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NEUTRAL HYDROGEN IN VIRGO CLUSTER GALAXIES

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SUMMARY

Twenty-one centimetre wavelength measurements with the Mark I and Mark II radio telescopes have been made of the neutral hydrogen content of 25 galaxies in the Virgo cluster. Spectra of some of the brighter galaxies are shown in Fig. 1; the neutral hydrogen parameters of each galaxy are given in Table I. A comparison of the neutral hydrogen mass-to-luminosity radio M_H/L and the neutral hydrogen surface density σ_H for the Virgo cluster galaxies with field galaxies indicates that on average the cluster galaxies are deficient in neutral hydrogen by a factor of $\sim$0·63. Calculations of galactic collision times suggest that collisions are likely to be responsible for the deficiency of gas in the Virgo cluster galaxies at the present epoch.

1. INTRODUCTION

The possibility that the gas content of galaxies within clusters may be substantially different from the gas content of field galaxies has been considered previously by Spitzer & Baade (1951) and by Osterbrock (1960). Frequent collisions between galaxies in rich clusters could alter the gas content at the present epoch as compared with the field galaxies. In his analysis of the numbers of E and SO galaxies showing the 3727 Å [O II] emission line as noted in the Humason, Mayall & Sandage (1956) catalogue, Osterbrock found that a significantly smaller fraction of the cluster objects showed the emission line. In fact no E or SO galaxies with 3727 Å emission were found in the rich clusters.

Neutral hydrogen observations provide a sensitive method of measuring the gas content of nearby clusters of galaxies. Robinson & Koehler (1965) made a survey of the neutral hydrogen content of 18 galaxies in the Virgo cluster; they detected emission of more than twice their quoted errors in seven cases. If these results are taken at their face value they indicate that the Virgo cluster galaxies are deficient in neutral hydrogen compared with field galaxies (Davies 1968). However, since Robinson and Koehler made limited observations in both position and velocity, it is likely that they obtained underestimates of the neutral hydrogen masses. The present observations give more complete neutral hydrogen data on 25 Virgo cluster galaxies which enable more definite conclusions to be drawn on the subject of the gas content of cluster galaxies.

2. THE OBSERVATIONAL TECHNIQUE

The observing system and the method of observation were the same as those described in the accompanying paper (Lewis & Davies 1973). The main parameters may be summarized as follows. Observations were conducted principally with the

TABLE I

Virgo cluster galaxies

NGC	Type	Size (′ × ′)	Mult. factor	M_H observed (× 10⁹ $M_\odot$)	M_H corrected (× 10⁹ $M_\odot$)	21 cm velocity rel. to Sun (km s^{-1})	¼ power width (km s^{-1})	Optical velocity rel. to Sun (km s^{-1})	$L/L_\odot$ (× 10^{10})	M_H/L	$C_0(0)$	σ_H (× 10^{-3} g cm^{-2})
4178	Sc$^+$ SBT8	7·3 × 3·1	1·12	4·5 ± 0·8	5·1	329 ± 25	376	233 ± 46	1·5	0·34	0·42	1·4
4192	Sb$^+$ SXS2	11·6 × 3·2	1·26	4·1 ± 1·4	5·2	−143 ± 48	499	−124 ± 40	8·7	0·059	0·69	0·56
4216	Sb$^-$ SXS3*	10·4 × 3·7	1·22	1·5 ± 0·5	1·8	−103 ± 60	348	38 ± 35	6·5	0·028	0·75	0·24
4254	Sc$^-$ SAS5	7·3 × 6·0	1·18	6·7 ± 0·7	7·9	2387 ± 14	277	2471 ± 38	3·8	0·21	0·48	2·2
4293	SO RSBSO	6·9^a × 2·7	1·10	0·65 ± 0·30	0·71	948 ± 40	382	750 ± 75	3·6	0·020	—	0·21
4294	Sc$^-$ SBS6	4·3 × 2·1	1·05	2·7 ± 0·5	2·8	312 ± 18	256	390 ± 85	0·72	0·39	0·44	2·1
4299	Sc$^+$ SB.7P	3·1 × 3·0	1·05					187 ± 65	0·40	0·70	0·36	4·1
4303	Sc$^-$ SXT4	10·7 × 7·4	1·09†	6·9 ± 0·6	7·5	1560 ± 5	174	1671 ± 160	5·7	0·13	0·50	1·3
4321	Sc$^-$ SXS4	10·0 × 9·1	1·37	1·9 ± 0·5	2·6	1663 ± 35	516	1617 ± 75	4·9	0·053	0·62	0·37
4374	SO E+1	10·7 × 10·5	1·44	0·99 ± 0·19	1·43	910 ± 17	290	954 ± 50	3·2	0·045	0·92	0·15
4394	Sb$^-$ RSBR3	4·5 × 4·5	1·08	<0·79	<0·85	—	[200]	772 ± 160	0·95	<0·09	0·76	<0·88
4406	E E+3	12·0 × 10·3	1·49	<2·6	<3·9	—	[400]	−292 ± 32	3·6	<0·11	0·89	<0·38
4472	E E.2	11·7 × 11·0	1·50	0·88 ± 0·40	1·32	868 ± 50	431	948 ± 37	7·3	0·017	0·89	0·11
4501	Sb$^+$ SAT3	9·4 × 5·5	1·23	0·72 ± 0·35	0·89	2016 ± 60	181	2120 ± 100	7·4	0·012	0·65	0·15
4526	SO LXSO*	8·1^a × 2·2	1·13	1·4 ± 0·3	1·60	448 ± 24	347	487 ± 45	4·0	0·040	0·85	0·35
4535	Sc$^-$ SXS5	9·9 × 8·9	1·35	4·1 ± 0·4	5·5	1942 ± 13	302	1943 ± 19	3·7	0·15	0·52	0·79

