we have not succeeded in detecting a sufficient number of galaxies to achieve our primary objective of defining the form and scatter in the proposed relationship. If not bound by requirement (i), the sample can be augmented, but the interpretation is difficult. In Table 3, data are compiled on those detected systems which do meet requirement (i), i.e., studied photometrically by Holmberg (1958), while in Table 4 are data on detected systems not meeting requirement (i). In the latter table the diameters are estimates from the Palomar Sky Survey (blue prints) from Nilson (1973), adjusted to Holmberg's scale; the major axis according to the relationship given by Paturel (1975) and the ratio of the minor and major axes according to Fisher and Tully (1975). The entries to these two tables are similar to those in Table 2 except several columns have been dropped. In the region of the Virgo cluster the correction due to galactic absorption is taken to be zero. Distance and, hence, absolute magnitude and diameter are not assumed to be known.

The inclination for NGC 4501 is from Danver (1942), NGC 4535 from Balkowski (1973) and NGC 4178, 4206, 4532, 4651, 4654 and IC 769 are our estimates from spiral structure or optical appearance. The remainder, mostly in Table 4, were derived from the axial ratios after Holmberg (1958):

$$\cos^2 \xi = \frac{(b/a)^2 - r_0^2}{1 - r_0^2}$$

where the constant $r_0 = 0.20$ is the assumed axial ratio for a system seen completely edge-on. To choose an inclination, we first sought literature values and if unavailable we used the above formula based on the ratio of the Holmberg dimensions. The systems were then intercompared with each other and with the calibrators to check that these preliminary values were reasonable on the basis of their optical appearance. If their spiral structure was well enough defined, the opening of the spiral structure was used to define the inclination. In cases where we seriously questioned the inclina-

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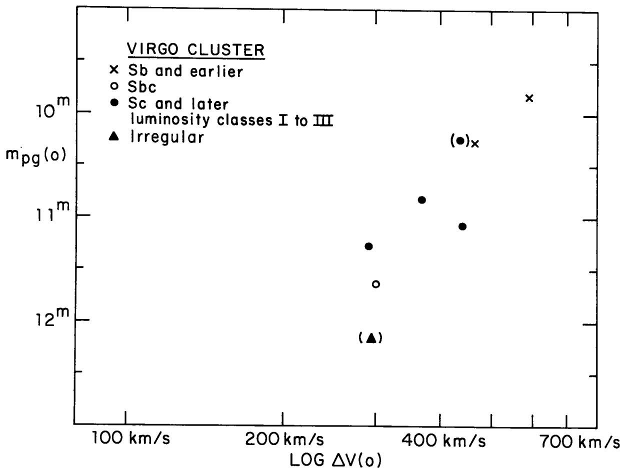


Fig. 3. Apparent magnitude – global profile width relation for those members of the Virgo cluster observed by Holmberg (1958). Morphological types are distinguished. NGC 4535 is in brackets because with $\xi = 42°$ the inclination correction to the global profile width is substantial

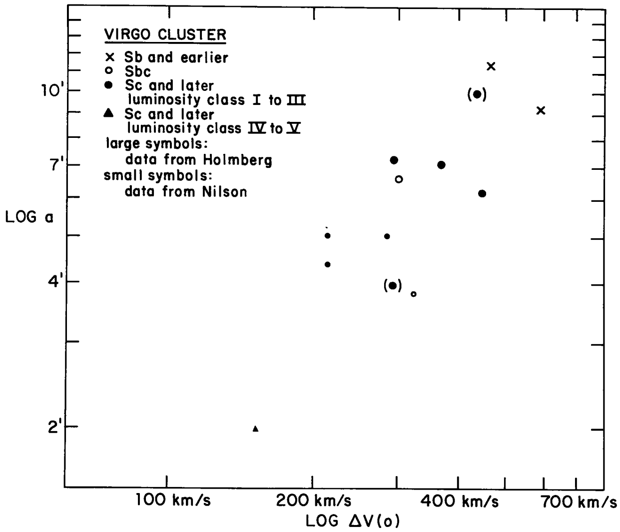


Fig. 4. Apparent diameter – global profile width relation for the Virgo cluster. The large symbols indicate systems observed by Holmberg (1958) and are the same as those in Figure 3. The small symbols locate galaxies with diameters by Nilson, adjusted to Holmberg's scale

tion given by the Holmberg dimensions our value was accepted. There is the disconcerting result that those significant differences that occurred were only in the sense that the Holmberg dimensions suggested certain systems were more face-on that we believed. The important cases are NGC 4532, 4651 and 4654 and there is also a conflict between the Holmberg axial ratio value and the inclination taken from Balkowski (1973) for NGC 4535. The signifiance of this question will be touched on again in the comparison of our Virgo distance with that by Sandage and Tammann. There is room for improvement in the definition of inclinations, but in general we have kept to sufficiently tilted systems that projection errors should rarely exceed 5% in $\Delta V(o)$ if $\xi > 60°$, rarely exceeding 10% if $\xi \sim 45°$.

The source of the radio data is our own observations with the 91-meter telescope at NRAO, and H I profiles are given in the appendix. Several of the galaxies discussed here have previously been observed by Davies and Lewis (1973), but the signal to noise ratio is improved with our profiles. We also have four galaxies in common with the high quality observations of Huchtmeier et al. (1976) and our profiles agree very well.

Global profile widths are plotted against corrected apparent magnitudes in Figure 3 and against apparent diameters in Figure 4. In the latter figure, the sample is augmented by the systems listed in Table 4; the systems with diameters by Nilson (1973).

