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EFFECTS OF ENVIRONMENT ON NEUTRAL HYDROGEN DISTRIBUTION FOR DISK GALAXIES IN THE VIRGO CLUSTER AREA

C. GIOVANARDI
Osservatorio Astrofisico di Arcetri, Firenze, Italy
GEORGE HELOU AND E. E. SALPETER
Center for Radiophysics and Space Research, Cornell University
AND
NATHAN KRUMM
University of Cincinnati
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ABSTRACT

A statistical analysis is carried out on H I observations of galaxies, which include mapping with the Arecibo beam (reported in previous papers), both inside and outside the direction of the Virgo cluster core (radius 5° or 6°). The galaxies were classified both according to the revised Hubble (RH) scheme and the RDDO scheme suggested by van den Bergh. S0 galaxies on the RH scheme have a larger detection probability outside than inside; "true S0" galaxies on the RDDO scheme have a small detection probability everywhere; "anemics" have a larger detection probability and are more common outside the cluster core.

Anemic and spiral galaxies of all types have an average H I mass content M_H which is smaller inside the Virgo cluster core by a factor of about 2 to 2.5 than galaxies of the same type outside the core. This result agrees with that obtained by Chamaraux *et al.*, using different methods, and seems now firmly established. H I diameters D_H, defined in terms of a scale length, are also smaller inside the core than outside so that the surface density $\sigma_H \propto M_H/D_H^2$ is almost the same inside and outside (always comparing galaxies of the same morphological type). Ram pressure stripping of an outer galactic disk by intracluster gas predicts just such results. By contrast, "anemics" have almost the same D_H as "true spirals" (or even larger) but smaller σ_H, suggesting they lost hydrogen gas by some means other than stripping.

Subject headings: galaxies: clusters of — interstellar: matter — radio sources: 21 cm radiation

I. INTRODUCTION

Two observational facts about the Hubble sequence of galaxy morphological types are uncontroversial: (1) Early type galaxies (ellipticals and S0's) predominate over late-type spirals in the high-density environment of a rich cluster core, whereas the opposite is the case in the low-density environment (loose groups and field galaxies); (2) the neutral hydrogen content, expressed as ratio of hydrogen mass M_H to optical luminosity L, is much smaller for early-type galaxies than for late-type spirals. However, questions of a causal connection between (1) and (2) are very controversial; two rival views in their extreme forms are (A) galaxies are born as late-type spirals, but recurring ram pressure stripping in a dense cluster environment eventually removes all the hydrogen gas from a galaxy, which results in an S0 galaxy (and somehow eventually in an elliptical?); (B) the environment determines the Hubble type of a galaxy *only* during the formation process, and the small hydrogen content of an early-type galaxy is due to internal causes, such as a more complete process of star formation and/or a galactic wind from the nuclear bulge. Model A in its extreme form can already be excluded (Sandage and Visvanathan 1978; Dressler 1980; Farouki and Shapiro 1980), but it is of interest to compare the neutral hydrogen content for galaxies of the *same* Hubble type in a dense cluster environment with those in less dense regions.

The Virgo cluster provides a particularly interesting case because its core is only moderately dense and contains some late type spirals (as well as early types). For S0 galaxies a preliminary study (Krumm and Salpeter 1979*a*, *b*) indicated a hydrogen deficiency in the Virgo Cluster core; earlier papers (Davies and Lewis 1973; Huchtmeier, Tammann, and Wendker 1976) had already indicated similar results for Virgo Cluster spirals, but some doubt remained (Bottinelli and Gouguenheim 1974). More recent Virgo studies have now been carried out with the Nançay and Arecibo radio telescopes, and the Nançay work has been analyzed by Chamaraux, Balkowski, and Gerard (1980); the new basic Arecibo[1] data were presented by Helou *et al.* (1981; hereafter Paper I) and are analyzed in the present paper.

[1] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center which is operated by Cornell University under contract from the National Science Foundation.

TABLE 1A

OPTICAL AND 21 CENTIMETER DATA FOR S0–Sa GALAXIES (RH)

NGC (1)	RH Type (2)	RDDO Type (3)	B_T^0 (4)	$(B-V)_T^0$ (5)	Opt. Size (arcmin) (6)	Δ_{VC} (deg) (7)	V_{LG} (km s^{-1}) (8)	V_{VC} (km s^{-1}) (9)	d Group (Mpc) (10)	M_H/L^* (solar units) (11)	M_H ($10^8\ M_\odot$) (12)	M_T ($10^{11}\ M_\odot$) (13)	D_H (arcmin) (14)
3384	SB(s)0$^-$	S0b	10.60	0.84	5.2 × 2.3	24.3	634	−323	10.4 N3368	<0.02	<1.3	...	...
3412	SB(s)0	S0a*	11.15	0.83	3.4 × 1.9	23.7	731	−230	10.4 N3368	<0.01	<0.5	...	...
3419	(R)SAB(r)0$^+$	S0?*	13.38N	...	1.1 × 0.9	23.6	2929	1967	41.8 F	0.14	13.3	...	4.4
3489	SAB(rs)0$^+$	S0a*	10.81	0.74	3.4 × 2.0	21.4	563	−415	8.2 N3627	<0.02	<0.6	...	...
3593	SA(s)0/a	Ab	11.24	0.64	4.9 × 2.1	17.9	489	−510	8.2 N3627	0.08	1.9	0.12	4.6
3611	SA(s)a, P	Ab	12.52	0.49	2.4 × 2.0	19.1	1385	393	19.8 F	0.32	15.2	...	3.7
3623	SAB(rs)a	SbnII:	9.59	0.76	8.1 × 2.7	16.8	674	−331	8.2 N3627	0.03	3.3	0.91	8.1
3626	(R)SA(rs)0$^+$	AbIII:	11.41	0.75	3.0 × 2.1	17.4	1369	367	14.9 N3607	0.02	1.4	0.48	5.5
4064	SB(s)a:P	ABb:	11.71	0.71	3.9 × 1.7	8.3	937	−102	15.0 V	<0.04	<1.9	...	...
4179	S0, sp	S0b	11.35	0.80	3.4 × 1.0	11.7	1105	77	15.0 V	<0.09	<7.2	...	...
4235	SA(s)a, sp	Ab	11.93	0.87	3.2 × 0.8	5.8	2050	1005	30.1 N4261	<0.07	<11.3	...	...
4260	SB(s)a	ABbIII:	12.20	0.82	2.3 × 1.2	6.6	1695	652	15.0 V	<0.11	<3.8	...	...
4262	SB(s)0$^-$?	SB0a	12.18	0.87	2.3 × 2.1	3.2	1260	212	15.0 V	0.15	5.6	(1.24)	4.6
4267	SB(s)0$^-$?	S0b:	11.59	0.85	3.6 × 3.4	2.0	1141	92	15.0 V	<0.04	<2.7	...	...
4270	S0	S0a	12.72	0.80	1.9 × 0.9	7.2	2193	1151	30.1 N4261	<0.08	<7.3	...	...
4293	(R)SB(s)0/a	Ac:III:	10.73	...	5.4 × 2.6	6.2	658	−386	15.0 V	<0.03	<3.7	...	...
4324	SA(r)0$^+$	Sa/SbIII:	12.19	...	2.2 × 1.1	7.2	1522	480	15.0 V	0.16	5.1	0.19	6.7
4340	SB(r)0$^+$	SB0b/ABb	11.74	0.91	4.0 × 3.2	4.5	1120	73	15.0 V	<0.07	<4.0	...	...
4350	SA0, sp	S0:a	11.52	0.80	2.7 × 1.0	4.4	1085	38	15.0 V	<0.03	<2.0	...	...
4371	SB(r)0$^+$	SBa	11.57	0.93	3.6 × 2.3	1.0	859	−191	15.0 V	<0.04	<2.7	...	...
4377	SA0$^-$	S0a	12.42	0.82	1.9 × 1.6	2.5	1196	147	15.0 V	<0.07	<2.2	...	...
4378	(R)SA(s)a	AbII:	11.91	...	3.4 × 3.2	7.5	2407	1366	34.4 F	0.44	111.6	(3.38)	4.9
4379	S0$^-$, P?	S(B)0a	12.40	0.91	2.1 × 1.9	3.3	1068	20	15.0 V	<0.07	<2.6	...	...

