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COLLISIONAL REMOVAL OF H I FROM THE INNER DISKS OF VIRGO CLUSTER GALAXIES

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ABSTRACT

There is sufficient observational evidence to show that many Virgo Cluster spirals are H I–deficient in their inner disks in addition to being H I–deficient globally as previously established. It is shown here that collisions between galaxies in a cluster can lead to the removal of H I gas from these galaxies while leaving the H_2 gas undisturbed. This follows directly from the application of the Spitzer-Baade collisional gas removal mechanism to galaxies consisting of stars and a two-component ISM consisting of H I and H_2, with H I having the largest filling factor. This can account for both the observed H I deficiency in the inner regions and the normal H_2 content of these galaxies. The frequency of galaxy collisions in the Virgo Cluster, which has been underestimated previously, is shown to be large enough to make collisional gas removal a viable mechanism.

Subject headings: galaxies: clustering — galaxies: interactions — galaxies: interstellar matter

I. INTRODUCTION

It has been well established observationally that a large fraction of spiral galaxies in clusters have far less atomic hydrogen (H I) than isolated field spirals of the same morphological type and possessing similar optical properties (cf. Haynes, Giovanelli, and Chincarini 1984). The global deficiency of H I in these galaxies arises mainly due to the loss of H I from their outer regions and consequently a shrinkage in the sizes of H I disks (Van Gorkom, Balkowski, and Kotanyi 1984). Gas removal is believed to occur due to the effect of the cluster environment on galaxies. The interactions of galaxies with the intracluster medium and between each other can affect their gas content. Various methods proposed for gas removal include collisional gas removal (Spitzer and Baade 1951), ram pressure stripping (Gunn and Gott 1972), thermal evaporation (Cowie and Songaila 1977), viscous stripping (Nulsen 1982), and tidal stripping.

Recent CO observations of H I–deficient spiral galaxies in the Virgo Cluster (see Kenney and Young 1989) have shown that the molecular gas content and distribution are normal even in severely H I–deficient galaxies. They have also shown from the H I data obtained by Warmels (1986) that Virgo Cluster spirals are not only H I–deficient globally but are also deficient in their inner galactic disks, i.e., within half the Holmberg radius ($R_0/2$). However the molecular component, H_2, is normal right up to the detection limit and typically has a higher surface density than H I over the entire H_2 extent. Helou (1982) has also pointed out that some galaxies in Virgo, classified in the DDO system as "anemic," are H I–deficient in the inner regions. Giovanelli and Haynes (1983) showed that the mean total H I mass surface density was constant irrespective of the H I deficiency of a galaxy. Kenney and Young (1989) argue that in order for this to be true, these galaxies must also be moderately deficient in their inner disks.

In this paper we analyze the data from Warmels (1986) and confirm that an H I deficiency also exists in the inner galactic disks of the Virgo Cluster spirals (§ II). We apply the Spitzer-Baade model of gas removal by galaxy-galaxy collisions to a three-component galaxy (stars, H_2, and H I) and show that the H I gas can be preferentially removed from the inner galactic disk while leaving the H_2 component undisturbed (§ III). We demonstrate that the collision frequency in the Virgo Cluster, which has often been considered insignificant, is in fact fairly high and may account for the H I deficiency in the inner disk regions of a large fraction of Virgo Cluster galaxies. In § IV, we examine the effectiveness of other gas removal mechanisms and argue that ram pressure stripping as described by Gunn and Gott (1972) may not explain the observed deficiency in the inner disks. Section V contains a summary of conclusions from this paper.

II. H I DEFICIENCY IN INNER DISK REGIONS

Detailed analysis of high-resolution synthesis observations (Warmels 1986) and single-dish observations (see Haynes and Giovanelli 1986) of the 21 cm line of neutral hydrogen has established beyond doubt that a large fraction of Virgo Cluster spirals are deficient in H I when compared with field galaxies of the same morphological type. Global H I deficiency is estimated by comparing the total H I mass of a cluster galaxy with the total H I mass of a field galaxy of the same morphological type and optical diameter. Of spirals in the Virgo Cluster, 62% are found to be H I–deficient globally, by an average factor of 2.5 (Haynes and Giovanelli 1986). It is assumed, as usual, that a galaxy's type classification and optical properties are unaffected by the gas loss.

