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H I DEFICIENCY IN CLUSTER SPIRAL GALAXIES: DEPENDENCE ON GALAXY SIZE

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ABSTRACT

From the available H I data on spiral galaxies in three rich Abell clusters and the Virgo Cluster, it is shown that galaxies with medium to large optical sizes tend to be more severely deficient in atomic hydrogen than the small galaxies. This is so both in terms of the fractional number of galaxies that are deficient and the amount of gas lost by a galaxy. The fraction of H I–deficient galaxies increases with size over most of the size range, saturating or dropping only for the largest galaxies.

We make a comparative study of various currently accepted gas removal mechanisms, namely those which are a result of galaxy–intracluster medium interactions, e.g., ram pressure stripping, as well as those due to galaxy-galaxy interactions, i.e., collisions and tidal interactions. We show that with the exception of tidal interactions, all of these mechanisms would produce a size dependence in H I deficiency that is the opposite of that observed. That is, the gas in the largest galaxies would be the least affected by these mechanisms. However, if there is significant mass segregation, these processes may give the trends observed in the size dependence of H I deficiency.

We propose that tidal encounters between galaxies in subclumps or groups, which then merged to form clusters or were subsequently accreted by them, could have led to significant gas removal from these galaxies at early epochs. This could qualitatively explain the dependence of H I deficiency on galaxy size.

Since all the gas removal mechanisms known are less effective on the galaxies of the largest sizes, the drop in the fraction of deficient galaxies for these sizes is accounted for.

Subject headings: galaxies: clustering — galaxies: evolution — galaxies: interactions — galaxies: interstellar matter — radio sources: 21 cm radiation

1. INTRODUCTION

The evolution of galaxies in clusters is believed to have been influenced significantly by the cluster environment. One striking piece of evidence in support of this is the fact that a high percentage of spiral galaxies in moderately rich and rich clusters seem to have lost a substantial fraction of their atomic hydrogen (H I) and appear H I–deficient when compared with isolated galaxies of the same morphological type and optical size (cf. Giovanelli & Haynes 1985, hereafter GH85; Haynes, Giovanelli, & Chincarini 1984). This is believed to be due to the evolution of cluster galaxies brought about either by interaction between the intracluster medium (ICM) and the interstellar medium (ISM) in these galaxies or by mutual interactions between the cluster galaxies.

In this paper (§ 2) we analyze H I data on galaxies in the three rich Abell clusters A262, A1367 (GH85), A1656 (Gavazzi 1987), and the Virgo Cluster (GH85; Haynes & Giovanelli 1986). We show that when galaxies in each cluster are binned according to their optical sizes, the fraction of H I deficient galaxies in each bin increases with size over most of the size range, dropping only for the largest size bin. Also, the most highly deficient galaxies, which are deficient by a factor of 10 or more, are invariably of the largest sizes. This behavior has not been noticed by earlier workers, although the data are not new. We also discuss possible selection effects and conclude that these are not responsible for the observed correlation between H I deficiency and galaxy size.

In § 3, we discuss the gas removal mechanisms involving galaxy–ICM interactions, such as ram-pressure stripping (Gunn & Gott 1972), stripping due to thermal evaporation by the hot ICM (Cowie & Songaila 1977), and turbulent viscous stripping (Nulsen 1982). We show that these mechanisms produce a size dependence in the H I deficiency which is the opposite of or weaker than that observed. We discuss the effect of mass segregation in clusters and conclude that if significant, this could result in the observed size dependence in the H I deficiency.

In § 4.1 we show that the frequency of collisions for which there is substantial overlap of the galactic disks, and consequently, significant gas removal from the galaxies (Spitzer & Baade 1951), decreases as a function of galaxy size and therefore cannot be responsible for the observed dependence of the fraction of deficient galaxies on size.

In the light of the evidence for significant subclumping in clusters (see Fitchett 1989) we propose (§ 4.2) that tidal encounters between galaxies in subclumps in a nonvirialized cluster could be the cause of the size dependence in H I deficiency.

In § 5 we summarize the results of this paper.

2. SIZE DEPENDENCE OF H I DEFICIENCY

The H I deficiency in spiral galaxies in clusters is believed to be due to the loss of a substantial fraction of the H I gas from their disks. For a cluster galaxy an estimate of the amount of H I gas lost globally is given by the H I deficiency parameter (cf. Haynes et al. 1984),

$$\mathrm{DEF} \equiv \log_{10}\left[\frac{\langle (M_{\mathrm{H\,I}}/D_0^2)_f \rangle_T}{(M_{\mathrm{H\,I}}/D_0^2)_c}\right], \qquad (1)$$

where $M_{\mathrm{H\,I}}$ is the total H I mass of the galaxy and D_0 is its optical Holmberg diameter. The quantity $\langle (M_{\mathrm{H\,I}}/D_0^2)_f \rangle_T$ is the mean value of the hybrid surface density of H I for a sample of isolated (field) galaxies of the same morphological type (T) as the cluster galaxy under consideration, and $(M_{\rm H\,I}/D_0^2)_c$ is the hybrid surface density of the cluster galaxy ("hybrid" since the optical diameter is used instead of the H I diameter). A cluster galaxy may be considered to be significantly deficient in H I if it has at least a factor of 2–3 times less H I than the field average (corresponding to a DEF ≥ 0.3 and DEF ≥ 0.47, respectively). We have used the more stringent criterion, DEF ≥ 0.47, to deem a galaxy to be H I–deficient (e.g., Haynes & Giovanelli 1986).