4548	Sb^+ SBT3	7·7 × 5·6	1·18	2·0 ± 0·4	2·3	495 ± 36	314	433 ± 50	3·1	0·074	0·77	0·55
4567	Sc^- SAT4	5·4 × 3·7	1·00†	0·58 ± 0·28	0·58	2297 ± 55	196	2253 ± 47	0·93	0·062	0·65	0·28
4568	Sc^- SAT4	6·8 × 3·5						2278 ± 48	1·5	0·038	0·73	0·12
4569	Sb^+ SXT2	11·7 × 5·8	1·07†	1·38 ± 0·46	1·48	−236 ± 50	313	−304	8·3	0·018	0·59	0·14
4579	Sb^- SXT3	9·6 × 6·4	1·26	1·40 ± 0·42	1·77	1808 ± 37	373	1752 ± 160	5·4	0·033	0·82	0·27
4651	Sc^- SAT5	6·1 × 4·5	1·11	4·2 ± 0·7	4·7	796 ± 12	397	733 ± 42	1·8	0·26	0·48	1·8
4654	Sc^- SXT6	7·0 × 4·9	1·14	3·0 ± 0·5	3·4	1027 ± 15	307	1022 ± 45	2·2	0·15	0·57	0·98
4698	Sa SAS2	6·5 × 4·5	1·12	1·4 ± 0·4	1·57	872 ± 35	270	1032 ± 50	1·7	0·092	0·74	0·50
4762	SO LBRO	8·4[a] × 1·1	1·13	< 0·79	< 0·89	—	[450]	939 ± 28	2·4	< 0·055	0·73	< 0·25

Notes

The distance of the Virgo cluster is taken as 14·8 Mpc (Sandage 1968).

† Mark II observation.

[a] de Vaucouleurs RCBG diameter multiplied by 1·5.

[ ] is linewidth assumed for calculating upper limits on M_H.

NGC 4136 There is some confusion by local hydrogen.

NGC 4294/9 are separated by 5′·5 arc and are both observed in the same beamwidth. Values of M_H/L and σ_H are given for each galaxy assuming all the hydrogen was associated with the galaxy. The values plotted in Figs 2, 3 and 4 are half the average of these two.

NGC 4374 has been observed by Bottinelli *et al.* (1973). They find $M_H < 1{\cdot}0 \times 10^9\ M_\odot$ corrected to a distance of 14·8 Mpc.

NGC 4472 has been observed subsequently with the MK IA telescope and an upper limit to M_H of $3{\cdot}6 \times 10^8\ M_\odot$ has been found. Bottinelli *et al.* (1973) and Gallagher find similar upper limits.

NGC 4526 has also been observed with the MK IA telescope. $M_H = 6{\cdot}3 \times 10^8\ M_\odot$; $v = 508$ km s^{-1}.

NGC 4567/8 are separated by 1′·2 arc and are both within the beam. Values of $M_{H/L}$ and σ_H are given for each assuming all the hydrogen was associated with the galaxy. The values plotted in Figs 2, 3 and 4 are half the average of these two.

NGC 4569 Observations were made of this galaxy at the Burbidge & Hodge (1971) velocity of −304 km s^{-1}. There was slight confusion by local hydrogen.

The luminosity is estimated from the Holmberg photographic magnitude and making the correction for absorption within the galaxy and within the Milky Way. The colour $C_0(0)$ is from the RCBG, and the angular diameters are from Holmberg (1958).

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Mark I radio telescope which had a beamwidth of 17′×13′ arc; NGC 4303, 4569 and the 4567/8 system were observed with the Mark II telescope (beamwidth 31′×33′ arc). The system noise in both cases was 100 K; the autocorrelation spectrometer provided a 5 MHz (1060 km s^{-1}) bandwidth and a velocity resolution of 7·4 km s^{-1}. Reference observations were made in a clear comparison field; these were subtracted from the observations on each galaxy. In the case of weaker signals a 2nd and 3rd order baseline was fitted to the region of the spectrum outside the neutral hydrogen emission. The uncertainty in fitting this baseline is included in the errors quoted for the neutral hydrogen data.

3. THE NEUTRAL HYDROGEN DATA FOR THE VIRGO CLUSTER

Galaxies were chosen for observation in the Virgo cluster so as to cover a wide range of morphological types; the galaxies were generally the largest and most luminous of their type. Care was taken to ensure that the chosen galaxies were not confused by nearby objects in the comparison field.

Upper limits to the neutral hydrogen mass were computed for those galaxies in which no signal was detected by taking an upper limit for the flux density and assuming a velocity spread appropriate to the morphological type (Brosche 1971).

In estimating the neutral hydrogen mass of the Virgo cluster galaxies a correction is made for the finite size of the emitting region relative to the beam. Following the procedure used in the accompanying paper, the correction assumes that the hydrogen has a diameter equal to the Holmberg (1958) diameter or 1·5 times the diameter given in the *Reference Catalogue of Bright Galaxies* (RCBG) (de Vaucouleurs & de Vaucouleurs 1964).

Table I gives the neutral hydrogen data for 25 Virgo cluster galaxies. Both the uncorrected and corrected hydrogen mass are given for each galaxy. A 21-cm systemic velocity and profile width are given for galaxies where a neutral hydrogen detection has been made. A distance of 14·8 Mpc has been assumed for the cluster (Sandage 1968). Table I also includes optical data on the type, size, velocity, luminosity and colour of each galaxy. The luminosity and colour have been corrected for inclination, morphological type and galactic latitude in accordance with the precepts of the accompanying paper. Also given are the distance-independent parameters M_H/L (the hydrogen-mass-to-luminosity ratio) and σ_H (the neutral hydrogen surface density). The latter is calculated for a neutral hydrogen diameter equal to the Holmberg optical diameter.

Spectra for the more intense neutral-hydrogen-emitting galaxies are shown in Fig. 1. In the case of the weaker galaxies in this group the signals have been averaged over a wider bandwidth to increase the sensitivity at the expense of velocity resolution. The galaxies with the best signal-to-noise ratio (NGC 4254, 4303, 4535, 4651 and 4654) have the characteristic flat-topped integral spectrum.