TABLE 1A—*Continued*

NGC (1)	RH Type (2)	RDDO Type (3)	B_T^0 (4)	$(B-V)_T^0$ (5)	Opt. Size (arcmin) (6)	Δ_{VC} (deg) (7)	V_{LG} (km s^{-1}) (8)	V_{VC} (km s^{-1}) (9)	d Group (Mpc) (10)	M_H/L^* (solar units) (11)	M_H ($10^8 M_\odot$) (12)	M_T ($10^{11} M_\odot$) (13)	D_H (arcmin) (14)
4382	SA(s)0$^+$, P	S0t?	9.82	0.81	6.9 × 5.1	5.8	674	−371	15.0 V	<0.01	<3.3	...	...
4385	SB(rs)0$^+$:	A:Bb	12.69	0.60	2.2 × 1.4	11.8	1967	939	28.1 F	0.13	9.9	0.05	3.1
4417	SB0:, sp	S0a	11.63	0.80	3.2 × 1.3	2.8	617	−432	15.0 V	<0.07	<4.5	...	...
4419	SB(s)a, sp	AbIII:	11.42	0.88	2.8 × 1.1	2.7	−69	−1118	15.0 V	0.02	1.0	...	4.9
4421	SB(s)0/a	SB0b	12.18	0.80	2.8 × 2.3	3.1	1588	540	15.0 V	<0.04	<1.6	...	...
4425	SB0:, sp	Ab	12.41	0.87	2.8 × 1.0	0.4	1766	716	15.0 V	<0.05	<1.4	...	...
4429	SA(r)0$^+$	S0a/Aa	10.69	0.84	4.9 × 2.3	1.3	989	−61	15.0 V	<0.02	<3.2	...	...
4438	SA(s)0/a:P	Irr*	10.39	0.72	8.0 × 3.3	0.6	−47	−1097	15.0 V	0.02	2.8	0.87	...
4442	SB(s)0^0	SB0a	10.93	0.84	4.1 × 1.7	2.6	449	−600	15.0 V	<0.03	<3.0	...	...
4457	(R)SAB(s)0/a	Ab	11.38	0.78	3.0 × 2.5	8.8	725	−313	15.0 V	0.04	3.0	...	3.3
4459	SA(r)0$^+$	S0a:	11.07	0.88	3.7 × 2.8	1.6	1000	−50	15.0 V	<0.02	<2.3	...	...
4461	SB(s)0$^+$:	S0at?	11.68	0.75	3.2 × 1.4	0.8	1772	722	15.0 V	<0.03	<1.6	...	...
4469	SB(s)0/a?, sp	A(B)b	11.73	...	3.2 × 1.2	3.7	329	−719	15.0 V	<0.05	<2.2	...	...
4474	S0, P:	S0:a	12.28	0.87	2.2 × 1.2	1.7	1416	366	15.0 V	<0.06	<2.1	...	...
4476	SA(r)0$^-$	S0a	12.90	0.76	1.9 × 1.3	0.5	2110	1060	15.0 V		continuum source		
4477	SB(s)0:?	S(B)0b	11.12	0.87	4.2 × 3.7	1.3	1151	101	15.0 V	<0.01	<1.2	...	...
4479	SB(s)0^0:?	S0a	13.21	0.87	1.9 × 1.5	1.3	710	−340	15.0 V	<0.07	<1.1	...	...
4503	SB0$^-$:	S0a/b	11.77	0.92	3.2 × 1.6	1.6	1260	210	15.0 V	<0.13	<7.0	...	...
4526	SAB(s)0^0:	S(B)0b	10.18	0.85	5.9 × 1.9	4.9	311	−735	15.0 V	<0.02	<3.8	...	...
4550	SB0$^+$?, sp	S0a	11.90	0.79	2.8 × 0.9	1.9	233	−816	15.0 V	<0.05	<2.2	...	...
4570	S0, sp	S0a/b	11.27	0.84	3.3 × 1.0	5.6	1590	545	15.0 V	<0.02	<1.7	...	...
4578	SA(r)0^0?	S0b	11.99	0.84	3.6 × 2.8	3.7	2153	1105	15.0 V	<0.06	<2.7	...	...
4586	SA(s)a:, sp	Ab(III?)	12.05	0.88	3.6 × 1.3	8.5	647	−391	15.0 V	<0.06	<2.1	...	...
4596	SB(r)0$^+$	SB0/ABb	11.16	0.91	3.9 × 2.8	3.7	2040	992	15.0 V	<0.04	<3.5	...	...
4608	SB(r)0^0	SB0b	11.83	0.89	3.2 × 2.7	4.0	1715	669	15.0 V	<0.06	<3.0	...	...
4623	SB0$^+$?, sp	S0:a	12.72	...	2.2 × 0.8	5.9	1889	845	15.0 V	<0.11	<2.3	...	...
4638	S0$^-$, sp	Sa, p	11.74	0.78	2.7 × 1.5	3.8	962	−86	15.0 V	<0.04	<2.2	...	...
4643	SB(rs)0/a	ABb	11.25	0.87	3.4 × 2.7	11.1	1185	155	15.0 V	<0.02	<1.5	...	...

TABLE 1A—*Continued*

NGC (1)	RH Type (2)	RDDO Type (3)	B_T^0 (4)	$(B-V)_T^0$ (5)	Opt. Size (arcmin) (6)	Δ_{VC} (deg) (7)	V_{LG} (km s^{-1}) (8)	V_{VC} (km s^{-1}) (9)	d Group (Mpc) (10)	M_H/L^* (solar units) (11)	M_H ($10^8 M_\odot$) (12)	M_T ($10^{11} M_\odot$) (13)	D_H (arcmin) (14)
4665	SB(s)0/a	SB0b/ABb	11.34	...	4.2 × 3.5	10.3	630	−403	15.0 V	<0.09	<7.9	...	...
4694	SB0, P	S0a/Aa	11.83	...	3.2 × 1.5	5.2	1067	21	15.0 V	0.04	1.6	0.03	3.2
4710	SA(r)0$^+$?, sp	Ab	11.25	0.70	3.9 × 1.1	6.0	1027	−17	15.0 V	<0.03	<2.3	...	...
4754	SB(r)0$^-$:	S(B)0b	11.17	0.88	4.4 × 2.4	6.1	1346	302	15.0 V	<0.02	<1.4	...	...
4762	SB(r)0^0?, sp	S0bt?	10.61	0.78	6.3 × 1.2	6.2	830	−214	15.0 V	<0.02	<2.7	...	...
4866	SA(r)0$^+$:, sp	AbIII	11.41	0.70	4.8 × 1.1	7.9	1888	848	27.0 F	0.18	38.6	2.03	9.3
5273	SA(s)0	S0a*	12.20	0.80	3.2 × 2.8	28.7	1048	127	15.0 F	<0.04	<1.6	...	...

Our study differs from the Nançay study in two respects: (1) we choose for the comparison "low-density region" mainly galaxies in the surroundings of the Virgo Cluster (the Local Supercluster). This has the advantage that the two samples of galaxies "inside" and "outside" the cluster core have nearly the same mean values for redshift, apparent and absolute magnitudes. Our reference sample, like the one by Balkowski (1973), mainly contains members of groups and few real "isolated galaxies" (Balkowski and Chamaraux 1981). (2) With a half-power beam width of 3'.3, the Arecibo 21 cm beam can resolve most of the galaxies we observed, and we compare neutral hydrogen diameters D_H for the two samples (as well as total hydrogen masses M_H).

Measuring D_H is particularly important because external rampressure stripping and most internal effects make *opposite* predictions for D_H, if D_H is defined as twice a *scale length* radius (and *not* as an isophotal radius): Ram pressure stripping is most effective in stripping gas from an outer galactic disk (where surface density $\sigma_H(r)$ is low), thus decreasing D_H without affecting the central surface density $\sigma_{H,c}$ much. On the other hand, a central galactic wind and/or many generations of star formation mainly decrease the interior density $\sigma_{H,c}$ but have little effect on the hydrogen radius or may even *increase* D_H by decreasing the logarithmic derivative of $\sigma_H(r)$.

Also of interest is the relation of hydrogen content and distribution to the two-dimensional RDDO classification scheme for morphological types (van den Bergh 1976), especially to the class of "anemic spirals" (A). One has to distinguish two questions: (*a*) the predictive power of the classification scheme, based on optical criteria, to estimate total hydrogen content M_H; and (*b*) the theoretical basis for the scheme, in particular the question of whether the sequence from "true spiral" through anemics to "true S0" is really caused by the increasing importance of ram pressure stripping or by some other phenomenon. For (*a*) the determination of total hydrogen mass M_H is sufficient, and this was already studied by Bothun and Sullivan (1980) and, for a related class of "smooth-arm spirals," by Wilkerson (1980); for (*b*) the determination of hydrogen diameters D_H is again important (since ram pressure stripping predicts smaller diameters for anemics than for spirals but most other causes do not). We shall see that anemics are *not* like spirals in the cluster core.

Section II summarizes the basic data and gives various definitions. In § III we discuss the detection statistics (but not detailed hydrogen properties) for early-type galaxies. In § IV we discuss optical data and hydrogen masses; in § V we analyze hydrogen radii, followed by a summary in § VI and a general discussion in § VII.

II. THE DATA

The data refer to a number of 21 cm spectra, obtained at the 305 m radio telescope of Arecibo, of galaxies in an area of the sky centered on the Virgo Cluster. More details about the observations and the selection of the samples will be found in Paper I and in Krumm and Salpeter (1979*a*, *b*, *c*).

To obtain a homogeneous set, some of the oldest data were reworked; the standard reduction procedure assumed here is the one described in Paper I. In total we observed 133 galaxies, including a number of ellipticals, of which 59 were detected and mapped. Morphological types are assigned in the Revised Hubble (RH) and in the RDDO classification systems. RH types are taken from the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976, hereafter RC2). RDDO types were taken from the original list (van den Bergh 1976) and from Krumm and Salpeter (1979*a*); if not included there, the galaxy was tentatively classified in this scheme by the authors,[2] in which case the RDDO type is followed by an asterisk. We do not discuss the elliptical galaxies in the present paper, and we treat early-type disk systems and spirals separately.