From a study of H I data for galaxies in nine clusters, GH85 concluded that five of the clusters have a high fraction (>0.4) of H I deficient galaxies (with DEF ≥ 0.3) and may be considered "deficient clusters." We have used four of these five in this study, namely A262, A1367, A1656 (Coma), and the Virgo Cluster. The fifth cluster A2147, has been excluded only because the sample in GH85 is too small to make a statistically meaningful analysis. It is also known (GH85) that H I–deficient galaxies in a cluster tend to be concentrated toward the cluster center and lie almost entirely within 1.5 Abell radii ($r_{\rm A}$) of it. For A262 and A1367, the samples used by us consist of all galaxies in the GH85 sample lying within $1.5r_{\rm A}$; the sample for A1656 also consists of all galaxies lying within $1.5r_{\rm A}$ in the sample of Gavazzi (1987); and the Virgo Cluster sample consists of all galaxies within $1.0r_{\rm A}$ of the cluster center (M87) from the samples of Giovanelli & Haynes (1983, 1985) and Haynes & Giovanelli (1986). Only spiral galaxies of types Sa–Sd (corresponding to the type code index 3–8 in GH85) have been considered in our analysis although the original samples contained earlier types and dwarf galaxies as well. These authors have obtained deficiency estimates using the definition of deficiency, DEF, as given in equation (1), and therefore we use the values of DEF obtained by them.

The linear optical sizes of the galaxies used in this analysis are calculated from their major axis blue angular diameters as given in the Uppsala General Catalogue of Galaxies (Nilson 1973) and from the mean cluster distances. We have used a Virgo Cluster distance of 20.5 Mpc (corresponding to a Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1}) as adopted by Haynes & Giovanelli (1986). For the other clusters, linear sizes were obtained using $H_0 = 100$ km s^{-1} Mpc^{-1} as in GH85, and Gavazzi (1987). In the subsequent analysis, we treat the rich clusters separately from the Virgo Cluster and the use of different values of H_0 for the two cases will not affect the main results. The mean cluster velocities used are 4704 km s^{-1} for A262, 6809 km s^{-1} for A1367, 7280 km s^{-1} for A1656, and 1026 km s^{-1} for the Virgo Cluster (GH85). Dickel & Rood (1978) have shown that the UGC blue diameters of a large sample of field galaxies are consistent with their Holmberg diameters. Hence we are justified in using the UGC diameters in our analysis rather than the Holmberg diameters which were not available for all the galaxies under study.

The galaxies in each cluster are distributed in bins of logarithmically increasing linear optical diameter (D_0). The results of the analysis that follows are insensitive to slight alterations in the binning. We have checked that errors in linear size estimation, arising out of uncertainties in the actual distances of individual galaxies with respect to the cluster center along the line of sight, are unlikely to affect the results of this analysis. After binning galaxies according to their linear dismeters we study the fraction (F_D) of galaxies in each bin which are H I–deficient, as a function of galaxy size.

2.1. *The Rich Clusters*

The three clusters A262, A1367, and A1656 (Coma) are rich clusters. We study the Virgo Cluster separately (§ 2.2) since it is only moderately rich. The effect of the cluster environment on the galaxies in these three rich clusters is likely to be fairly similar and hence we combine them into a single "*composite rich cluster*" sample (CRC). Since this sample is large, (91 galaxies), it allows us to perform statistical tests with more reliability.

In Figure 1, histograms of the fraction of H I–deficient galaxies, F_D, as a function of $\log_{10}$ (optical diameter) are given for A262, A1367, A1656, and the CRC. From the histograms, it is clear that there is an increase in the fraction of H I–deficient galaxies with size, and the fraction drops only for the largest size bin. It must be noted here that the number of galaxies in the largest bin ($D_0 > 45$ kpc) in each sample is much smaller than the numbers in the other bins, and hence the error associated with this value of F_D is larger than the other cases. Therefore it is reasonable to conclude that *F_D increase over most of the size range*, probably saturating for the largest sizes.

It is important to determine how statistically significant this trend is when compared with a uniform (i.e., flat) distribution of F_D versus size. A χ^2-test of significance confirms that the distribution of galaxies in the CRC sample is significantly different from the uniform distribution at a 90% level of confidence. The χ^2-test cannot be used on the rich clusters individually since the samples are too small. Instead we apply a Kruskal-Wallis test of one-way analysis of variance (see Siegel 1956), to intercompare the F_D distributions of the three clusters. This test indicates that there is a less than 5% probability that the three samples are drawn from different populations. Hence the visual similarity of the curves of the three clusters is *statistically* significant.

2.2. *The Virgo Cluster*

In Figure 2(*left*); the histogram of F_D as a function of galaxy size is given for galaxies in the Virgo Cluster. As in the case of Figure 1, we notice that F_D increases with log (D_0). However, for the Virgo Cluster sample, the increase is less significant and F_D saturates at the larger diameters but does not drop for the largest sizes ($D_0 > 45$ kpc). Since the Virgo Cluster is the closest cluster and is moderately rich, it has been extensively studied. Consequently, this sample has a much wider range of linear sizes than the rich cluster samples and is also more complete. In the Virgo Cluster, F_D is seen to decrease with decreasing galaxy size right down to the smallest diameters (~ 3 kpc), where the galaxy size is a factor of 3 less than for the smallest size bin of the rich cluster samples.

Dressler (1986) showed that of the spiral galaxies in the five "H I–deficient" clusters of GH85, the early-type galaxies are more frequently deficient than the late-type galaxies. Also, from their velocity dispersions, the deficient early-type galaxies (Sa–Sbc) appear to be on predominantly radial orbits and therefore would pass very close to the cluster core. The late-type spirals (Sc–Sm) are on predominantly circular or isotropic orbits and are therefore less easily stripped of their H I gas since they do not pass through the high density core regions. In order to rule out the possibility that the behavior in Figures 1 and 2(*left*) is due to a dependence on morphological type, we have obtained values of F_D for only the late-type galaxies (Sc–Sd) in the Virgo Cluster (Fig. 2[*right*]). For this subsample of late-type galaxies also, F_D increases with size indicating that