Warmels (1986, 1988*a*) has obtained ($\sigma_{\rm H\,I}$), the mass surface density of H I averaged over half the optical (Holmberg) radius ($R_0/2$), for 36 galaxies in the Virgo Cluster area. His comparison sample consists of 62 field galaxies (Warmels 1986, 1988*b*). The subscripts "VC" and "f" will be used to denote Virgo Cluster galaxies and field galaxies, respectively. In this paper, H I deficiency in the inner galaxy ($r < R_0/2$) is defined by

$$\mathrm{Def_{IN}} = \log\left[\frac{\langle(\sigma_{\rm H\,I})_f\rangle_T}{(\sigma_{\rm H\,I})_{\rm VC}}\right] \qquad (1)$$

where $\langle(\sigma_{\rm H\,I})_f\rangle_T$ is defined to be the average over field galaxies of the same morphological type, T. For types (Sa, Sab), $\langle(\sigma_{\rm H\,I})_f\rangle_T = 1.6 \pm 1.5\ M_\odot\ \mathrm{pc}^{-2}$; (Sb, Sbc), $\langle(\sigma_{\rm H\,I})_f\rangle_T = 3.65$

$\pm 1.2\ M_\odot\ \mathrm{pc}^{-2}$; $\langle(\sigma_{\mathrm{H\,I}})_f\rangle_T = 6.2 \pm 2.2\ M_\odot\ \mathrm{pc}^{-2}$ (Warmels 1986).

We consider galaxies to be H I–deficient if $\mathrm{Def}_{\mathrm{IN}} \geq 0.3$, which corresponds to a factor of 2 less H I than in a normal galaxy (Giovanelli and Haynes 1985). This cut-off has frequently been used in the past in the study of global H I deficiency (see Giovanelli and Haynes 1985). We exclude galaxies of types Sa and Sab from the analysis since the sample is too small to do a meaningful analysis.

Kenney and Young (1987, 1989) have combined CO observations and the H I observations of Warmels to show that galaxies which are H I–deficient globally are deficient in their inner disks, on an average, by a factor of 2–3 ($\mathrm{Def}_{\mathrm{IN}} \geq 0.3$). This further justifies our choice of 0.3 as the cut-off value for the deficiency criterion. Warmels did not find any correlation between inner H I deficiency of a galaxy and its distance from M87. Since global H I deficiency of these galaxies is strongly correlated with their distances from M87, he concluded that a lack of correlation indicated that these galaxies were not H I–deficient in the inner disks, and all deficiency was due to gas-loss from the outer regions of these galaxies.

We obtain the value of $\mathrm{Def}_{\mathrm{IN}}$ for each galaxy in Warmels's sample lying within the Abell radius, i.e., within a 5° circle centered on M87. These values are presented in Table 1, along with Warmels's data. Of the 29 galaxies, 24% are characterized by $\mathrm{Def}_{\mathrm{IN}} \geq 0.3$ and are therefore deemed to be H I–deficient in their inner disks.

The standard deviation of the mean surface density is fairly large for each of the morphological types. If the galaxies of each morphological type bin have a Gaussian distribution in $(\sigma_{\mathrm{H\,I}})$, then for a sample of field galaxies we would expect 7% of galaxies in each bin to lie more than 1.5 standard deviations (corresponding to a $\mathrm{Def}_{\mathrm{IN}} = 0.3$) below the mean $\langle(\sigma_{\mathrm{H\,I}})_f\rangle_T$, purely from the statistical spread in the surface density. From Table 1, we find that 25% ($\frac{2}{8}$) of Virgo Cluster galaxies of type Sb, Sbc and 24% (4/17) galaxies of type Sc, Scd have $\mathrm{Def}_{\mathrm{IN}} \geq 0.3$, both of which are much larger than 7%.

