THE ASTROPHYSICAL JOURNAL, 301:35–43, 1986 February 1

THE MORPHOLOGICAL TYPES AND ORBITS OF H I–DEFICIENT SPIRALS IN CLUSTERS OF GALAXIES

ALAN DRESSLER
Mount Wilson and Las Campanas Observatories of the Carnegie Institution of Washington
Received 1985 May 28; accepted 1985 July 30

ABSTRACT

Further analysis of the Giovanelli and Haynes catalog of the H I content of cluster spirals reveals that H I deficiency is strongly correlated with morphological type. Those spirals deficient in H I by a factor of 3 or more for their type and optical diameter are predominantly early-type galaxies; spirals of type Sbc and later are rarely found to be gas deficient, even though they often reside in the same dense environments.

Comparison of the velocity dispersion as a function of radius for gas-poor and gas-rich spirals indicates that the gas-poor spirals are on radial orbits which carry them into the dense environment of the cluster core, while the orbits of gas-rich spirals are more likely to be isotropic or even circular. The simplest interpretation of these data is that ram pressure stripping of spiral galaxies on radial orbits is responsible for H I deficiency. The data are consistent with, but do not demonstrate, that the morphological type dependence of H I deficiency is similarly a result of more anisotropic orbits for early-type galaxies. Alternatively, early types may be easier to strip because of lower gas pressures in their disks. In either case, the observation that H I–deficient galaxies are usually early types may explain why S0 galaxies in clusters are preferentially large-bulge systems.

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

I. INTRODUCTION

In a recent paper, Giovanelli and Haynes (1985, hereafter GH) present an extensive set of H I measurements for spiral galaxies in nine rich clusters. New observations and data culled from the literature are combined to provide the most complete and uniform sample to data. GH have been careful to compare the gas content of the cluster spirals with that of isolated galaxies of the same morphological type and diameter (Haynes and Giovanelli 1984, hereafter HG), thereby removing the strongest trends that might mask or bias the results. Furthermore, GH have obtained redshifts from optical spectra for all nondetections, thus guaranteeing the cluster membership of all gas-poor spirals in their sample.

The GH analysis reveals a marked pattern of gas deficiency in spirals in five of the nine clusters, A2147, A1656 (Coma), A1367, A262, and Virgo, all of which are detected as extended X-ray sources. As shown in their Figure 7, spirals that are gas-poor for their type and size are primarily found within an Abell radius ($\sim 1.5\ h^{-1}$ Mpc, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}). Examples of gas-deficient spirals are also found, though more rarely, in the other four clusters, Cancer, Pegasus, A2151 (Hercules), and Z1400+0949, which are more loosely arranged and are relatively weak X-ray sources.

The interpretation of these observations, as GH point out, is not straightforward. The good correlation found by GH between the fraction of H I–deficient galaxies and the X-ray luminosity in the cluster is suggestive of gas ablation by the intracluster medium. On the other hand, X-ray luminosity is also correlated with cluster density and dynamical state, so the H I deficiency could alternatively be a result of more frequent interactions between galaxies, or even a relic of galaxy formation in denser environments. GH discuss this difficulty in identifying the cause of H I deficiency; for example, a correlation of H I deficiency with galaxy radial velocity, an expected signature of ram pressure stripping, is weak at best.

The present paper examines the distribution of morphological types and the kinematics of the H I–deficient spirals in the GH sample. In § II, relevant parameters are tabulated and explained. Section III contains a comparison of the morphological type distributions of H I–deficient and H I–normal galaxies, and in § IV the orbits of the gas-rich and gas-poor galaxies are investigated in light of kinematical data in the GH catalog. Finally, § V discusses the mechanism of gas deficiency in terms of the morphological and kinematical data.

II. THE DATA

The data used for this analysis came directly from GH and therefore derive both from their observations and from those of numerous workers cited in their paper. The relevant parameters for this study are the morphological type, the position in the cluster, and the deficiency factor.

Determination of the morphological types is described by HG. The types have largely been taken from the UGC (Nilson 1973) and the Revised Shapley-Ames Catalog (RSA, Sandage and Tammann 1981), but in addition, HG have attempted to verify these by examining plate copies of the Palomar Sky Survey or higher scale plates when available. They adopt a continuous classification scheme (similar to the de Vaucouleurs' "*T* type") which runs from $t = 0$ for ellipticals to $t = 9$ for irregular or dwarf galaxies. The class $t = 10$ is reserved for peculiar galaxies. Most of the galaxies in the present sample run only from Sa ($t = 3$) to Sd ($t = 8$) on the Hubble system (as described in the RSA). Although their classification scheme is continuous like de Vaucouleurs', this advantage over the Hubble system has mainly been lost because galaxies were usually assigned types on the Hubble system and were then converted to numerical equivalents. The distributions therefore retain the psychological bias against intermediate classes and appear to jog up and down. Note that although both de Vaucouleurs' "*T*" types and HG "*t*" types have the same scale (i.e., a difference of 2 is equal to a difference of 1 Hubble class), they are offset; an Sb is equivalent to $T = 3$ but $t = 5$.

Morphological types for such a sample are uncertain at best, since the range in sizes and distances results in a large variation in *resolution*, even if the plate material is homogeneous. It is not uncommon to find differences of a class or two between the types given in GH and other papers, such as Kennicutt, Bothun, and Schommer 1984, hereafter KBS), but the differences appear to be more random than systematic. Nevertheless, for this study it is only important that the classifications be *internally consistent*, since the purpose here is to look for *differences* between gas-poor and gas-rich galaxies in the sample. Furthermore, this comparison will be made for galaxies in the same cluster, and thus at the same distance (and resolution), which reduces the chief source of systematic error.

A galaxy's position in the cluster is specified by its distance from a cluster center (determined by GH) divided by the Abell radius r_A. Because most of the H I–deficient galaxies are found with $r/r_A < 1$, the sample studied here has been subdivided into $r > r_A$ and $r \leq r_A$. Further subdivision would be desirable, but the numbers of galaxies in different morphological type bins become unattractively small.