The observations include two instances of close pairs of galaxies lying in the same beamwidth. These are NGC 4294/9 which are separated by 5′·5 arc and NGC 4567/8 separated by 1′·2 arc. The galaxies in each pair have similar sizes, redshifts, morphological types and colours. In the statistical investigation which follows, the neutral hydrogen data have been taken with the mean optical properties to give one value of the relevant parameters for each pair of galaxies. This should not produce any statistical bias in the results.

TABLE II

A comparison of neutral hydrogen in the Virgo cluster galaxies measured at Jodrell Bank and Parkes

Galaxy (NGC)	Diameter (′ × ′)	Jodrell Bank* M_H (observed) units of $10^9 M_\odot$	M_H (corrected) units of $10^9 M_\odot$	v (H I) km s^{-1}	Δv km s^{-1}	Parkes† M_H units of $10^9 M_\odot$	V_{sig} km s^{-1}
4303	10·7 × 7·4	6·9‡	7·5	1560	174	3·3	1670
4321	10·0 × 9·1	1·9	2·6	1663	516	1·5	1630
4472	11·7 × 11·0	0·88	1·32	868	431	0·4	1010
4501	9·4 × 5·5	0·72	0·89	2016	181	< 1·0	2120
4535	9·9 × 8·9	4·1	5·5	1942	302	1·9	1950
4569	11·7 × 5·8	1·38	1·48	1024	245	< 0·28	960
4579	9·6 × 6·4	1·40	1·77	1808	373	< 0·8	1750

* Observations with a beamwidth of 13′ × 17′, a velocity resolution of 7·4 km s^{-1} and an overall bandwidth of 1060 km s^{-1}.

† Observations made with a beamwidth of 14′ arc in a band 320 km s^{-1} wide centred on v_{sig}.

‡ An observation made with the Mark II radio telescope (beamwidth = 31′ × 33′ arc).

The present results are compared with the earlier observations of Robinson & Koehler in Table II for the seven galaxies common to the two lists. The Robinson & Koehler neutral hydrogen masses have been adjusted to the distance of 14·8 Mpc used in this analysis. Their observations were made with a 14′ arc beamwidth and a single receiving band of 320 km s^{-1} half-power width centred on the velocities tabulated. In all cases except NGC 4501 the Jodrell Bank observed M_H values exceed the Parkes values. This difference can in most cases by attributed to the fact that the Parkes 320 km s^{-1} receiving band did not include the entire velocity range of neutral hydrogen emission. Further, most of the galaxies are comparable in size with the Mark I and Parkes beamwidths and appreciable corrections are required as indicated in Table I. In the case of NGC 4303 which was observed with the Mark II radio telescope the correction for the contribution from outside the beam is estimated to be 9 per cent and its neutral hydrogen mass is well determined. The Parkes estimate is 0·44 of this value.

4. A COMPARISON OF VIRGO CLUSTER GALAXIES WITH FIELD GALAXIES

The neutral hydrogen content of Virgo cluster galaxies can be compared with that of field galaxies in a number of ways. The distance independent parameters M_H/L and σ_H are considered the most suitable for the study. Virgo galaxies of a given morphological type or colour can then be compared with the corresponding field galaxies. Data on field galaxies which have been assembled in the accompanying paper provide a good comparison set. Although these galaxies have been measured by a number of observers the intensity scales have been normalized among themselves. It should be emphasized that a majority of the so-called field galaxies are members of small groups containing 10 or so galaxies. Our comparison is thus being made between these galaxies and the galaxies in the Virgo