Early-type disk systems.—We include in this sample the galaxies classified from $S0^-$ to Sa in the RH scheme. The data are listed in Table 1A, where column (1) gives the NGC name; column (2), RH type; column (3), RDDO type; column (4), apparent magnitude $B_T{}^0$ (references in the previously mentioned papers); if followed by *N*, $B_T{}^0$ was derived from other kinds of magnitudes according to de Vaucouleurs and Pence (1979); column (5), corrected color $(B-V)_T{}^0$ from RC2; column (6), optical size in arcmin derived from D_0 and R_{25} listed in the RC2; column (7), angular distance, in degrees, from the center of the Virgo Cluster, R.A. = $12^h25^m.4$, decl. = 12°40' (van den Bergh 1977); column (8), radial velocity reduced to the centroid of the Local Group according to Yahil, Tammann, and Sandage (1977) (velocities are derived from the 21 cm data or, for the undetected objects, from recent optical data); column (9), Virgocentric velocity, according to Hoffman, Olson, and Salpeter (1980); column (10), distances in Mpc (*upper entry*) and group membership (*lower entry*); the group is identified by the NGC number of the brightest member except for F (field galaxy) and V (Virgo cluster) (the group membership was assigned following de Vaucouleurs 1975 and Turner and Gott 1976; distances are derived from the average recession velocity of the group and $H_0 = 75$ km s^{-1} Mpc^{-1}); column (11), M_H/L^* ratio (in solar units) or upper limit; L^* is the blue luminosity derived from the blue magnitude $B^* = \frac{1}{2}(B_T + B_T{}^0)$; for more details see Paper I and Krumm and Salpeter (1979*b*); column (12), hydrogen mass M_H (or upper limit) at the assumed distance, in $10^8 M_\odot$; column (13), total mass M_T in $10^{11} M_\odot$, calculated as in Krumm and Salpeter (1980), for the inclination we use a modified Holmberg formula: $\cos^2 i = (R_{25}{}^{-2} - 0.04)/(1 - 0.04) - 0.04$, the last term being a tentative correction for face-on systems (if the inclination is less than 30°, M_T is enclosed in parentheses); column (14), hydrogen diameter D_H in

[2] By C. G. and N. K. independently, using plate copies of the blue POSS.

TABLE 1B

Optical and 21 Centimeter Data for Sab through Im (RH)

Name (1)	RH Type (2)	RDDO Type (3)	B_T^0 (4)	$(B-V)_T^0$ (5)	Opt. Size (arcmin) (6)	Δ_{VC} (deg) (7)	V_{LG} (km s^{-1}) (8)	V_{VC} (km s^{-1}) (9)	d Group (Mpc) (10)	M_H/L^* (solar units) (11)	M_H ($10^8 M_\odot$) (12)	M_T ($10^{11} M_\odot$) (13)	D_H (arcmin) (14)
NGC 3239	IB(s)m, P	Irr*	11.92N	...	4.9 × 3.5	30.0	644	−265	10.4 N3368	0.60	13.4	0.10	3.6
NGC 3338	SA(s)c	Sc*	10.97	0.47	5.3 × 3.6	25.8	1175	230	10.4 N3368	0.63	32.3	0.55	9.7
NGC 3367	SB(rs)c	ScI	11.81	0.50	2.4 × 2.2	24.7	2917	1963	41.7 F	0.15	62.1	(1.20)	3.7
NGC 3368	SAB(rs)ab	Sbp	9.79	0.78	6.8 × 4.9	24.7	768	−186	10.4 N3368	0.14	22.5	0.79	10.4
NGC 3370	SA(s)c	Sb*	11.91N	...	2.9 × 1.7	24.8	1171	218	16.7 F	0.36	18.9	0.27	4.1
NGC 3389	SA(s)c	Sc?*	11.95	0.45	2.5 × 1.4	24.3	1166	209	10.4 N3368	0.27	5.7	0.13	3.2
NGC 3455	(R′)SAB(rs)b	Ab?*	12.35N	...	2.6 × 1.7	23.1	1014	48	14.5 N3457	0.27	7.0	0.14	≤2.0
NGC 3627	SAB(s)b	Sb$^+$(t?)II:	9.26	0.60	7.8 × 3.9	16.5	576	−431	8.2 N3627	0.04	5.8	0.66	≤9.5
NGC 3628	SbP, sp	Sb*	9.47	0.64	11.2 × 2.8	16.5	791	−288	8.2 N3627	0.49	55.2	1.02	12.5
NGC 3681	SAB(r)bc	Aa*	12.20	0.65	2.6 × 2.5	15.5	1133	121	14.9 N3607	0.49	18.4	(0.39)	7.8
NGC 3684	SA(rs)bc	Sb*	12.00	0.56	3.2 × 2.3	15.3	1048	35	14.9 N3607	0.36	15.5	0.20	3.7
NGC 3686	SB(rs)bc	Sb*	11.73	0.51	3.2 × 2.6	15.3	1047	34	14.9 N3607	0.11	6.2	0.22	4.0
NGC 3800	SAB(rs)b:, P	Ab?*	12.82N	...	1.7 × 0.5	12.0	3194	2167	45.6 F	0.07	12.5	...	≤2.0
NGC 3810	SA(rs)c	ScI	10.94	0.47	4.1 × 3.0	11.5	862	−167	15.0 V	0.21	24.1	0.39	4.0
NGC 4178	SB(rs)dm	Sc*	11.38	0.38	4.2 × 1.7	4.0	246	−801	15.0 V	0.37	26.1	0.25	3.2
NGC 4192	SAB(s)ab	Ab/Ac*	10.29	0.66	7.8 × 2.6	4.3	−246	1293	15.0 V?	0.16	29.9	1.39	8.9
NGC 4212	SAbc?	Sa?*	11.54	0.61	2.9 × 2.0	3.3	−198	−1245	15.0 V		See text		
NGC 4216	SABb:	SbII	10.26	0.84	6.3 × 1.7	3.0	19	−1030	15.0 V	0.08	13.9	1.39	
NGC 4254	SA(s)c	ScI	10.18	0.51	5.5 × 4.9	3.0	2293	1244	15.0 V	0.17	40.7	0.78	4.4
NGC 4274	(R)SB(r)ab	SbII:III	10.69	0.81	5.9 × 2.4	17.3	895	−107	15.0 V	0.05	4.6	0.95	4.2
NGC 4321	SAB(s)bc	ScI	9.86	0.67	7.1 × 6.3	3.6	1471	423	15.0 V	0.08	25.9	1.08	5.5
IC 3258	SB(s)m:, P	Irr*	13.51	...	1.6 × 1.4	1.0	−547	−1597	15.0 V	0.18	2.0	0.03	...
NGC 4351	SB(rs)ab:, P	Ab*	12.47	0.30	2.0 × 1.4	1.0	2203	1153	15.0 V	0.08	2.2	0.03	≤2.0

TABLE 1B—*Continued*

Name (1)	RH Type (2)	RDDO Type (3)	B_T^0 (4)	$(B-V)_T^0$ (5)	Opt. Size (arcmin) (6)	Δ_{VC} (deg) (7)	V_{LG} (km s^{-1}) (8)	V_{VC} (km s^{-1}) (9)	d Group (Mpc) (10)	M_H/L^* (solar units) (11)	M_H ($10^8 M_\odot$) (12)	M_T ($10^{11} M_\odot$) (13)	D_H (arcmin) (14)
NGC 4380	SA(rs)b: ?	Ab	11.98	...	3.4 × 2.0	2.5	832	−217	15.0 V	0.10	4.5	0.26	3.6
NGC 4388	SA(s)b:, sp	A?b*	11.17	0.62	4.0 × 1.1	0.6	2397	1347	15.0 V	0.05	3.7	0.48	4.0
NGC 4394	(R)SB(r)b	SBbII	11.51	0.76	4.1 × 3.7	5.8	823	−222	15.0 V	0.04	2.5	(0.33)	2.0
NGC 4413	SB(rs)b:, P	A(B)bIII:	12.63	...	2.3 × 1.6	0.4	−13	−1063	15.0 V	0.07	1.7	0.07	4.8
NGC 4450	SA(s)ab	AbII	10.62	0.74	4.7 × 3.4	4.7	1861	815	15.0 V	0.02	2.5	0.61	3.3
NGC 4501	SA(rs)b	Sb*	9.86	0.65	6.3 × 3.5	2.3	2012	963	15.0 V	0.03	8.2	2.30	3.4
NGC 4517	SA(s)cd: sp	Sc*	10.30	0.54	7.2 × 1.3	12.3	952	−74	15.0 V	0.25	41.0	0.59	7.9
NGC 4527	SAB(s)bc	Sb*	10.73	0.74	5.2 × 1.9	9.9	1579	545	15.0 V	0.29	35.3	0.64	6.2
NGC 4536	SAB(rs)bc	Sb*	10.50	0.48	6.5 × 3.0	10.3	1637	604	15.0 V	0.18	29.0	0.75	5.6
NGC 4548	SB(rs)b	A(B)bII	10.71	0.73	5.4 × 4.4	2.8	378	−671	15.0 V	0.03	4.1	0.57	4.4
NGC 4559	SAB(rs)cd	Sc*	9.84	0.34	8.9 × 4.2	15.7	773	−238	11.0 F	0.36	57.6	0.42	9.3
NGC 4565	SA(s)b?, sp	SbI	9.49	0.64	11.2 × 1.9	13.7	1179	159	13.0 N4725	0.30	77.2	2.03	11.3
NGC 4569	SAB(rs)ab	Ab/AcI–II	9.80	0.65	8.3 × 4.1	2.3	−348	−1397	15.0 V	0.01	4.1	0.96	...
NGC 4579	SAB(rs)b	A/S(B)bII	10.33	0.76	5.4 × 4.4	2.5	1402	353	15.0 V	0.02	4.7	1.38	3.5
NGC 4631	SB(s)d, sp	Sc	9.03	0.37	10.7 × 2.3	20.4	599	−385	10.4 N4631	0.40	105.9	0.55	15.0
NGC 4639	SAB(rs)cd	Sc*	11.90	0.62	2.8 × 2.0	3.7	939	−109	15.0 V	0.18	8.6	0.32	3.4
NGC 4651	SA(rs)c	A(?)b*	10.99	0.50	3.6 × 2.6	5.5	703	−342	15.0 V	0.28	31.1	0.68	4.6
NGC 4654	SAB(rs)cd	S(?)a*	10.75	0.55	4.4 × 2.8	4.0	929	−118	15.0 V	0.40	54.2	0.46	6.0
NGC 4656	SB(s)m, P	Sctt	10.00	0.25	10.0 × 2.4	20.1	621	−365	10.4 N4631	0.41	43.6	0.17	17.3
NGC 4698	SA(s)ab	AbIII	10.99	0.77	3.9 × 1.1	6.4	878	−165	15.0 V	0.13	13.2	0.70	7.1
NGC 4826	(R)SA(rs)ab	AbII	8.96	0.75	8.7 × 5.0	11.6	345	−684	4.5 N4736	0.03	1.9	0.41	13.3
NGC 5005	SAB(rs)bc	Sb$^-$II	10.19	0.71	4.8 × 2.4	26.5	970	30	13.8 N5005	0.03	8.1	1.19	5.9
NGC 5665	SAB(rs)c?, P	A(?)b(?)*	12.39N	...	2.0 × 1.4	30.9	2127	1226	30.4 F	0.05	7.2	...	≤2.0

arcmin defined as the full width at the $\frac{1}{3}$ level with respect to the central value of the integrated flux. D_H is measured along the major axis; in the face-on cases we report the average of the measurements in the N–S and E–W directions. These estimates are corrected for sidelobe contamination and the size of the main beam. The overall rms accuracy is around 1′ (see § V and Paper I).