The crucial quantity, the deficiency factor *Def*, is described in detail in HG. Basically, *Def* is the $\log_{10}$ (M_H observed/M_H expected), where the "expected" H I mass is derived from a sample of isolated spirals of the same morphological type and optical diameter. Most measurements of $Def > 0.3$ (a factor of 2 low in H I mass) are likely to be real, but, to be conservative, the "deficient" sample used here has been defined by $Def \geq 0.48$. In fact, the analysis that follows was carried out with other values of the *Def* that separated H I–deficient from H I–normal. The results were found to be insensitive to the value chosen. (In this paper, the terms "H I–deficient" and "gas-poor" are used interchangeably; similarly, "gas-rich" is equivalent to "H I–normal". This shorthand terminology has the disadvantages of [1] hiding the fact that an H I–normal Sc galaxy may have lost more total gas than an H I–deficient Sa, since the absolute gas content of the former is, on average, much larger; and [2] ignoring the possibility that molecular hydrogen may account for a significant fraction of the gas [Kenney and Young 1985], i.e., some galaxies may not be as gas-poor as their H I deficiencies indicate.)

Table 1 presents the four relevant distributions for galaxies in each of the nine clusters. First and second are the distributions of morphological types for all galaxies (independent of *Def*), given separately for $r > r_A$ and $r \leq r_A$. Third and fourth are the same distributions but only for those galaxies with $Def > 0.48$ (including a few cases where lower limits of $Def > 0.35$ were given). These distributions form the data base for the following analysis.

TABLE 1

MORPHOLOGICAL TYPE DISTRIBUTIONS

Cluster	HG Type 3	4	5	6	7	8	9	10	Total
				$r > r_A$					
Abell 262	3	2	13	5	10	1	16	5	
Abell 1367	5	4	8	0	5	2	0	0	
Abell 1656	4	7	16	3	13	1	1	1	
Abell 2147	1	2	7	2	8	0	0	0	
Abell 2151	1	1	8	2	8	0	0	0	
Cancer	3	0	5	4	8	2	1	0	
Pegasus	6	3	21	0	25	5	7	2	
Virgo	6	1	7	3	16	3	4	0	
Z1400+0949	1	0	2	2	9	0	0	0	
Totals	30	20	87	21	102	14	29	8	311
				$r \leq r_A$					
Abell 262	2	4	8	0	7	1	2	1	
Abell 1367	5	1	7	3	2	0	1	0	
Abell 1656	4	2	6	5	0	0	0	0	
Abell 2147	1	3	6	3	1	0	0	0	
Abell 2151	2	2	8	6	1	0	0	0	
Cancer	0	2	5	2	4	1	0	0	
Pegasus	0	0	6	0	3	0	8	0	
Virgo	2	0	13	2	19	1	11	0	
Z1400+0949	0	0	5	2	8	0	2	0	
Totals	16	14	64	23	45	3	24	1	190
				$r > r_A$ and $Def \geq 0.48$					
Abell 262	0	1	1	0	1	0	0	0	
Abell 1367	1	1	0	0	0	0	0	0	
Abell 1656	2	1	0	0	1	0	0	0	
Abell 2147	0	0	0	0	0	0	0	0	
Abell 2151	0	0	0	0	0	0	0	0	
Cancer	1	0	1	0	0	0	0	0	
Pegasus	1	0	1	0	0	0	0	0	
Virgo	2	0	0	0	1	0	1	0	
Z1400+0949	0	0	0	0	0	0	0	0	
Totals	7	3	3	0	3	0	1	0	17
				$r \leq r_A$ and $Def \geq 0.48$					
Abell 262	2	2	2	0	1	0	0	1	
Abell 1367	4	0	3	0	0	0	0	0	
Abell 1656	4	0	4	2	0	0	0	0	
Abell 2147	1	2	3	0	0	0	0	0	
Abell 2151	0	0	1	2	0	0	0	0	
Cancer	0	1	2	0	0	0	0	0	
Pegasus	0	0	1	0	0	0	0	0	
Virgo	2	0	9	0	5	0	4	0	
Z1400+0949	0	0	0	0	0	0	0	0	
Totals	13	5	25	4	6	0	4	1	58

III. RESULTS: THE DISTRIBUTION OF MORPHOLOGICAL TYPES FOR GAS-POOR AND GAS-RICH SPIRALS

The first aim of this paper is to compare the distributions of morphological types of H I–deficient and H I–normal spirals. It is important to realize that the GH sample is not complete to a given flux in any wavelength; thus it would be of little use to compare it to any external sample selected according to this or other criterion. Fortunately, this difficulty can be averted by making only *internal* comparisons with the GH sample. Specifically, most of the GH spirals are not gas-poor; therefore their distribution in morphological type can be used as a template with which to compare the gas-poor subset.

Some caution is still necessary, since, as pointed out by GH, the gas-poor spirals are primarily found in the central regions of the clusters, $r < r_A$. Thus, if the morphological type distribution is a strong function of *radius*, a different type distribution for the gas-poor galaxies might reflect nothing more than their *position* in the cluster. The top panels of Figures 1 and 2 demonstrate that this is not a serious concern. The distribution of types for spirals with $r \leq r_A$ is compared in Figure 1 to those with $r > r_A$ for all nine clusters. In Figure 2 the same comparison is made for the subsample of five clusters that GH designate as showing a strong pattern of H I deficiency. In both cases the distributions for $r \leq r_A$ and $r > r_A$ are very similar; for the whole sample there is a marginal trend for the galaxies