Overlaying Figure 1 and 3 or 2 and 4 give a provisional distance to the Virgo cluster. The former set have been best-fit by eye (vertical shift) with the results shown in Figure 5a. The distance modulus follows directly from a comparison of the apparent and absolute magnitude scales at best fit and for the Virgo cluster is $30\overset{\mathrm{m}}{.}6$ corresponding to a distance of 13.2 Mpc. The estimated error is ± 1 Mpc or $\pm 0\overset{\mathrm{m}}{.}2$ (indicated in Fig. 5a) and is as poor as this because neither Figure 1 nor 3 alone is sufficient to define the form of the relationship.

To a reasonable first approximation, a straight line describes the relationship shown in Figure 5a. Amazingly enough, the observed scatter could be accounted for by residual distance uncertainties. In the case of the Virgo cluster its projected extent would imply a finite cluster depth of about $\pm 10\%$ ($0\overset{\mathrm{m}}{.}2$) of its distance. The projected extent of the M81 group is about twice that of Virgo, but we would conclude (with ST II) that the depth is not large; like Virgo, on the order of $\pm 10\%$. We cannot claim to know the intrinsic scatter in the magnitude $-\Delta V(O)$ relation.

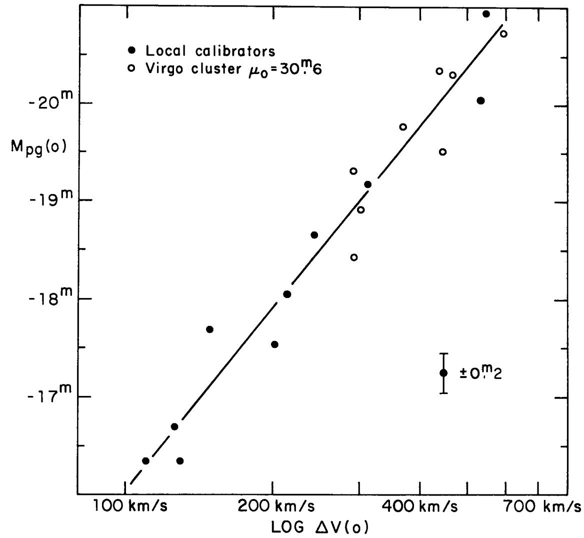


Fig. 5 (a) Absolute magnitude – global profile width relation produced by overlaying Figure 3 on Figure 1, adjusting Figure 3 vertically to arrive at a best visual fit with a distance modulus of $\mu_0 = 30\overset{\mathrm{m}}{.}6 \pm 0\overset{\mathrm{m}}{.}2$

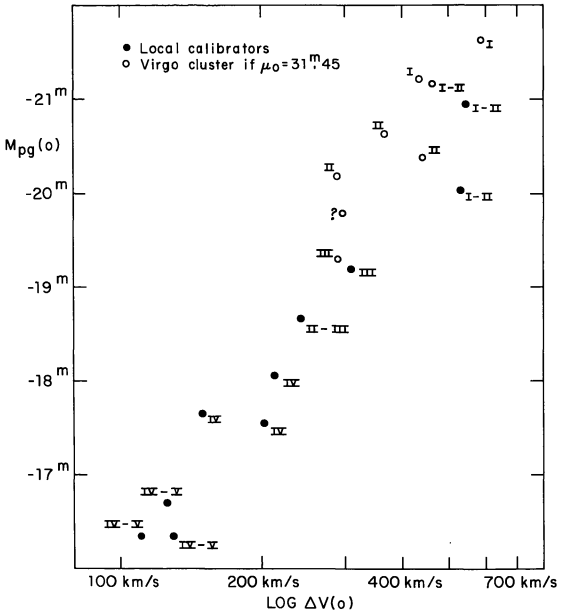


Fig. 5 (b) The same relation as in Figure 5a but illustrating what the fit is like if one assumes $\mu_0=31^{\mathrm{m}}\!.45$, the value claimed in ST IV. Luminosity classes have been indicated beside each entry

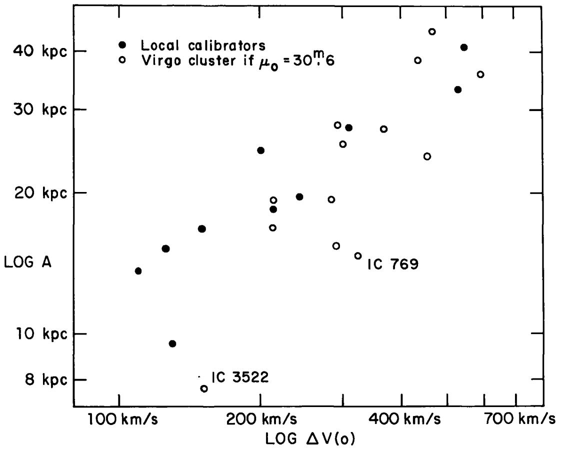


Fig. 6. Absolute diameter – global profile width relation produced by overlaying Figure 4 on Figure 2, adjusting Figure 4 vertically to correspond to a distance modulus of $\mu_0=30^{\mathrm{m}}\!.6$. The best visual fit for this overlay differs slightly from this value as discussed in the text

The slope of -6.25 to the straight line in Figure 5a means that there is an empirical correlation between the luminosity and our global profile parameter of the form

$$L \propto \Delta V(o)^{2.5\pm0.3}$$

where the error is estimated. The exponent of the relationship is actually quite sensitive to the definition taken for the global profile width; in preliminary work we had a full width at the half intensity level which lead to a flatter slope since narrow profiles were much more affected than wide ones by the alternate definition. In that case the exponent was 2.15. The slope would also be flattened if luminosity classes IV and V were to receive a correction for internal absorption but steepened if the Sb's received the correction suggested by Holmberg (1958).

This empirical relation is in reasonable accord with the concept that the total galaxian mass, M_T, is related to the global profile width, $\Delta V(O)$, and the radius, R, by

$$M_T \propto \Delta V(o)^2 R$$

and the well known property of disk systems (Roberts, 1969) that

$$M_T/L \simeq \text{constant}.$$

Using the further empirical relationship found by J. Heidmann (1969) $L \propto R^{2.8}$ for spiral members of the Virgo cluster, then one would anticipate $L \propto \Delta V^{3.1}$.