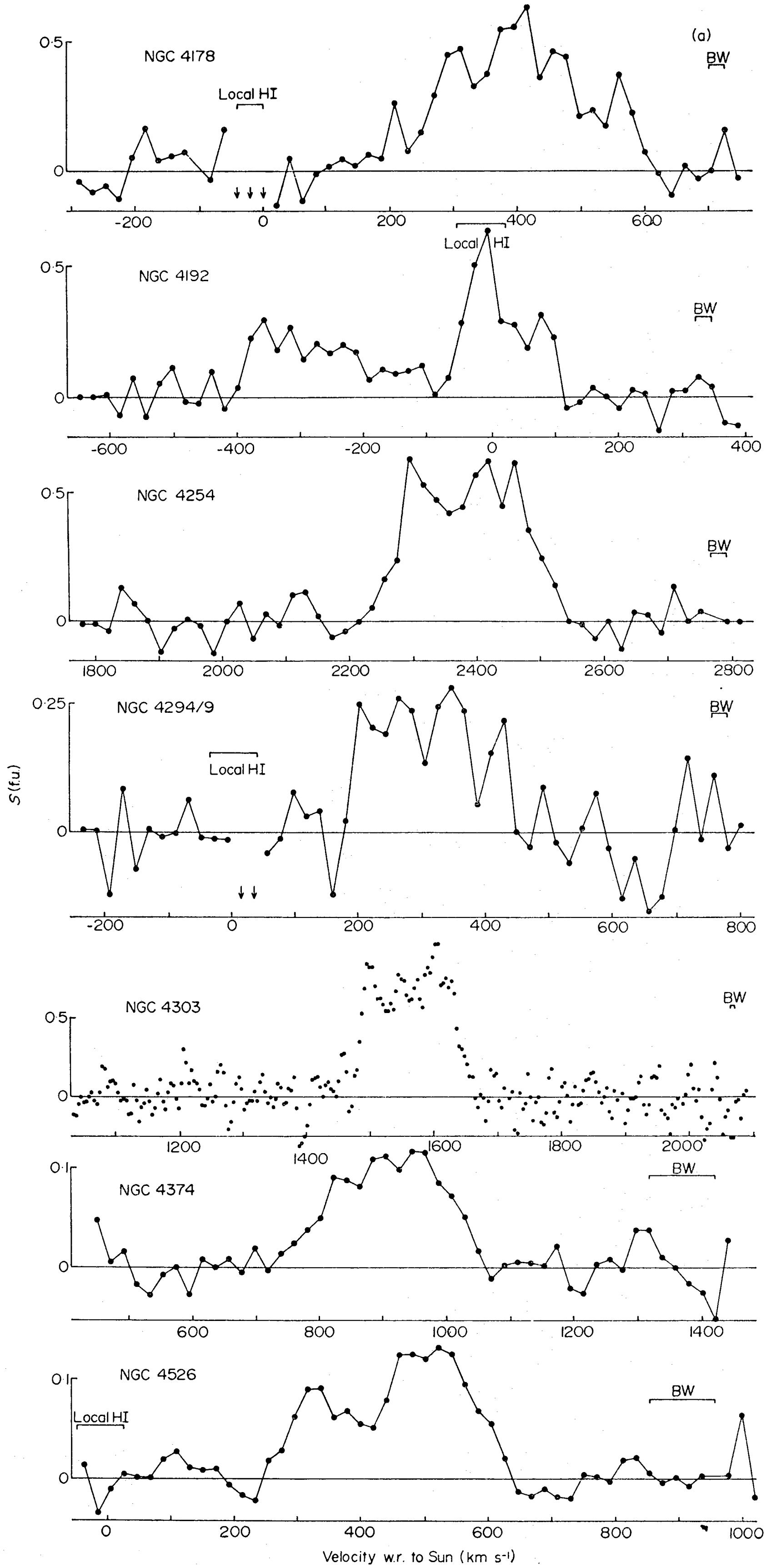

Fig. 1. *Neutral hydrogen spectra of the more intense galaxies seen in the present Virgo cluster survey. The velocity range of local Milky Way hydrogen emission is indicated. The bandwidths (BW) shown are those used in smoothing the data to delineate the spectra more clearly.*

cluster which contains some 200 galaxies brighter than $M_{pg} = 13{\cdot}5$ (de Vaucouleurs 1961) and thousands of fainter members.

Fig. 2 shows the comparison plot of M_H/L against morphological type T. Fig. 3 shows M_H/L against corrected colour $C_0(0)$ and Fig. 4 shows σ_H plotted against morphological type.

The Virgo cluster galaxies in the M_H/L against T plot (Fig. 2) are spread amongst the field galaxies in each morphological type. On closer examination, the distribution of M_H/L in Virgo cluster galaxies is found to be displaced to lower values relative to the field galaxies. The average Virgo cluster galaxy has a value of $M_{H/L}$ equal to $0{\cdot}65 \pm 0{\cdot}11$ of that for field galaxies of the same type. A similar analysis of the colours of the Virgo cluster galaxies shows that M_H/L is $0{\cdot}67 \pm 0{\cdot}10$ of the value for field galaxies of similar colours.

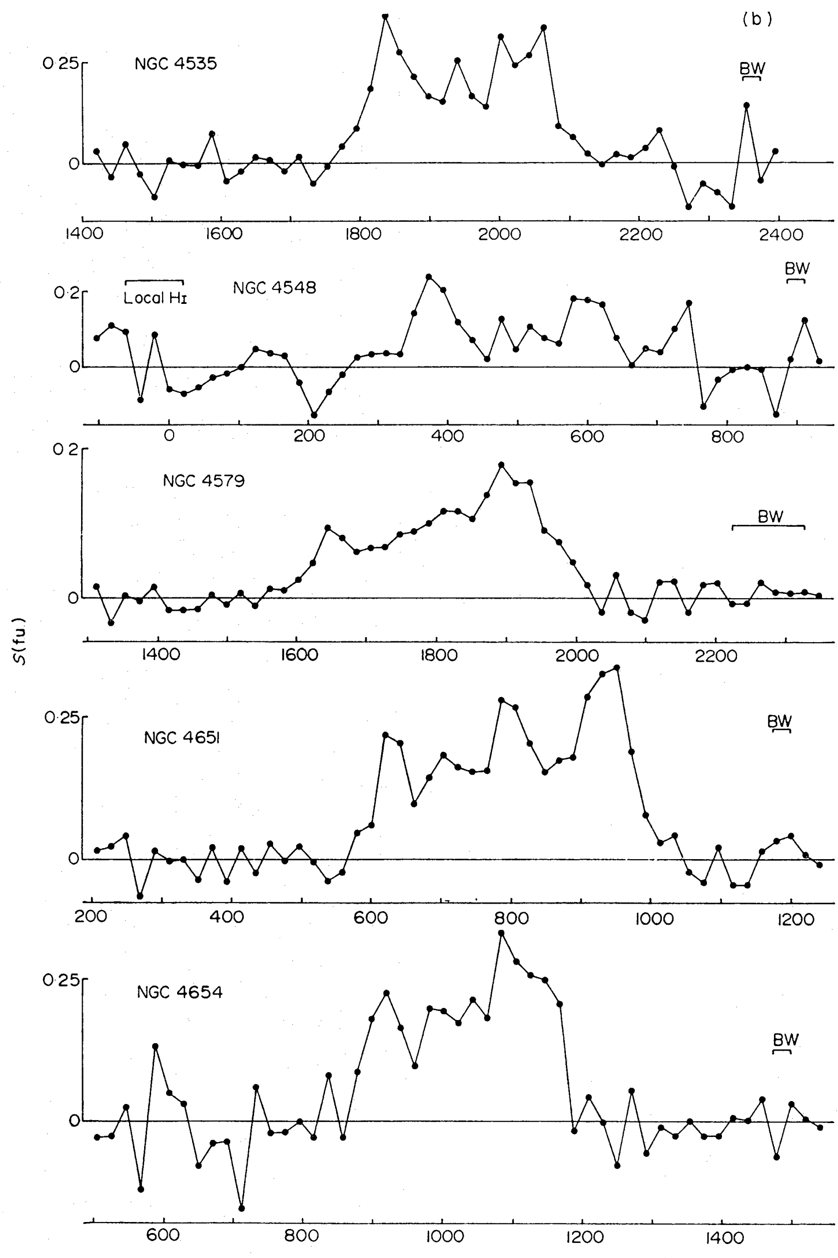

FIG. 1(*b*).