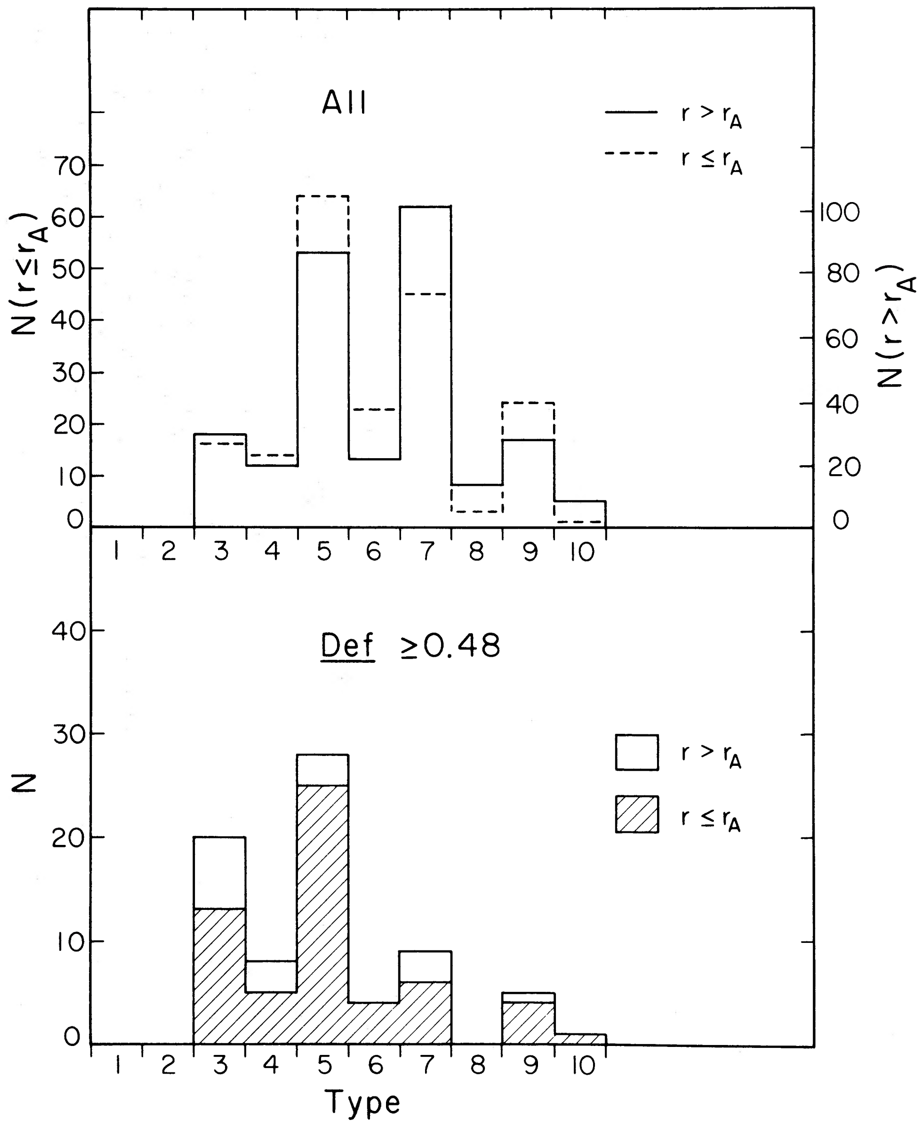

FIG. 1.—(*top*) Histogram distribution of the HG "*t* types" for galaxies in all nine clusters in the GH sample. The distributions for $r \leq r_A$ (where most of the H I–deficient galaxies are found) and $r > r_A$ are very similar, in contrast to (*bottom*) the type distribution of H I–deficient galaxies, which is significantly shifted toward earlier type galaxies.

with $r \leq r_A$ to be somewhat earlier in type, but for the five-cluster subsample the two distributions are indistinguishable.

It may be surprising that the distributions of *spiral* morphological types are not a strong function of radius; it is well known that there is a strong preference for early-type galaxies in regions of high galaxy density (Dressler 1980). That no such trend is evident among the spiral subclasses in this sample is, in fact, a result of strong selection effects that went into choosing the galaxies (Haynes and Giovanelli 1985). Since there is a paucity of late-type systems $t \gtrsim 7$ in the dense regions, GH and other workers preferentially obtained H I data for such galaxies. Thus, the $r \leq r_A$ subset includes a larger fraction of the late-type galaxies present than does the $r > r_A$ sample. As discussed in the Appendix, this bias is not very strong except for the very latest types, but it is present. The similarity $r \leq r_A$ and $r > r_A$ distributions is, then, a result of conscious effort, one that masks the actual gradient of morphological type.

Because the type distributions for $r > r_A$ and $r \leq r_A$ are so similar, a simple comparison can be made of the H I–deficient and H I–normal galaxies. The type distribution for H I–deficient galaxies (*Def* ≥ 0.48) is shown in the bottom panels of Figures 1 and 2. These distributions are markedly different from their parent distributions (any value of *Def*) shown in the top panel, in that the former are substantially shifted toward earlier morphological type. A Kolmogorov-Smirnov test confirms that these distributions are different from their parent distributions at greater than the 99% confidence level. Note from Figure 1 that even for the small number of H I–deficient galaxies with $r > r_A$ it appears that they are systematically of earlier type.

This trend is more striking when cast in differential terms. Figure 3 shows a histogram of the percentage of galaxies at a given type that are deficient in H I. For an Sa spiral with $r \leq r_A$ in either the nine- or five-cluster sample, there is a 80%–90% chance that the galaxy is H I–deficient. (Note from item [1] in the Appendix that this percentage could be somewhat lower