The distance to an individual field galaxy could be determined based on the relationship shown in Figure 5a, the corrected distance modulus, μ_0, being

$$\mu_0 = 3.5 + 6.25 \log \Delta V(o) + m_{pg}(o)$$

where care has been taken to assure that m_{pg} and $\Delta V(o)$ are consistent with our definitions. The uncertainty appears to be about $\pm 0^{\mathrm{m}}\!.3$ ($\pm 15\%$).

In Figure 5b we show the overlay of Virgo and nearby systems assuming a distance modulus of $31^{\mathrm{m}}\!.45$ to the Virgo cluster, the result found by ST IV. The inconsistency is discussed in Section V.

Comparison of the two diameter relations, Figure 2 and 4, provide an alternate determination of the Virgo distance. Two fits were made

(i) using the Holmberg sample alone (data in Table 3), we found a distance modulus of $30^{\mathrm{m}}\!.65 \pm 0^{\mathrm{m}}\!.4$,

(ii) using the total Virgo sample (data in Tables 3 and 4) but ignoring IC 769 and IC 3522, we find a distance modulus of $30^{\mathrm{m}}\!.8 \pm 0^{\mathrm{m}}\!.4$.

These fits are made difficult because in both these cases the Virgo scatter is greater than that seen with the nearby calibrators and, moreover, the slope seems steeper. We suspect that the cause may be due to the reduced galaxian interaction time-scale in the Virgo cluster (the cluster traversal time-scale is 10^9 years). Small systems in Virgo may have a reasonable chance of being tidally truncated. For this reason and because diameters are a characteristic of the *outer* disk while both luminosity and the line profile width (related to turnover in the rotation curve) are characteristics of the

Table 5. Distance to virgo cluster

Magnitude – ΔV	$30^{\mathrm{m}}\!.6 \pm 0^{\mathrm{m}}\!.2$	(est. error)
Diameter – ΔV (Holmberg sample)	$30^{\mathrm{m}}\!.65 \pm 0^{\mathrm{m}}\!.4$	(est. error)
Diameter – ΔV (entire sample)	$30^{\mathrm{m}}\!.8 \pm 0^{\mathrm{m}}\!.4$	(est. error)
Accepted $\mu_0=$	30.6 ± 0.2	
	$= 13.2 \pm 1$ Mpc	

Table 6. Ursa major cluster

Name	Type	Lc	a	b	ξ	ΔV	$\Delta V(o)$
NGC 3556	SBcd	–	11'.1$^{\mathrm{c}}$	4'.6	75°$^{\mathrm{a}}$	328 km/s	340 km/s
NGC 4157	SXb	II:	9.9	2.4	82	427	431
NGC 3992	SBbc	I	9.6$^{\mathrm{c}}$	6.5	58$^{\mathrm{a}}$	473	558
NGC 3953	SBbc	I	9.4$^{\mathrm{c}}$	6.5	60$^{\mathrm{a}}$	418	483
NGC 4100	SAbcp	I–II:	7.5	3.0	69	385	412
NGC 3877	SAc	–	7.5	2.1	78	338	346
NGC 4217	S.b	–	7.4	2.6	73	408	427
NGC 4183	SAcd	IV:	7.4	1.4	90	253	253
NGC 4013	S.b	–	6.9	2.0	78	397	406
NGC 3917	SAcd	–	6.9	2.0	78	277	283
UGC 6917	SBm	–	6.6	4.4	(50)	197	257
NGC 4088	SXbcp	I–II:	6.5$^{\mathrm{c}}$	2.8	67	375	407
NGC 3893	SXc	–	6.4	3.7	56	307	370
UGC 6983	SBcd	–	6.1	4.6	42$^{\mathrm{b}}$	192	(287)
NGC 3972	SAbc	–	5.8	1.8	76	262	270
NGC 4010	S.m	–	5.6	1.6	78	277	283
UGC 6667	S.c	–	5.0	1.1	85	197	198
UGC 7089	S.m	–	5.0	1.6	75	155	160
UGC 6399	S.m	–	4.8	1.5	76	170	175
NGC 4085	SXc	III:	3.7	1.5	69	290	310
UGC 6818	pec	–	3.3	1.6	64	154	171
NGC 3782	SXcd	–	2.3	1.3	58	135	159

[a] Inclination derived from spiral structure or optical appearance; otherwise, from ratio of axes

[b] Inclination outside bounds of requirement $\xi > 45°$

[c] a and b from Holmberg (1958)

main body of the disk, we give most weight to the distance derived by the luminosity relation. We summarize our results on the distance to the Virgo cluster in Table 5. Our result is in good agreement with a mean of several determinations of $\mu_0 = 30^{\mathrm{m}}.65$ given by de Vaucouleurs (1972).

Figure 6 is an overlay of Figure 2 and 4 at the assumed distance modulus of $30^{\mathrm{m}}.6$. Again, the distance modulus of $31^{\mathrm{m}}.45$ proposed in ST IV would seem inadmissible. The system IC 769 is a very well formed "grand design" spiral and must be suspected of being a background object. Its corrected systemic velocity of 2143 km/s supports this view although not entirely excluding the possibility of Virgo membership.

IV. Ursa Major Cluster

The Virgo cluster poses the difficulties that it is not abundant in hydrogen rich systems and that the scatter in at least the diameter relation is greater than displayed by the local "field" galaxies. The Ursa Major cluster is predominately composed of late disk systems and the dispersion in systemic velocities within the cluster is only a fifth that found in Virgo, hence the crossing time scale is significantly increased and the interaction rate should be lower. We have H I observations of 36 members of which 22 meet the criteria of our study *except* that of these, only four have photometric data provided by Holmberg (1958) and another two have $B(o)$ magnitudes by de Vaucouleurs and de Vaucouleurs (1964).