TABLE 1

DATA ON VIRGO CLUSTER GALAXIES LYING WITHIN THE ABELL RADIUS[a]

Galaxy	Type	R-M87[b]	D_0[c] (kpc)	$(\sigma_{\mathrm{H\,I}})_{\mathrm{VC}}$ ($M_\odot$ pc^{-2})	$\mathrm{Def}_{\mathrm{IN}}$
NGC 4178......	Sc	4°9	18.6	9.8	−0.19
NGC 4189......	Sc	4.5	11.0	9.5	−0.19
NGC 4192......	Sb	5.0	33.9	2.3	+0.20
NGC 4206......	Sc	4.0	17.0	4.1	+0.18
NGC 4216......	Sb	3.9	27.5	1.1	+0.52
NGC 4222......	Scd	3.8	10.0	2.8	+0.35
NGC 4254......	Sc	3.7	24.6	7.5	−0.08
NGC 4294......	Scd	2.6	11.5	9.5	−0.19
NGC 4299......	Scd	2.5	7.8	13.4	−0.33
NGC 4321......	Sc	4.0	30.9	4.4	+0.15
IC 3258.........	Sc	1.8	7.2	7.6	−0.10
NGC 4351......	Sc	1.8	8.7	3.8	+0.21
NGC 4388......	Sab	1.3	17.4	3.6	−0.35
NGC 4394......	Sb	6.0	17.8	2.0	+0.26
NGC 4402......	Sc	1.4	14.1	3.6	+0.24
NGC 4413......	Sbc	1.1	10.2	3.6	0.00
NGC 4501......	Sbc	2.1	27.5	3.5	+0.02
NGC 4519......	Sbc	3.7	13.2	7.5	−0.31
NGC 4535......	Sc	4.3	28.8	2.7	+0.36
NGC 4548......	Sb	2.4	23.4	0.9	+0.61
NGC 4569......	Sab	1.7	36.3	1.0	+0.21
NGC 4571......	Sc	2.4	17.6	2.9	+0.33
NGC 4579......	Sab	1.9	23.4	1.9	−0.10
NGC 4639......	Sb	3.2	12.3	4.5	−0.10
NGC 4647......	Sc	3.4	13.2	4.7	+0.12
NGC 4651......	Sc	5.2	15.8	6.3	+0.00
NGC 4654......	Sc	3.5	19.5	7.0	−0.05
NGC 4689......	Sc	4.6	17.8	2.3	+0.43
NGC 4698......	Sa	5.9	17.0	0.5	+0.51

[a] From Warmels 1986.

[b] R-M87: angular distance from M87.

[c] Holmberg diameter.

We consider this to be evidence for the existence of H I deficiency in the inner regions of galaxies which were previously known to be globally deficient.

III. COLLISIONAL GAS REMOVAL

In this section we show that collisions between galaxies in a cluster can lead to H I deficiency in the inner disks of cluster galaxies and yet leave the H_2 gas in these galaxies unaffected. It is reasonable to reexamine the viability of the collisional gas removal mechanism (Spitzer and Baade 1951) in the inner disk regions, as is done here. First, the other possible mechanisms such as ram pressure stripping are likely to be less effective in the inner disk regions where both σ_D and $\sigma_{\mathrm{H\,I}}$ are much higher than in the outer regions (e.g., Mihalas and Binney 1981; Bosma 1978) and second, the molecular hydrogen gas distribution is concentrated in the inner disk regions (see Sanders, Solomon, and Scoville 1984).