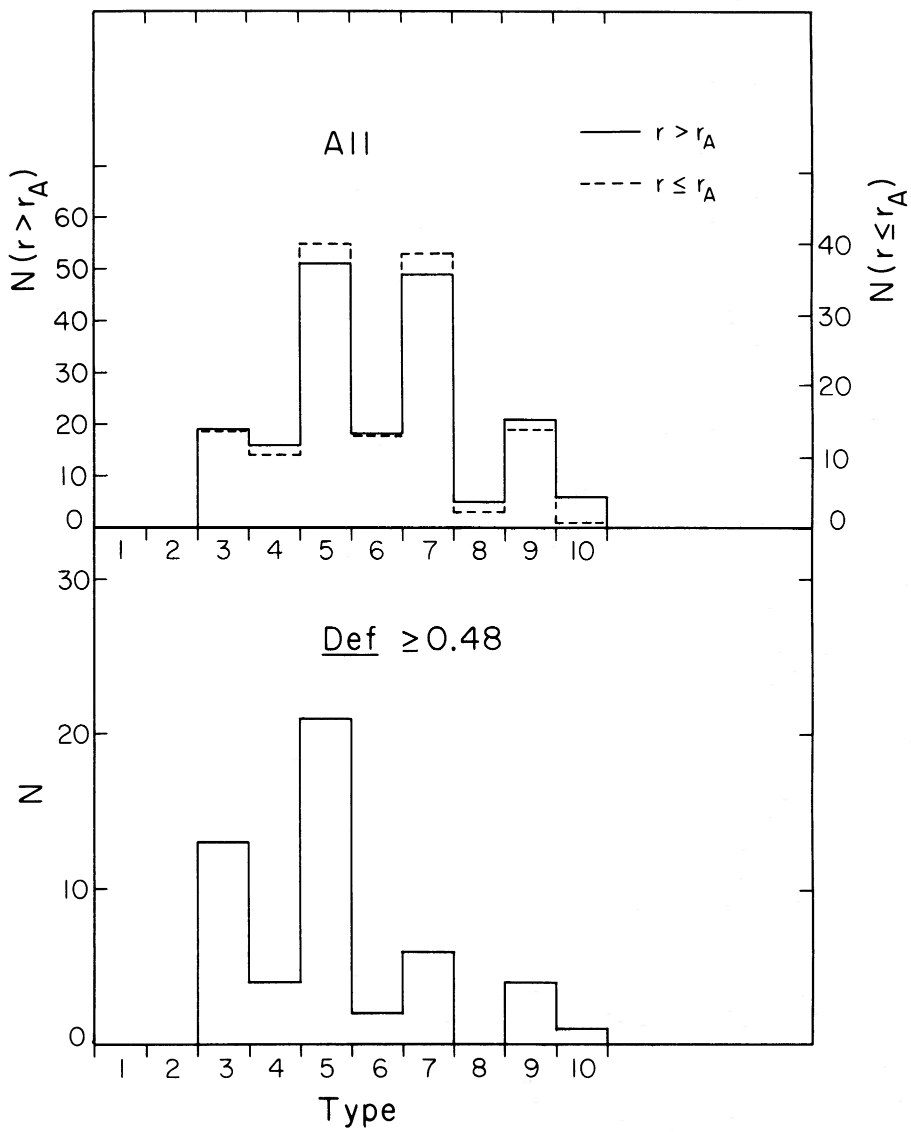

FIG. 2.—Same as Fig. 1 for the five "deficient" clusters, A262, A1367, A1656, A2147, and Virgo

due to the way the *Def* criteria is defined by HG, but is at least 60%–70%). This probability of H I deficiency drops rapidly to 40%–50% for Sb galaxies and levels off at about the 20%–30% level for the latest types. Even for the $r > r_A$ sample, where the incidence of H I deficiency is low, the earlier types are more likely to be gas-poor than the later types. (As mentioned above, an H I–normal Sc may actually have lost more gas than an H I–deficient Sa by the definition used here. It is assumed here that it is the *fractional* gas loss which is more important in the evolution of a spiral.)

This strong dependence of gas deficiency on morphological type is the first result of the present study. This trend has been noted for the Virgo spirals by Stauffer (1983) and Guiderdoni and Rocca-Volmerange (1984). Those who are familiar with this subject will recognize that certain selection effects (e.g., classification errors, projection effects, H I detection thresholds) might be partially or wholly responsible for this result. These are discussed in more detail in the Appendix, where it is concluded that selection effects are not a serious problem. The different morphological type distributions for gas-rich and gas-poor galaxies, then, appear to be a manifestation of one or more physical processes that deplete gas in cluster spirals.

IV. KINEMATICS: THE ORBITS OF GAS-POOR AND GAS-RICH SPIRALS

Two important clues to the nature of gas deficiency in cluster spirals are now apparent. First, as found by GH, the gas-poor systems are almost exclusively confined to within one Abell radius of the cluster center; and second, the gas-poor systems are much more likely to be early-type galaxies, as discussed above. It is reasonable to ask whether, in addition to these positional and morphological properties, gas-poor spirals have kinematical properties that distinguish them from spiral galaxies with normal H I contents.

Many studies have addressed this question by searching for a correlation of gas deficiency with radial velocity. If ram pressure stripping is responsible for H I depletion, one might naively expect that gas-poor spirals are likely to be those with high velocities. Even with the much improved and enlarged sample

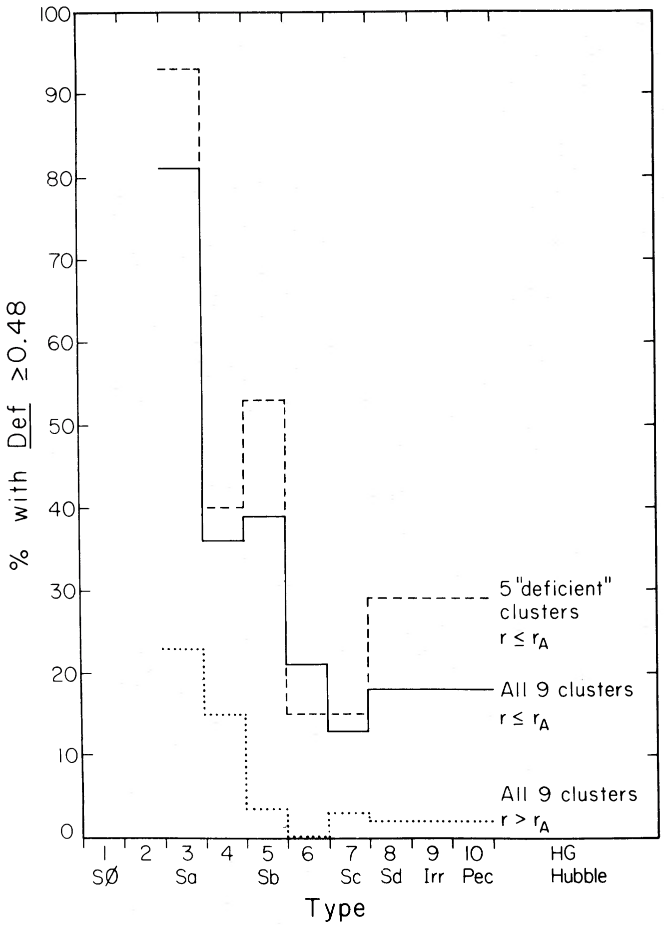

FIG. 3.—The fraction of H I–deficient galaxies in the samples as a function of HG or Hubble type. For both the whole sample of nine clusters and the five "deficient" clusters, a galaxy within one Abell radius of the cluster center is much more likely to be deficient in H I if it is an early type. The same is true for the relatively few H I–deficient galaxies found outside the Abell radius. The data show that very few H I–normal spirals of Hubble type earlier than Sb are found within one Abell radius of such clusters.

of GH, this test has failed to provide any evidence that this is the case. As GH discuss, their Figure 11 is little more than a scatter diagram, and, in fact, the effects of projection on the three-dimensional distribution of positions and velocities make this a poor diagram in which to look for such a correlation.

A combination of H I deficiency, velocity, and *position* can increase the power of the test, however. For example, for more-or-less radial orbits, a galaxy seen near the cluster core is likely to have a large component of its motion along the line of sight, but a galaxy at an Abell radius or further should have a small radial velocity even if its space motion is very large. Just the opposite is expected if the orbits are largely circular. Clearly, some information about the orbits is crucial in estimating the environmental effects, because a galaxy on a radial orbit at, say, 10 core radii from the cluster center will make its way into an area of much greater galaxy and gas density, while those on more circular orbits will not.