Our temporary solution is unsatisfactory, but we present in Figure 7 a global profile width-diameter plot based on blue major diameters from Nilson (1973) adjusted as described with the Virgo systems. The data are tabulated in Table 6. Comparison with Figure 2 leads to an eye best fit of $\mu_0 = 30^{\mathrm{m}}.5 \pm 0^{\mathrm{m}}.35$ or $\Delta = 12.6 \pm 2$ Mpc. The fit is shown in Figure 8. NGC 4085 is probably interacting with NGC 4088. NGC 3782 is

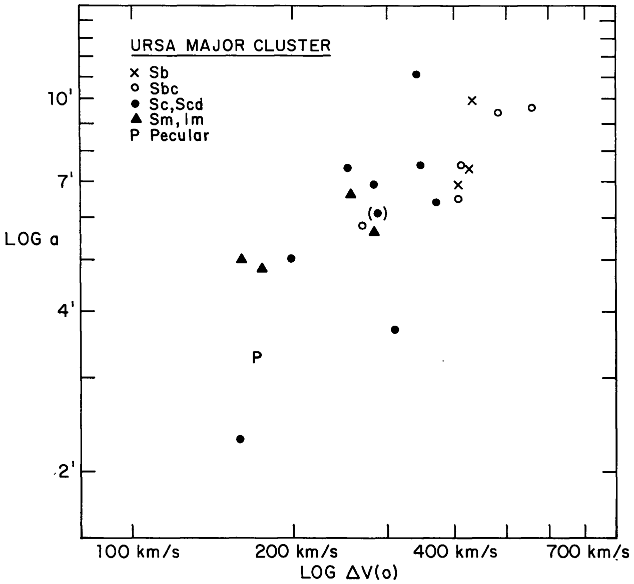


Fig. 7. Apparent diameter – global profile width relation for the Ursa Major cluster. Four diameters are from Holmberg (1958) and the rest from Nilson (1973). Morphological types are indicated

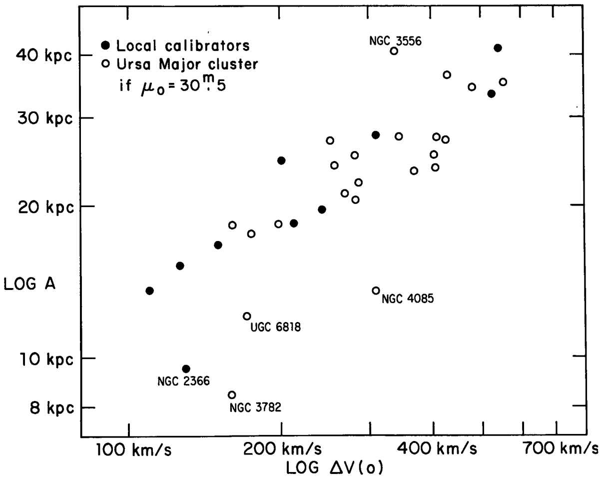


Fig. 8. Absolute diameter – global profile width relation produced by overlaying Figure 7 on Figure 2, adjusting Figure 7 vertically to arrive at a best visual fit with a distance modulus of $\mu_0 = 30\overset{\rm m}{.}5 \pm 0\overset{\rm m}{.}35$. The strongly deviant points were given low weight in the visual fit

small but the surface brightness is high. It seems that the scatter in the profile-diameter relation toward the dwarf end is real. This effect might be related to that found by Balkowski et al. (1974) comparing low surface brightness dwarfs with blue compact dwarfs; these two types of systems appear to occupy separate zones on a diameter-profile width diagram (their Fig. 7). It might be noted that four galaxies in the Ursa Major cluster fit our criteria for the magnitude-profile width relationship (NGC 3556, 3953, 3992 and 4088), and, although the statistics are poor, this solution for the distance agrees with the diameter-profile width solution given above.

It is very difficult to resolve whether the relationships have a type dependence. There is nothing evident in either the nearby or the Virgo samples although the statistics and limited overlap of types in these figures do not offer a decent measure of the possible effect. The Ursa Major sample is richer, and a first impression from Figure 7 is that there may be a tendency for earlier systems to have somewhat smaller diameters at a given value of $\Delta V(o)$. However, this impression is much less convincing if only one ignores NGC 3556, the system with the largest apparent diameter. (NGC 3556 is near the cluster limit both spatially and in systemic velocity and conceivably could be somewhat to the foreground.)

We conclude that to a first approximation there is no type dependence in the correlations of absolute luminosity or absolute diameter with the global H I profile width. We had reason to hope that this would be the case from the fact that types mix well in the magnitude-diameter relationship for spirals shown by J. Heidmann (1969), suggesting that the basic mass distribution in the main body of the disks of spiral galaxies is not strongly type dependent in spite of the variations possible in structural appearance. We have not searched for relations between the H I profile and the total H I flux density (dependent on the distance squared) because it is well-known that there are strong type dependences with this latter parameter, and with our limited sample they would be difficult to calibrate.

The Ursa Major sample was also inspected for an effect suggesting that an inclination correction to diameter may be required (after Heidmann, Heidmann and de Vaucouleurs, 1971). No suggestion of such an effect was found, but the sample is limited and does not include very face-on systems.

To use the diameter-profile width relation for the determination of distances to field galaxies, we have crudely fit a straight line to the data in Figure 8. This line has a slope of 0.74, and the distance modulus, μ_0, is given by

$$\mu_0 = 25.6 + 3.7 \log \Delta V(o) - 5 \log a .$$

The uncertainty is roughly $\pm 0\overset{\rm m}{.}6$ (±30%).

