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GALAXY MORPHOLOGY IN RICH CLUSTERS: IMPLICATIONS FOR THE FORMATION AND EVOLUTION OF GALAXIES

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ABSTRACT

A study of the galaxy populations in 55 rich clusters is presented together with a discussion of the implications for the formation and/or evolution of different morphological types. A well-defined relationship is found between local galaxy density and galaxy type, which, in agreement with previous studies, indicates an increasing elliptical and S0 population and a corresponding decrease in spirals with increasing density.

Three lines of evidence are presented which contradict the interpretation that these gradients in population result from the production of S0 galaxies when spirals are swept of their disk gas by an IGM. (1) The relation between density and morphological type is a very slow function of density, so that a significant percentage of S0 galaxies exists in regions where gas density and temperature are too low to effect removal of the gas from spirals by evaporation or ram pressure stripping. (2) The relation between density and morphological type is virtually identical in irregular clusters of low concentration which are presumably not yet relaxed, and regular, high concentration clusters which are thought to be relaxed, despite the expectation that S0 production by gas ablation from spirals should only be important in the latter. (3) The bulges and bulge/disk ratios of S0 galaxies are systematically larger than those of spiral galaxies in all density regimes. Since the tightly bound inner bulges should be unaffected by ablation, the dissimilarity in the bulge and bulge/disk distributions in all density regimes is inconsistent with the idea that most S0 galaxies result from the removal of disk gas from a spiral by ram pressure stripping or evaporation.

As an alternative to the hypothesis of spiral sweeping, it is suggested that the local density/morphological-type relation reflects the long time scale associated with the formation of the disk component of galaxies. If this time scale is comparable to or greater than several billion years, an increase in local galaxy density may slow or even halt the growth of the disk components. This could generally account for the large number of elliptical galaxies in very high density regions and the prevalence of spiral galaxies at very low densities.

The data also indicate a trend of increasing luminosity of the spheroidal component with increasing local density. This may be interpreted as evidence for: (1) relatively late formation of galaxies, (2) mergers, (3) a formation mechanism that is highly sensitive to density, or (4) phase coupling between the high-frequency (galaxy) and low frequency (cluster) perturbations in the early universe.

Subject headings: galaxies: clusters of — galaxies: evolution — galaxies: formation — galaxies: structure

I. INTRODUCTION

Morphological studies are no substitute for physics in the study of natural phenomena, but they often provide the foundations of comprehensive theories and can be powerful tools for evaluating hypotheses. Extragalactic astronomy has seen the development of many, sometimes elaborate, systems of classification of the types of galaxies, but as yet, only rudimentary connections can be made between these forms and the processes of galaxy formation. The purpose of this paper is to present new observations of clusters of galaxies which could prove as useful in the development of theories of galaxy formation and evolution as studies of star clusters were in the understanding of stellar evolution.

Basic to most systems of classification of galaxy types is the recognition of two fundamental components of galaxy structure: a more or less flat disk of stars (and often of gas and dust) and a generally spheroidal component. Most galaxies possess both structures (cf. Sandage 1961), but there are abundant examples of galaxies without a significant disk (ellipticals) and without a noticeable spheroidal component (some spirals and [perhaps] irregulars of the Magellanic Cloud type). Assuming that these two components reflect different formation mechanisms, their relative importance must be fundamental. Among disk galaxies themselves there exists a dichotomy

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between those rich in gas and dust and resulting star formation (spirals and irregulars) and those in which this activity is virtually absent (S0 galaxies). This difference can only be considered fundamental if there is no substantial evolutionary connection between spiral and S0 galaxies.

The contrast between the populations of the low-density field, largely spiral galaxies, and the densest regions of clusters of galaxies, largely composed of S0 and elliptical galaxies, is well known (see, e.g., Hubble and Humason 1931; Morgan 1961; Abell 1965; Oemler 1974). This has often been interpreted as evidence for the common origin of all galaxies coupled with the subsequent evolution of one type to another, as, for example, the development of an S0 after the removal of the gas from a spiral galaxy (see, e.g., Gunn and Gott 1972). The alternative is that the major differences are either native in the formation process or that they reflect evolution at a relatively early epoch (e.g., Sandage, Freeman, and Stokes 1970; Gott and Thuan 1976). The present work provides new observational evidence that serves as a tool to help assess the validity of these admittedly oversimplified alternatives, with the aim of providing empirical constraints for theories of galaxy formation and evolution.

II. THE DATA

A complete compilation and description of the data used in this study can be found in Dressler (1980).

In summary, photographic plates of 55 rich clusters of galaxies were obtained using the Las Campanas 2.5 m and to a lesser extent the Kitt Peak 4 m and Palomar 1.5 m telescopes. Most of the clusters were studied on 50 × 50 cm du Pont (2.5 m) plates with a plate scale of 10″.9 mm^{-1} and an area of 2.1 deg^2. The higher plate scale and lower contrast of the 103a-O emulsions offer a substantial improvement over previous work using Schmidt telescopes and enables accurate classifications out to a redshift of $z \sim 0.06$.

The 55 clusters were chosen by (1) redshift ($z \lesssim 0.06$), (2) richness ($N \gtrsim 50$), and (3) the requirement that they be substantially contained in a few square degrees of sky. The cluster redshift, if previously unknown, was determined from spectra of at least two cluster galaxies. The clusters in the sample are listed in Table 1.

The data reduction consisted in the determination of (1) positions, (2) approximate total and "bulge" magnitudes, (3) morphological types, and (4) ellipticities for each of the ~6000 galaxies distributed among the 55 clusters, as described in detail in Dressler (1980). In the present work only the most rudimentary classification scheme is used. Three types—elliptical, S0, and spiral + irregular, as defined in Dressler (1980)—are retained.

In addition to the program clusters, 15 plates photographically equivalent to the cluster plates, but taken at random sky positions, were obtained to determine the field galaxy contribution to the counts.

TABLE 1

CLUSTERS IN THE SAMPLE

No.	Name	z[a]	Tel[b]	N
1	A14	0 064	M	79
2	A76	0.038	D	73
3	A119	0.042	D	118
4	A151	0.053	D	105
5	A154	0.066	M	80
6	A168	0.045	M	106
7	A194	0.018	D	75
8	A376	0.047	M	120
9	A400	0.023	D	92
10	A496	0.036	D	85
11	A539	0.028	D	99
12	A548[c]	0.040	D	235
13	A592	0.062	D	61
14	A754	0.054	D	150
15	A838	0.051	D	62
16	A957	0.044	D	84
17	A978	0 053	D	69
18	A979	0.055	D	87
19	A993	0 053	D	103
20	A1069	0.063	D	48
21	A1139	0.038	D	64
22	A1142	0.036	D	60
23	A1185	0.035	P	44
24	A1377	0.051	P	52
25	A1631	0.048	D	139
26	A1644	0.049	D	145
27	A1656	0.023	D	247
28	A1736	0.048	D	170
29	A1913	0.053	D	88
30	A1983	0.046	D	124
31	A1991	0.059	D	61
32	A2040	0.045	D	111
33	A2063	0.034	D	115
34	A2151	0.036	D	157
35	A2256	0.060	M	88
36	A2589	0.042	M	72
37	A2634	0.031	M	132
38	A2657	0.041	M	84
39	0003−50	0.035	D	80
40, 41	0107−46, 0103−47 [d]	0.023	D	111
42	0247−31	0.021	D	48
43	0317−54	0.055	D	66
44	0326−53	0.058	D	164
45	0329−52	0.057	D	196
46	0410−62	0.017	D	67
47	0428−53	0.041	D	132
48	0559−40	0.049	D	116
49	0608−33	0.035	D	125
50	0622−64	0.027	D	98
51	1842−63	0.015	D	55
52	2048−52	0.046	D	233
53	2103−39	0.052	D	113
54	2345−28	0.027	D	95
55	2349−28	0.028	D	68
56	Centaurus	0.011	D	75

NOTES.—[a] Sources of redshifts given in Dressler (1980). [b] D = du Pont 2.5 m; M = Mayall 4 m; P = Palomar 1.5 m. [c] Possibly two clusters. [d] One cluster.