Spitzer and Baade (1951) suggested that during a fast physical collision between two galaxies, the gravitational effect on their stellar components would be very small since the change in the stellar velocity following an encounter is comparable to its initial random velocity and is therefore negligible in comparison with its rotational velocity in the disk. However, their interstellar gas components would collide inelastically. If two galaxies collided with a relative velocity V_{rel} and the escape velocity from each galaxy is V_{esc}, then the H I masses involved in the collision (considered to be in the same ratio as masses of the parent galaxies), would be left behind at the center of mass of the two galaxies, provided $V_{\mathrm{rel}}/2 > V_{\mathrm{esc}}$. The kinetic energy of the collision is thermalized, heating the gas to a temperature of $T \sim 5 \times 10^7$ K for $V_{\mathrm{rel}} \sim 2000\ \mathrm{km\ s^{-1}}$ (see § III*b*), thereby giving the gas particles sufficient kinetic energy to escape since the typical $V_{\mathrm{esc}} \sim 300\ \mathrm{km\ s^{-1}}$ at R_0 is much less than $V_{\mathrm{rel}}/2$. Even if the gas cools rapidly, it will be left behind (Sarazin 1986). Hydrodynamic simulations of this process have recently been carried out by Mair *et al.* (1988) and Muller, Mair, and Hillebrandt (1989). Their model treats only the hot intercloud medium of the ISM with a filling factor of 1.

In the following sections, the importance of the filling factor of a component in determining whether or not it will be removed during a collision is considered. The frequency of collisions between galaxies in clusters is also estimated.

a) The Importance of Filling Factor

During a physical collision between two galaxies, gas clouds of a particular ISM component will collide if their mean free path is less than the dimensions of the region of overlap of the two galaxies. The mean free path (λ) of clouds of a particular ISM component and the volume filling factor (f) of the component are related by the expression

$$\lambda = \frac{2}{3}\frac{R_c}{f}\,, \tag{2}$$

where we assume that spherical clouds, each of radius R_c, collide with a collision cross section $2\pi R_c^2$. The clouds from the two galaxies will collide if λ is less than d, the maximum extent of the overlapping volume. In the extreme case of a face-on collision, d is a minimum ($= 2Z_{1/2}$), where $Z_{1/2}$ is the HWHM of the gas distribution normal to the galaxy plane.

The H_2 clouds with radii $R_c \sim 25$ pc each, and $f \sim 0.01$ (Sanders, Scoville, and Solomon 1985), will have a mean free path $\lambda = 1.7$ kpc. The average value of the scale height of the H_2 component for the Galaxy, $Z_{1/2}$, is 65 pc (Sanders, Solomon and Scoville 1984). Hence the GMCs from the two galaxies will rarely collide since $\lambda = 1.7$ kpc $\gg d \approx 0.13$ kpc, unless the galaxies are undergoing an edge-on collision, which has only a small probability of occurring. Thus, for a majority of galaxy collisions, the H_2 component would remain undisturbed.

The interstellar H I is believed to consist of four components, a cold neutral medium (CNM), a warm neutral medium (WNM), a warm ionized medium (WIM), and a hot ionized medium (HIM) (Kulkarni and Heiles 1988). Each of these components has a different filling factor and spatial distribution, with the CNM having the smallest filling factor. If we assume that the CNM component is distributed in spherical clouds, each of radius $R_c \simeq 5$ pc (the standard Spitzer cloud) with a filling factor $f \simeq 0.1$, the resulting mean free path λ is $\simeq 35$ pc (eq. [2]). This mean free path of ~ 35 pc is much less than twice the scale height $2Z_{1/2}$ of the H I distribution ($\simeq 200$ pc; see Kulkarni and Heiles 1988), hence, even in a face-on collision between the galaxies, the spherical neutral clouds will always collide. The H I clouds are believed to be largely filamentary or sheetlike in nature and have a large surface area when seen perpendicular to the disk (Kulkarni and Heiles 1988). By assuming that the clouds are spherical as we have done above, we would only be underestimating the probability of collision. Hence, all the H I gas in the overlapping volume will undergo collisions and be removed from the parent galaxies.