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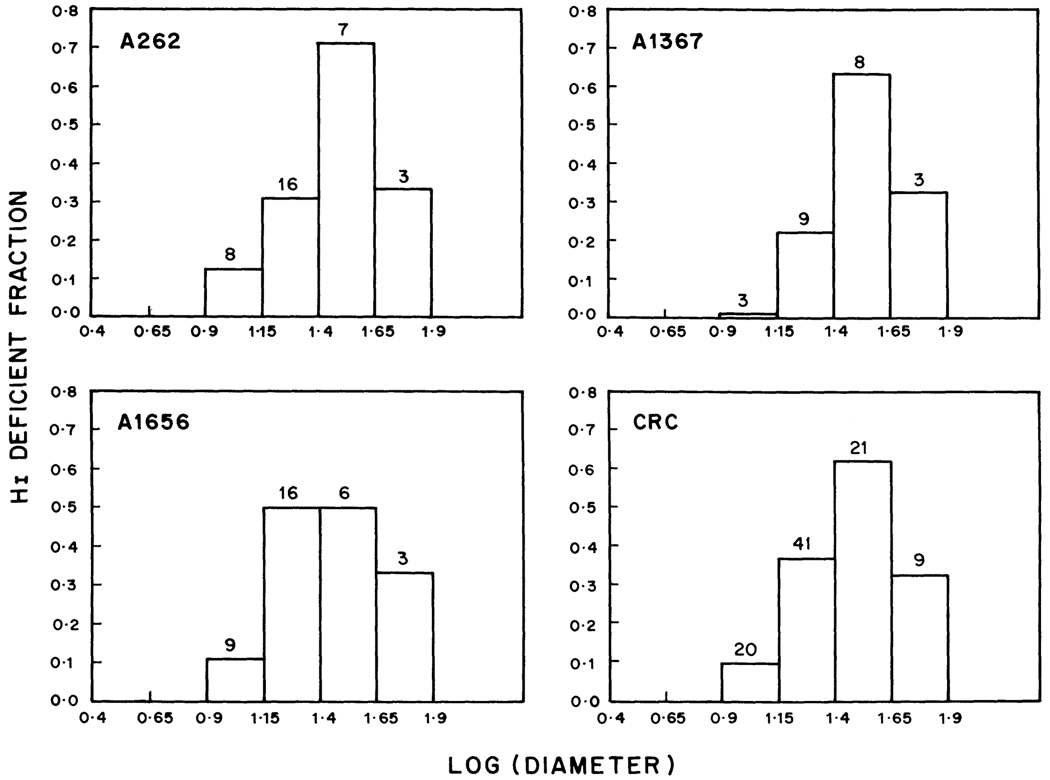

FIG. 1.—Fraction of H I deficient-galaxies (with DEF ≥ 0.47) (F_D) as a function of log (D_0), for A262, A1367, A1656, and the *composite rich cluster* sample (CRC). The numbers above each bin in the figures indicate the total number of galaxies in that bin. The error associated with the value of F_D decreases with increase in the number of galaxies in the bin. On a linear scale the bin limits (in kpc) are 2.5, 4.5, 8.0, 15.0, 25.0, 44.5, 79.4.

the trend is not a secondary effect of a type dependence in the galaxy sizes or distributions.

In Figure 2(*left*) the increase of F_D with size is gradual, and a χ^2-test of significance indicates that it is not significantly different, statistically, from the uniform distribution at a 90% level of confidence. However, a Kruskal-Wallis test indicates that there is only a 10% chance that it is drawn from a population that is different from that of the three rich clusters. Therefore, we conclude that the increasing trend is real even for the Virgo Cluster.

As mentioned earlier the total number of galaxies in the largest size bin is small indicating that the value of F_D for this bin has a much larger uncertainty associated with it than for the intermediate size bins. We are therefore justified in saying that F_D increases over most of the size range, saturating or dropping for the largest sizes. In § 5 we will discuss the significance of this drop for the largest galaxies.

2.3. *Degree of* H I *Deficiency as a Function of Galaxy Size*

So far we have shown that for a predefined value of the deficiency criterion (in this case DEF ≥ 0.47), the fraction of H I deficient galaxies increases with size. We now investigate if there is any relationship between the degree of H I deficiency of a galaxy and its linear size. In order to do this, we produced

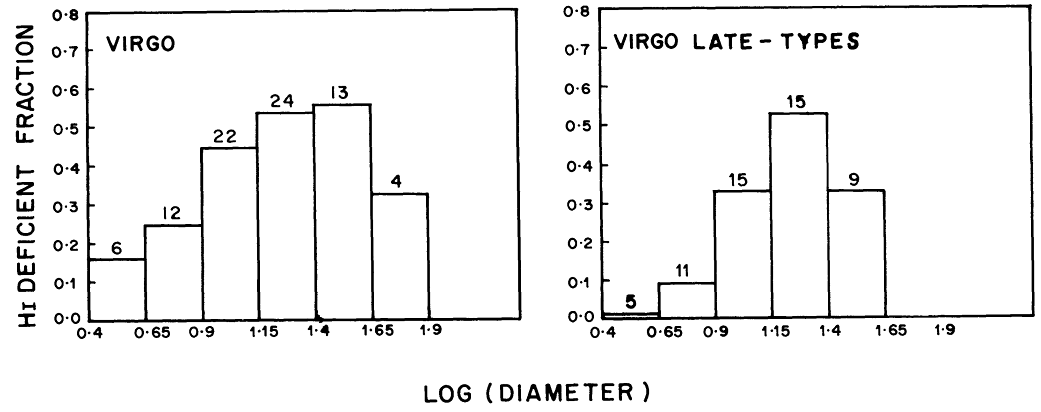

FIG. 2.—Same in Fig. 1, for (*left*) the entire Virgo Cluster sample and (*right*) only the late-type spirals (Sc–Sd) in the Virgo Cluster sample

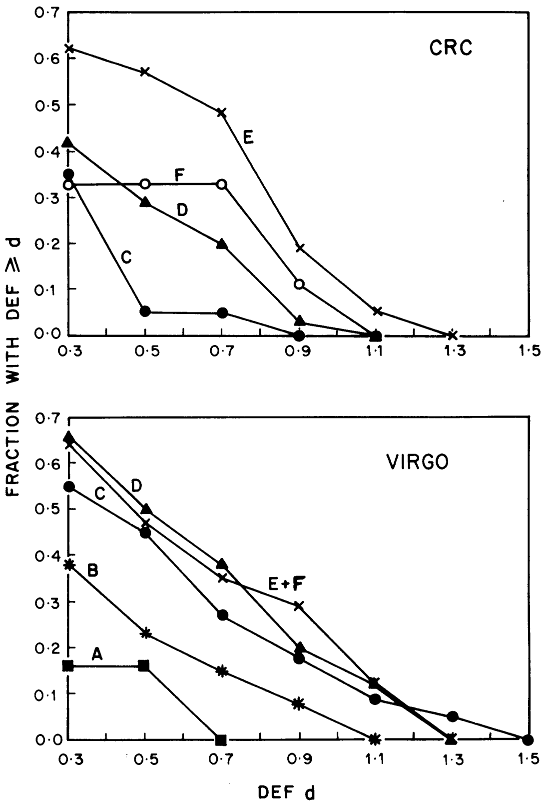

FIG. 3.—Cumulative distribution functions of the fraction of H I–deficient galaxies with deficiency DEF $\geq d$, vs. the deficiency d, where d is a discrete, variable value of the H I deficiency. Each of the curves represents a different size bin, with size increasing from A through F, for (*top*) the *composite rich cluster* sample and (*bottom*) the Virgo Cluster sample.