V. Comparison with the Sandage and Tamman Distance to the Virgo Cluster

In ST IV the distance to the Virgo cluster was determined to be 19.5 Mpc, corresponding to the distance modulus $\mu_0 = 31\overset{\rm m}{.}45$. It is clear from our Figure 5 and 6 that this result and our own are inconsistent, and it is of importance to understand why.

With regard to our relationships, we have noted that there is increased scatter in the Virgo data compared with that in the nearby calibrators, particularly in the diameters. It might be feared that there may be systematic differences in intrinsic magnitudes and, particularly, diameters between objects in the crowded Virgo environment and objects locally.

Nevertheless, (a) the Ursa Major observations give some confidence that the diameter relation is valid in a situation intermediate between that of the Virgo cluster and that of the local calibrators, (b) both diameters and magnitudes give a *comparable* distance to Virgo, and (c) to accept the distance given in ST IV would give *no overlap* in the Virgo and local calibrator data points in our magnitude plot (Fig. 5b) and essentially none (lowest three points) in our diameter plot (Figure 6 translated to $\mu_0 = 31\overset{\rm m}{.}45$).

In comparing the ST IV distance to the Virgo cluster with our own, it should be noted that we accept as members only those systems within 6° of the center of the cluster, and we argue that the southern extension is not physically associated. Of the 32 galaxies used in ST IV to calibrate the Virgo cluster distance, 21 lie in the southern extension. Although the final result of the ST IV analysis is not substantially affected by eliminating the southern extension, except for poorer statistics, we believe it should not be included for the following reasons.

De Vaucouleurs and de Vaucouleurs (1973) have argued that the southern extension (they prefer the name Virgo II cloud) is not physically part of the Virgo cluster. We add the argument that while the systemic velocities within the 6° radius region are well mixed in all subspaces of the cluster, the southern extension breaks up into rather easily identifiable groups with relatively small internal velocity dispersions. The situation is fairly clean in the region adjacent to the main cluster. All of the galaxies near the Virgo cluster shown by Becvar (1957) are plotted in Figure 9. A circle of 6° radius encloses the region that we accept as the Virgo cluster. Beyond this radius southward to the arc at 12° radius, the figure has been separated into four zones. In Figure 10 we give histograms of all known systematic velocities within each of these four zones (note that the galaxies with known velocities are not entirely the same as the galaxies plotted in Figure 9). It seems clear that there is a separate, well defined group in each of the four zones with some possible interlopers in zone *b*. De Vaucouleurs (1975) has identified the galaxies in zone *c* as Virgo W (his group 46) and zone *b* borrowing on zone *a* as Virgo X (his group 26).

Similarly, the region more to the south is found to break down into groups, but the occurrence of superpositions in projection complicates matters. A complete discussion of group identifications is beyond the scope of this paper. Abell and Eastman (1975) have studied the spatial distribution of galaxies in the declination range −20° to +25° around the Virgo cluster using DDO luminosity classes. They, too, find that galaxies south of the main Virgo cluster break up into concentrations with distances differing by more than a factor of two.

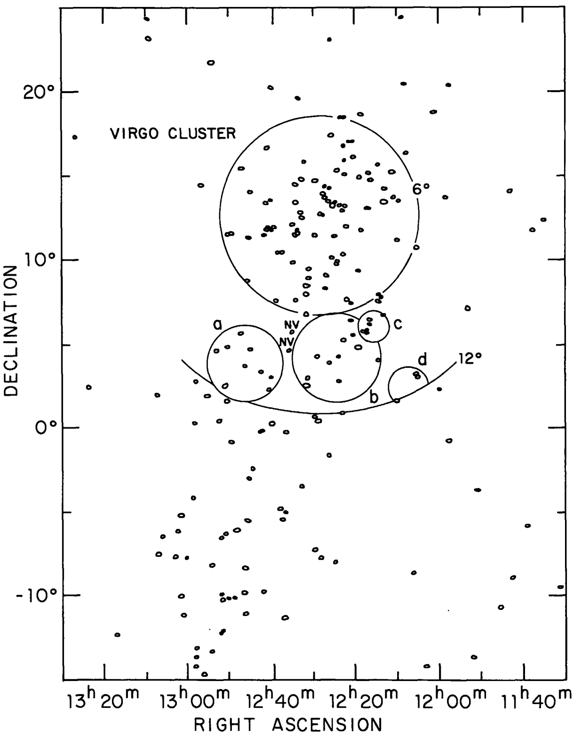


Fig. 9. The distribution of bright galaxies in the region of the Virgo cluster and the southern extension. A circle of 6° radius indicates the region we accept as the Virgo cluster. The area between this region and the one at 12° radius to the south has been divided into four zones lettered *a* through *d*. For the two galaxies marked NV we have no velocity

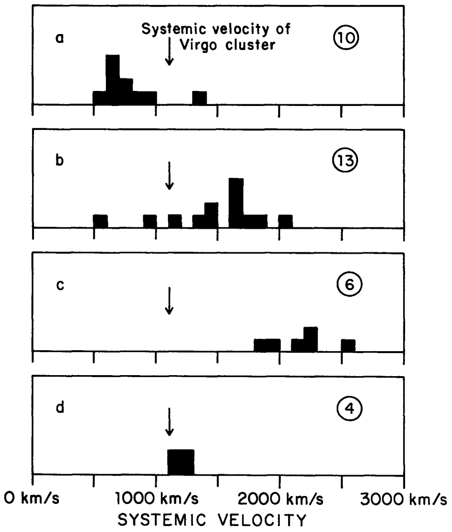


Fig. 10. Histograms are given for the distribution of systemic velocities (corrected for solar motion) in each of the four zones *a* through *d* indicated in Figure 9. The mean systemic velocity of the Virgo cluster given in ST IV is indicated. There is a close but not complete correspondence between the bright galaxies plotted in Figure 9 and the galaxies for which we have velocities

A more crucial comparison between the ST IV result and ours comes from examination of the luminosity classifications of our local and Virgo galaxies. In effect, we are proposing an alternate method of luminosity classification of late type galaxies. In Figure 5b luminosity class designations (van den Bergh, 1960a) are indicated for each galaxy represented. If the distance modulus in ST IV is correct, then the Virgo Sc II systems have comparable absolute magnitudes to the local Sb I-II systems. If our modulus is correct, then the Virgo Sc II systems overlap with NGC 2403, an Sc III of *typical luminosity* according to ST IV (their table 3). Just to the left of the Virgo Sc II's would be the subluminous Sc II-III, M33 (again from ST IV Table 3) and a group of Sc IV's.