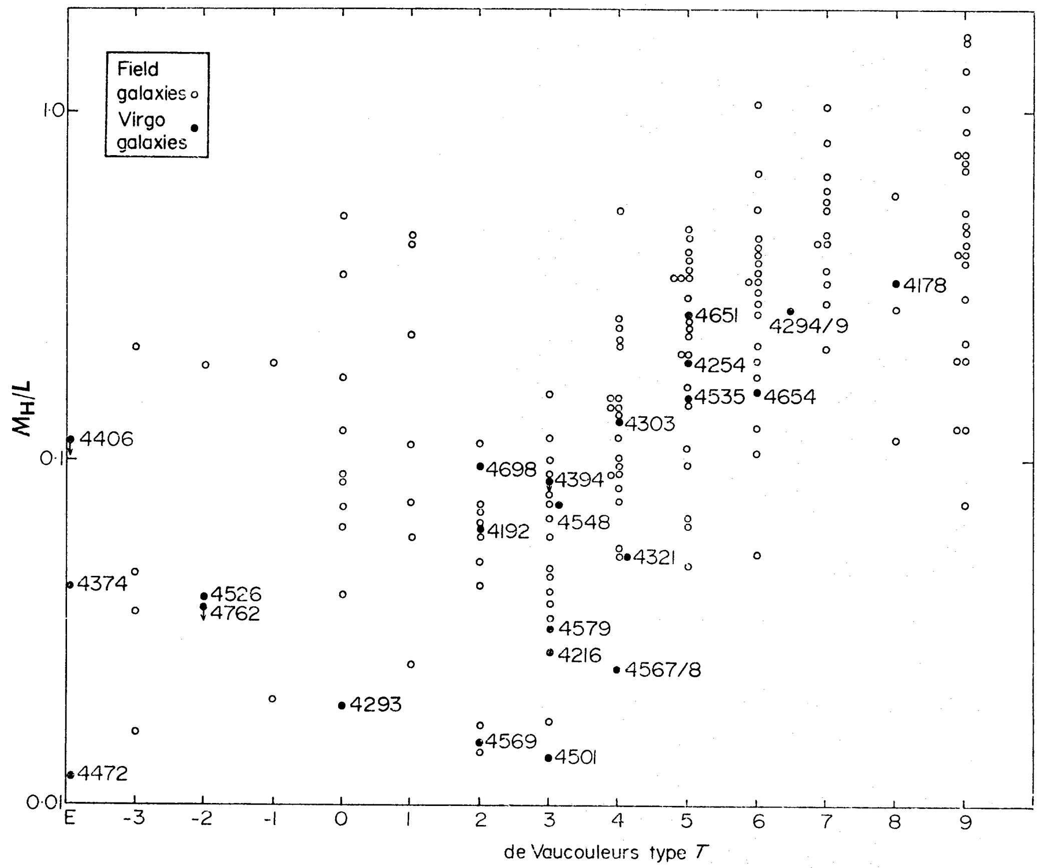

FIG. 2. *M_H/L plotted against de Vaucouleurs morphological type T. Virgo cluster galaxies are shown as ● and the field galaxies as ○.*

The surface density σ_H also shows a lower value for a given morphological type in the Virgo cluster galaxies than field galaxies by a fraction 0·52 ± 0·09. Any possible variation of the neutral hydrogen to optical diameter ratio with type (Bottinelli 1971) is eliminated in this analysis because the comparison is made within each morphological type.

A difference between the colours of Virgo cluster galaxies and field galaxies has been noted by several authors. Holmberg (1958) has found that the Virgo cluster galaxies are redder than field galaxies of the same morphological type; the average difference ΔC_0 in his list (Table 15) of 53 Virgo cluster galaxies was $\Delta C_0 = 0{\cdot}08 \pm 0{\cdot}015$. Chester & Roberts (1964) concluded that 10 Sc galaxies in the Virgo cluster were too red for their absolute magnitude when compared with field galaxies. Seventeen of the galaxies in the present investigation are listed in Holmberg's Table 15; the mean value of $\Delta C_0 = +0{\cdot}04$, again indicating that for their morphological type they are redder than the field galaxies.

It has been shown in the various statistical investigations above that the neutral hydrogen content of the Virgo cluster galaxies is less than in field galaxies of the same morphological type by a factor of ~0·63. Also the colour is redder for a sample of these galaxies by $0^m{\cdot}04$ for a given morphological type. The variation of $M_{H/L}$ with $C_0(0)$ in Fig. 3 would suggest a fall in $M_{H/L}$ by a factor of 0·79 for $\Delta C_0 = 0{\cdot}04$; this is a change in the sense actually observed but not of the full magnitude. These results relating to the $M_{H/L}$ ratio and the colour index cannot be taken to imply that the Holmberg classification of the Virgo galaxies is incorrect