cumulative distribution functions of the fraction of deficient galaxies in each size bin, with DEF $\geq d$, where d is a discrete, variable value of the deficiency.

In Figure 3(*top*) (CRC) and Figure 3(*bottom*) (Virgo Cluster) we present the cumulative distribution functions for galaxies in size bins labeled in the figures as A: $0.4 \leq \log(D_0) < 0.65$; B: $0.65 \leq \log(D_0) < 0.90$; C: $0.90 \leq \log(D_0) < 1.15$; D: $1.15 \leq \log(D_0) < 1.40$; E: $1.40 \leq \log(D_0) < 1.65$; F: $1.65 \leq \log(D_0) < 1.90$. From these graphs we see that at an arbitrary value of deficiency d, there is an increase in the fraction of deficient galaxies (F_D) with size (A → D). Hence the trend seen in Figure 1 *is not peculiar to a particular choice of the deficiency criterion*. The graphs also clearly show that while there is a spread in d within each bin, the most highly deficient galaxies (DEF > 1.0, i.e., deficient by more than a factor of 10) are invariably of the largest sizes and there are no small galaxies ($D_0 < 10$ kpc) which have lost such a large fraction of their gas. For the Virgo Cluster (Fig. 3 [*bottom*]), the curves merge for the largest bins (D and E & F combined) as we might have expected from the saturation of F_D seen in the curve in Figure 2(*left*). In Figure 3(*top*) for the CRC, the curve for size range F lies below the curve for E and represents the drop in F_D seen in Figure 1(*lower right*) for the largest bin.

These graphs indicate that the *larger galaxies are not only more likely to be deficient in* H I *than the smaller galaxies but they also have a higher degree of deficiency*. This indicates that at least one of the gas removal mechanisms is more effective on large galaxies than on small galaxies, both in terms of the fraction of galaxies it affects and the extent of gas removal it causes.

2.4. *Inner Cluster versus Outer Cluster*

It has been noticed that H I–deficient galaxies tend to concentrate toward the cluster core (e.g., GH85). We have subdivided the CRC sample as well as the Virgo Cluster sample into two two subgroups. The group "IN" containing galaxies with projected radial distance from the cluster center, $R_C \leq 0.75\,r_A$ and "OUT" containing galaxies outside this radius.

The distribution of F_D with size was obtained for each of these subsamples (Fig. 4). It was found that for both the CRC sample and the Virgo Cluster sample there is an increase of F_D with size for the "OUT" subsample (*cross-hatched* in figure) as in the earlier cases (Figs. 1 and 2). However, in the case of the "IN" subsample, the distribution of F_D with size appears to be more or less flat with a lot of noise.

An application of the Mann-Whitney U-test (see Siegel 1956) showed that for the CRC sample, the probability that the IN and OUT subsamples are drawn from the same sample is less than 5%, and it is less than 3% for the Virgo Cluster sample. Being a one-tailed test it also showed that the values of the H I deficient fraction in the IN sample are stochastically higher than the values in the OUT sample. This is in agreement with

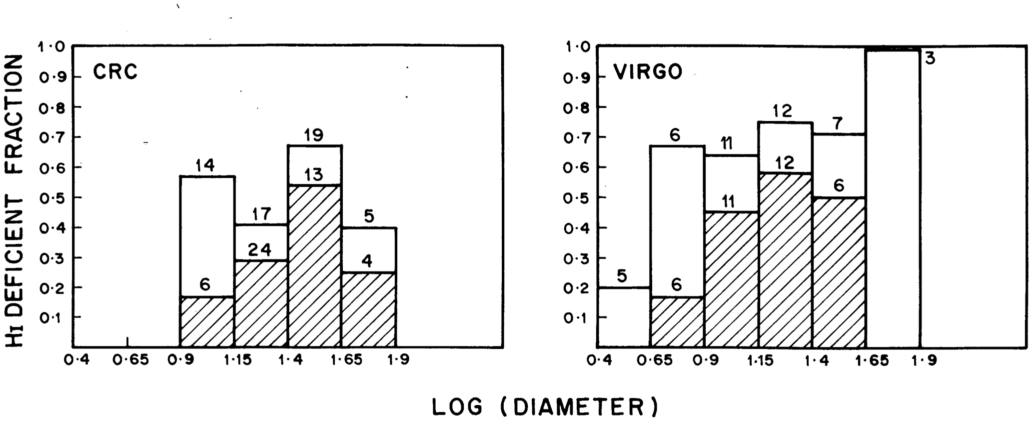

FIG. 4.—Comparison of distribution of F_D vs. size ($\log D_0$) for galaxies in subsample "IN" (with the projected radial distance from the cluster center, $R_C \leq 0.75 r_A$) with the distribution for galaxies in subsample "OUT" (with $R_C > 0.75 r_A$) (*cross-hatched*) for (*left*) *composite-rich-cluster* sample and (*right*) Virgo Cluster sample.

the observation that H I deficient galaxies are concentrated toward the cluster center (GH85).

We discuss possible implications of the features of Figure 4 in a later section (§ 4.2).

2.5. *Possible Selection Effects and Biases*

It is necessary to rule out selection effects and intrinsic biases that may be responsible for the observed trend.

First, since the galaxies in the original samples were selected by their optical morphological types (Sa–Sd only), there is no reason to suspect that H I–deficient galaxies have been preferentially omitted from the sample only in the case of the small size galaxies.