A median value of 8 galaxies deg^{-2} was obtained down to $m_v = 16.5$, in good agreement with the work of previous studies (Oemler 1974; Rainey and Abell 1977). On the other hand, the field sample, which is probably a combination of isolated galaxies and loose groups, was found to be 50% spiral + irregular, 35% S0, and 15% elliptical, which is markedly different from the values of ~80% S+I, ~10% S0, and ~10% E found in studies of nearby field galaxies (Sandage and Tammann 1979; Burstein 1979*a*). The reason for this discrepancy is well understood, however. Although the luminosity function falls off rapidly for galaxies brighter than M^*, these galaxies can be at large distances and still satisfy the magnitude limit for the present sample, $m_v < 16.5$. Because of the rapid increase in volume, a significant fraction (~50%) of counted field galaxies have redshifts $0.06 < z < 0.12$. Galaxies in this redshift range cannot be classified reliably. Since many distant spirals appear indistinguishable from S0 galaxies, it is not surprising that the spiral population counted here is substantially below the true value. The proportions of S+I, S0, and E galaxies are 63/24/13 for $m_v < 15.5$ and 70/18/12 for $m_v < 14.5$; these ratios are consistent with the above interpretation. The ratios 80/10/10 for the field are adopted in this paper; however, the proportions 50/35/15 are used to correct the present plate material for field contamination, since it is the visual impression and not the true population that matters in this application.

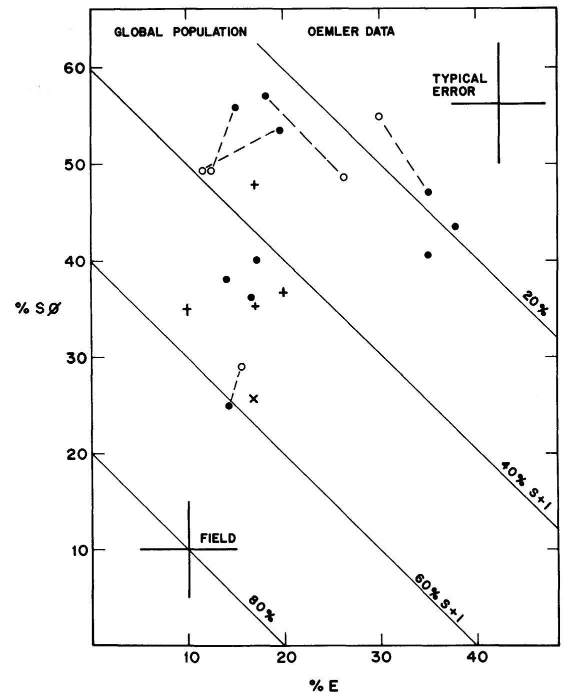


FIG. 1.—Global populations from previous studies. Key: *closed circles*, Oemler (1974) data; *open circles*, comparison between present work and clusters in common with Oemler; *plus signs*, Melnick and Sargent (1977); *cross-Virgo clusters*, Sandage and Tammann (1979).

III. GLOBAL POPULATIONS

Oemler (1974) made the first serious attempt to quantify the morphological content of clusters of galaxies. Using Palomar Schmidt plates, Oemler classified the brighter members of 10 of his sample of clusters whose distances were sufficiently small ($z \lesssim 0.04$).

Classifying down to about 3 mag below the brightest cluster member over a substantial area of the cluster, Oemler derived what is here referred to as the global population. Oemler's data are plotted in Figure 1 as the percent of elliptical versus S0 galaxies. Oemler noticed that these clusters fell into three representative groupings, which he called "spiral rich," "spiral poor," and "cD." The size of the error bars due to Poisson statistics immediately suggests, however, that the "clustering" is accidental. Also plotted in Figure 1 are the determinations of the same percentages from the present study for those clusters in common with Oemler's work. The agreement is good, considering the differences in magnitude range and area covered, and especially considering the difficulties Oemler says he encountered in working with small plate scale material.

To see if Oemler's suggested subgroups are real, the same diagram is shown in Figure 2 for 24 clusters in the present sample whose membership exceeds $N \gtrsim 100$, so that the population ratios are better determined. Corrections have been made for field galaxy contamination, but in all cases this correction is a few percent or less. It is interesting to note that the region covered by the points in the diagram agrees well with the range found in Oemler's study; however, no discrete groupings are evident. In view of the expected statistical errors, it would be difficult to recognize any subclustering in such a small area (only ~20% of the available space) even if it did exist. In Figure 3 the data for all the clusters are plotted. Although the associated errors are larger for the additional points, the same space again appears to be filled, and there are no strong concentrations or gradients. Because there is *no evidence for discrete types of clusters*, these groups should simply be considered, as Oemler intended, as boundaries of a continuous range of cluster population mixes.

IV. POPULATION GRADIENTS

a) *A Relationship Between Local Density and Population*

Since it has been well established that population gradients exist in clusters (see, e.g., Melnick and Sargent 1977, hereafter MS), the concept of global population is of questionable value. While it can be concluded that (1) variations in the populations of clusters are fairly restricted compared with the total range possible and (2) these overall populations are *in all cases different from that of the field*, the exact proportions of various types are sensitive to some

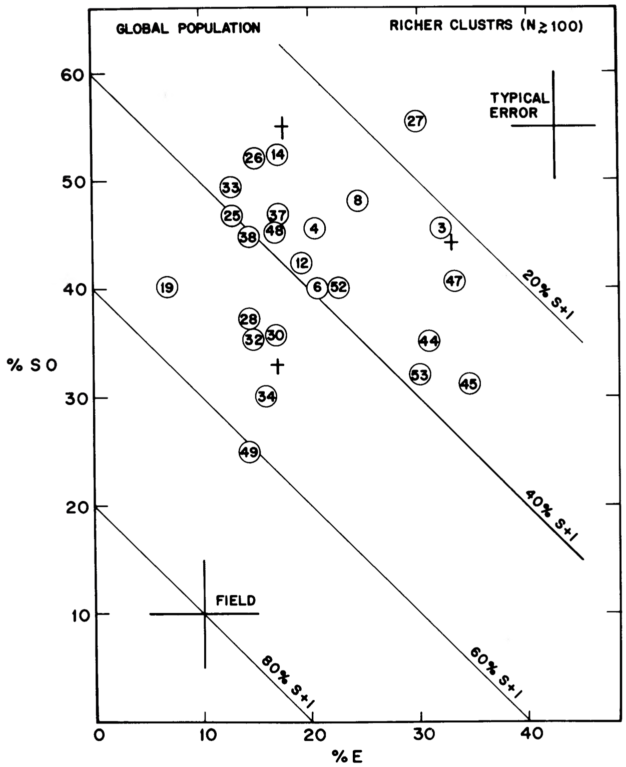


FIG. 2.—Global populations for the richer ($N \gtrsim 100$) clusters in this study, showing the absence of strong gradients or clustering into discrete subgroups.