A simple test was made to investigate these issues. Using the samples of five "deficient" and four "normal" clusters, plots were made of the velocities of galaxies as a function of radius for different ranges of morphological type and *Def.* These data were then abstracted by calculating the velocity dispersion in radial bins that each contained at least 15 galaxies. Four such distributions of the run of velocity dispersion with radial distance are shown in Figure 4. Each point represents the median radial distance for galaxies in that bin and the velocity dispersion and (for some cases) the error in the dispersion, assuming Poisson statistics. The jagged appearance of these relations is likely to be the result of subclustering. Considering that subclustering and projection effects will act to weaken correlations present in true spatial coordinates, the trends discussed below are even more remarkable.

The bottom panel of Figure 4 shows that the velocity dispersion for gas-poor galaxies in the five "deficient" clusters falls dramatically from near 1300 km s^{-1} near one core radius to $\sim$700 km s^{-1} at $\sim$10 core radii. As pointed out by Kent and Gunn (1982), such a precipitous drop in velocity dispersion with projected radius is characteristic of *radial orbits.* On the other hand, the gas-rich (H I–normal) galaxies in the same sample show nearly the opposite effect, rising from an average value of $\sim$900 km s^{-1} at several core radii to $\sim$1300 at $\sim$10 core radii. A rising velocity dispersion such as this indicates more circular orbits than would be present in an isotropic distribution. With such large transverse velocity components, the gas-rich galaxies at a distance of several Abell radii would never penetrate into the core of the cluster.

These data suggest a straightforward, and perhaps too simple, interpretation. Spirals that are gas-poor are on radial orbits that have carried them into the very dense cores of the clusters, while those that are gas-rich have avoided the cores by virtue of large angular momenta. The projected velocity dispersion for the gas-poor systems reaches a high value near the center, consistent with the idea that ram pressure stripping is the mechanism at work.

The idea that the "stripped" spirals are on radial orbits is in disagreement with the work of Pryor and Geller (1984), who, in a detailed modeling of the Coma Cluster, concluded that highly radial orbits were ruled out. Although their criterion of what qualified as a stripped galaxy is not identical to the *Def* criterion, it is still important to ask whether the result presented here contradicts their conclusion. Kent and Gunn (1982) concluded that the radial profile in density and velocity dispersion in the Coma Cluster is consistent with an isotropic distribution of orbits, or one in which the orbits were highly radial, but not a composite model which makes the transition from one to the other at a radial distance of a few core radii. Pryor and Geller added to this the radial distribution of "stripped" spirals as judged by their ratios of H I mass to blue luminosity, concluding that the small fraction of stripped systems at $r > 2°$ is *inconsistent* with a distribution of orbits that is very anisotropic. However, the strength of this conclusion relies heavily on the assumption that all galaxies in the cluster have the same distribution in radial density and velocity. In fact, observations of velocity distribution functions in Coma (Kent and Gunn 1982) and Virgo (Huchra, Davis, and Latham 1984) strongly suggest that spirals do not share the kinematics of E and SO galaxies in these clusters. The models and their interpretation are greatly complicated if the degree of anisotropy is different for spirals and ellipticals, for example, or if the velocity dispersion or core radius or both are different for subsets of the sample. Furthermore, even if the above assumptions are granted, the lack of stripped spirals at large radii *can* be reconciled with an anisotropic distribution if spirals must penetrate to within $\sim$1 core radius in order to be "stripped." Although Pryor and Geller rejected this requirement as being

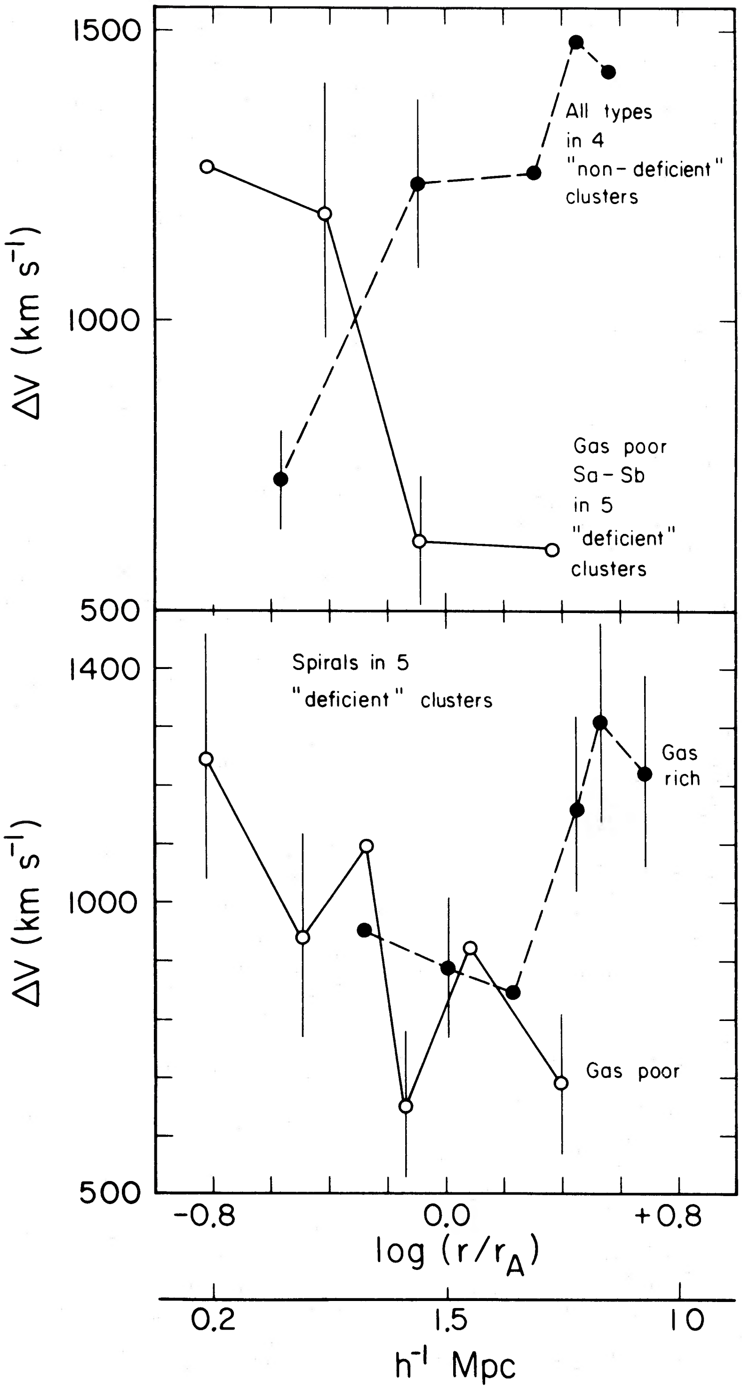

FIG. 4.—The run of velocity dispersion ΔV with the log of projected radius/Abell radius for spirals in the GH sample. (*bottom*) Comparison of the data for gas-poor (*Def* > 0.3) and gas-rich (*Def* < 0.15) galaxies in the sample of five "deficient" clusters (see Fig. 2). The points represent bins of at least 15 galaxies and are placed at the median radii for the bin. The error of the velocity dispersion is shown for some points. The sharp drop in ΔV with radius for the gas-poor spirals indicates that they are on highly anisotropic (radial) orbits, while the rising dispersion of the gas-rich galaxies indicates that their orbits are more isotropic or even circular. (*top*) An even more marked difference for gas-poor, early-type galaxies in the H I–deficient clusters compared to all spirals in the four "normal" clusters.