Second, could the deficiency parameter itself have a strong built-in dependence on the optical diameter? For a sample of field galaxies, Haynes & Giovanelli (1986) have found that the total H I mass, $M_{\rm H\,I}$, is related to the optical diameter of a galaxy by the empirical relation

$$\log M_{\rm H\,I} = 7.07 + 0.92 \log D_0^2 \,. \tag{2}$$

We see that the quantity $(M_{\rm H\,I}/D_0^2)$ does have a weak dependence on D_0. Hence from equations (1) and (2), DEF $\propto \log_{10} (D_0^{0.16})$. Thus, the H I deficiency parameter also has a small dependence on D_0. However, this intrinsic size dependence is insufficient to account for the size dependence seen in Figures 1 and 2. Even in the case of the Virgo Cluster for which the size dependence is the weakest, $F_D \propto D_0^{0.89}$ in the increasing part of the curve. It appears that the size dependence of the H I deficiency discussed in this paper is intrinsic to the gas removal mechanism and is not a secondary effect of the dependence of the hybrid surface density on galaxy size.

3. GAS LOSS BY GALAXY–ICM INTERACTIONS

Three gas removal mechanisms involving interaction between the intercluster medium and the interstellar medium in galaxies are generally considered likely causes for the H I deficiency in cluster galaxies. They are (1) ram-pressure stripping (Gunn & Gott 1972), (2) thermal evaporative stripping (Cowie & Songaila 1977), and (3) turbulent viscous stripping (Nulsen 1982).

In this section we discuss these mechanisms and study the size dependence of the H I deficiency produced by each of them. H I deficiency is the measure of the fraction of H I mass $F_m = (\dot{m}_{\rm H\,I} \Delta t/M_{\rm H\,I})$ lost by a galaxy during its lifetime (Δt). We use expressions for the mass-loss rate $\dot{m}_{\rm H\,I}$ to study dependence of the deficiency on galaxy size and show that none of these mechanisms can produce an increase in the fraction of deficient galaxies with size unless mass segregation in clusters is significant (§ 3.4).

3.1. *Ram Pressure Stripping*

Gunn & Gott (1972) suggested that a spiral galaxy moving through the intracluster medium with a velocity, V, would experience a ram pressure $\rho_{\rm ICM} V_\perp^2$, where $\rho_{\rm ICM}$ is the density of the ICM and $V_\perp$ is the velocity component perpendicular to the disk. The interstellar gas would be stripped from the disk if this ram pressure exceeded the gravitational force per unit area binding the gas to the disk, i.e., if $\rho_{\rm ICM} V_\perp^2 > 2\pi G \sigma_{\rm ISM} \sigma_D$, where $\sigma_{\rm ISM}$ and σ_D are the mass surface densities of the gas and disk, respectively. In a realistic ISM, the molecular clouds with their low filling factors and high densities are not much affected by ram pressure (Kritsuk 1983), but the low-density H I component can be stripped fairly easily, particularly from the outer regions where both σ_D and $\sigma_{\rm ISM}$ are smaller than in the inner disk.

For isolated spirals the ratio $\sigma_D/\sigma_{H\,I}$ is nearly constant in the outer regions of the galaxies and has a value between ~10 and 20. We therefore take $\sigma_D/\sigma_{H\,I} = K_T$, to be a constant for each galaxy (e.g., Bosma 1978). Thus the condition for the occurrence of ram pressure stripping becomes

$$\rho_{\rm ICM} V_\perp^2 > 2\pi G(\sigma_D^2/K_T) \,. \tag{3}$$

Hoffman, Helou, & Salpeter (1988) showed that for spiral galaxies in the Virgo Cluster, the total mass surface density $\langle \sigma_D \rangle$ of a galaxy averaged over its optical diameter is correlated with the optical diameter (D_0) via the relation, $\langle \sigma_D \rangle \propto D_0^{0.35}$. Since this is a property of the stellar disk, it is probably also valid for galaxies in other clusters. The ram-pressure stripping criterion expressed as a function of galaxy size now becomes

$$\rho_{\rm ICM} V_\perp^2 \geq \frac{2\pi G}{K_T} D_0^{0.7} \,. \tag{4}$$

This expression implies that larger galaxies would be harder to strip of their H I content than smaller galaxies. Clearly, this mechanism alone is not responsible for producing the increase in the fraction of deficient galaxies with size seen in § 2. Further, H I observations of dwarf irregular galaxies in the Virgo Cluster (Hoffman et al. 1988) show that these galaxies are no more deficient as a class than the larger spiral galaxies. Thus, this is another independent indication that the smaller galaxies are not as deficient as we would have expected if ram-pressure stripping had been the dominant gas removal mechanism.

3.2. *Thermal Evaporative Stripping*

Cowie & Songaila (1977) showed that conductive heat transfer from the hot intracluster gas ($T_{\rm ICM} \sim 10^8$ K) to the cooler interstellar gas within galaxies can heat the ISM. If the rate of heating exceeds the cooling rate of the ISM, gas will evaporate from the galaxy.

For classical, unsaturated thermal conduction, the mass-loss rate due to evaporation, $\dot{m}_{\rm ev}$, is

$$\begin{aligned} \dot{m}_{\rm ev} &= \frac{16\pi\mu m_p \kappa R}{25 k_{\rm B}} \\ &= 700\, M_\odot\ {\rm yr}^{-1} \left(\frac{T_{\rm ICM}}{10^8 {\rm K}}\right)^{5/2} \left(\frac{R_{\rm H\,I}}{20\ {\rm kpc}}\right) \left(\frac{\ln \Lambda}{40}\right)^{-1} \end{aligned} \tag{5}$$

(Cowie & McKee 1977; Sarazin 1986), where κ is the classical thermal conductivity, Λ is the Coulomb logarithm, R is the radius of the galaxy, μ is the mean mass per particle in units of m_p, the proton mass, and $k_{\rm B}$ is the Boltzmann constant. This expression is for an oblate spheroidal galaxy and the mass-loss rate for a spiral (disk) galaxy differs by a factor of $2/\pi$ (Cowie & Songaila 1977). However, if the conduction saturates, as is believed to be the case in disk galaxies, the mass-loss rate will be reduced, but it will only vary as the 1.7th power of $R_{\rm H\,I}$.