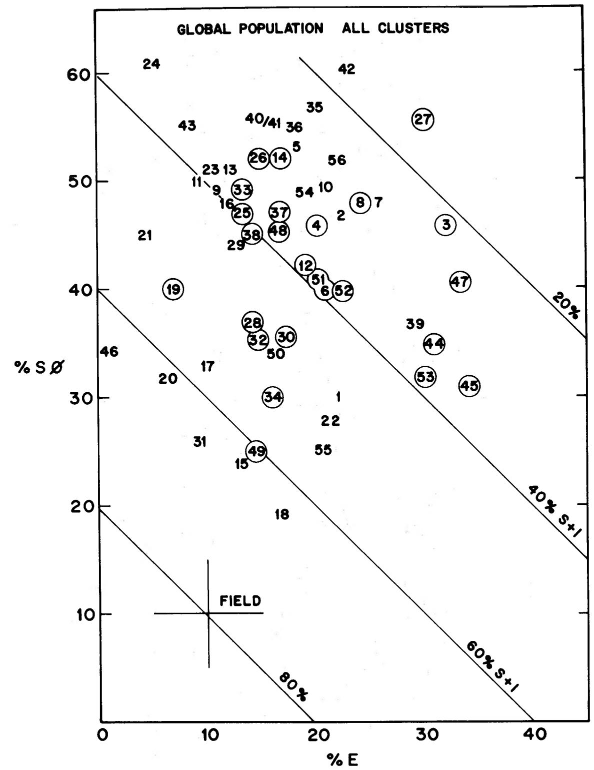


FIG. 3.—Global populations of all clusters in the sample.

degree on how far out in the cluster one counts. This in turn raises the problem of determining the outer boundary of a cluster, and because of the uncertainties in the field contribution, this is never well defined. Furthermore, some clusters seem to be embedded in an envelope of galaxies that connect several clusters (Gregory and Thompson 1977). Are these to be considered part of the cluster or not?

An obvious alternative is to study the gradient of the population and not the integral. MS have studied the change in cluster populations as a function of radius from the cluster centers and find a general increase in the proportion of spirals and a corresponding decrease in the proportion of S0 galaxies with increasing distance. Although radius seems a natural choice for the independent variable for regular clusters which are reasonably symmetrical and have well defined centers, it is not well suited to the majority of clusters which are more irregular. The centers of these clusters are poorly defined, and often the distribution of galaxies appears chaotic and lumpy. The high-density lumps scattered throughout these irregular distributions are similar to the dense cores of regular clusters, i.e., rich in S0 and elliptical galaxies and poor in spirals. This motivated a different approach in which the local density is used as the independent parameter. Since the density is a rather smooth function of the radius in the regular clusters, these two approaches will differ little in this case. However, in the case of the irregular clusters, the present method can better test if the same changes of population with density occur as in the regular clusters.

Hence a computer program was developed which found the 10 nearest (projected) neighbors to each of the $\sim$6000 galaxies in the sample, and after computing the area involved and correcting for field galaxy density, computed the local surface density in galaxies Mpc^{-2}. A correction was made for the different magnitude limits reached at different redshifts, as described in Dressler (1980), so that the final computed density reflects the number of galaxies $M_v < -20.4$ ($H_0 = 50$) in all cases. The galaxies were then sorted by type so that three separate number distributions as a function of local density were stored. That is, it was possible to determine what fraction of galaxies at a given local density were spirals + irregulars, S0's, or ellipticals.

Figure 4 shows the strikingly well-behaved relationship that results when the data for all galaxies in the 55 clusters are combined. There exists an excellent correlation between the local density and the populations of different galaxy types, qualitatively similar to one discussed by Oemler (1977). The relative proportion of S+I decreases monotonically with increasing density, and conversely, the proportions of S0 and E galaxies increase. Furthermore, the proportions of field galaxies, at the estimated projected density of the field, are very reasonable extrapolations of these relations. Figure 4 also contains estimates of the true space density at these projected densities, which

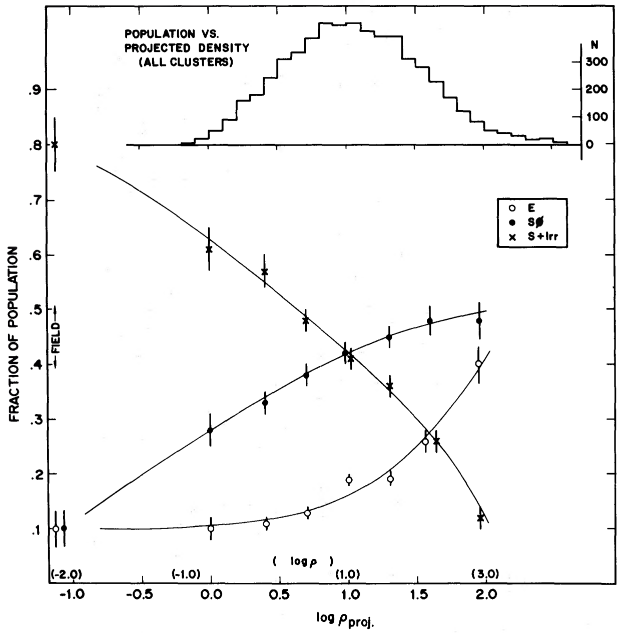


FIG. 4.—The fraction of E, S0, and S+I galaxies as a function of the log of the projected density, in galaxies Mpc^{-2}. The data shown are for all cluster galaxies in the sample and for the field. Also shown is an estimated scale of true space density in galaxies Mpc^{-3}. The upper histogram shows the number distribution of the galaxies over the bins of projected density.

demonstrates that the populations change smoothly with density over five orders of magnitude, from 10^{-2} to 10^3 galaxies Mpc^{-3}.

The advantage afforded by the use of density instead of radius as the independent parameter in the study of population gradients is illustrated in Figure 5. The population gradients in six moderately irregular clusters have been determined as a function of surface density and as a function of radial distance from the centroid of the galaxy distribution. The gradients are much more striking when the density is employed as the independent parameter, which indicates that the local density enhancements represent real physical associations and that populations are largely a function of local rather than global conditions.

The data of Figure 4 and subsequent diagrams have not been corrected for contamination by field galaxies, which constitute a fraction of the population running from about 40% at $\log \rho_{\rm proj} = 0.0$ to less than 5% at $\log \rho_{\rm proj} = 2.0$. Using the "observed" proportions 50/35/15 for S+I/S0 E, as discussed in § II, it can easily be shown that the field introduces a negligible error in the determination of the proportions at each density. The densities themselves have been corrected to reflect the density of the local region with the field removed.

It is interesting to note that the Oemler data fit well onto the relationship of Figure 4. The representative populations "spiral rich," "spiral poor," and "cD" are close to the proportions at projected densities of 0.5, 1.5, and 1.8, respectively.

Analyses of individual clusters indicate that the relation between population and density holds within individual clusters as well as, on the average, from cluster to cluster. Since, as will be shown, this relationship holds among clusters of different morphology (i.e., regular or irregular, concentrated or diffuse), it is clearly basic in the understanding of cluster populations.

b) *Discussion*

Spitzer and Baade (1951) first suggested that cluster S0 galaxies result when disk gas is removed from