too strict, their own discussion emphasizes the difficulty of predicting the efficacy of such mechanisms as ram pressure stripping. It seems fair to conclude, therefore, that the model proposed here of a subpopulation of gas-poor spirals on very radial orbits is tenable. A detailed analysis like that done by Pryor and Geller would be far superior to the simple test provided in this paper, of course. Unfortunately, neither the structural nor the kinematic data provided by Kent and Gunn (1982) for the Coma Cluster is available for the other clusters in the present sample.

Referring back to § III, then, it is reasonable to ask: Is this the cause of the morphological type dependence on H I deficiency? In other words, Are the early-type spirals on radial orbits while the late-type spirals have a more isotropic distribution? Here the data are not able to give a definitive answer. A plot like Figure 4 for galaxies of types 0–5 and 6–10 (all values of *Def*) was constructed. It showed that the velocity dispersion for the early types first falls with increasing radius, then rises again on the outside. This is consistent with a model wherein there is a population of early types that are gas-poor that are on radial orbits but also a more isotropic distribution of H I–normal, early-type galaxies at large radii. The run of velocity distribution for late-type galaxies is very noisy but basically flat, consistent with an isotropic distribution. This means that there are likely to be some late-type galaxies with radial orbits, but whether these are, in fact, the small number of gas-poor late types that are observed is impossible to determine, due to small number statistics. In summary, the data are consistent with a larger fraction of early-type galaxies on radial orbits than for late types, but any statement stronger than this cannot be supported.

Finally, in order to emphasize the difference in kinematics found for different populations, the two most disparate cases are shown in the top panel of Figure 4. The run of velocity dispersion for just the Sa–Sb, gas-poor spirals is contrasted to that of all spirals in the four clusters that show no marked pattern of H I deficiency. The remarkable rise in velocity dispersion for this latter group makes it completely obvious why, if environmental effects are responsible for H I deficiency, few gas-poor spirals are found in these clusters. It might be argued that many of these outlying spirals are not actually members of their clusters, hence the rise in velocity dispersion. This may be true to some extent but would do little more than provide a different reason why these spirals are immune to the disease of H I deficiency. In either case, it seems unlikely that the spirals in these clusters have been or will ever be in very dense regions of clusters.

That such a striking kinematic difference is found for groups of galaxies with different gas contents is strong evidence that some sort of environment-dependent mechanism is responsible.

V. IMPLICATIONS: IDENTIFYING THE MECHANISM OF H I DEPLETION

The observations that spirals deficient in H I are mainly found within one Abell radius and are usually early Hubble types moving with high space velocities on basically radial orbits support the idea that ram pressure (Gunn and Gott 1972) or turbulent viscous stripping (Nulsen 1982) are the mechanism for gas removal. Furthermore, the H I mapping of spirals in the Virgo Cluster (Van Gorkom, Balkowski, and Kotanyi 1984) shows that those spirals that are H I–deficient have very small H I disks, as would be expected for stripping by these mechanisms. More such data on the spatial distribution of H I gas will undoubtedly be very valuable in determining the cause of gas deficiency.

Although the data presented here are consistent with other gas-removal mechanisms, such as evaporation (Cowie and Songaila 1977) or star formation by tidally induced shocks (Icke 1985), they do little to confirm these alternative models. It is proposed, then, that the first-order effect is simply that spirals must be on nearly radial orbits if they are to pass within 1–2 core radii of the cluster center, where ram pressure stripping is likely to be important. This is, of course, consistent with the falling velocity dispersion with radius found in § IV for the gas-poor galaxies. The fact that the gas-rich galaxies actually have a rising dispersion can be thought of as the result of an initially isotropic distribution whose radial orbits have been depleted, but it could also be a sign that galaxies on the outsides of clusters have received additional angular momentum from tidal torques on supercluster-size mass scales.

The dependence of H I deficiency on morphological type might arise simply if the distributions of orbits for early types is more anisotropic than for later types. Again, this might be expected if the early-type galaxies participated in the initial collapse of the cluster, but later types, which formed preferentially in the lower density, outer regions, fall in much later from great distances,[1] and are thus more likely to have their orbits isotropized by tidal torquing. As mentioned in § IV, the present data are unable to confirm such a relation of orbit isotropy and morphological type, so it may be that a radial orbit is a necessary but not sufficient condition for stripping a spiral galaxy. In particular, gas pressure in the disk of a late-type spiral is several times higher than in an early type, on average, which means that any dynamical form of gas removal will exhibit a type dependence unless the stripping mechanism is overwhelming. This means that the requirement for anisotropy may be even more severe for a late-type spiral, requiring that it pass even closer to the cluster center if it is to be stripped. Of course, if the conditions are only marginal, not even a pass through the cluster center may be sufficient to strip an Sc, even though an Sa might be easily stripped. This suggestion that late-type galaxies might be harder to strip was first made by Gisler (1979) on the basis of a theoretical expectation that higher star formation rates lead to a rapid replenishment of the interstellar medium.[2] Kent's (1980) hydrodynamic treatment of stripping suggests other possible explanations of why gas-rich systems might be more resistant to ram pressure by a hot intracluster gas. Furthermore, the survival of star-forming galaxies in dense, high-redshift clusters implied by the photometric observations of Butcher and Oemler (1985), and confirmed spectroscopically by Dressler, Gunn, and Schneider (1985) for Cl 0024+1654, could be taken as evidence that spirals in the past were more resistant to stripping due to higher gas contents for all types.

[1] The suggestion that gas-rich spirals, falling in for the first time to the dense cluster environment, are the likely victoms of stripping has also been made by Guiderdoni and Rocca-Volmerange (1984), based on their study of Virgo spirals.