In order to estimate the fraction of the H I mass lost by a galaxy of diameter D_0, we use the dependence of the total H I mass on D_0 which was given in equation (2). Thus for an isolated galaxy $M_{\rm H\,I} \propto D_0^{1.84}$. Using $D_{\rm H\,I}/D_0 \sim 1.5$ (see discussion in § 4), and assuming that all mass loss from a galaxy is via thermal evaporation, the fraction of mass lost in time Δt (from eq. [2] and eq. [5]) is

$$(F_m)_{\rm ev} \propto D_0^{-0.84} . \qquad (6)$$

Thus, the fraction of H I mass lost by the galaxy decreases with an increase in D_0 and hence large galaxies would be less deficient in H I than small galaxies. We conclude that thermal evaporative stripping cannot result in the observed dependence of H I deficiency on galaxy size discussed in § 2.

3.3. *Turbulent Viscous Stripping*

A realistic treatment of the flow of the intracluster medium past the ISM in galaxies must include the viscosity of the fluids involved and the turbulent mixing processes. Nulsen (1982) considered turbulent viscous flow and showed that the formation of Kelvin-Helmholtz instabilities at the interface between the low-density ICM and the high-density ISM can result in enhanced stripping of the interstellar gas. The mass-loss rate can be higher than that due to ram-pressure stripping and, in addition, is fairly insensitive to the orientation of the galactic disk. The mass-loss rate due to turbulent viscous stripping, $\dot{m}_{\rm TV}$, for a galaxy of radius R, and velocity V, is given by

$$\dot{m}_{\rm TV} = \pi R^2 \rho_{\rm ICM} V . \qquad (7)$$

The fraction of H I mass that would be lost by this process in a time Δt (from eq. [2] and eq.[7]) is

$$(F_m)_{\rm TV} \propto D_0^{0.16} . \qquad (8)$$

The fraction of H I mass lost increases slightly with size, but the dependence is insufficient to produce the trends seen in Figures 1 and 2. As mentioned earlier for the Virgo Cluster sample (Fig. 2[*left*]), the dependence is $F_D \propto \langle D_0 \rangle^{0.89}$, in the increasing part of the curve, and is a much stronger size dependence than that in equation (8). This conclusion would also be true for the rich clusters which show a stronger dependence on size.

3.4. *Effects of the Spatial and Velocity Distributions of Galaxies*

From the discussions in the preceding sections, it is evident that all gas removal mechanisms involving galaxy–ICM interaction are dependent on either the temperature ($T_{\rm ICM}$) and density ($\rho_{\rm ICM}$) of the intracluster gas or both. The X-ray emission from the ICM is known to peak at the core of the cluster indicating that both the temperature and density are highest there (see Sarazin 1986). Consequently, the gas removal mechanisms would be expected to be more effective in the cluster core. This may result in a size dependence in H I deficiency for two cases; (1) if there is significant mass segregation and (2) for certain velocity distributions.

When mass segregation occurs in a cluster, the larger galaxies are more concentrated toward the cluster core while smaller galaxies occupy a much larger volume. The larger galaxies would then be more severely affected by the ICM than the smaller galaxies. The trends seen in § 2 could then be attributed to the spatial distribution of galaxies arising out of mass segregation.

Hoffman et al. (1988) have found for the Virgo Cluster that a comparison of the distributions of the smallest dwarfs and the largest spirals located within and beyond the Abell radius do not indicate that mass segregation has occurred.

Also, Figure 4 shows that F_D increases with size for the galaxies in the outer regions of the cluster but not in the inner regions which would not be the case if this dependence was due the combined effect of segregation and ICM processes.

Davis & Djorgovski (1985), on the other hand, have shown that high surface brightness galaxies tend to be more clustered than low surface brightness galaxies. The correlation scale length found by them is ~3 Mpc for the small galaxies and ~6 Mpc for the large galaxies. Hence mass segregation may be responsible for some of the observed size dependence, but since the degree of segregation is not known, it is difficult to estimate quantitatively its importance. It is likely that this may have some bearing on the observation that the H I–deficient galaxies in clusters are more centrally concentrated than the general spiral population, with the most deficient galaxies being located closer to the cluster center (GH85).

A second important parameter in determining mass-loss rates due to ram-pressure stripping and viscous stripping is the velocity of a galaxy with respect to the ICM (see eq. [4] and eq.[7]). For the Virgo Cluster sample Haynes & Giovanelli (1986) showed that there is no evidence for a correlation between the line-of-sight velocity of a galaxy and its H I deficiency. Magri et al. (1988) have shown that this is also true of the deficient galaxies in six rich clusters. The size dependence is therefore not a result of the velocity distribution of the galaxies.

As mentioned earlier (§ 2) Dressler (1986) showed that the orbits of H I–deficient late-type spirals (Sc and later) are isotropic or circular. In Figure 2(*right*) we saw that even the late-type galaxies which are on predominantly circular orbits and therefore rarely pass through the high-density cluster core show a dependence of F_D on size indicating that the enhanced effect of ram-pressure stripping in the inner regions of the cluster is unlikely to be the cause of the size dependence.

The discussions above indicate that all the gas removal mechanisms involving interactions between the ICM and the ISM, would produce the observed trend of an increase in F_D with galaxy size if there is significant mass segregation in clusters but not otherwise. However, this dependence is not likely to be due to the velocity distribution of the galaxies.

4. GALAXY-GALAXY INTERACTIONS

4.1. *High-Velocity Collisions*

Spitzer & Baade (1951) proposed that during a physical collision between two cluster galaxies with high relative velocity (greater than twice $V_{\rm esc}$, the escape velocity from a galaxy), their interstellar gas components would undergo inelastic collision and would be left behind at the center of mass of the pair. However, their stellar components would be unaffected since the gravitational perturbation to their stellar velocities would be of the order of their random velocities and much less than the rotational velocities of stars in the disks. Valluri & Jog (1990) have extended this idea to a multicomponent interstellar medium consisting of H_2 and H I, each having a different filling factor. During a collision between two galaxies, the H I clouds with their high volume-filling factor collide and are stripped from the galaxies, whereas the molecular clouds with their lower volume-filling factor almost never collide, (except in the case of an edge-on collision between galaxies), and are unaffected by the encounter. This is in agreement with the normal molecular hydrogen contents observed in H I–deficient galaxies in the Virgo Cluster (Stark et al. 1986, and Kenney and Young 1989).