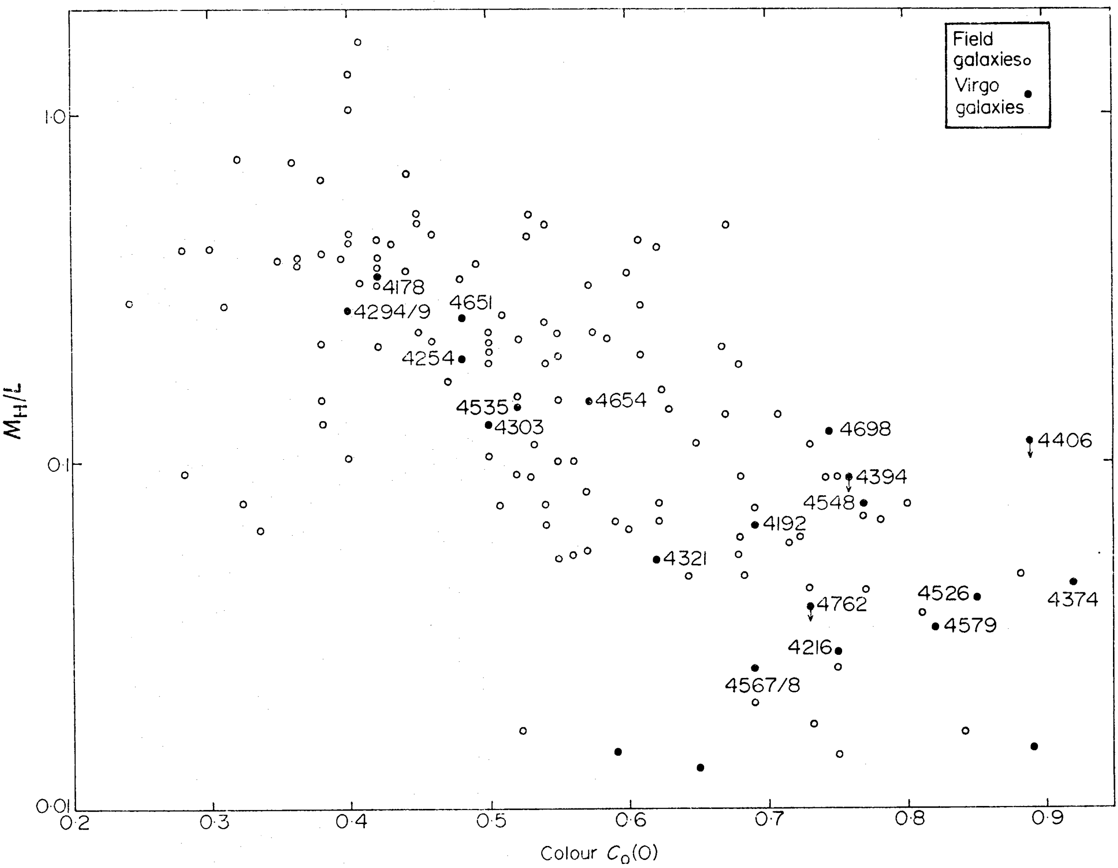

FIG. 3. *M_H/L plotted against colour C_0(o). Virgo cluster galaxies are shown as ● and the field galaxies as* ○.

since the classification agrees closely with that made independently by Humason *et al.* (Holmberg 1958). Both the deficiency of neutral hydrogen and the reddening of the Virgo cluster galaxies are observed properties which require explanation.

Finally, a comment will be made on the optical and neutral hydrogen velocities of the Virgo cluster galaxies. The mean difference velocity (optical minus radio) is 10 ± 20 km $^-$s^1 giving equal weight to all observations. There is no support from the present observations of Virgo cluster galaxies for the claim by Roberts (1972) that optical redshifts derived from blue plates in the range 1200–2400 km s^{-1} are systematically too large by 100 km s^{-1}.

5. DISCUSSION

The Virgo cluster may be composed of two overlapping clouds of galaxies (de Vaucouleurs 1961). One contains E galaxies with a mean velocity of 950 ± 70 (pe) km s^{-1}; it is centred on RA = $12^h\,26^m{\cdot}5$, Dec = $+13^\circ{\cdot}2$. The other contains spiral and irregular galaxies with a mean velocity of 1450 ± 120 (pe) km s^{-1}; it is centred on RA = $12^h\,27^m{\cdot}5$, Dec = $+13^\circ{\cdot}9$. A more recent study by Tammann (1972) suggests that there is no significant difference in the velocity distribution of the two groups of galaxies. The present study has included galaxies from both clouds, although mainly from the spiral and irregular cloud since these galaxies are more readily detected in neutral hydrogen studies. Heidmann *et al.* (1972) listed some galaxies in this region of sky which they thought likely to be foreground

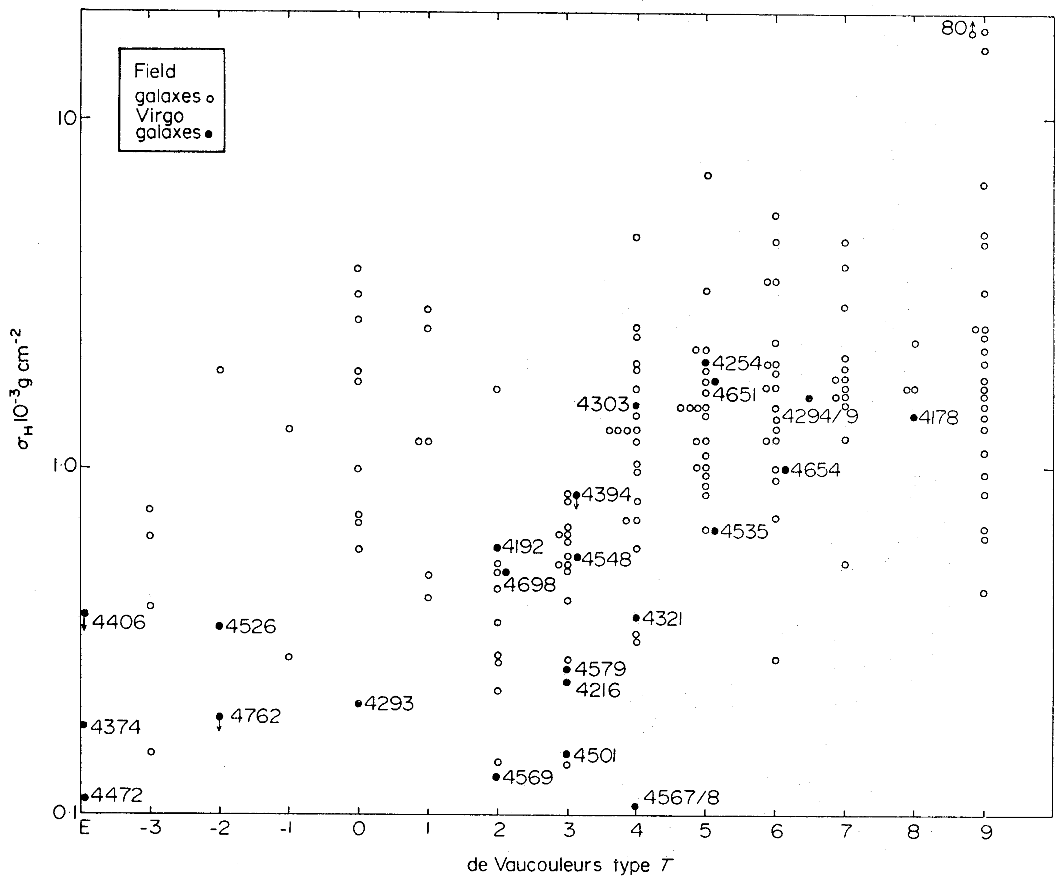

FIG. 4. *Neutral hydrogen surface density σ_H plotted against morphological type. Virgo cluster galaxies are shown as ● and the field galaxies as ○.* 10^{-3} *g* cm^{-2} = $6{\cdot}0 \times 10^{20}$ *atoms* cm^{-2} = $5{\cdot}0\ M_\odot\ pc^{-2}$.