Spirals.—These are all the RH types Sab or later. These galaxies are listed in Table 1B; the format is the same as in Table 1A. NGC 4212 was listed as "undetected" in Paper I, partly because of an erroneous published optical redshift, and partly because of masking by Galactic emission. We detected this galaxy in the course of a new systematic survey, at $V_{LG} = -198$ km s^{-1}, in agreement with a more recent optical redshift (Stauffer 1981).

III. DETECTION STATISTICS FOR EARLY-TYPE GALAXIES

An earlier survey for Virgo ellipticals and S0 galaxies was reported by Krumm and Salpeter (1979*a*). The survey described in Paper I was carried out with similar sensitivity, although it covered a somewhat more complete sample. However, we also carried out a subsidiary survey to investigate a possible detection bias in the main survey which used only a single beam direction per galaxy centered on the optical image. Some of the detected S0 galaxies mapped by Krumm and Salpeter (1979*b*) have rather large hydrogen radii compared to the Arecibo beam, and it was conceivable that other galaxies have a hydrogen distribution with "a hole in the middle." For that reason undetected S0 and elliptical galaxies from our main survey were reobserved (with the *same* integration time per point) at +2′ and −2′ from the galaxy center along the optical major axis (a linear separation of ∼20 kpc at the Virgo distance). We have the unequivocal negative result that these additional 58 observations did not lead to *any* additional detections! This does not eliminate the possibility of "holes in the middle" but speaks in favor of detection

TABLE 2

DETECTION STATISTICS

System	In$_{5°}$		Out$_{5°}$	
	Obs	Det.	Obs.	Det.
RH:				
S0	24	1	18	6
S0/a	3	1	5	2
Sa	1	1	7	3
RDDO:				
S0	20	1	12	1
A	13 (15)	10	24	15
S	10 (8)	8	23	23

surveys which concentrate on the central beam area (of course, for samples with a comparable or larger beam/galaxy size ratio). We are in the process of a more sensitive Arecibo survey of this type, but give here a short summary of the detection statistics from Paper I.

The numbers of galaxies observed and those actually detected are given for S0, S0/a, and Sa galaxies in Table 2, counting separately those inside a circle of 5° *radius*, centered on $\alpha = 12^h25^m.4$, $\delta = 12°50'$ (van den Bergh 1977), and those outside. These data are also presented in Figure 1. The results are similar to those found by Krumm and Salpeter (1979*a*) but with slightly better statistics: including the few Sa galaxies with S0 and S0/a gives a lower detection probability in neutral hydrogen inside the Virgo Cluster circle than outside, reliable at a confidence level of 0.03. If only S0 galaxies (on the RH Hubble classification system) are considered, the total numbers are smaller but the detection probabilities are even more disparate and the statistical significance of the difference is improved (confidence level 0.02). Both the apparent and absolute mean blue magnitudes of the "inside" and "outside" S0 are almost the same (∼ +11.8 and −19.2 mag, respectively), so the difference cannot be due to luminosity effects. Nor is there any significant systematic difference in the

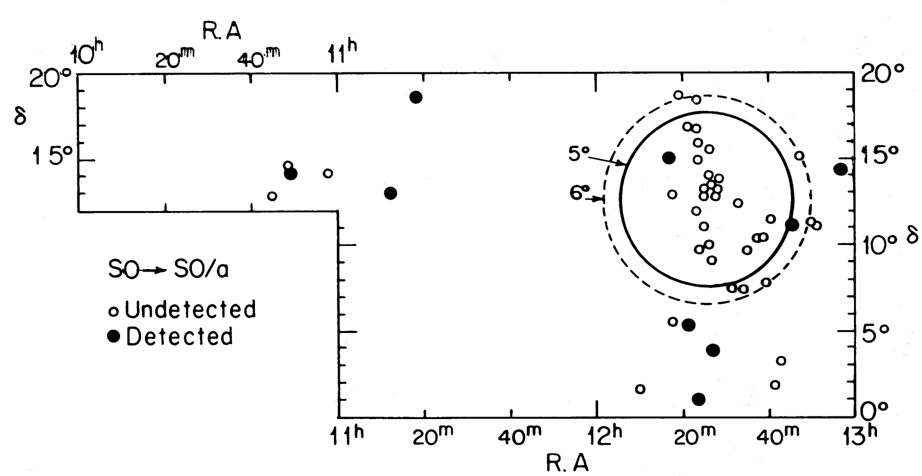

FIG. 1.—Space distribution of lenticular galaxies. The two circles (5° and 6° radius) are centered on the center of the Virgo Cluster core (van den Bergh 1977).

TABLE 3

DISTRIBUTION OF THE SAMPLE IN THE RH AND RDDO SYSTEMS

	RH			
	S0–S0/a	Sa	S_E (Sab–Sb)	S_L (Sbc–Irr)
RDDO:				
S0(RDDO)	32	0	0	0
A	14	7	13	3
S(RDDO)..........	3	1	8	22

inclination or observing procedure (zenith angles, integration times, etc.) between the two samples. We conclude that S0 galaxies on the RH system, S0(RH), really have a much smaller probability of having an appreciable neutral hydrogen mass if they are situated inside the high-density environment of the Virgo Cluster core.

As seen in Table 3, galaxies of Hubble type S0 (RH) are classified on the RDDO scheme partly as "true S0," S0(RDDO), and partly as anemics, A (and many Hubble Sa types as type A). The second half of Table 2 retabulates the detection statistics according to the RDDO scheme. There are three striking features of these results (compatible with the conclusions of Bothun and Sullivan 1980): (1) the neutral hydrogen detection probability for S0 (RDDO) galaxies is much smaller than for A and is also smaller than for S0(RH), if "inside" and "outside" are combined; (2) for a given RDDO type [in contrast to the case for S0(RH)] the detection probability is not much smaller inside the Virgo Cluster core than outside; but (3) the ratio of numbers of A to S0(RDDO) present (whether detected or not) is appreciably larger outside than inside [on the other hand, the number of spirals S(RDDO) to A is only slightly larger outside than inside]; (4) since S0(RH) shows a rather strong positional effect and S0(RDDO) and A's do not, it is an intriguing possibility that other parameters (delineating a more complex classification scheme) might also show some correlation with the distance from the cluster center. Unfortunately, the present sample is too small to test for such a possibility, so we defer the question until the analysis of the already mentioned new survey (Giovanardi, Krumm, and Salpeter 1982).

Because of its detection after the main survey, NGC 4212 is not included in Table 2. Two additional galaxies, NGC 4371 and 4638, were initially classified as S(RDDO), but reexamination on the POSS plates (*after* the Arecibo results were known) showed that this was probably a misclassification. If these two galaxies are reclassified as A, the numbers in parentheses in Table 2 result. Statistics on hydrogen masses for A and spiral galaxies of various kinds are given in the next section, but a discussion of S0's will require a more sensitive survey.

IV. H I CONTENT

The first few entries in Table 4 refer to mean[3] optical data, in particular apparent and absolute magnitudes B^* and $\mathfrak{M}^*$ and color indices $(B-V)_T{}^0$. S_E denotes early spirals (Sab and Sb), S_L denotes later types (Sbc to Im) on the RH classification scheme; A and S(RDDO) denote anemics and spirals on the RDDO classification scheme. For many of the galaxies in Table 1 we have velocity widths and hence "indicative values" M_T for the total gravitational mass and the average of (M_T/L^*) for those galaxies is also given in Table 4. The notation "$IN_{6°}$" and "$OUT_{6°}$" refers here to a circle of *radius* 6° (centered as before). In fact, due to the more spread distribution of spirals in the cluster, if compared to ellipticals and S0's, the definition of 6° (instead of 5°) as the "critical" radius allows a better balance in numbers of objects between the inner and outer samples. As already mentioned, the mean apparent absolute magnitudes for each morphological class are almost the same for the $IN_{6°}$ and $OUT_{6°}$ groups. For S(RDDO) galaxies the color index is slightly bluer for the $OUT_{6°}$ than the $IN_{6°}$ group [the difference is slightly smaller than that between all S(RDDO) and all A], but there is no such effect for the other morphological classes, and it is not clear if the difference is physically significant or a statistical fluctuation. For both S_E and A classes the mean ratio M_T/L^* is slightly larger $OUT_{6°}$ than $IN_{6°}$.

[3] The means and their uncertainties are linear when referring to logarithmic quantities (like magnitudes and colors) and logarithmic in all other cases.