There is suggestive evidence in this sample that the Virgo galaxies in the interval $250<\Delta V(O)<450$ km/s are overclassed by about half of a class (or the local galaxies underclassed) in the sense that a system classed III when seen nearby (e.g. NGC 2403) might be classed II-III or even II when seen in the Virgo cluster. The effect may be one of resolution or it could be the result of the Virgo cluster environment. Certainly, if diameters have been affected in Figure 4 it is reasonable

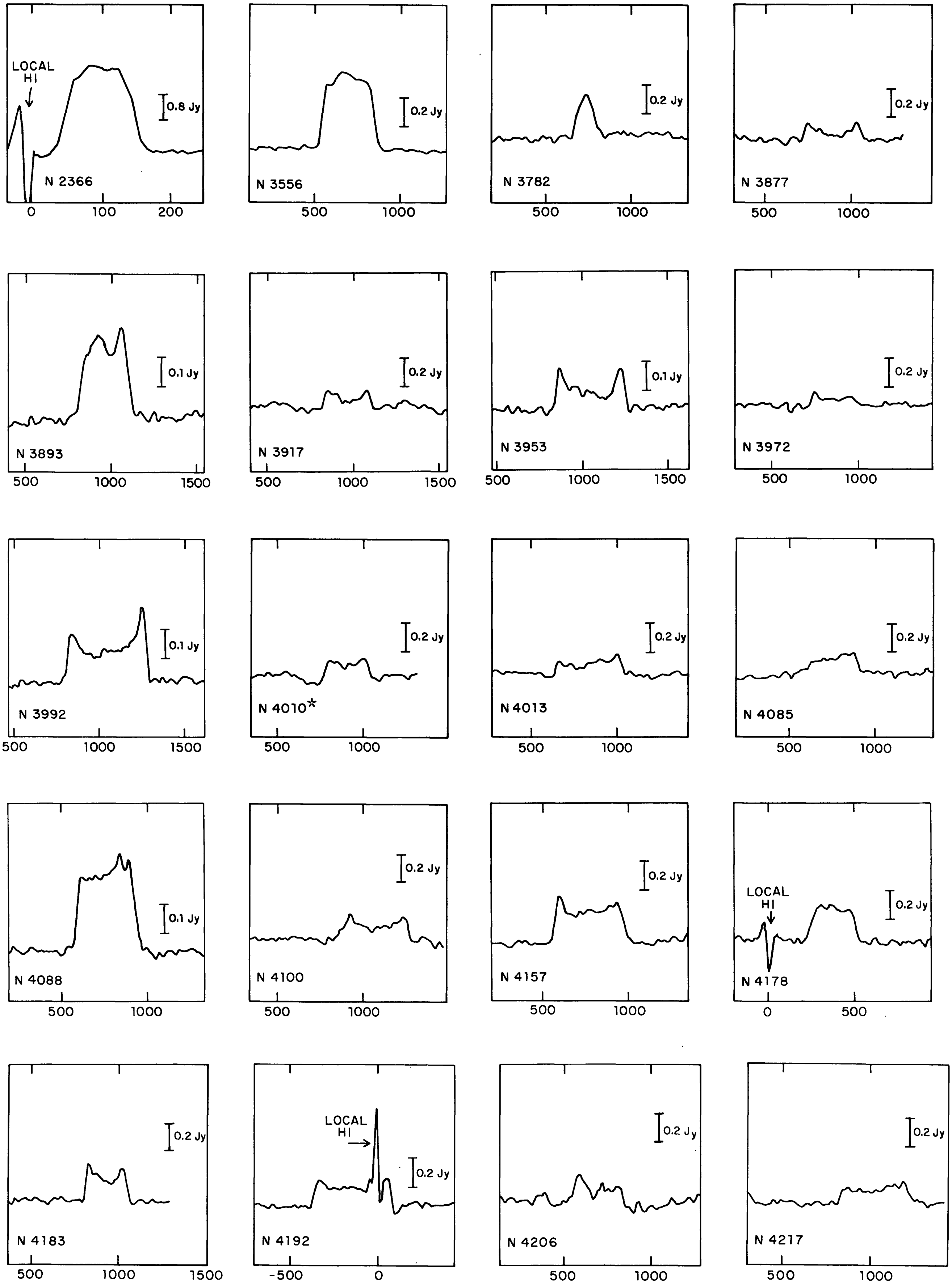
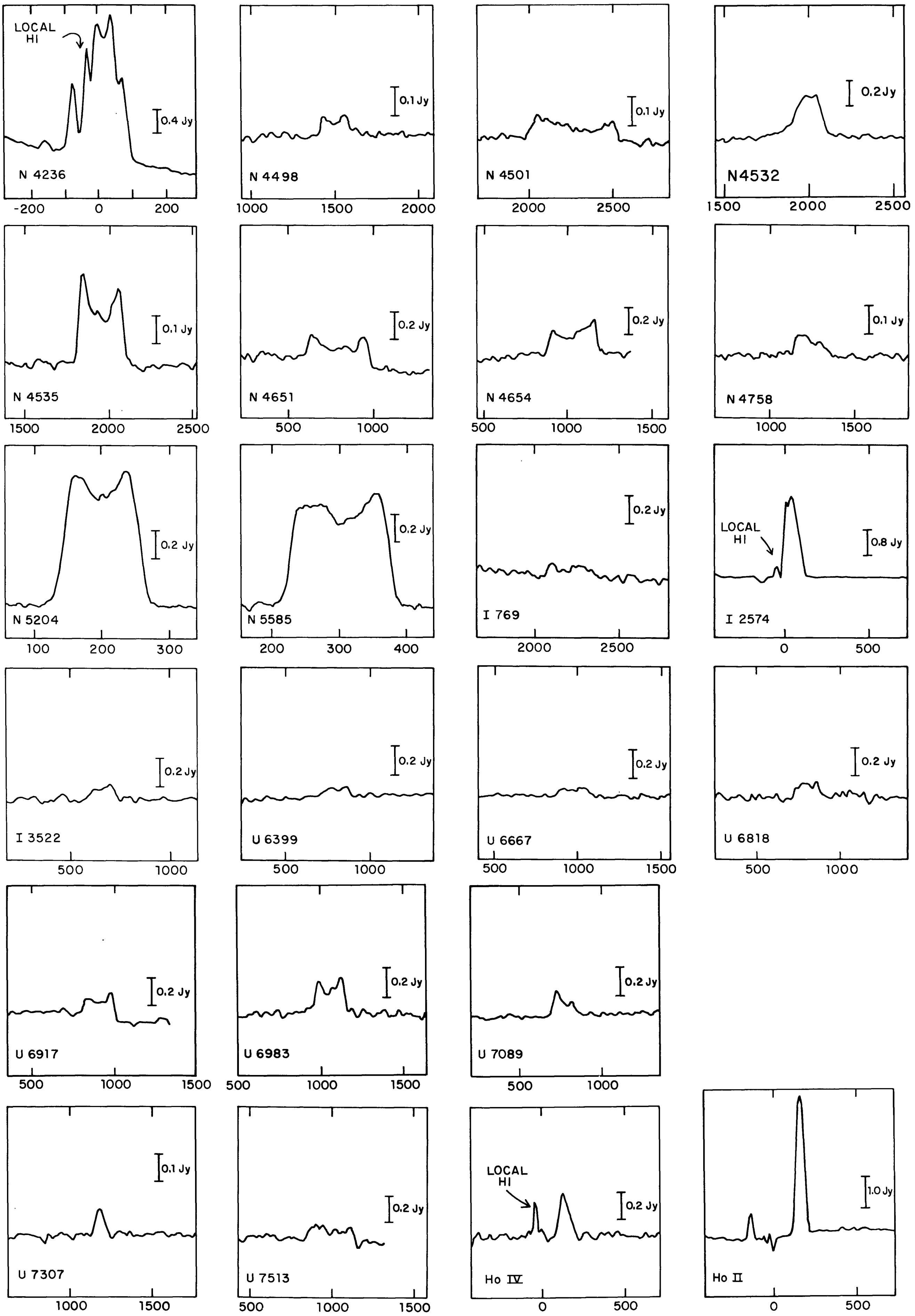