objects. These included NGC 4192 and 4216 with optical (neutral hydrogen) velocities of -124 (-143) and $+38$ (-103) km s^{-1} respectively. Holmberg (1958) and Tammann (1972), however, include them in their lists of Virgo cluster galaxies. Table I indicates that the dimensions, luminosities and neutral hydrogen masses are in no way exceptional compared with other Virgo cluster galaxies. We therefore conclude that NGC 4192 and 4216 belong to the Virgo cluster. Burbidge & Hodge (1971) also argue that several other negative velocity galaxies belong to the Virgo cluster.

5.1 *Optical evidence for a deficiency of gas in clusters of galaxies*

Spitzer & Baade (1951) first suggested that collisions between galaxies in clusters might remove gas from the galaxies. A qualitative study of the gas content of galaxies in clusters in comparison with field galaxies was made by Osterbrock (1960) who investigated the occurrence of 3727 Å emission from E galaxies in clusters and in the field as listed by Humason *et al.* He found that none of the 25 E galaxies listed in the dense clusters (Perseus, Coma, Hercules and Pegasus II) showed 3727 Å emission whereas 15 ± 5 per cent of isolated elliptical galaxies or ellipticals in small groups showed emission. In the Virgo cluster, which is an intermediate density cluster, the situation is similar although less marked. Table III compares the incidence of 3727 Å emission in dense clusters, the Virgo cluster and non-cluster E and SO galaxies as given by Humason *et al.* Of the three E galaxies with emission lines in the Virgo cluster, one is NGC 4486, the intense radio source Virgo A which is a peculiar galaxy, and probably should not be included in the statistics. Table III shows that, in SO and E galaxies belonging to the Virgo cluster, the frequency of occurrence of emission is about half that found in the field (non-cluster) galaxies. This amounts to the same conclusion as found in the present neutral hydrogen study, that is, on average the Virgo cluster galaxies contain less gas than the field galaxies. The neutral hydrogen data suggest further that the deficiency is shared by all morphological types.

TABLE III

The occurrence of the 3727 Å *oxygen* [O II] *line emission in galaxies listed by Humason* et al. (1956)

	SO Galaxies			E Galaxies		
	Number with emission	Number without emission	Percentage with emission	Number with emission	Number without emission	Percentage with emission
Non-cluster galaxies	24	64	27·3	14	110	11·3
Virgo cluster	2	13	13·3	3 (2)*	26	10·3 (7·2)*
Dense clusters	0	9	0·0	0	25	0·0

* Excluding NGC 4486, the radio source Virgo A.

5.2 *Galactic collisions in clusters*

One obvious difference between cluster and field galaxies is the high possibility of collisions experienced by cluster galaxies. There are several ways in which collisions might remove gas from galaxies. During galactic collisions, gas atoms collide, although stars of one galaxy pass the distribution of stars in the other galaxy with a negligible chance of collisions. The gas could be swept out of the galaxies into the intergalactic medium, there either to remain as gas or condense to produce new galaxies. Alternatively, during the collisions phase, the density may be made locally large enough in one galaxy so that it condenses to stars. In this section we consider the frequency of galactic collisions in clusters and the Virgo cluster in particular.

First of all we will summarize the available data on the distribution of galaxies in the Virgo cluster. According to de Vaucouleurs (1961) there are 212 galaxies brighter than $m_{pg} = 13{\cdot}5$ in the region RA = 12^h to 13^h, Dec = $0°$ to $20°$ (1950 coordinates). The majority of these galaxies lie within $5°$ of the centre of the cluster. Zwicky (1957) states that in addition to the 205 galaxies of the Shapley–Ames catalogue which belong to the Virgo cluster there are thousands of fainter member galaxies; they are clearly seen on the Palomar Sky Survey prints. For the following calculations we will assume that there are 200 galaxies within $5°$ of the centre of the cluster. At an adopted distance of 14·8 Mpc, the cluster diameter is 2·6 Mpc and the volume density of galaxies is 22×10^{-18} pc^{-3}. The rms radial velocity dispersions of the galaxies in the E and S clouds given by de Vaucouleurs (1961) are 550 and 750 km s^{-1} respectively. We will adopt the mean value of 650 km s^{-1} as the representative value for the cluster as a whole.

Following the approach of Spitzer & Baade (1951), we simply calculate the number of collisions in crossing the cluster to be