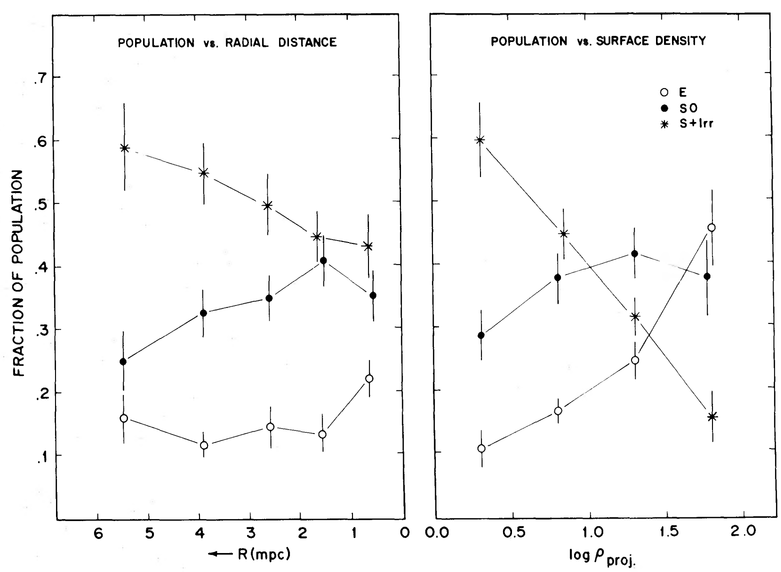
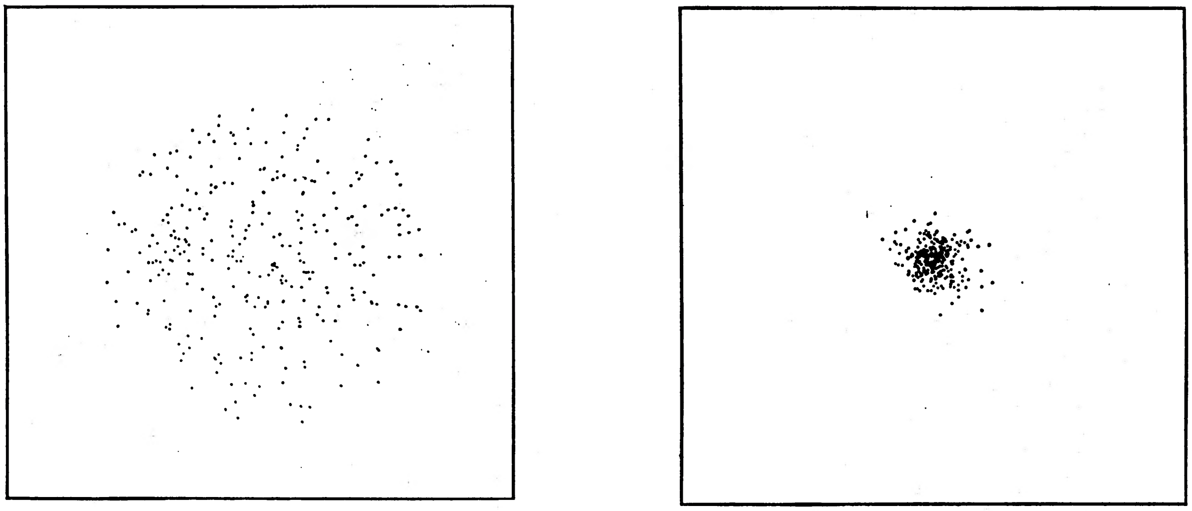
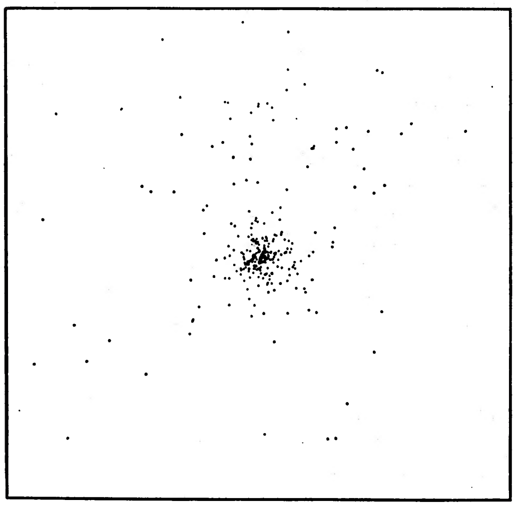


FIG. 5.—Population gradients in 6 moderately irregular clusters (A754, A993, A1736, A1983, 0326−53, 0559−40) as a function of radial distance from the cluster centroid and as a function of local surface density, showing the advantage of density as the free parameter.



(a) (b)



(c)

FIG. 6.—Peebles's (1970) collapse model for the Coma cluster showing the phases of (*a*) contraction, (*b*) violent relaxation, and (*c*) post-virialization equilibrium.

spirals by galaxy-galaxy collisions. Two other gas removal mechanisms, ram pressure stripping (Gunn and Gott 1972) and gas evaporation (see, e.g., Cowie and Songaila 1977), are more commonly cited as possible explanations for the greatly enhanced representation of S0 galaxies in rich clusters relative to the field (e.g., Bierman and Tinsley 1975; van den Bergh 1976; Oemler 1977; Melnick and Sargent 1977; Bahcall 1977*a*; Tytler and Vidal 1978; Butcher and Oemler 1978; Sullivan and Johnson 1978; Gallagher 1978; Bierman and Shapiro 1979; Strom and Strom 1979). Because of the popularity of stripping and evaporation as S0 production mechanisms, much of the following discussion is devoted to tests of these hypotheses using the present data. It is important to reemphasize that what is being tested is S0 production via gas removal from the disks of spiral galaxies by interactions with an *external* IGM, which shall be referred to as *sweeping* and not, for example, to gas exhaustion by star formation.

A review of sweeping processes is given by Gisler (1979). These mechanisms depend strongly on the density and, in the case of evaporation, the temperature of the intergalactic medium, which is responsible for the supposed removal of gas from spirals. Therefore, they should be much more important in regions of high density, such as the dense cores formed during cluster collapse and virialization.

The traditionally adopted picture of cluster collapse is described in studies such as Peebles (1970). Originally a bound cluster is an extended region where the average density at some time is above ρ_{crit}, the critical density necessary for the total energy of the region to be negative. Such a region is destined to secede from the general Hubble expansion and subsequently collapse. To the extent that the density enhancement is uniform, the cluster collapses essentially in free-fall with density increasing monotonically with time, until the density becomes sufficiently high and virialization (violent relaxation) occurs (see, e.g., Lynden-Bell 1967). The central density stabilized at this point, and subsequently the system is characterized by a high-density core and low-density envelope. Figure 6, reproduced from Peebles (1970), illustrates these three phases. The model is oversimplified in the sense that the original density enhancement will probably not be uniform, so that one expects a range of densities (subcondensations) in the contracting system and continuing infall of additional material onto a previously relaxed cluster.

Butcher and Oemler have identified irregular clusters with the stage of contraction and regular clusters, particularly those with a high central condensation of galaxies, with the post-virialization stage. They further argue that it is during the development of the high-density core that the spirals are swept of their