TABLE 4

MEAN VALUES OF OPTICAL AND 21 CENTIMETER DATA FOR THE VARIOUS SUBSAMPLES

	n	B^*	$\mathfrak{M}^*$	$(B-V)_T{}^0$	M_T/L^* (solar units)	$10\ M_H/L^*$ (solar units)	u_{MHL}	D_H/D_{opt}	$10\ \sigma_H/\sigma_{opt}$ (solar units)
$S_E(IN_{6°})$	11	11.24 ± 0.29	−19.64 ± 0.29	0.67 ± 0.05	4.40 ± 0.55	0.42 ± 0.08	0.62 ± 0.13	0.84 ± 0.12	0.59 ± 0.13
$S_E(OUT_{6°})$	10	10.67 ± 0.41	−19.78 ± 0.22	0.71 ± 0.03	6.62 ± 0.44	1.17 ± 0.34	1.83 ± 0.54	1.16 ± 0.11	0.88 ± 0.33
$S_L(IN_{6°})$	7	11.38 ± 0.46	−19.50 ± 0.46	0.54 ± 0.04	4.00 ± 0.52	2.10 ± 0.44	0.90 ± 0.17	1.00 ± 0.11	2.16 ± 0.53
$S_L(OUT_{6°})$	17	11.30 ± 0.24	−19.53 ± 0.22	0.50 ± 0.04	4.29 ± 0.42	2.40 ± 0.48	1.17 ± 0.22	1.27 ± 0.10	1.49 ± 0.33
$A(IN_{6°})$	16	11.60 ± 0.20	−19.28 ± 0.20	0.71 ± 0.05	3.24 ± 0.68	0.32 ± 0.08	...	1.09 ± 0.12	0.43 ± 0.12
$A(OUT_{6°})$	21	11.81 ± 0.20	−19.38 ± 0.16	0.73 ± 0.03	5.75 ± 0.74	0.69 ± 0.19	...	1.41 ± 0.14	0.62 ± 0.19
$S(RDDO)(IN_{6°})$	13	11.17 ± 0.23	−19.72 ± 0.23	0.68 ± 0.05	4.90 ± 0.55	0.78 ± 0.25	...	0.80 ± 0.11	1.94 ± 0.45
$S(RDDO)(OUT_{6°})$.......	21	10.90 ± 0.22	−19.71 ± 0.18	0.56 ± 0.04	4.79 ± 0.36	1.94 ± 0.38	...	1.22 ± 0.08	1.30 ± 0.29

TABLE 5

COMPARISON OF HYDROGEN PROPERTIES

	10 M_H/L^* (solar units)	D_H/D_{opt}	10 σ_H/σ_{opt} (solar units)	u_{MHL}
[$S_E + S_L$]:				
$IN_{6°}$	0.79 ± 0.18	0.90 ± 0.09	0.99 ± 0.23	0.72 ± 0.11
$OUT_{6°}$	1.84 ± 0.32	1.23 ± 0.07	1.22 ± 0.24	1.38 ± 0.23
[A + S(RDDO)]:				
$IN_{6°}$	0.48 ± 0.10	0.96 ± 0.09	0.80 ± 0.21	...
$OUT_{6°}$	1.16 ± 0.21	1.29 ± 0.07	0.98 ± 0.19	...
A	0.49 ± 0.10	1.26 ± 0.10	0.53 ± 0.11	...
S(RDDO)	1.37 ± 0.25	1.10 ± 0.08	1.43 ± 0.26	...

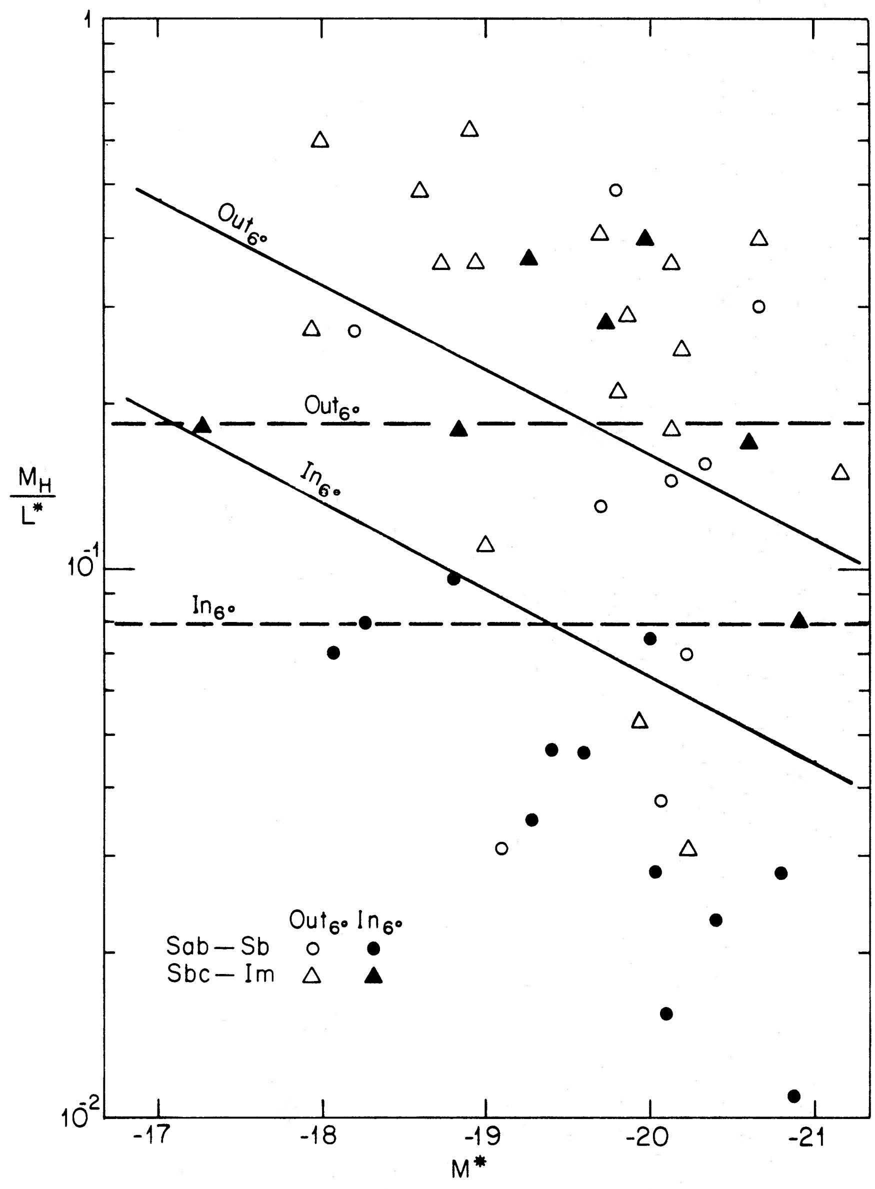

FIG. 2.—The hydrogen content M_H/L^* vs. the absolute blue magnitude $\mathfrak{M}^*$. Solid lines are the regressions fitting the luminosity dependence of the $IN_{6°}$ and $OUT_{6°}$ samples ($\frac{1}{2}$ of the upper limit in parentheses). Dashed lines are the mean values from Table 5.

One of the two main results of this paper is the statistics on hydrogen masses M_H. Table 4 gives the (distance independent) mean ratio M_H/L^* for each group (using half the upper limit for M_H of an undetected galaxy). M_H/L^* is larger $OUT_{6°}$ than $IN_{6°}$ for each of the four morphological classes, more strongly for early types. Table 5 summarizes the data: with A and S(RDDO) combined, M_H/L^* is again larger for $OUT_{6°}$ than $IN_{6°}$ by a significant factor, 2.42 ± 0.67 (with S_E and S_L combined, the factor is 2.33 ± 0.67); with $IN_{6°}$ and $OUT_{6°}$ combined, M_H/L^* is larger for the "true spirals" S(RDDO) than for the anemics A by a factor 2.80 ± 0.77.

The relative hydrogen content M_H/L^* varies greatly from case to case, may depend on the absolute luminosity (Bottinelli and Gouguenheim 1974; Fisher and Tully 1975; Huchtmeier, Tammann, and Wendker 1976), and does depend on morphology (Roberts 1975; Bothun and Sullivan 1980). As suggested by Huchtmeier, Tammann, and Wendker (1976) and by Chamaraux, Balkowski, and Gerard (1980), the scatter can be decreased somewhat (and biases tested for) by taking some of this dependence into account: In Figure 2 the individual galaxy values of log (M_H/L^*) (for both S_E and S_L Hubble types) are plotted against absolute magnitude $\mathfrak{M}^*$. Also shown are two linear regression lines of the form:

$$\log_{10} (M_H/L^*) = 0.4\alpha\mathfrak{M}^* + \log_{10} \beta ,$$

fitted separately for all $IN_{6°}$ and all $OUT_{6°}$ galaxies, with the slope α forced to be the same but $\beta_{IN_{6°}}$ and $\beta_{OUT_{6°}}$ fitted separately. We obtained $\alpha = 0.39 \pm 0.22$, $\gamma \equiv \beta_{OUT}/\beta_{IN} = 2.53 \pm 0.71$. With $IN_{6°}$ and $OUT_{6°}$ combined, average values $\langle M_H/L^* \rangle$ for four Hubble types are given in Table 6. Defining u_{MHL} for an individual galaxy as $(M_H/L^*)/\langle M_H/L^* \rangle$, the data in Figure 2 are replotted as u_{MHL} against $\mathfrak{M}^*$ in Figure 3. The equivalent regression lines give $\alpha = 0.27 \pm 0.12$, $\gamma = 2.53 \pm 0.71$. The equivalent to Figure 2, but for RDDO types A and S(RDDO) combined, is shown in Figure 4 and gives $\gamma = 2.17 \pm 0.48$. Note that the improvements derived from Figures 2 and 3 have decreased the statistical error in γ, the "excess factor for M_H/L^* OUT versus IN," but have hardly altered the value of $\gamma \approx 2.5$ itself. Whether the positive values of α are real or due to a selection effect, the positive value of $\gamma - 1$ is certainly real.