$$\sqrt{2}\sigma N(r)$$

where σ is the collisional cross-section of a galaxy, $N(r)$ is the number of galaxies in a column of unit area passing within a distance r of the centre and the $\sqrt{2}$ factor accounts for the motion relative to the other galaxies. σ is estimated from the neutral hydrogen dimensions of the galaxies. Although we do not have a direct measure of the neutral hydrogen diameter of the Virgo cluster galaxies the diameters of many field galaxies have been measured—typical values of 20–40 kpc are found for Sa to Sc galaxies. The corresponding angular diameters at a distance of 14·8 kpc are 4′·6 and 9′·3 arc. Table I shows that the major axis optical diameters are in this range. For field galaxies of the spiral type, the ratio of neutral hydrogen to optical diameters is close to unity. The effective collision diameters will be twice the actual diameters. A further factor which must be taken into account in calculating σ is the inclination of the galaxy. Since the neutral hydrogen is distributed in a thin disk the mean cross-sectional area averaged over all orientations will be less by a factor of $2/\pi$. For neutral hydrogen diameters of 20 and 40 kpc the corresponding values of σ are 8 and 32×10^8 pc^2. $N(0)$, the number of galaxies in a line of sight through the centre of the cluster, is the volume density multiplied by the depth of the cluster. For the parameters given above, $N(0) = 5{\cdot}7 \times 10^{11}$ pc^{-2} and the corresponding number of collisions per crossing of the cluster is $6{\cdot}4 \times 10^{-2}$ and $2{\cdot}6 \times 10^{-1}$ for hydrogen diameters of 20 and 40 kpc. The time for one crossing of the cluster calculated for a true (three-dimensional) velocity of $\sqrt{3}$ times the observed radial velocity dispersion, namely 1130 km s^{-1}, is $2{\cdot}4 \times 10^9$ yr. If we adopt an age for the cluster of 10^{10} yr then a typical galaxy will have made four crossings and undergone 0·27 or 1·1 collisions for a hydrogen diameter of 20 or 40 kpc.

It is likely that this simple calculation will give an underestimate of the number of collisions for the following reasons. A near approach of two galaxies, even if it is not close enough to produce a geometrical collision, will result in a tidal disruption of the galaxies as has been shown in recent studies by Toomre & Toomre (1972). In this way the effective collision cross-section could be increased by a factor of 4, and the collision frequency would also be increased by this factor.

This collision time may be compared with the Chandrasekhar relaxation time for a galaxy in a cluster, the time it takes the galaxy to undergo a significant change of its energy by interaction with its neighbours. The relaxation time T_R can be written (Oort 1960)

$$T_R = 0{\cdot}50 \times 10^9 \frac{(\bar{V}^2)^{3/2}}{m_2{}^2 N(\log_{10} y - 0{\cdot}26)} \text{yr}$$

where m_2 is the mass of the galaxy in solar masses,
N is the galactic density in pc^{-3},
$\bar{V}^2$ is the mean square velocity in (km s^{-1})^2,

$$y = \frac{155 \bar{V}^2 n^{1/3}}{(m_1 + m_2)\, N^{1/3}},$$

n = the total number of galaxies in the system.

For the Virgo cluster, we take $n = 200$ galaxies, $N = 22 \times 10^{-18}$ pc^{-3} and $\bar{V}^2 = 1{\cdot}27 \times 10^6$ (km s^{-1})^2. The galactic masses m_1 and m_2 are taken to be $2 \times 10^{11}\, M_\odot$ rather than $6 \times 10^{11}\, M_\odot$ as given by Oort (1960); the former value is probably a more realistic estimate for bright galaxies typical of those in the Virgo cluster (Morton & Chevalier 1973 and references therein). Using these parameters, $T_R = 3.0 \times 10^{11}$ yr. We see that the Virgo cluster is not relaxed since T_R is ~ 30 times its present age. Nevertheless, as has been shown above, the average galaxy will have undergone one sufficiently close collision so that a significant proportion of its gas will have undergone a direct collision with the gas of the other galaxy and be swept into intergalactic space (Spitzer & Baade 1951). In addition it may have suffered tidal disruption from several more distant encounters. Since the gas in galaxies has a broader distribution than the stars it is more likely to be removed. The frequency of both types of encounter is too low to alter the kinematics of the cluster as a whole (Spitzer & Baade 1951); this is in agreement with the large relaxation time calculated above.

It is evident from the above calculations that, in the richer clusters where the volume density is a factor of 10 or more greater than in the Virgo cluster, all the galaxies will have suffered multiple collisions; furthermore the cluster is likely to be relaxed. These galaxies would be expected to be severely denuded of gas. This is indeed the situation found in the analysis of the 3727 Å data made by Osterbrock. The galaxies in the Virgo cluster will have suffered fewer collisions and are likely to have lost a smaller fraction of their gas compared with those in the rich clusters. The loss of gas indicated by the 3727 Å data in Table III is significant, although less than in the compact clusters. The present neutral hydrogen observations indicate that on average the Virgo cluster galaxies contain 60–70 per cent of the neutral hydrogen found in field galaxies.

An entirely different reason for the lack of gas in galaxies belonging to rich compact clusters has been advanced by Gunn & Gott (1972). The gaseous debris remaining in a cluster after the collapse into galaxies will exert such a large ram pressure on the interstellar gas within the galaxies moving through it that they will become denuded of gas. It is estimated that, if the density of intracluster gas exceeds 5×10^{-4} atoms cm^{-3}, it will strip gas from typical galaxies. Although such gas densities are inferred for the Coma cluster, no clear evidence for gas of this density has yet been proposed for the Virgo cluster. This possibility cannot be ruled out, however. Any swept-out gas is likely to be accreted by the massive cD galaxies. The above processes would appear to be a possible alternative mode of reducing the neutral hydrogen content of spiral galaxies in the Virgo cluster, provided the intracluster gas density is sufficiently high.

6. CONCLUSIONS

The present observations were designed to give accurate information about the neutral hydrogen content of galaxies in the Virgo cluster in comparison with field galaxies. The detailed comparison was made in terms of the distance-independent parameters M_H/L and σ_H. The parameters were compared within each morphological class (T) for the Virgo cluster and the field galaxies. This study showed a significant decrease of the neutral hydrogen content in the Virgo cluster galaxies. A similar comparison in terms of colour rather than morphological type also showed a decrease in the neutral hydrogen content. Optical studies of the 3727 Å emission from the E and SO galaxies in the Virgo cluster had previously indicated a deficiency of gas in the cluster galaxies compared with field galaxies.

Our calculations show that on average each galaxy in the Virgo cluster will have suffered a collision during the lifetime of the cluster. Without considering the processes in detail it is suggested that some gas is removed from the galaxies in such collisions; the gas may be removed by star formation in the regions of locally high density or it may be dispersed into the intergalactic medium. We conclude that the observed deficiency of gas in the Virgo cluster galaxies is either the result of galactic collisions or the effect of the primeval intergalactic gas.

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