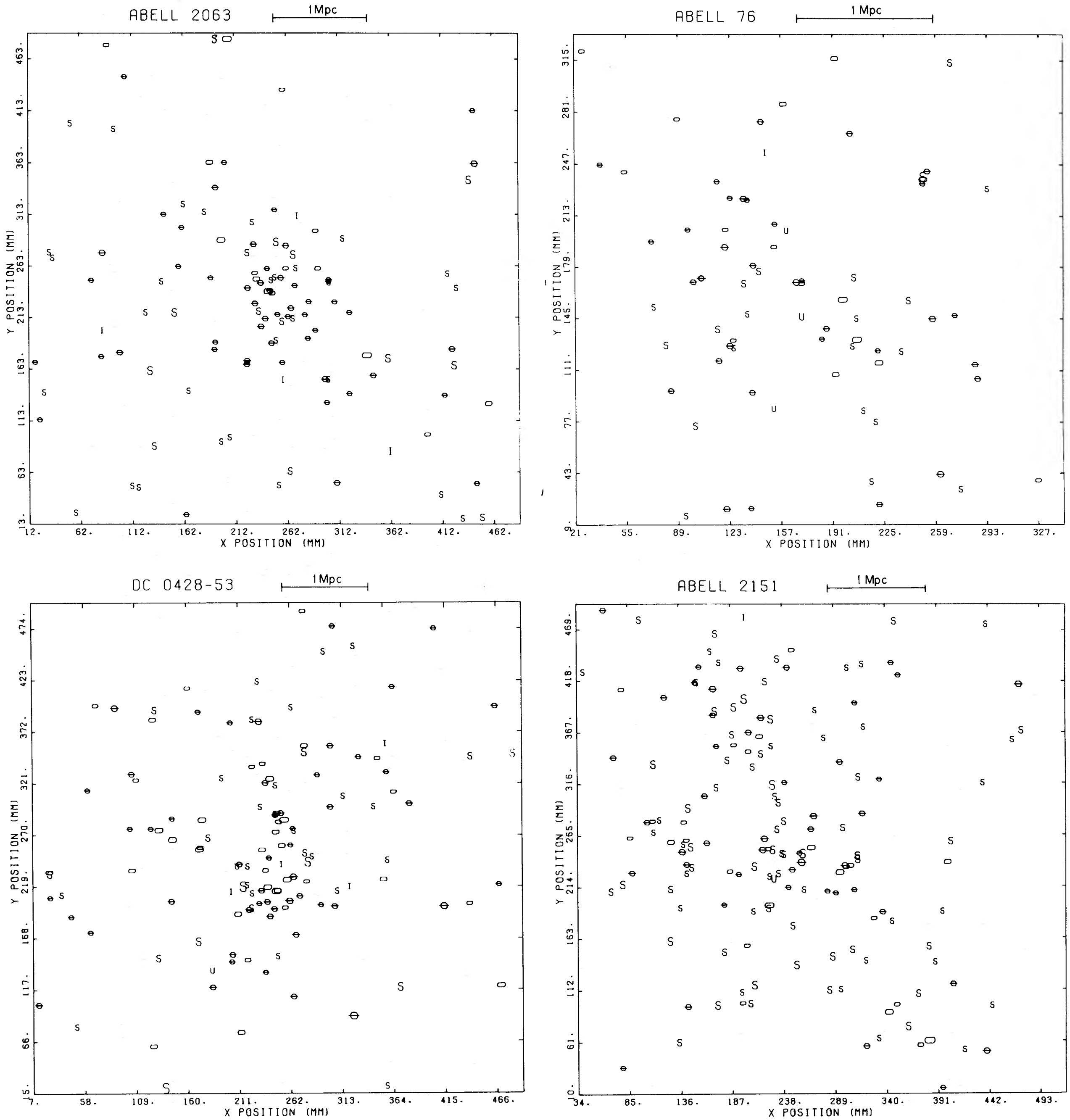


FIG. 7.—Maps of four sample clusters representing the high concentration, regular clusters (*left*), and low concentration, irregular clusters (*right*).

gas to form S0 galaxies, thus accounting for the noticeable deficiency of spiral galaxies in the regular clusters compared with the irregular clusters where central concentration is low.

To test this interpretation, the 10 highest concentration clusters and the 10 lowest concentration clusters of the present sample have been selected by the concentration criterion used by Butcher and Oemler (1978). Examples of each type are shown in Figure 7. If spirals are stripped in the dense cores of the rich clusters, one expects to see a substantial difference in the population gradients of the two types. Specifically, the clusters of high concentration should be depleted of spirals, and there should be no significant gradients in the low concentration, presumably prerelaxation clusters. Figures 8 and 9 plot the relationship between

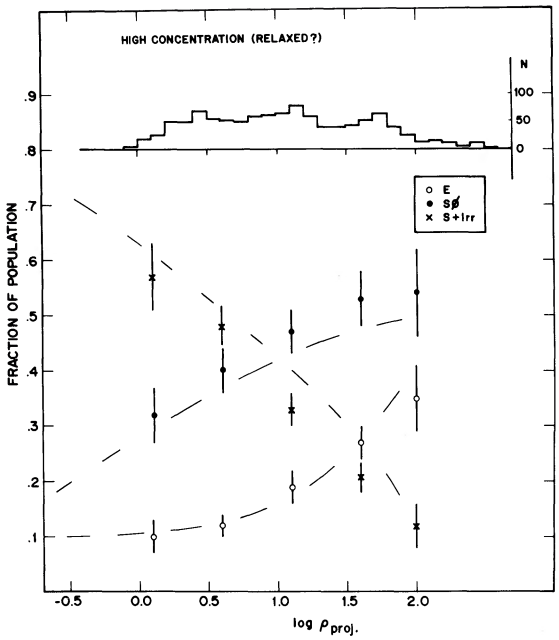


FIG. 8.—High-concentration clusters (A151, A539, A957, A1656, A1913, A2040, A2063, 0247−31, 0428+53, 1842−63).

FIGS. 8–10.—Same format as Fig. 4 for three subsamples of the data.

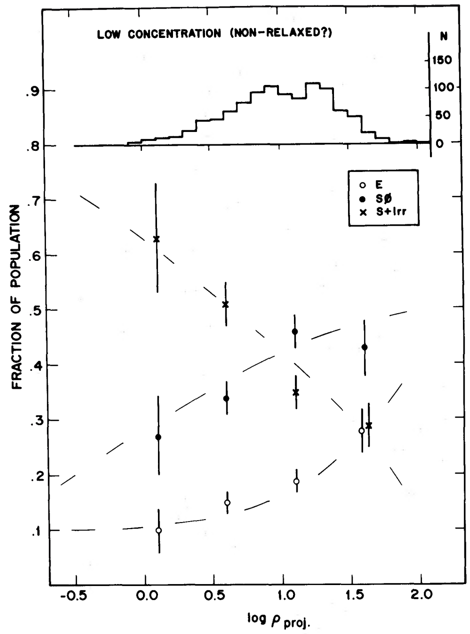


FIG. 9.—Low-concentration clusters (A76, A119, A168, A978, A979, A1644, A1736, A2151, 0030−50).

population and density for these two subgroups. There is no significant difference between the relationships defined in the two groups and that for all of the data (Fig. 4)! *The relationship between population and local density appears to hold without regard to the type of cluster involved.* This result contradicts the interpretation that spirals have been swept of their gas to form S0's in the high concentration clusters. In particular, there are abundant S0 galaxies in many irregular clusters, and in no part of any cluster is the spiral population as high or the S0 fraction as low as that of the field. If the idea of sweeping is to be kept, it would have to be argued that the process is common even in regions where the space density of galaxies, and thus presumably of gas, is 10^2–10^3 times lower than in the rich cores of the regular clusters. This is improbable, considering the strong density dependence of both the ram pressure stripping and evaporation hypotheses, and is completely untenable in the likely event that the gas is relatively cold and more-or-less comoving with the galaxies prior to relaxation. The fact that the population/density relation is so similar in these different types of clusters implies, on the contrary, that cluster populations are essentially independent of the dynamical global history of the cluster.

MS have also attributed the population gradients they found in clusters with strong X-ray emission to the ram pressure stripping of spiral galaxies by the hot cluster gas. The present sample of clusters includes eight strong X-ray emitters ($L_x \gtrsim 10^{44}$ ergs s^{-1}) which have been combined to form another population/density diagram (Fig. 10). Again, the same basic relationship between population mix and local density holds. There does seem to be a noticeable excess of S0 galaxies and a deficiency of spirals in comparison to the average relationship. This could be the contribution of stripping or gas evaporation, but the effect is small enough to make this difficult to verify and clearly only a perturbation on the normal trends. In any case, it is apparent that MS could have

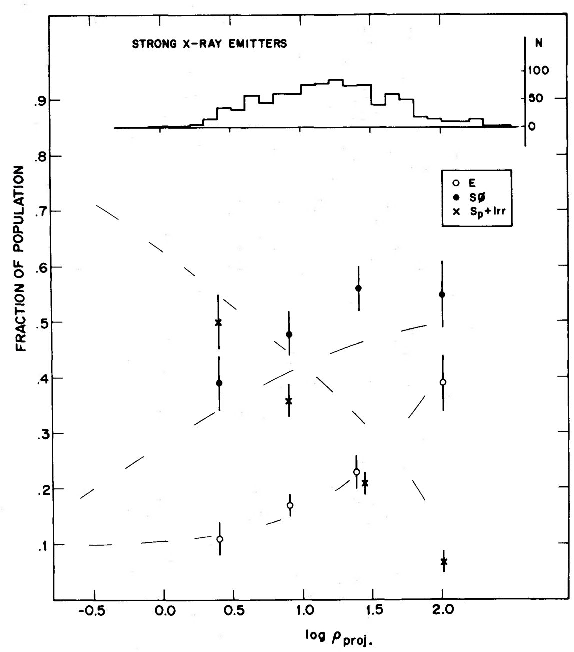


FIG. 10.—Strong X-ray emitters ($Lx \gtrsim 10^{44}$ ergs s^{-1}) (A119, A496, A539, A754, A1656, A2256, A2589, 2345−28).