Collisions between H_2 clouds and H I clouds are neglected because the mass of H I swept up by a GMC during a two-galaxy collision is $\sim 10^4\ M_\odot$, which is much less than the typical mass of a GMC ($5 \times 10^5\ M_\odot$; see Sanders, Scoville, and Solomon 1985).

Therefore, the filling factor of a particular component is critical in determining whether or not it will undergo collision and be stripped from the colliding galaxies. This is simply an extension of the Spitzer-Baade idea applied to a three-component galaxy (stars, H_2, and H I) instead of a two-component system (stars and the ISM), with different filling factors for each component and $f_{\rm stars} \ll f_{H_2} \ll f_{\rm H\,I}$, where the subscripts "stars," "H_2," and "H I" stand for each of the three components.

For the complementary case when $V_{\rm rel}/2 < V_{\rm esc}$, as would be the case for field galaxies, the Spitzer-Baade model of gas removal cannot work. During a slow collision between two field galaxies with a two-component ISM (H I and H_2), the atomic clouds from the two galaxies undergo collisions, while the GMCs, with their lower filling factor, do not. The collisions between the H I clouds lead to the formation of hot, high-pressure remnants which cause a shock compression of the outer layers of a GMC, and a burst of massive star formation follows. Thus, a slow collision between two field galaxies results in a super starburst rather than in H I gas removal as considered here for the cluster galaxies (Jog and Solomon 1990).

It has been suggested that the interstellar gas in spiral galaxies in clusters can be removed by collisions between them leading to the formation of S0 galaxies (Spitzer and Baade 1951). It has also been suggested that a merger of spiral galaxies in clusters leads to the formation of elliptical galaxies (Toomre and Toomre 1972; White 1979). In this section the effectiveness of the collisional gas removal mechanism has been shown to be dependant on the filling factor of the gas component. Thus, even if H I were to be removed via collisions, the H_2 component would be undisturbed. This is an important argument, in addition to the others proposed by Ostriker (1980), which makes it hard to see how S0's or ellipticals could form from spirals via collisions.

b) *Collision Frequency*

We estimate the collision frequency between spiral galaxies in the Virgo Cluster by making use of the fact that of the galaxies within the Abell radius, over 50% of the spirals are of types Sbc–Sm and only 8% are of type Sa–Sb, the rest being irregulars (Hoffman, Helou, and Salpeter 1988). Dressler (1986) showed that early-type spirals in clusters have predominantly radial orbits, but the later type spirals (Sbc–Sm) have either circular or isotropic orbits. Since the spirals in the Virgo Cluster are dominated by the later types, we can expect the dynamics of the cluster to be determined largely by these galaxies. We consider, therefore, the case where all galaxies have isotropic orbits. For Virgo Cluster spirals the line-of-sight velocity dispersion is 800 km s^{-1} (Huchra 1985). This gives $V_{\rm rel}$, the three-dimensional relative velocity between galaxies to be $6^{1/2} \times 800 = 2000$ km s^{-1}. At these high velocities, gravitational focusing is negligible. We also assume that these galaxies are distributed within a volume of 5° radius centered on M87 with a constant number density of $n = 15$ spiral galaxies Mpc^{-3}. Collisions of spirals with ellipticals and S0 galaxies do not lead to gas removal in our picture, and therefore we do not consider their contribution to n. We assume that Warmels's sample is representative of the entire population of Virgo Cluster spirals. We distribute all galaxies in this sample into three bins of logarithmically increasing Holmberg diameter D_0 (see Table 2). These bins are well separated, and the standard deviation of the mean diameter $\langle D_0 \rangle$ is small in each case. We find that the number of galaxies (N_i) in each of the three bins is almost the same and therefore assume that the number density of galaxies in each bin is $n/3$. The following discussion is not affected if the binning were to be altered. The net collision frequency, (ω_{ci}), for a galaxy in the ith bin with mean diameter $\langle D_0 \rangle_i$, with galaxies in that bin and other bins is given by

$$\omega_{ci} = 2\pi \frac{n}{3} V_{\rm rel} \sum_{j=1}^{3} \left(\frac{\langle D_0 \rangle_i + \langle D_0 \rangle_j}{4} \right)^2 .$$