TABLE 6

MEAN HYDROGEN CONTENT OF DIFFERENT RH TYPES

RH Type	n. $IN_{6°}$	n. $OUT_{6°}$	$\langle M_H/L^* \rangle$
Sab–Sb	11	10	0.07 ± 0.02
Sbc–Sc	4	12	0.20 ± 0.04
Scd–Sd	2	3	0.30 ± 0.09
Sdm–Im	2	2	0.36 ± 0.09

V. H I DISTRIBUTION AND DIAMETERS

For most of the detected galaxies, the neutral hydrogen distribution is resolved by the Arecibo beam and we can obtain a measure of the hydrogen extent along the major axis. It is important to adopt a "scale length" measure rather than an "isophotal" one (which would depend strongly on central surface density). We adopt as our definition for hydrogen diameter D_H twice the distance from the center of the galaxy to the point on the major axis where the flux (integrated over velocity) is one-third of the flux at the center. These estimates are corrected for the sidelobe contribution and finite size of the main beam (Paper I), but not for self-absorption or inclination effects (Shostak 1978). It is worth noting that D_H is not obtained by model fitting. We derive it by simply interpolating the flux measurements, usually 5, at different locations along the major axis after removing sidelobe contributions. Despite the crudeness of the procedure, the resulting estimates should have an rms accuracy of $\sim 1'$ and be largely insensitive to inclination, and to details of the gas distribution and rotation curve. In Tables 4 and 5 we present mean values for the ratio D_H/D_{opt} which is independent of distance (for galaxies which have only upper limits to D_H, this was used in evaluating the mean). We also give mean values for the ratio[4] of the mass and optical surface densities, $\sigma_H/\sigma_{opt} \equiv (M_H/L^*)(D_H/D_{opt})^{-2}$.

The dependence of D_H/D_{opt} on morphological type (with $IN_{6°}$ and $OUT_{6°}$ combined) is unclear at the moment: The ratio appears to be slightly larger for A (which include some Hubble types S0 and Sa) than for S(RDDO), but slightly smaller for S_E (which does not include S0 and Sa) than for S_L. For different collections of galaxies (and different definitions for D_H) Bottinelli (1971) and Krumm and Salpeter (1979*c*) reported different results. Surveys over a larger range of morphological types, with careful mapping, will be necessary to settle this controversy, but one important point is already clear: while M_H/L^* and σ_H/σ_{opt} depend *strongly* on morphological type, D_H/D_{opt} does *not*.

The most important result of the present paper is the fact that D_H/D_{opt} is systematically larger $OUT_{6°}$ than $IN_{6°}$, verified separately for each of A, S(RDDO), S_E, and S_L. With the morphological classes combined, the $OUT_{6°}/IN_{6°}$ ratio is 1.36 ± 0.14. We also obtained linear regression lines of log (D_H/D_{opt}) against log D_{opt} (Fig. 5) for the $OUT_{6°}$ and $IN_{6°}$ groups (forced to have a common slope). It is not clear whether the negative slope, -0.30 ± 0.10, is a real effect[5], but the fit gives an $OUT_{6°}/IN_{6°}$ ratio of 1.40 ± 0.14, in good agreement with the value above. It is important to note that the smaller area $\propto D_H^2$ for the $IN_{6°}$ group accounts almost fully for the smaller value of M_H/L^*, i.e., σ_H/σ_{opt} is *not* appreciably smaller $IN_{6°}$ than $OUT_{6°}$ (except, possibly, for the "earlier classes" A and S_E).

[4] The quantity σ_H/σ_{opt} is a "reduced face-on" parameter, whereas D_H is usually measured only along one direction across the galaxy; because of the strong asymmetries often observed in the gas distribution, this ratio might be more uncertain than a straightforward error propagation formula would suggest.

[5] A bias could be introduced by the finite size of the beam, in the sense of an overestimate of the small D_H's.

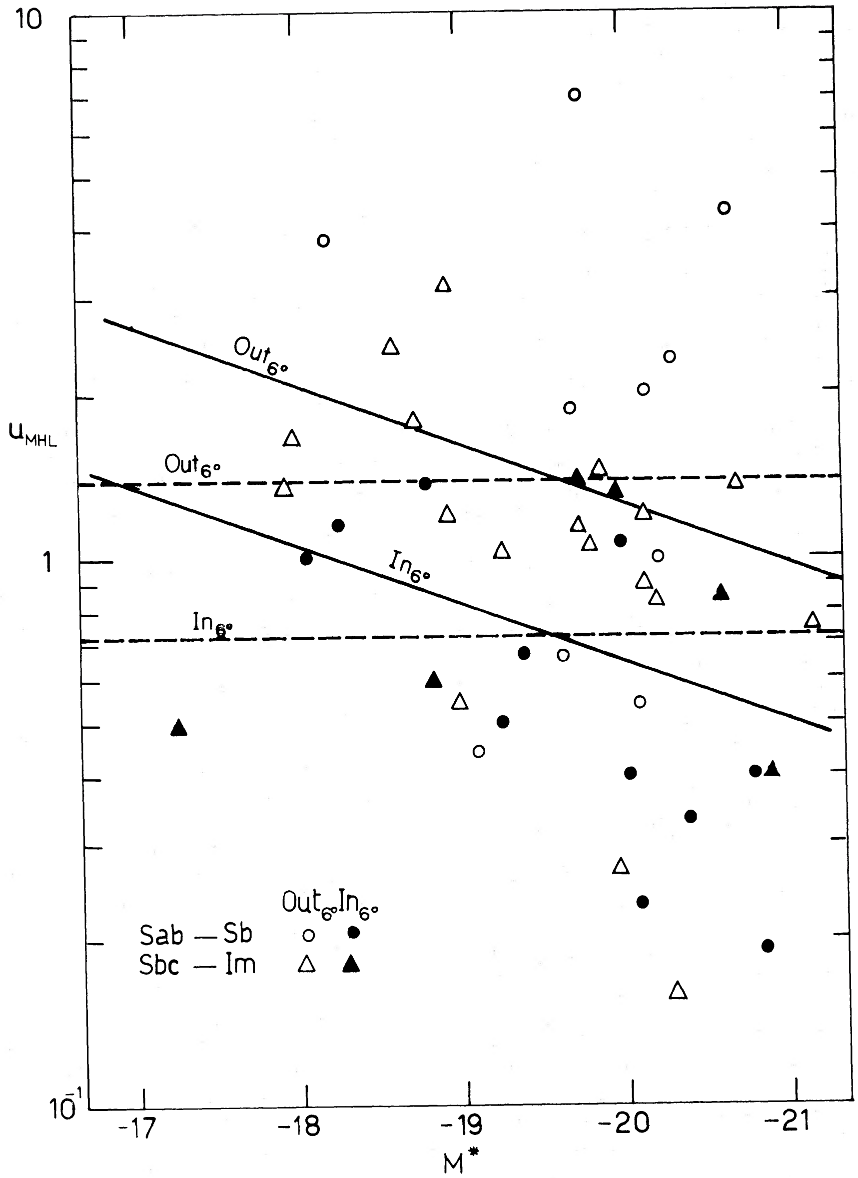

FIG. 3.—Same as in Fig. 2 but corrected for the dependence of the gas content upon the morphology. The correction is applied dividing by the mean values of Table 6.

For many galaxies we have at least a very rough distribution for the velocity integrated flux $F(r)$ as a function of distance r from the galaxy center along the major axis (corrected for the sidelobe contribution but not for the spread of the main beam). In Figure 6 we plot the ratio of $F(r)$ to $F(0)$ against $y \equiv 2r/D_{opt}$ for the individual galaxies (S_E and S_L). With S_E and S_L combined, but separately for $IN_{6°}$ and $OUT_{6°}$, we fitted the data to a simple one-parameter function,

$$\frac{F(r)}{F(0)} = \begin{cases} 1 & \text{if} \quad y < \alpha \\ \exp\left(-\dfrac{y}{\alpha} + 1\right) & \text{if} \quad y > \alpha \,, \end{cases} \tag{2}$$

which seems to fit the data slightly better than a straight exponential. We obtained $\alpha_{IN_{6°}} \approx 0.60$ and $\alpha_{OUT_6} \approx 0.81$ so that the ratio $\alpha_{OUT_{6°}}/\alpha_{IN_{6°}} \approx 1.35$ is close to the $OUT_{6°}/IN_{6°}$ diameter ratio given above.

VI. SUMMARY OF RESULTS

The present paper gives a statistical analysis of a 21 cm neutral hydrogen survey reported in Paper I. The survey involved mainly galaxies in the direction of the Virgo Cluster core as well as its surroundings. The main aim of the survey was to compare the neutral hydrogen properties of galaxies (of various morpho-