found the same gradients in clusters that are 10–100 times less powerful as X-ray sources. The fact that only eight of the 55 clusters in this sample are strong emitters is good evidence that gas density and temperature vary greatly from cluster to cluster. Since the proportion of spiral galaxies and the X-ray flux both seem to be functions of cluster density, it is not surprising that a correlation appears to exist between X-ray emission and spiral content, as found by Bahcall (1977*b*) and Tytler and Vidal (1978). The relationship, however, is apparently *not* the result of the gas both emitting the X-rays and sweeping the spirals. Rather it is the high galaxy density, also noted by Bahcall (1977*a*), that seems to be the common cause of both effects.

c) *Cluster Evolution*

If the Butcher and Oemler interpretation that irregular and regular clusters exemplify pre- and post-virialization states of cluster evolution is correct, one should see very different density distributions in these types, as illustrated in Figure 6. Relaxed clusters should have a wide range of densities, while unrelaxed clusters, contracting at more-or-less uniform density, should have a narrower range. The number distributions as a function of density, seen at the top of Figures 7 and 8, support this interpretation. The low-concentration clusters have a small density range compared with the high-concentration clusters, although this is hardly surprising since the criterion of concentration selects for this.

The widths of the individual distributions are in each case similar to the combined distribution. For example, the high-concentration clusters do not have a wide range of densities because many clusters with small but different ranges are added together. The distribution in individual clusters is very broad, and the medians show surprisingly little variation.

Assuming, therefore, that the Butcher and Oemler interpretation of the dynamical state of a cluster is correct, one can make two interesting observations. One is that the majority of clusters, as evidenced by the density distribution on the top of Figure 4, are of the low-concentration type. Thus most of the clusters must be in the contraction phase, although in view of the relatively high density which has been reached in many, they are within a small fraction of a Hubble time of virialization. At first it seems an untenable interpretation that so many clusters have been caught "in the act" of collapse. It should be emphasized, however, that there is a strong bias to select only clusters relatively advanced in their evolution and now at high density, and to ignore "younger" clusters which presently have a density enhancement of only a factor of 2 or 3 over the field and occupy comparatively large regions of the sky. There has been, to this time, no systematic study like the Abell catalog of structures such as these, and their recognition is by no means trivial. As with the faint ends of luminosity functions, digging the last objects out of the noise is difficult but would be important for studying the spectrum of cluster-size perturbations in the early universe.

The second point concerns the evolutionary state of the X-ray clusters. The number-density histogram (top of Fig. 10) reveals that this subset includes, on the average, the densest of the clusters studied (see also Bahcall 1977*a*). Looking again at Peebles's models, it is very tempting to identify these clusters as those closest in time to virialization, when the average density peaks. At this point the gravitational potential well is deepest; galaxy and presumably gas density is high, and heating of the intracluster gas is maximized. The small number of strong X-ray emitting clusters in this sample is consistent with the virialization stage lasting a small but nonnegligible fraction of a Hubble time. In this interpretation one would place Figure 10 between Figures 8 and 9. An evolving cluster would have a frequency distribution of galaxies with density like that of Figure 8; the peak would move steadily toward higher density until it reaches maximum density at virialization. An X-ray cluster would presumably be at or near this phase. As the cluster becomes more distended again (Fig. 9) with a new halo of lower density, its potential well will become, on the average, somewhat more shallow, so that the X-ray flux may decrease. Whether or not a cluster would remain a strong X-ray emitter might depend on how much of the cluster remains at a sufficiently high density. The Coma cluster, for example, would remain a strong X-ray source because its overall density is unusually high.

Two facts indicate that this model of uniform initial perturbations collapsing coherently as isodensity clouds of galaxies is oversimplified. One is that even the contracting clusters show a range of densities greater than would be expected by random projection effects of a *uniform* distribution. Second, population gradients exist even in presumably relaxed clusters, although all such gradients should be erased in the virialization phase. Both of these observations suggest that there is a *range* of densities in the original perturbation. Since $T_{\mathrm{collapse}} \propto \rho^{-1/2}$, these early density differences grow as the cluster collapses, thus preventing the cluster from virializing all at once. Thus a very evolved cluster like Coma can have a continuous infall of galaxies and material which come from a region of smaller density enhancement. Strom and Strom's (1978*c*) study of the radii of elliptical galaxies in the cores and halos of rich clusters can be interpreted as evidence that many of these outer galaxies have not participated in a high-density collapse phase.

If the recent history of a cluster does not affect its population of morphological types, specifically, if spirals do not become S0 galaxies via sweeping in the cores of dense clusters, what, in fact, accounts for the relation presented here between population and local density? One possibility can be found in the model of cluster collapse discussed above. Since density differences in clusters grow monotonically with time from the beginning of collapse to the virialization stage, then the local density is uniquely related to the initial density perturbation and its evolution. That is, the dense regions today have always been more dense than their surroundings. Thus, if there is a relation between the type of galaxy formed and the density at formation or early evolution, this relation will be retained and will be especially obvious if most clusters have not yet virialized. The consequence of this for the relation between population and local density is explored in § VI.

d) *Summary*

There is a well-defined relationship between the local density of galaxies in a region of space and the representation of different morphological types. This relationship extends from the low-density field to the dense cores of clusters, some five orders of magnitude in space density. This, combined with the existence of S0 galaxies in substantial numbers in regions where the gas density and temperature are presumably too low to effect the ram pressure stripping or evaporation of gas from spirals, argues that most S0 galaxies are not created by such processes. The similarly of the relationship between population and density in irregular and regular clusters, which, following Butcher and Oemler, are identified as pre- and post-virialization stages, further supports the view that cluster populations are largely independent of later cluster evolution. Density distributions within the clusters studied imply that ~20–30% have reached the violent relaxation phase and suggest that clusters with strong X-ray emission may be those closest in time to this phase.

V. FURTHER EVIDENCE THAT S0 GALAXIES ARE NOT SWEPT SPIRALS

The Hubble sequence, from late-type spirals to ellipticals, is a sequence of ever increasing dominance of the spheroidal component or bulge over the disk. While Hubble (1936) considered S0 galaxies to be a transition from spirals to ellipticals, S0 production by spiral sweeping would place them on a branch parallel to that of the spirals.

Faber and Gallagher (1976), Sandage and Visvanathan (1978), and Burstein (1979*b*) suggest that field S0's have noticeably smaller disk/bulge (hereafter D/B) ratios than field spirals and point out that this runs counter to the hypothesis that most S0's are swept spirals.

To check this effect in rich clusters, in which domain sweeping and gas evaporation are expected to be most effective, the bulge light contribution has been estimated in each of the disk galaxies, as described in Dressler (1980). The bulges were compared at a bright isophotal level with a sequence of elliptical galaxies in the Coma and Hercules clusters selected from photometry kindly provided by Oemler (1978). In effect, an isophotal size of the bulge was determined using an approximately logarithmic scale 0–13. Assuming that the spheroidal components in the disk galaxies are like elliptical galaxies out to a much fainter isophotal level, one can estimate the total brightness of these components. (Or, even if this assumption is incorrect, spiral and S0 galaxies can be treated in a consistent manner.)

Figure 11 shows a comparison of the distribution of bulge "size," as determined from the comparison scale, for the different morphological types in 22 clusters with $0.035 < z < 0.055$. Since the tightly bound inner bulges will not be disturbed or altered when the gas is removed from the disk of a spiral, the bulge distributions of spirals and S0's should be very similar if S0 galaxies descend from typical spirals which have been swept. Clearly, the data show that they are not similar, as the S0 galaxies have systematically much larger bulges. Even in the strong X-ray emitting clusters, where one might expect sweeping to be important, there is a gross difference between the bulge distributions and S0's and spirals (Fig. 11).