[2] Gisler (1980) later argued that observational evidence contradicted his theoretical predictions, but he neglected the possibility of *a priori* segregation of morphological types. For example, if bulge-dominated spirals were preferentially formed in dense regions, these would necessarily become the ancestors of S0 galaxies. Gisler should only have concluded from his observations that ram pressure stripping was *by itself* insufficient to turn a typical population of spirals into a typical population of cluster S0's. His predictions concerning the ease of stripping as a function of gas replenishment rates could still be valid.

Whether the dependence of H I deficiency arises because of different orbits for early- and late-type spirals or as the consequence of ease of stripping, the observation that early-type galaxies are being stripped more frequently than late types may explain why the population of S0's in rich clusters is skewed toward large bulge systems. If large bulge spirals are, at any epoch, more gas-poor than their small bulge counterparts (for example, due to more rapid internal time scales for gas exhaustion by star formation) or have more anisotropic orbits, these would be the likely ancestors of S0's, in agreement with the observations.

It might even be possible to explain the small but significant number of H I–deficient galaxies at $r > r_A$ as those that fell through the cluster core and were returned to large distances. This speculation is particularly appealing because, as shown in Figure 3, these galaxies also have bias toward early morphological type.

In a recent discussion of the molecular gas content of spiral galaxies, Kenney and Young (1985) present CO luminosities which indicate that the *molecular cloud component* of a few Virgo spirals deficient in H I may be *normal.* They argue that this is the result expected for ram pressure stripping, since the higher densities of the molecular clouds make them more resistant to sweeping. Confirmation of an unusually high ratio of CO to H I luminosity for H I–deficient spirals in other clusters would strengthen the case that ram pressure stripping is the cause of H I deficiency.

The virtues of this simple picture of ram pressure stripping are obvious, but some observations remain difficult to interpret. For example, KBS find that the distribution of Hα equivalent widths $W_{H\alpha}$ for spirals in the Cancer, Coma, and A1367 Clusters is very similar to that of field spirals, leading them to conclude that (1) field and cluster spirals have similar rates of star formation (see Table 2 of KBS), and (2) H I content and $W_{H\alpha}$ are poorly correlated for their sample. In other words, although the H I observations indicate a marked difference in gas content for field and cluster spirals, the rates of star formation do not scale simply with the H I deficiency. This, of course, might indicate that the molecular gas component is largely intact. Although one might conclude from their data that star formation in H I–deficient galaxies is more often anemic than robust, the data do not support a simple connection of stripping H I deficiency, and anemic star formation.

Furthermore, the idea that ram pressure stripping of early-type spirals is responsible for the S0 populations in clusters must be reconciled with Burstein's (1979) claim that S0 galaxies possess a thick disk not found in spirals. Considering that most S0 galaxies are found outside dense cluster environments and that their properties are similar to cluster S0's, it may be more reasonable to conclude that stripped spiral galaxies remain, by and large, spirals.

As mentioned earlier, stripping by ram pressure or by evaporation are certainly not the only mechanisms that could result in H I deficiency, and it is likely that the others could produce the morphological type distribution found here. For example, if the earlier type galaxies have been resident since birth (or merely for a longer time) than the later types, which presumably fell in from outlying regions of lower density, then these early types will have been subjected to more numerous interactions and longer contact with the high-pressure intracluster medium. Star formation rates may have been enhanced (Bothun and Dressler 1985), hastening the evolution of these galaxies to a dormant state. A rather different mechanism, shutting off infall in dense environments (Larson, Tinsley, and Caldwell 1980; Gunn 1982), would have similar effects.

Finally, one cannot yet dismiss the possibility that H I deficiency in early-type galaxies results from very early environmental influences that limited the reservoir of H I for the early-type galaxies resident in the dense regions but left outlying later types unaffected. In this case, the H I deficiency and anemic star formation for early types would be the result of a birth defect, highlighted at the present epoch by the infall into the clusters of later type galaxies which were born in an environment more like that of field galaxies. In all these additional mechanisms, a correlation of gas deficiency with orbit anisotropy would simply reflect the mechanism's dependence on local galaxy density.

VI. CONCLUSIONS

Using the GH catalog, strong correlations have been found between the gas deficiency of cluster spirals, their morphological types, and their kinematics. Early-type galaxies are much more likely to be gas poor, and gas-poor galaxies are likely to be on radial orbits that carry them close to the cluster core. These correlations do not seem to be the result of selection effects, but instead appear to be a signature of whatever process is responsible for gas depletion.

A simple interpretation of the above data is that early-type spirals are both easier to strip, due to lower gas pressures in their disks, and on elongated orbits that carry them into regions of high galaxy and gas density. Although a number of mechanisms may affect the removal of the disk gas, ram pressure remains the most straightforward explanation.

The author gratefully acknowledges useful discussions with Martha Haynes, Riccardo Giovanelli, Margaret Geller, Rob Kennicutt, Jim Gunn, and Greg Bothun. Special thanks go to Jeremy Goodman and Paul Schechter for suggesting the investigation of orbital parameters, to Basil Katem for assistance with the data handling, and to Maria Anderson for help with the manuscript.

APPENDIX

POSSIBLE SELECTION EFFECTS THAT COULD RESULT IN A CORRELATION OF MORPHOLOGICAL TYPE WITH H I DEFICIENCY

Does the observed correlation of H I deficiency and morphological type reflect characteristics of the data sample that have little to do with the physical mechanism of H I depletion? Some possible biases are here suggested and discounted.

1. HG calculated the *Def* criteria based on *detected galaxies only*. This presents a problem for the Sa ($t = 3$) class, since almost one-third of the Sa's were not detected (see their Fig. 4) but is unimportant for the other types. This means that the expected H I content is probably artificially high for this class, though Haynes and Giovanelli (1985) suspect that many of these objects are too distant to have been detected, in which case the bias may be quite small. The result of setting the expected H I level too high can be seen in the cluster data alone, as shown in Table 1 of this paper, where 7/30 Sa galaxies are H I–deficient for $r > r_A$, where

environmental effects are expected to be small. Correcting for this bias would drop the deficiency fraction of Figure 3 to 60%–70% in the worst case. Since only the one bin is affected, and the trend is not greatly altered, this bias does not qualitatively change the results of the present study.

2. The tendency for H I–deficient galaxies to be of early type may reflect nothing more than the well-known tendency for galaxies in denser regions to be of earlier types. One might expect, therefore, any sample of spirals in a dense region to be shifted to earlier types, when compared with a sample from a lower density environment.

As discussed in § III, this bias is not operating in the GH data sample, which, by design, has little or no morphological type segregation by radius, at least within the crude binning of $r < r_A$ compared to $r > r_A$.