In this section we estimate the collision frequency as a function of size for galaxies in each cluster and thereby estimate the fraction of galaxies in each of the size bins which could have lost sufficient gas to have a deficiency DEF > 0.3, as a result of such a collision.

By and large, clusters of galaxies are not virialized, and consequently the velocity distribution of their galaxies is not isotropic. In the Virgo Cluster, for instance, the galaxies are concentrated into two or more spatial and velocity clumps (e.g., Binggeli, Tammann, & Sandage 1987), and, in addition, the spiral galaxies are believed to be falling into the cluster on radial orbits (Tully & Shaya 1984). Nevertheless, the assumption that the velocity distribution of galaxies within 1.5 Abell radii is isotropic will enable us to obtain an approximate estimate of the collision frequency and is likely to give an indication of the trends to be expected if collisional gas removal is an important mechanism.

The mean relative velocity between galaxies is derived from the line-of-sight velocity dispersion of galaxies in the cluster, σ_V. The mean relative velocity is the $\langle V_{\rm rel} \rangle = 6^{1/2}\sigma_V$, where we use $\sigma_V = 820$ km s^{-1} for Virgo, $\sigma_V = 540$ km s^{-1} for A262, $\sigma_V = 760$ km s^{-1} for A1367, and $\sigma_V = 920$ km s^{-1} for A1656 (Magri et al. 1988).

In § 2 the galaxies in each cluster were distributed in bins of logarithmically increasing linear optical diameter. In order to estimate the number density of galaxies in each bin, one needs the total number density of galaxies (n) in the 1.5 $r_{\rm A}$ region of each cluster, as well as information on the mass spectrum of galaxies in these clusters. The Virgo Cluster sample is used to estimate the fraction ($f_{\rm ni}$) of galaxies of the total spiral sample lying within each bin since this sample has a much larger range of galaxy sizes and is reasonably complete. The number density of galaxies in the ith bin is then, $n_i = n \cdot f_{\rm ni}$. It is likely that the detailed dynamics of other clusters may yield mass spectra that are different from that of the Virgo Cluster. However, for the other clusters we do not have large enough samples from which to obtain mass spectra. Hence we use the values of $f_{\rm ni}$ obtained from the Virgo Cluster data, along with the spiral number density (n) for each of the clusters. We use the average *spiral* number densities, $n = 15$ galaxies Mpc^{-3} for the Virgo Cluster and $n = 30$ galaxies Mpc^{-3} for the three rich clusters.

The collision cross section for the galaxies is obtained from the geometric means of the diameters of galaxies in each of the i bins ($\langle D_0 \rangle_i$). The H I disks of field galaxies generally extend well beyond their optical (stellar) disks. For a sample of field galaxies, Warmels (1986) has shown that the ratio of H I diameter ($D_{\rm H\,I}$) to Holmberg diameter (D_0) has only a small dependence on morphological type. The value of $D_{\rm H\,I}/D_0$ varies from 1.23 ± 0.4 (for types Sa–Sab) to 1.79 ± 0.6 (for type Sc). We therefore use a mean value of $D_{\rm HI}/D_0 \sim 1.5$, (also see Bosma 1978).

All collisions would result in gas loss from the overlapping regions of each of the colliding galaxies. *But only those collisions where the overlap of the gas disk is at least 50% will result in sufficient gas loss to make the galaxy appear* H I*–deficient with DEF > 0.3.* We do not need to consider cumulative gas loss by successive collisions because the collision probability in the crossing time of the cluster ($T_{\rm cross} \sim 6 \times 10^9$ yr) is much smaller than unity. For our data this implies that collisions of a galaxy with galaxies in bins smaller than itself do not result in DEF > 0.3. Hence, to obtain the frequency of collisions which would result in H I deficiency for a galaxy in the ith bin, we sum over bins of increasing size from i to k, where k is the total number of bins.

TABLE 1

COLLISION PROBABILITY AS A FUNCTION OF GALAXY SIZE

SIZE RANGE [log (D_0)[a]]	COLLISION PROBABILITY[b]			
	A262	A1367	A1656	Virgo
A: 0.40–0.65..........	...	...	...	0.1
C: 0.65–0.90..........	...	...	...	0.1
C: 0.90–1.15..........	0.2	0.3	0.3	0.2
D: 1.15–1.40..........	0.2	0.2	0.3	0.2
E: 1.40–1.65..........	0.1	0.2	0.3	0.2
F: 1.65–1.90..........	0.1	0.1	0.1	0.1

[a] D_0 = optical diameter in kpc.

[b] Obtained from eq. (9).

Thus the probability that a galaxy in the ith bin will collide with other galaxies within that bin as well as with galaxies in bins of larger galaxy size in crossing time ~6 × 10⁹ yr is given by

$$P_{\rm Ci} = 0.13\left[\frac{V_{\rm rel}}{2000 \text{ km s}^{-1}}\right]\left[\frac{T_{\rm cross}}{6 \times 10^9 \text{ yr}}\right] \times \sum_{j \geq i}^{k}\left[\frac{n_j}{30 \text{ Mpc}^{-3}}\right]\left[\frac{\langle D_0 \rangle_i + \langle D_0 \rangle_j}{20 \text{ kpc}}\right]^2 . \quad (9)$$

On substituting the relevant values of parameters for each of the clusters we find that $P_{\rm Ci}$ is nearly flat or decreases with a small negative slope (Table 1). This indicates that collisional gas removal cannot explain the increasing size dependence in H I deficiency, but it may explain the drop for the last bin.