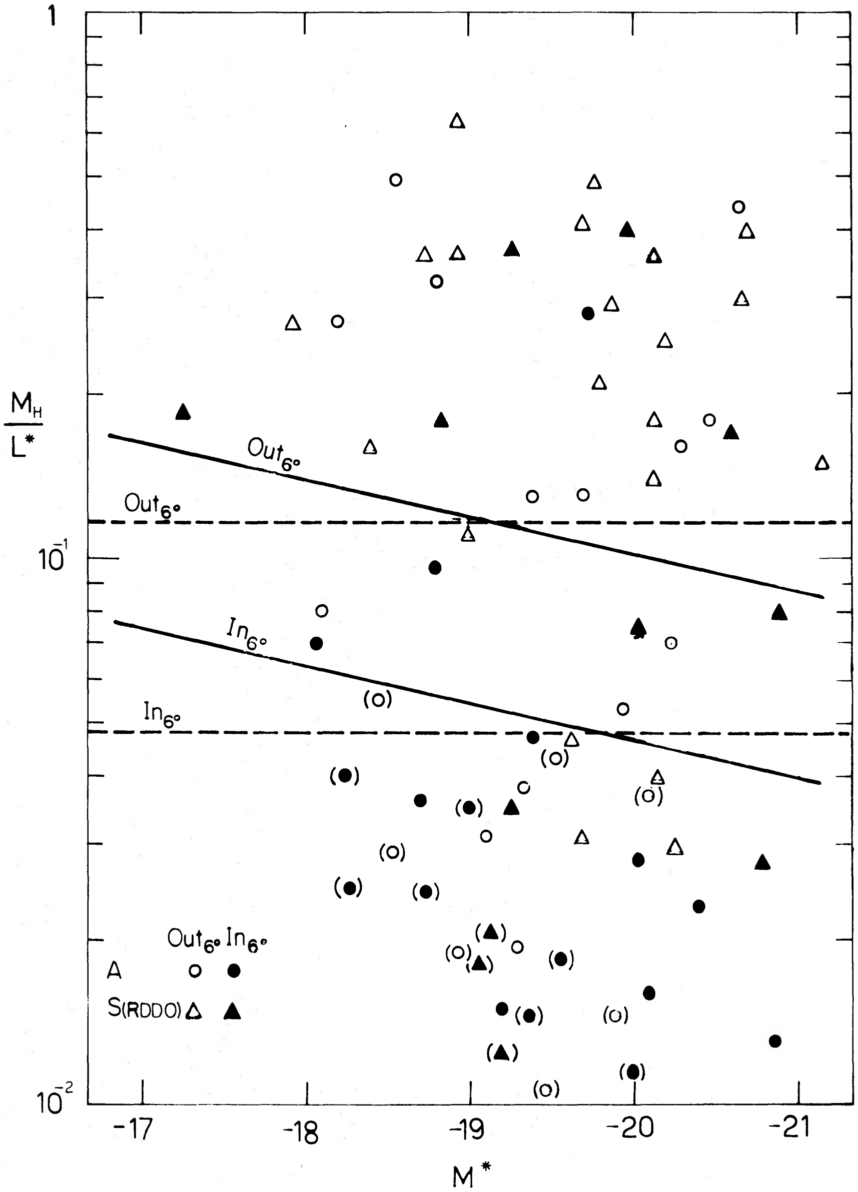

FIG. 4.—The hydrogen content M_H/L^* vs. the absolute blue magnitude $\mathfrak{M}^*$ when the galaxies are classified in the RDDO system. Regression lines, mean values and data in parentheses as in Fig. 2.

logical types) inside the relatively dense environment of the Virgo Cluster core with those outside. Two separate comparisons were carried out, one of the mere detection statistics and the other of means of various galaxy properties, especially of hydrogen mass M_H and hydrogen diameter D_H. The morphological classification of all the galaxies was considered both according to the revised Hubble scheme (RH) and according to the van den Bergh (1976) scheme (RDDO), but keeping only the distinction between true S0's, anemics A, and true spirals. Our Table 3 is compatible with the more detailed findings of Bothun and Sullivan (1980) that RH type S0(RH) corresponds partly to S0(RDDO) and partly to A and that RH type Sa has considerable overlap with A. The Bothun and Sullivan (1980) study referred to a sample of noncluster galaxies whereas about half of our galaxies reside in the cluster core; this can be an important point per se, and speaks in favor of a certain uniformity of the RDDO classification scheme, irrespective of the particular environment.

The main results of the detection survey (in agreement with, but slightly more reliable than, Krumm and Salpeter 1979*a*) are: (1) Hardly any ellipticals are detected (because of the modest sensitivity, upper limits were usually around 4.5 Jy × km s^{-1}). (2) Both for ellipticals and for S0's the detection probability is not improved by observing $\pm 2'$ away from the galaxy center. (3) For RH type S0 galaxies the detection probability is appreciably larger outside the Virgo Cluster core (circle radius 5°) than inside. (4) For RDDO type S0, the detection probability is very small both outside and inside [most of the detected S0(RH) outside galaxies correspond to A]. (5) The number ratio of galaxies outside to inside (whether detected or not) increases from S0(RDDO) to A to S(RDDO).

For comparison of mean properties, $\mathrm{IN}_{6°}$ and $\mathrm{OUT}_{6°}$ refers to a circle of radius 6°. For the Hubble classification we omitted S0 to Sa entirely and divided Sab and later into S_E (early) and S_L (late). A future survey for Sa galaxies as sensitive as Bottinelli, Gouguenheim, and Paturel (1980) would be useful. For RDDO we omitted only S0(RDDO) and kept A and S(RDDO). Our main results regarding total hydrogen mass M_H corroborate the results of Chamaraux, Balkowski, and Gerard (1980), but with slightly different procedures. (6) The result found by a number of previous authors that the mean hydrogen mass M_H is larger $\mathrm{OUT}_{6°}$ than $\mathrm{IN}_{6°}$ is confirmed, separately for each morphological class tested, and is not due to any selection bias. (7) The distance-independent ratio M_H/L^* is larger $\mathrm{OUT}_{6°}$ than $\mathrm{IN}_{6°}$ by a factor 2.5 overall; the factor seems to be slightly larger still for earlier types than for late, but this may not be significant. (8) M_H/L^* varies greatly from galaxy to galaxy, but increases from anemics A to true spirals S(RDDO) (see also Bothun and Sullivan 1980), as it does from early to late Hubble spirals. (9) There is an indication that the hydrogen-deficient $\mathrm{IN}_{6°}$ galaxies are, on the average, not redder than $\mathrm{OUT}_{6°}$ and are slightly overluminous (especially the early types), but it is not clear whether this effect is real. Our most important results concern the distribution of hydrogen, especially the distance-independent ratio D_H/D_{opt}. (10) Unlike M_H/L^*, D_H/D_{opt} does not depend strongly on the morphological type. (11) For each type D_H/D_{opt} is larger $\mathrm{OUT}_{6°}$ than $\mathrm{IN}_{6°}$ to such a degree that (12) the relative hydrogen surface density $\sigma_H/\sigma_{\mathrm{opt}} = (M_H/L^*)\,(D_H/D_{\mathrm{opt}})^{-2}$ is almost the same $\mathrm{IN}_{6°}$ and $\mathrm{OUT}_{6°}$, at least for the later types.

VII. DISCUSSION

We have already stressed that the smaller neutral hydrogen content and extent for galaxies inside the Virgo Cluster core is a real effect, but the "missing mass of gas" could still reside in the individual galaxies but be in ionized form due to the proximity of M87, a powerful source of soft X-rays. The emission from M87 (Fabricant, Lecar, and Gorenstein 1980) is approximately 2×10^{43} ergs s^{-1} with a color temperature of ~ 3 keV. Even as close as 1 Mpc to M87, an outer portion of a galactic disk with column density 2×10^{20} H cm^{-2} and a scale-length as large as 500 pc would have only about the outer 2% of its mass ionized. The "missing mass of gas" could not therefore have been ionized by M87; if it resides as intergalactic gas in the Virgo Cluster core one may ask if it has observable effects. Assuming the typical deficiency observed here, the gas removed from all the spirals in Virgo contributes only $\sim 10^{61}$ cm^{-3} to the (volume integrated) X-ray emission measure of the core, compared with an observational limit of 10^{65} cm^{-3} (Lea *et al.* 1981). It is not therefore directly observable.

Before discussing other implications of our neutral hydrogen results, we summarize the considerable body of evidence against Model A described in § I (each galaxy is born as a late type spiral but is successively turned into earlier Hubble types by ram pressure stripping of gas due to cluster gas, by tidal disruption and by galaxy mergers). Not only the bulge-to-disk ratio but the absolute bulge sizes are larger for S0 galaxies than for spirals (Sandage and Visvanathan 1978; Dressler 1980), whereas ram pressure (and tidal) stripping can alter only outer layers but not the central regions (Toomre and Toomre 1972; Farouki and Shapiro 1980). Furthermore, ram pressure could give complete stripping *only* in a *very high density* environment, *especially* for the gas-rich late-type spirals (Gisler 1980), contrary to the observations of large numbers of S0's in loose Virgo-type clusters (see aso Bothun *et al.* 1982). Galaxy mergers cannot be the main agent "manufacturing" S0 galaxies because, at a given density, they would be more effective in small groups with small velocity dispersions than in large clusters with large dispersions; observations (Bhavsar 1981) give the opposite tendency, compatible with ram pressure.

We therefore must accept "at birth" a full range of morphological types along at least a one-dimensional sequence (not counting absolute luminosity), e.g., the bulge-to-disk (B/D) ratio. However, this still leaves lots of controversy since present-day galaxies show *at least* one more variable parameter (for given B/D), e.g., the hydrogen content M_H/L and/or the hydrogen size ratio D_H/D_{opt} and/or the optical disk surface brightness and/or the distinctness (or clumpiness) of the spiral arms. The RDDO classification scheme into "true spirals S," "anemics A," and "true S0," suggested by van den Bergh (1976), is an attempt at a classification scheme with only *one* additional variable. It is reasonably successful in predicting the hydrogen content from the optical appearance of the disk, although there are large variations. However, this presumably is due to the hydrogen content affecting the present rate of star formation and the abundance of young stars affecting the optical appearance, whatever the cause of the differences in the hydrogen content. We shall argue that more than one additional variable is required and that the RDDO sequence is not caused by ram pressure stripping.