3. The H I–deficient spirals may have been optically misclassified because of lower star formation rates, and comparison with "normal" spirals in order to estimate *Def* may be unreliable. For example, a large fraction of Sc galaxies may actually be gas-poor (in contradiction to Fig. 3) but appear too anemic to be classified Sc.

This bias probably runs the wrong way. An anemic Sc would likely be classified as an *earlier* type, and, because H I content (as distinguished from H I deficiency) is also a strong function of morphological type, such a galaxy might not look H I–poor. This would tend to increase the population of Sa "normal" H I galaxies, which is almost null. Furthermore, the end state of this wholesale conversion of Sc galaxies into gas-poor systems would probably result in a large population of *small bulge S0's*, few of which seem to exist (Dressler 1980). (Present data do not exclude the existence of some such systems, but they are not a dominant population in any cluster which has been surveyed.)

4. Earlier types like Sa may have a larger intrinsic and observational scatter in *Def* because their fractional gas contents are smaller than those of later types. If so, the fact that earlier types have the extreme values of $Def > 0.48$ may simply reflect this scatter.

If this were true, a search for H I–*overabundant* spirals would yield the same bias toward earlier types. Actually, the 31 galaxies for which $Def < -0.3$ in the nine-cluster sample have the same morphological type distribution as the entire sample. Even if the scatter in *Def* is larger for earlier type galaxies, it is still too small to affect the present data.

5. The Sa galaxies may be the only spirals that are actually in the central regions of the cluster, with later types belonging to a more extended halo population which is projected onto the cluster. If so, it could be that all spirals actually in the inner regions are gas-poor, regardless of morphological type. This last suggestion does not question the reality of the trend of gas deficiency with morphological type but merely seeks to dismiss it as the expected result if only the earlier types were actually in the dense environments.

This model can be ruled out by comparing the number of late-type galaxies inside and outside of r_A. Figure 4 of GH shows that the typical cluster was sampled out to $2–3r_A$, so that if the surface density of types Sc or later were relatively constant (i.e., projected galaxies would show no central concentration), there whould be at least four times as many late-type galaxies in the $r > r_A$ sample in order to achieve the required number of projections. Haynes and Giovanelli (1985) report that, at best, this might be the case for the latest types, $t \geq 8$; types 4–7 are more or less equally sampled for $r \leq r_A$ and $r > r_A$. The observed ratio of 1.6 for the $r > r_A$ and $r \leq r_A$ samples of these types is so low that projections should have little effect on the distributions. Apparently, then, the late types 4–7 (Sbc–Scd) are also resident in the central regions of the clusters (within an Abell radius), and this is the range over which the strong dependence of H I deficiency on morphological type is observed. (Note, however, that this does not necessarily imply that all these galaxies within an Abell radius penetrate into the *core* of the cluster. In fact, as discussed in § IV, the data suggest that they do not.)

The inability of these biases or artifacts of the sample to explain the steep dependence of H I deficiency on morphological type leads to the conclusions that: (1) with the possible exception of the very latest types, both early- and late-type spirals in the sample reside within an Abell radius of a cluster center; and (2) within this sample, early-type galaxies are much more likely to be gas-deficient than later types.

REFERENCES

Bothun, G. D., and Dressler, A. 1985, in preparation.
Burstein, D. 1979, *Ap. J.*, **234**, 435.
Butcher, H., and Olmler, A. 1985, *Ap. J. Suppl.*, **57**, 665.
Cowie, L. L., and Songaila, A. 1977, *Nature*, **266**, 501.
Dressler, A. 1980, *Ap. J.*, **236**, 351.
Dressler, A., Gunn, J. E., and Schneider, D. P. 1985, *Ap. J.*, **294**, 70.
Giovanelli, R., and Haynes, M. P. 1985, *Ap. J.*, **292**, 404 (GH).
Gisler, G. R. 1979, *Ap. J.*, **228**, 385.
———. 1980, *A.J.*, **85**, 623.
Guiderdoni, B., and Rocca-Volmerange, B. 1985, in *ESO Conference and Workshop Proceedings*, No. 20, *The Virgo Cluster of Galaxies*, ed. O.-G. Richter and B. Binggeli (Munich: ESO), p. 81.
Gunn, J. E. 1982, in *Astrophysical Cosmology: Proceedings of the Vatican Study Week on Cosmology and Fundamental Physics*, ed. H. A. Brück, G. V. Coyne, M. S. Longair (Rome: Specola Vaticana), p. 233.
Gunn, J. E., and Gott, J. R. 1972, *Ap. J.*, **176**, 1.
Haynes, M. P., and Giovanelli, R. 1984, *A.J.*, **89**, 758 (HG).
———. 1985, private communication.
Huchra, J. P., Davis, R. J., and Latham, D. W. 1984, in *Clusters and Groups of Galaxies*, ed. F. Mardirossian, G. Giuricin, and M. Mezzetti (Dordrecht: Reidel), p. 79.
Icke, V. 1985, *Astr. Ap.*, **144**, 115.
Kenney, J. D., and Young, J. S. 1985, in *ESO Conference and Workshop Proceedings*, No. 20, ed. O.-G. Richter and B. Binggeli (Munich: ESO), p. 165.
Kennicutt, R. C., Jr., Bothun, G. D., and Schommer, R. A. 1984, *A.J.*, **89**, 1279 (KBS).
Kent, S. M. 1980, Ph.D. thesis, California Institute of Technology.
Kent, S. M., and Gunn, J. E. 1982, *A.J.*, **87**, 945.
Larson, R. B., Tinsley, B. M.,and Caldwell, C. N. 1980, *Ap. J.*, **237**, 692.
Nilson, P. 1973, *Uppsala General Catalog of Galaxies* (Uppsala Astr. Obs. Ann., Vol. **6**).
Nulsen, P. E. J. 1982, *M.N.R.A.S.*, **198**, 1007.
Pryor, C., and Geller, M. J. 1984, *Ap. J.*, **278**, 457.
Sandage, A., and Tammann, G. A. 1981, *A Revised Shapley-Ames Catalog of Bright Galaxies* (Washington: Carnegie Institution of Washington).
Stauffer, J. R. 1983, *Ap. J.*, **264**, 14.
Van Gorkom, J. H., Balkowski, C., and Kotanyi, C. 1984, in *Clusters and Groups of Galaxies*, ed. F. Mardirossian and M. Mezzetti (Dordrecht: Reidel), p. 261.

ALAN DRESSLER: Mount Wilson and Las Campanas Observatories, 813 Santa Barbara Street, Pasadena, CA 91101-1292