Assuming that galaxies have been undergoing collisions for over half a Hubble time ($H_0 = 75$ km s^{-1} Mpc^{-1}) which is also equal to the crossing time $\simeq 6 \times 10^9$ yr, we can obtain a prob-

TABLE 2

COMPARISON OF COLLISION PROBABILITY WITH DEFICIENT FRACTION

i	Size Range[a] D_0 (kpc)	Mean Size $\langle D_0 \rangle_i$	Number of Galaxies N_i	Collision Probability P_c	Deficient Fraction F_D
1....	<13	9 ± 2	8	0.06 ± 0.02	0.13 (1/8)
2....	13–21	16 ± 2	9	0.09 ± 0.03	0.22 (2/9)
3....	>21	28 ± 4	9	0.15 ± 0.05	0.33 (3/9)

[a] Holmberg diameter.

ability of collision (P_c) for galaxies in each bin. We have also obtained the fraction of galaxies (F_D) in each bin that are H I–deficient ($\mathrm{Def}_{\mathrm{IN}} \geq 0.3$) (Table 2). It is interesting to note that the observed trend of increasing fraction of H I–deficient galaxies with size is in qualitative agreement with the increase in collision probability with size, although the number of galaxies in each bin is too small to make a stronger statement. For each bin F_D is approximately twice P_c. Since all quantities in equation (3) are uncertain by a factor of few (for instance, a galaxy passing through the core will see a galaxy number density of $\simeq 33$ spirals Mpc^{-3}), these values of P_c could be underestimates.

It is clear, however, that in the alternative picture of ram pressure stripping, larger galaxies with large σ_D are less easily stripped than smaller spirals, and the opposite trend is expected to exist between F_D and $\langle D_0 \rangle_i$.

Optical observations of the Virgo Cluster have shown (Huchra 1985) that the elliptical galaxies form a relaxed system, but the spirals and irregulars do not. Observations show that spiral galaxies appear to be falling into the cluster (Tully and Shaya 1984). Besides the 3° core with a mean velocity of 1190 km s^{-1}, it is known that there are clumps or subclusters of galaxies which are falling into the Virgo Cluster. Of these, a low-velocity clump, Virgo B, with a mean heliocentric velocity of 300 km s^{-1} lies largely within 5° of M87 and appears to be falling toward the Virgo A clump, also lying in this region, from behind it (Binggeli, Tammann, and Sandage 1987). Obtaining the collision probability in such a complex system is difficult, but a rough estimate may be obtained from the observations. An alternative way to estimate the probability of collision (Salpeter 1989) of a Virgo B galaxy with Virgo A galaxies is to assume that all galaxies within 5° of M87, with heliocentric velocity less than 600 km s^{-1} (Virgo B galaxies) have passed through an imaginary disk of radius 5° perpendicular to the line of sight, centered on M87. This assumes that galaxies are on radial orbits and are falling into the cluster core. The fractional target area projected on the 5° region by the optical disks of Virgo A galaxies is 9.2×10^{-3}. There are ~ 50 galaxies with known velocities ≤ 600 km s^{-1} (Binggeli, Sandage, and Tammann 1985), which can be considered as infalling Virgo B galaxies. The probability of collision is then $P_c = 2 \times 9.2 \times 10^{-3} \times 3^{1/2} = 0.03$ (accounting for a three-dimensional velocity distribution introduces a factor of $3^{1/2}$). This value is not very different from the values obtained for isotropic orbits, earlier in this section. This agreement is interesting given that these two estimates are for the two extreme cases of purely radial and purely isotropic orbits.