4.2. *Tidal Encounters in Subclumps within Clusters*

It is becoming progressively more evident that clusters of galaxies are highly clumpy and show a large amount of substructure both in the spatial and velocity distribution of galaxies (for a recent review, see Fitchett 1989). A cluster is believed to go through an early clumpy phase prior to virialization (White 1976). Galaxy velocities within subclumps are typically a few 100 km s^{-1}, and at these velocities tidal encounters between the galaxies become important. Further, the number density of galaxies in clumps is high, being of the order of that in the cluster core, and hence the encounter frequency would be high.

A tidal encounter between two galaxies of very different sizes will have the greatest effect on the material in the larger galaxy; in particular, it will result in the removal of gas from its outer regions. Thus gas removal via tidal interactions may produce a size dependence in H I deficiency which would be similar to that seen in § 2. The largest galaxies would suffer frequent encounters with much smaller galaxies which would lead to capture of the satellite (Hausman and Ostriker 1978) rather than gas loss. This process would lead to an increase in the H I content of the large galaxy and hence may be partly responsible for the drop in F_D for the largest galaxies. The gas removed by tidal interaction is subsequently swept away from the interacting galaxies by the ICM, or it could be removed during the merging of clumps.

Combes et al. (1988) have studied a pair of galaxies in the Virgo Cluster whose gas distributions (both H I and H$_2$) are highly disturbed indicating a recent tidal interaction. They emphasize that the frequency of close interactions between cluster galaxies has been greatly underestimated.

Although tidal encounters appear to qualitatively produce the right dependence of H I deficiency on galaxy size, this mechanism does not explain why the H_2 content is normal even in regions where H I is deficient. However, since most of the H I deficiency is due to gas loss from the outer regions (where H_2 is not found), this may not be a serious problem.

Figure 4 shows that galaxies in the outer region show a size dependence in H I deficiency whereas the galaxies in the inner regions do not. *We propose that this size dependence could be produced by tidal interactions in subclumps which later merged to form virialized clusters.* In this case the galaxies in the outer regions which have fallen into the cluster more recently, either individually or as a clump (Tully & Shaya 1984), would still show signatures of this early evolution, but the galaxies in the inner regions would have experienced further gas removal due to the various processes mentioned earlier and would therefore have had traces of the early evolution washed out by recent galaxy-ICM stripping. Through speculative, this seems to be a plausible explanation. It is important to note here (see Fig. 4) that the overall fraction of deficient galaxies in the IN sample is higher than that in the OUT sample which is expected since the ICM processes are more effective in the inner cluster.

It is interesting that recent observations of the Hydra I cluster by McMahon et al. (1990) show that spiral galaxies in the core region have extended H I disks. This probably indicates that this cluster is still in the process of forming and galaxies falling into the cluster for the first time are seen projected on the cluster core (J. H. van Gorkom 1991, personal communication).

There are other indications that at least part of the gas loss may have occurred due to interactions at an epoch prior to cluster formation. Magri et al. (1988) find a strong correlation between the deficiency of a galaxy and its projected local galaxy number density. Based on this correlation, they conclude that the present-day characteristics of spirals are determined mainly by initial conditions at the time of galaxy formation and are later modified slightly by evolution effects. Rubin, Whitmore, & Ford (1988) have found that the rotation curves of galaxies in four rich clusters are lowered with respect to the rotation curves of field spirals of the same optical size and morphological type, and, in addition, these curves flatten and drop at relatively smaller galactic radii than in the case of field galaxies. They conclude that cluster galaxies have either lost a large amount of the dark mass from their halos or the formation of halos was inhibited at the time of galaxy formation by the high-density environment. If dark matter halos were indeed lost from the galaxies, it is most likely that they were stripped tidally either at early epochs (via galaxy-galaxy interactions in subclumps) or later by the tidal field of the overall cluster potential (Merritt 1984). Such encounters would necessarily affect all the material components in the galaxies, including their H I contents.

We therefore propose that tidal encounters at early epochs may have been responsible for some of the global H I deficiency and its dependence on galaxy size as discussed here.

5. DISCUSSION AND SUMMARY

The available H I data on galaxies in four clusters—A262, A1367, A1656 (Coma), and Virgo Cluster—have been used to show that the H I deficiency of a galaxy depends on its optical size. When galaxies in each cluster are binned according to optical diameter, the fraction of deficient galaxies in each bin, F_D, is found to increase with galaxy size over most of the size range.

Cumulative distribution functions for F_D versus the deficiency parameter show that while there is a spread in deficiency within each size bin, the most highly deficient galaxies are among the largest in each sample. This dependence of H I deficiency on galaxy size is the major result of this paper.

We have shown analytically that ram-pressure stripping and thermal evaporation of the ISM would be less effective on the larger galaxies and would lead to a decrease of F_D with galaxy size rather than an increase. The size dependence produced by turbulent viscous stripping is insufficient to explain the observed increase in F_D with size.

In those clusters where there is strong mass segregation, this along with the various ICM processes may be partly responsible for some of the observed size dependence. However, it is difficult to quantitatively estimate its importance.

The frequency of collisions (Spitzer & Baade 1951) which would result in deficiency DEF > 0.3 is also a decreasing function of galaxy size with a small negative slope. Therefore, this mechanism is not responsible for the observed size dependence, either.

While it is true that F_D increases as a function of galaxy size over most of the size range, it is likely that the drop in F_D for the largest size bin is real. This is not surprising, since as we have discussed in earlier sections, irrespective of which gas removal mechanism we consider, it is difficult to remove gas from the largest galaxies since both their disk and gas surface densities are large (§ 3), also the probability of gas loss via collisions would be lower for large galaxies (§ 4). It is more surprising that the turnover occurs at such large radii. It is essential to do similar analysis with magnitude-limited samples of galaxies from many more clusters to establish the actual form of the distribution of F_D with size.

We propose that at least part of the gas deficiency must have occurred via tidal gas removal in groups which subsequently merged to form clusters. In conclusion, the increase in F_D with size for small- to intermediate-size galaxies could be due to tidal interactions in subclumps, or it could be due to various ICM processes if there is strong mass segregation. The decreasing part of F_D versus size, for large galaxy sizes, could be due to the fact that ICM processes as well as collisions are least effective for the largest galaxies. The observed gas contents of galaxies then arise due to the cumulative effect of various gas removal mechanisms.

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