Bierman and Shapiro (1979) have argued that after stripping, the disks of spirals "fatten up" in response to the loss of mass in the form of gas, adding luminosity to the spheroidal component. In fact, the gas content of an average spiral is less than 10% by mass (Roberts 1975), which indicates that the effect will, at best, be small and should certainly be negligible in a region where disk surface brightness is small compared with bulge surface brightness. Since the comparison made here is done in a region where the bulge clearly

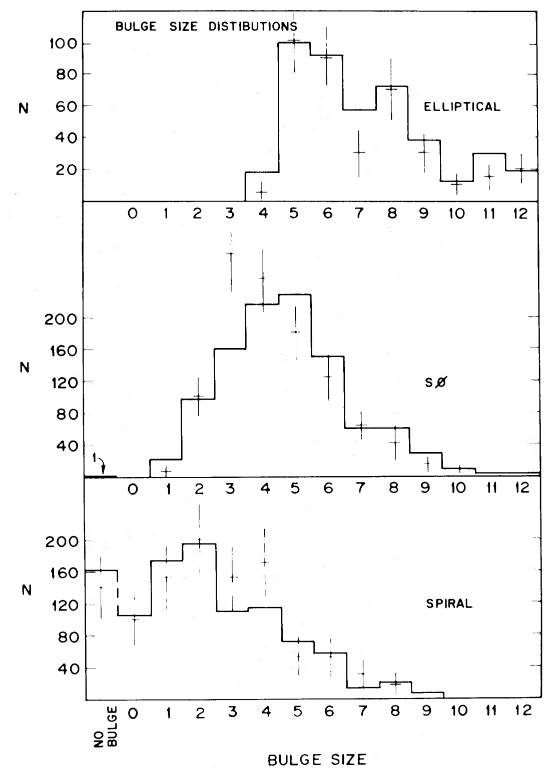


FIG. 11.—The number distributions (*bar histogram*) of bulge sizes for different morphological types for 22 clusters with $0.035 < z < 0.055$. Also shown is the renormalized distribution (*points with error bars*) of the subset of the 22 clusters which are strong X-ray emitters (A119, A496, A754).

dominates in both spirals and S0's, any additional contribution caused by alteration of the disk can be neglected.

The dissimilarity between the bulge distributions seems to argue quite strongly against the sweeping or gas evaporation hypotheses; however, there is a counterargument to consider. If the disks of spirals are allowed to fade some arbitrary amount, due to the cessation of star formation, for example, the small bulge spirals could drop out of this magnitude-limited sample, thereby accounting for the dearth of small bulge S0 galaxies. To check this possibility, the following experiment was performed. Each spiral galaxy was decomposed into a disk and bulge component, using the bulge and total magnitude estimates. The disk was faded 1 and then 2 mag, the total magnitude of the galaxy was then recomputed, and the galaxy deleted if it fell below the $m_v = 16.5$ limit. Figure 12 shows the comparison of the S0 and spiral bulge distributions after fading the spiral disks 0, 1, and 2 mag. (The spiral distribution has been renormalized so that the bright end, where completeness is assured since the bulges themselves are brighter than $m_v = 16.5$, matches that of the S0 distribution.)

It is obvious that at least a 2 mag fade, i.e., an 85% drop in luminosity, is required to bring the two distributions into agreement. If spirals are required to fade so substantially so as to remove the small bulge S0's from detection, one would expect an obvious difference in the luminosity functions of S0 and spiral galaxies. On the contrary, the luminosity functions of the two types, shown in Figure 13, are practically identical, a result consistent with the work of other authors (e.g., Tammann, Yahil, and Sandage 1979). Further evidence against the fading of spirals to form S0's can be seen by noting that the luminosity function of the spiral-rich Hercules cluster is virtually identical to that of the S0-rich Coma cluster (Oemler 1974). If spirals have to fade substantially in order to become S0's, then no present epoch spiral-rich cluster could evolve into a cluster like Coma.

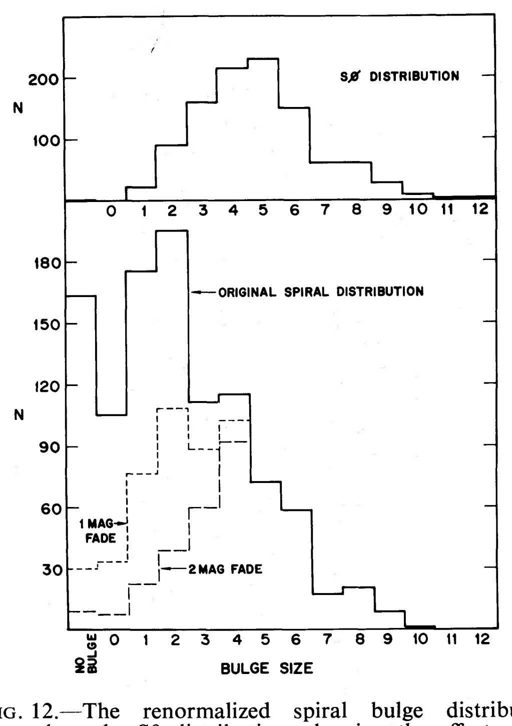


FIG. 12.—The renormalized spiral bulge distribution compared to the S0 distribution, showing the effect of incompleteness if the disks of the spirals are faded 1 or 2 mag.

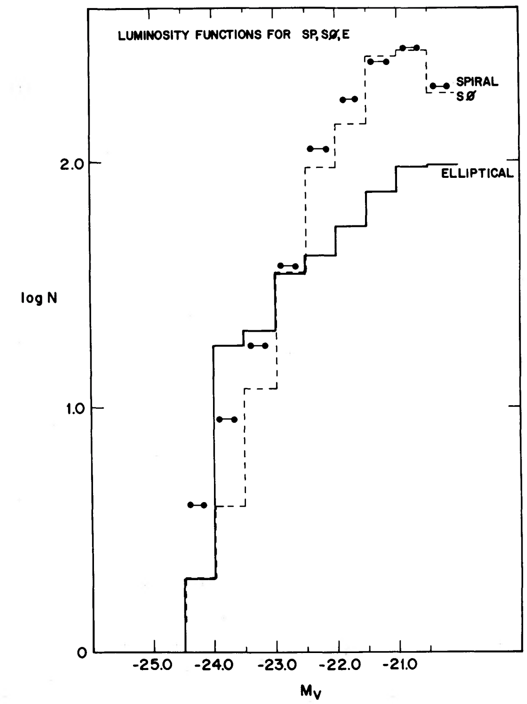


FIG. 13.—The luminosity functions for the galaxies which are treated in Figs. 10 and 11.

Internal extinction in the spirals and irregulars, which should average between 0.5–1.0 mag in the blue depending on inclination, has been ignored. Its effect cancels in the above discussion, since including extinction would shift the spiral luminosity function to higher luminosities but also increase, to the same degree, the amount of fading necessary to account for the differences in bulge distributions. It should be kept in mind, however, that the true spiral luminosity function is brighter than that of the S0 galaxies.

Consequently, it seems one can argue quite strongly, as in § IV, that most S0's are not swept spirals because the former have systematically larger bulges and bulge/disk ratios. To explain this difference, one would have to admit a fading of the disks of spirals which is ruled out by the luminosity functions.