Thus we have shown here that collisions between spiral galaxies in a cluster can remove H I gas from the inner disk regions while leaving the H_2 gas undisturbed. In fact, in rich clusters like Coma, collisions and tidal stripping could have been the dominant gas removal mechanisms at earlier epochs when the intracluster gas density was smaller (Sarazin 1979). We have shown that the collisional rate for galaxies in clusters, though small, is not negligible. Hence the main objection against the collisional gas removal mechanism raised in the past (e.g., Chamaraux, Balkowski, and Gerard 1980) is not valid. The collisional gas removal mechanism should be taken into account when studying the gas contents of the inner disks of galaxies in clusters. In a future paper we will show that this relationship between F_D and P_c holds for global H I deficiency in galaxies in three rich clusters and the Virgo Cluster. In addition, the most highly deficient galaxies are always of the largest sizes. These features of the global H I deficiency in galaxies are accounted for qualitatively, only by the collisional gas removal mechanism (Valluri and Jog 1990).

An indication of the collisional gas removal mechanism at work, rather than other mechanisms for continuous gas removal such as ram pressure stripping, for example, would be the detection of intergalactic H I clouds in closely interacting groups and clusters of galaxies. However, the lifetime of such a cloud would depend on the rate of evaporation by the hot ICM and could be less than 10^8 yr as deduced from the application of results by Cowie and McKee (1977) thus decreasing the possibility of its detection. A particular nearby instance of collisional gas removal could be the intergalactic H I cloud in the Leo group (Schneider *et al.* 1983). Indeed, Rood and Williams (1985) have proposed that this cloud could have been created by a collisional interaction between NGC 3384 and NGC 3368. However, Schneider (1985) has contested this explanation because of kinematic problems such as the origin of the rotation associated with the ring structure of the H I cloud distribution.

IV. ALTERNATIVE GAS REMOVAL MECHANISMS

In this section we examine the effectiveness of alternative gas removal mechanisms, in particular, ram pressure stripping, in causing H I deficiency in the inner regions of galactic disks.

Ram pressure stripping is widely accepted as the most effective mechanism for global H I removal (Warmels 1986; Kenney and Young 1989). Interstellar gas will be removed from a galaxy if the ram pressure generated due to its motion through the ICM exceeds the gravitational restoring force per unit area binding the gas to the disk, i.e., if $\rho_{\mathrm{ICM}} V_{\perp}^2 > 2\pi G \sigma_D \sigma_{\mathrm{gas}}$ (Gunn and Gott 1972), where ρ_{ICM} is the density of the intracluster gas, $V_{\perp}$ is the velocity component of the galaxy perpendicular to its disk, and σ_D and σ_{gas} are the surface densities of the disk and the gas, respectively.

Since both σ_D and $\sigma_{\mathrm{H\,I}}$ peak in the central regions, falling exponentially with radius (e.g., Mihalas and Binney 1981; Bosma 1978), one expects that it should be more difficult to remove gas from the inner disk than from the outer disk.

Kritsuk (1983) has reexamined the ram pressure stripping process in view of the fact that a large fraction of the H I gas is in the form of discrete clouds rather than as a uniform disk. Since the mean free path of ICM particles is ~ 6 pc which is comparable to the dimensions of the standard Spitzer cloud, the flow is that of a corpuscular stream of particles rather than a hydrodynamic fluid. His model galaxy has a mass of 10^{11} $M_{\odot}$ and a disk scale length of 6 kpc. For an ICM density of $n_{\mathrm{ICM}} = 10^{-3}$ cm^{-3} (typical for the gas within 1° of M87; Fabricant and Gorenstein 1983), he finds that a galaxy moving with velocity $\simeq 1000$ km s^{-1} will be stripped of clouds with surface density less than 18.0 $M_{\odot}$ pc^{-2}. Therefore, both the H_2 clouds and low filling factor H I clouds (§ III*a*) would not be stripped.

Although Kritsuk's treatment may be justified for galaxies moving subsonically, galaxies in clusters move transsonically through the ICM (Sarazin 1986). Any treatment of gas flow must include shock formation at the cloud–ICM interface. Work on supernova shocks has shown that an interaction of a shock with a clumpy ISM (Norman *et al.* 1987) leads to a "heating up" of the cloud distribution. As a result of successive reflections of shocks, there is an increase in the random velocities of clouds, rather than a systematic collective motion.