Fig. A1. Spectra of H I emission from galaxies listed in this paper. Horizontal scales are in km/s with respect to the sun, and the resolution is 22 km/s HPW except for NGC 2366, 4236, 5204 and 5585 where it is 5.5 km/s. *The spectrum of NGC 4010 is confused slightly by H I radiation from NGC 3949 in the reference spectrum


LOCAL HI
0.4 Jy
N 4236
-200
0
200
0.1 Jy
N 4498
1000
1500
2000
0.1 Jy
N 4501
2000
2500
0.2 Jy
N4532
1500
2000
2500
0.1 Jy
N 4535
1500
2000
2500
0.2 Jy
N 4651
500
1000
0.2 Jy
N 4654
500
1000
1500
0.1 Jy
N 4758
1000
1500
0.2 Jy
N 5204
100
200
300
0.2 Jy
N 5585
200
300
400
0.2 Jy
I 769
2000
2500
LOCAL HI
0.8 Jy
I 2574
0
500
0.2 Jy
I 3522
500
1000
0.2 Jy
U 6399
500
1000
0.2 Jy
U 6667
500
1000
1500
0.2 Jy
U 6818
500
1000
0.2 Jy
U 6917
500
1000
1500
0.2 Jy
U 6983
500
1000
1500
0.2 Jy
U 7089
500
1000
0.1 Jy
U 7307
1000
1500
0.2 Jy
U 7513
500
1000
1500
LOCAL HI
0.2 Jy
Ho IV
0
500
1.0 Jy
Ho II
0
500

to suspect spiral features governing luminosity classifications. In fact, van den Bergh (1960b) has noted that there are morphological distinctions between field and cluster spirals. It should be kept in mind that we base our conjecture on a very small number of galaxies and that there are very few galaxies in common with the ST IV sample because their method works better for face-on galaxies, and we prefer nearly edge-on systems.

As an aside, it will probably turn out that there is intrinsic link between the phenomenological concept of luminosity class and our more quantitative global profile width. For example, there could be a scale length to the spiral structure which is related to the angular velocity.

VI. The Hubble Constant

If we are correct that the luminosity classifications in the Virgo cluster are systematically different from those in the galaxies for which we have more fundamental distances, then the Hubble constant derived from the Virgo cluster in ST IV must be revised. Since the Virgo cluster provides a crucial test of the luminosity class-absolute magnitude scale for field galaxies, the Hubble constant derived from more distant galaxies (Sandage and Tammann, 1975a, b-ST V and ST VI) may need re-scaling.