We have seen that the overall H I mass to blue light ratio M_H/L^* is smaller for "anemics" than for "RDDO spirals" (with $\mathrm{IN}_{6°}$ and $\mathrm{OUT}_{6°}$ locations combined) by a factor of about 0.4; M_H/L^* is smaller for the $\mathrm{IN}_{6°}$ location than for $\mathrm{OUT}_{6°}$ (for the same Hubble type) by about the same factor (although this factor would presumably have been more extreme if IN referred to the

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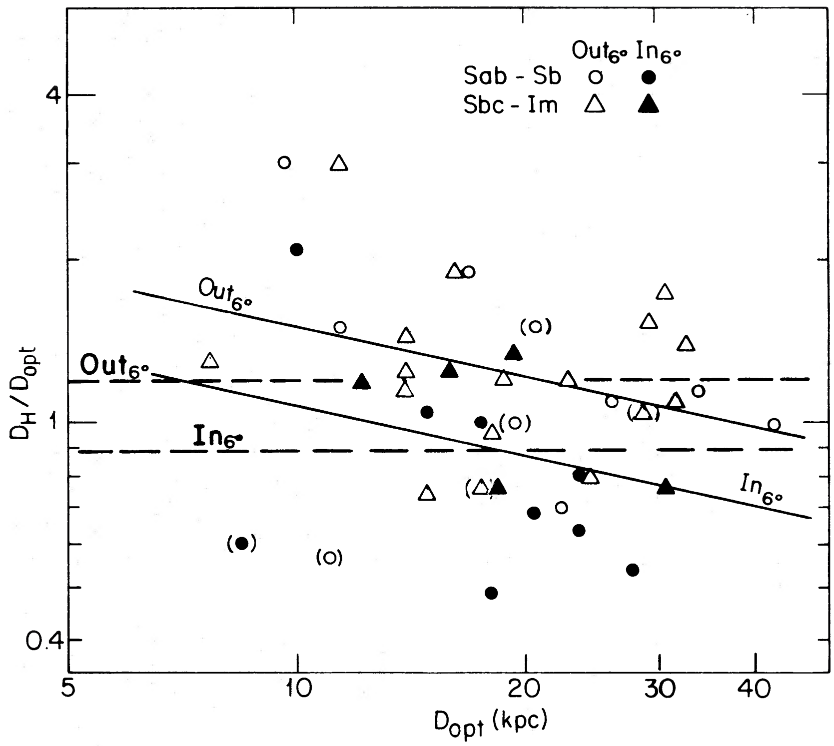

FIG. 5.—The hydrogen extent normalized to the optical diameter (D_H/D_{opt}) vs. the absolute linear diameter (optical) in kpc, for S_E and S_L only. Solid lines are the regression lines fitting the data referring to the IN and OUT samples (upper limits in parentheses). Dashed lines are the mean values from Table 5.

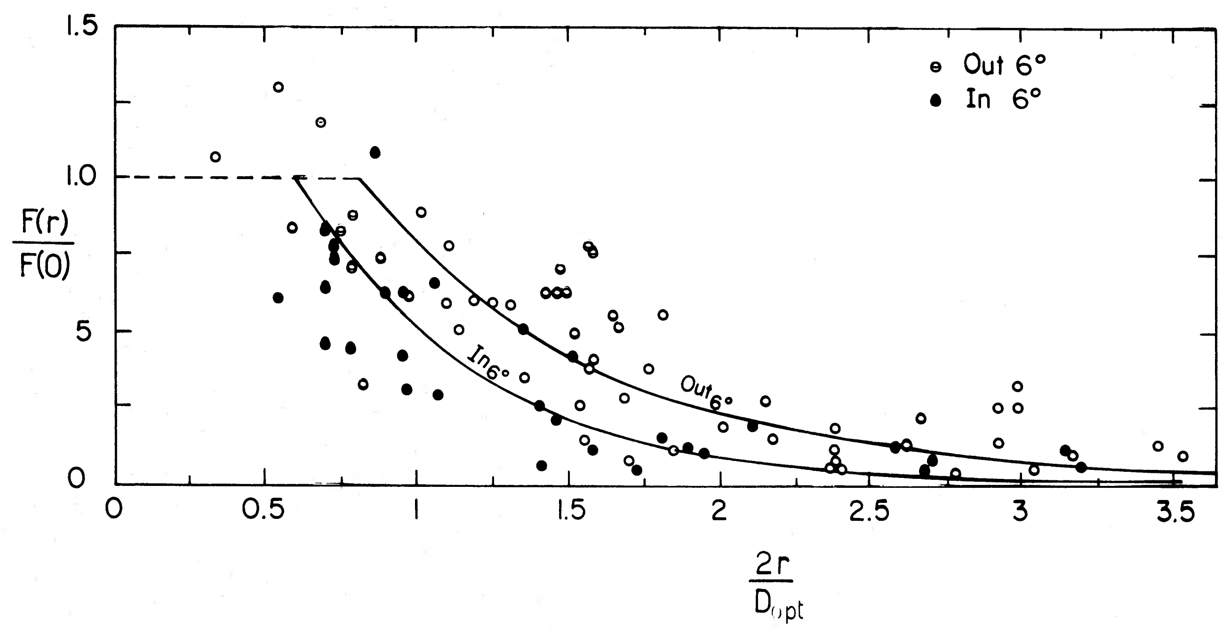

FIG. 6.—The integrated flux, measured at a distance r from the optical center of a galaxy (S_E and S_L only) normalized to the central value $F(0)$, vs. the normalized distance from the center. The two solid lines refer to the (truncated) exponential distributions fitted to the $IN_{6°}$ (*lower fit*) and $OUT_{6°}$ (*upper fit*) data.

core of a denser cluster[6] and/or OUT referred to true field galaxies instead of the supercluster environment). There are at least four possible causes for a decrease in M_H/L^*: two "internal" ones [(*a*) an enhanced galactic wind and (*b*) an overall increase in the rate of star formation (Strom 1980)], and two "external" ones [(*c*) tidal encounters (or collisions with dwarf systems) disturbing galactic gas and giving a local enhancement of star formation (Larson and Tinsley 1978) and (*d*) ram pressure stripping by extragalactic gas (and, possibly, tidal disturbances leading indirectly to local gas ejection)]. Fortunately the internal and external mechanisms make different predictions for the central value σ_{Hc} of the hydrogen surface density and the scale length diameter D_H. A galactic wind (originating in a central bulge) and star formation (whose rate per unit gas mass, in the most naive picture, increases with gas density) both depress the gas density most in the inner regions of a galactic disk. Thus (*a*) and (*b*) strongly depress σ_{Hc} but actually *increase* the scale length D_H by depressing the logarithmic density gradient (whereas an "isophotal" hydrogen radius would be increased slightly).[7] On the other hand, tidal disturbances and ram pressure stripping are most effective on an outer disk where the gas column density is already smaller. Thus (*c*) and (*d*) leave σ_{Hc} almost unchanged (although secondary redistribution of the remaining gas decreases σ_{Hc} slightly; see Gunn and Gott 1972; Gisler 1976; Lea and De Young 1976; Shaviv and Salpeter 1982) but decreases D_H strongly if this is defined at a level low enough for the sweeping to be effective, and our $\frac{1}{3}$ level is perhaps the lowest feasible if a large sample of galaxies is to be analyzed.

We saw (results 11 and 12 in § VI) that our observational data for the $IN_{6°}/OUT_{6°}$ comparison of σ_H and D_H/D_{opt} are just as predicted by (*c*) and (*d*), assuming our estimates of σ_H are representative of σ_{Hc}.[8] The scatter in D_H/D_{opt} (Fig. 5) is large, but since (*a*) and (*b*) make the *opposite* prediction, there is little doubt that (*c*) or (*d*) (or "something else"), rather than (*a*) or (*b*), causes the gas depletion in the Virgo Cluster core. Fortunately, (*c*) and (*d*) make opposite predictions for the absolute values of D_{opt}: For (*c*) the depression in gas in the outer disk leads to larger star density and optical surface brightness there, hence increasing D_{opt}, whereas (*d*) leads to a slight loss of the outer stellar disk and hence a slight decrease in D_{opt}. Dressler (1980) reports that absolute disk sizes (unlike bulge sizes) decrease slightly in environments of higher density, thus favoring (*d*) over (*c*). For anemics (in comparison with RDDO spirals), on the other hand, Table 5 shows that σ_H is appreciably smaller and D_H/D_{opt} the same or slightly larger as predicted by (*a*) or (*b*). We therefore feel that anemic galaxies are not produced by ram pressure stripping but by some internal cause; other statistical arguments (Bothun and Sullivan 1980) also point in this direction. There is also some evidence for the possibility of mechanism (*b*) with the opposite sign, since a (rare) class of spiral galaxies with anomalously low optical disk surface brightness σ_{opt} tend to have anomalously large values of M_H/L (Romanishin *et al.* 1982). Variations of σ_{opt} with class are likely to be important; measurements of scale-length optical diameters (and σ_{opt}) would be very useful in the future, since isophotal diameters depend too much on σ_{opt}.

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[6] The studies now available of the gas content of spirals in other clusters (e.g., Sullivan, Bothun, and Bates 1981; Schommer, Sullivan, and Bothun 1981; Giovanelli, Chincarini, and Haynes 1979) show that H I properties of the members correlate with the morphology and X-ray properties of the cluster. In this respect Virgo, with an overall deficiency factor of ~ 2–2.5, could be considered of an intermediate type.

[7] Isophotal sizes will also convey information regarding the depletion mechanism, but we do not have a substantial and/or homogeneous sample of isophotal sizes: isophotal measurements imply longer observing time, and are more sensitive to instrumental effects; data reduction is more involved, and inevitably more error prone.

[8] We tested the variations of the proportionality constant $K \equiv \sigma_{Hc}/\sigma_H$ for a variety of simple models (exponential, Gaussian, and variously truncated distributions of convenient size) when observed with an Arecibo-sized beam. These variations turn out to be confined within $\pm 10\%$.

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C. GIOVANARDI: Osservatorio Astrofisico di Arcetri. Largo E. Fermi 5, 50125 Firenze, Italy

GEORGE HELOU and E. E. SALPETER: Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853

NATHAN KRUMM: Physics Department, University of Cincinnati, Cincinnati, OH 45221