Hydrodynamic calculations have shown that a pure momentum-transfer treatment does not describe the gas removal process completely in the case of elliptical galaxies (Gaetz, Salpeter, and Shaviv 1987). Similar calculations need to be done for spiral galaxies with a clumpy ISM, to estimate the effectiveness of ram pressure stripping for a realistic ISM.

Observations of dwarf irregular galaxies in the Virgo Cluster show that these galaxies do not seem to be more heavily stripped as a class than the spirals (Hoffman, Helou, and Salpeter 1988). This is extremely surprising, since they have much smaller disk surface densities than spirals and ram pressure would be expected to affect them more than the spirals. The fact that the gas distribution is highly clumpy probably reduces the effective ram pressure experienced by them. A gas component with an area filling factor f_A would experience a ram pressure of only $f_A \rho_{\mathrm{ICM}} V_{\perp}^2$ which could be even a factor of ~ 10 (for $f_A \sim 0.1$ for the CNM) less than it would be if the gas were spread out uniformly over the disk. The same argument holds even better for the H_2 component which is almost unaffected by ram pressure.

Combes *et al.* (1988) have shown that the observed H I and H_2 features of the Virgo Cluster galaxy NGC 4438 can be explained only as a result of a close tidal interaction with a nearby neighbor and cannot be accounted for by the ram pressure stripping mechanism. They also emphasize that the frequency of close galaxy-galaxy interactions has been greatly underestimated in the past.

We therefore conclude that although ram pressure stripping is probably an important mechanism for removing H I globally, there are many indications that it may not be equally effective in the inner disks of galaxies. In addition, there may be many competing gas removal mechanisms at work. It has been suggested that turbulent viscous stripping (Nulsen 1982) may be more important than ram pressure stripping, particularly in the inner disk (Haynes and Giovanelli 1986). Nulsen (1982) also showed that the mass loss due to thermal evaporation could be 3.5 times that due to viscous stripping.

In this paper we do not attempt to make a quantitative comparison of the effectiveness of the various gas removal mechanisms. In a realistic detailed treatment, one would need to take account of all the competing mechanisms operating simultaneously. Our aim here was to point out that collisional gas removal is another important and viable gas removal mechanism and it should be taken into account while studying the gas contents in the inner disks of galaxies in clusters.

V. CONCLUSIONS

H I observations of Virgo Cluster galaxies by Warmels (1986) have shown that a large fraction of galaxies are not only deficient in H I globally but also in their *inner galactic disk regions*. We have shown that collisions between galaxies in a cluster is a mechanism by which atomic hydrogen can be removed from the inner galaxy without disturbing the H_2 gas. This follows when one applies the Spitzer-Baade mechanism to a three-component galaxy (stars, H_2, and H I) with vastly different filling factors, with $f_{\mathrm{H\,I}}$ being the largest. Thus the collisional process described here can explain both the H I deficiency in the inner disks and the normal H_2 contents of the Virgo Cluster spiral galaxies. The frequency of collisions for Virgo Cluster galaxies is large enough to affect gas evolution in galaxies in 6×10^9 yr. The efficiency of ram pressure stripping may have been overestimated in the past, as inferred from the observations that dwarf irregulars are not as severely deficient as would be expected from the Gunn-Gott criterion. Thus, collisions could in fact be the dominant gas removal mechanism for the inner galactic regions. The observed fraction of H I–deficient galaxies in various size bins agrees with the fraction predicted by the collision picture. The complementary case of a slow collision between two galaxies with $V_{\mathrm{rel}}/2 < V_{\mathrm{esc}}$, as would be the case for field galaxies, results in a superstarburst (Jog and Solomon 1990), rather than in H I gas removal as considered here for the cluster galaxies.

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