In ST IV a tentative Hubble constant of $H_0 = 57$ km/s/Mpc was determined based on their Virgo cluster distance of 19.5 Mpc and a systemic velocity of 1111 km/s. It is argued in ST IV that a good fit of the brightest Virgo E galaxy NGC 4472 to the magnitude-redshift relation given by Sandage (1973) suggests that the Virgo cluster has a negligible peculiar motion. Moreover, this value of H_0 agrees closely with the values determined for nearby field galaxies in ST V and more distant field galaxies in ST VI, where each of these determinations are indirectly coupled to the Virgo distance which we cast in doubt.

In sum, if we accept Sandage and Tammann's (i) distances to our local calibrators, (ii) magnitude scale, (iii) Virgo cluster systemic velocity and (iv) contention of negligible Virgo motion, but take by preference our distance of 13.2±1 Mpc to the Virgo cluster, then the Hubble constant is:

$$H_0 = 84\ \mathrm{km/s/Mpc}\,.$$

The weakest assumption is probably (iv) concerning Virgo peculiar motion, a possibility suggested by the results of Austin et al. (1975). An indication of the potential error from this source is given by evaluating the Hubble constant based on the Ursa Major cluster: with our distance of 12.6±2 Mpc and a mean systemic velocity corrected for solar motion (solar motion constant of 250 km/s) of 949±19 km/s (44 galaxies) then $H_0 = 75$ km/s/Mpc.

Note on going to press. Recently, Sandage and Tammann (private communication) have used the method we are proposing here to independently determine a Virgo distance, and, contrary to our result, they find good agreement with their result in ST IV. Their data differ from our own in two respects: (a) for galaxies in common with us (calibrators and Virgo members) they have sometimes preferred other profile widths or inclinations from the literature, and (b) they have augmented the sample, primarily by accepting more face on galaxies. Where inclinations are concerned the question centers on whether our estimates are better than those derived from axial ratios since instances of significant differences in the Virgo sample are systematically in the sense that *we* choose inclinations to be *more edge-on*. Four cases were noted in the discussion of Virgo galaxy inclinations (NGC 4651 is of greatest concern) and for the moment our only explanation of this systematic difference is the statistics of small numbers. For the sample in common we will certainly not dispute (but not prefer either) data leading to a Virgo modulus of $30^{m}.8 \pm .3$ and with considerable difficulty we could entertain data leading to a fit of $31^{m}.0$.

With the augmented sample, the more face on systems tend to lie to the right on the profile width-magnitude plots and consequently give support for the ST IV distance modulus of $31^{m}.45$. There are several possible reasons for this separation between edge on and face on systems: (a) since a strictly face-on galaxy will still have an H I profile of finite width due to random motions there is a component to ΔV that should not be adjusted for inclinations, (b) in individual cases inclinations derived from the ratio of major and minor axes might give inclinations which are much too face on (for example, judging from their spiral structure, NGC 4321 and NGC 4651), (c) because of the nature of the sine function toward face on, errors in inclinations will cause much larger scatter to higher $\Delta V(o)$ values than to lower values, although plotting logarithms somewhat offsets this effect, or (d) perhaps inclination corrections to magnitudes are in error. However, no single explanation here seems satisfactory. It should be kept in mind that unless M101 and possibly Ho II are added, all of the calibrators are more edge-on than $\xi = 50°$.

In the light of the Sandage and Tammann reanalysis, it is conceivable that our method could be reconciled with the Virgo distance given in ST IV since we do not understand the separation between edge and face on systems. Restricted to a sample with $\xi > 45°$, our method gives a distance that still seems to be significantly different from that given in ST IV although our estimated errors obviously do not take into account the possibility of systematic effects. Over the long term, these difficulties will be resolved with more and better radio and optical data. For the moment it can only be concluded that the extragalactic distance scale is in doubt.

VII. Conclusions

Magnitude-global profile width and diameter-global profile width relationships have been demonstrated for three samples which are reasonably free of relative distance uncertainties: nearby galaxies, the Virgo cluster, and the Ursa Major cluster. The absolute calibration is done through the nearby sample and gives the following preliminary equations for the determination of distances to individual galaxies. From the magnitude relation:

$$\mu_0 = 3.5 + 6.25 \log \Delta V(o) + m_{\mathrm{pg}}(o) \quad (\pm 0\overset{\mathrm{m}}{.}3)$$

and from the diameter relation:

$$\mu_0 = 25.6 + 3.7 \log \Delta V(o) - 5 \log \mathrm{a} \quad (\pm 0\overset{\mathrm{m}}{.}6)$$

we find $\mu_0 = 30\overset{\mathrm{m}}{.}6$ for the Virgo cluster and $\mu_0 = 30\overset{\mathrm{m}}{.}5$ for the Ursa Major cluster.

To improve our method in the future we must concentrate on (a) obtaining photometric data for the systems we observe in the radio, and (b) extending the study to field galaxies. For the present, we propose a preliminary value for the Hubble constant of $H_0 = 80$ km/s/Mpc.

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Appendix

The neutral hydrogen line profiles upon which much of this paper is based are shown in Figure A1. Note that the velocity scales are from the radio definition $V_r = c\Delta f / f_0$ instead of the usual optical $V_0 = c\Delta\lambda/\lambda_0$. The conversion is $V_0 = V_r c/(c - V_r)$. Since the angular size of some of the galaxies is comparable to the antenna beam size, and the relative H I to optical size ratio is not well established for early spirals, we choose not to quote H I radiation flux densities for the present. The line profile widths are not significantly affected by missing some of the H I at the edge of the beam, however, because the radius of the rotation curve peak is a small fraction of the galaxy size.

Calibration and observing procedures are given in Fisher and Tully (1975). All but 4 objects (NGC 2366, 4206, 4236 and Ho II) were observed on the 91-meter telescope. The above exceptions were measured with the 43-meter with the spectrum of NGC 4236 being the sum of three spectra taken at 10′ intervals along its major axis.

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