The preceding arguments do not preclude the possibility that spirals may suffer environmental effects that result in an anemic spiral pattern (van den Bergh 1976) or a deficiency in gas compared with field spirals (Sullivan and Johnson 1978). Nor do the present data contradict the idea that S0 galaxies, at some point in their lifetimes, were spiral galaxies. These

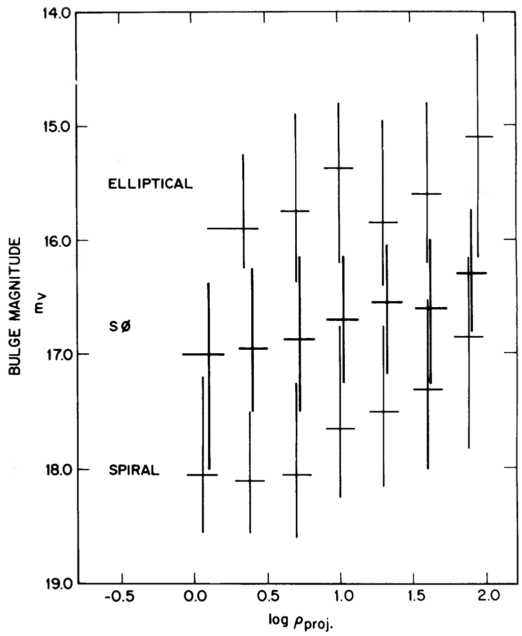


FIG. 14.—The bulge magnitudes as a function of the local projected density (see Fig. 4 and text). Displayed are the *medians* and *quartile points* of the binned number distributions in bulge magnitude.

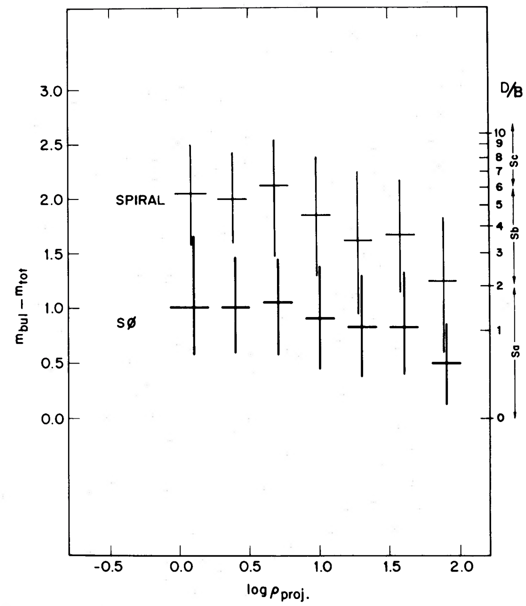


FIG. 15.—The quantity $m_{\text{bulge}} - m_{\text{total}}$, and a derived D/B estimator, as a function of the local projected density. Medians and quartile points are displayed.

large bulge systems may well have been early-type spirals when star formation was prevalent in their disks. Here it is argued only that the abundance of S0 galaxies in regions of low gas density and the dissimilarity of the bulge distributions of S0's and present epoch cluster spirals indicate that sweeping is not a primary factor in the formation or evolution of most S0 galaxies.

Figure 14 shows medians and quartile points of the distributions of bulge magnitudes for spiral and S0 galaxies as a function of the local density, presented in the same manner as Figure 4. It is clear that the dissimilarity of the bulge distributions is not a function of density, as might be expected if, for example, sweeping were the dominant production mechanism in high-density regions, but another process (e.g., formation) is responsible for the S0's in the field and low-density cluster environments. Both the spiral and S0 bulge sizes (and luminosities) seem to rise steadily with increasing density, but the difference between the two distributions is maintained.

Likewise, the D/B estimates computed with these data show a marked difference between spirals and S0 galaxies (Fig. 15). This is in agreement with the work of Burstein (1979*b*) who has found that field S0's have systematically smaller D/B ratios than field spirals. Gisler (1979) has predicted that in rich clusters, where ram pressure stripping or gas evaporation is expected to be more effective than in the field, the D/B ratios for the two types should be the same if stripping has gone to completion. He adds, however, that galaxies with a high star-formation rate, such as high D/B Sc galaxies, should be more resistant to gas removal, and thus, in regions where not all spirals have been swept, the large bulge Sa galaxies will be the progenitors of the S0 galaxies. But Figure 15 shows, on the contrary, that difference in D/B for the two types is *maintained* as a function of density. Furthermore, rather than the S0 D/B distribution shifting toward higher values in the high-density region in which sweeping is presumably complete (indicated by the small percentage of spirals), D/B ratios of spirals and S0's are both decreasing.

The possibility should be considered that the gradients in Figures 14 and 15 are due to a selection effect resulting from a magnitude limit, similar to that described earlier. That is, if the disks were whittled away by tidal encounters in the high-density regions, those systems which fell below the magnitude limit would drop from the sample. High D/B systems would obviously be affected most, producing the impression that the D/B ratios are decreasing with increasing galaxy density. Such tidal effects have been discussed at length by Strom and Strom (1978*a*, *b*). Again, however, a fading of the disks of approximately 2 mag is required to account for the total range in bulge or D/B as a function of density for the spiral galaxies. (This can be easily appreciated by comparing the total change in the spiral distribution alone to the difference, on the average, between the spiral and S0 distributions. The latter, as shown in Figure 12, requires a 2 mag fade.) But in the same manner as before, the luminosity functions for low and high-density regions are virtually identical, indicating that no such fading has occurred (Fig. 16). If anything, the spirals and S0's in the high-density regions are a bit brighter than their counterparts in regions of low density. Apparently, then, the gradient is real; larger

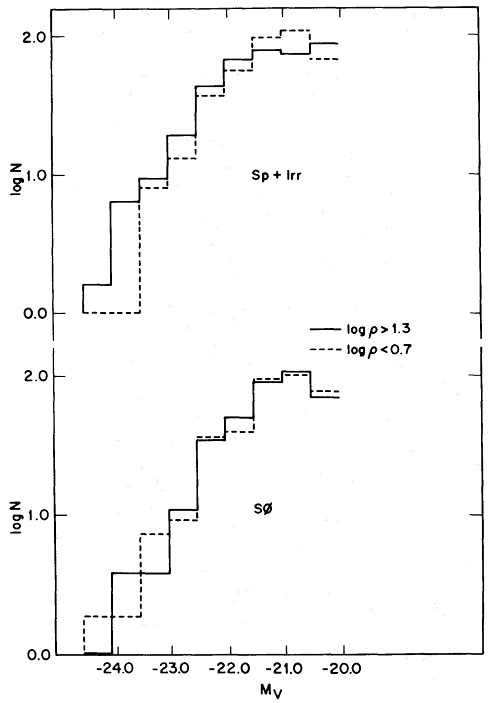


FIG. 16.—Comparison of the luminosity functions of disk galaxies in low and high-density regions.

bulge and smaller D/B systems are favored in regions of high galaxy density. From the equality of the luminosity functions, it appears that the total luminosity is equivalent, but more luminosity is tied up in the spheroidal component at the expense of the disk in regions of higher galaxy density.

VI. INTERPRETATION

The primary conclusion of the discussion in § IV and § V is that the majority of S0 galaxies are not produced by the removal of gas from spiral galaxies by ram pressure stripping or gas evaporation. The existence of S0's in low gas density regions, the insensitivity of the population/density relation to cluster history (i.e., relaxation), and the dissimilarity of the S0 and spiral bulge and D/B distributions provide strong evidence for this conclusion.

Put in the simplest terms, Figure 4 demonstrates that spheroidally dominated systems are increasingly favored in regions of higher galaxy density and that spirals and irregulars, galaxies with active star formation, are only prevalent in low-density regions. Figure 15 demonstrates that even within disk galaxies as a class, the trend is toward larger D/B in lower density regions.

Gott (1977) argues that at the time of galaxy formation ($z \sim 20$–30), a density enhancement that is to become a cluster of galaxies has a very small amplitude, perhaps an order of magnitude less than the amplitude of individual protogalaxies. Therefore, if galaxies form early and rapidly ($T_{\rm collapse} < 10^9$ years), they cannot know as they are forming in what kind of environment they are eventually to reside, i.e., rich, dense cluster or the low-density field. In this picture the cluster-size perturbations become important much later ($z < 10$), and thus there should be no relation between local galaxy density and morphological type.

The disk components of galaxies, on the other hand, are suggested to have a much longer formation time ($T_{\rm collapse} \gtrsim 2 \times 10^9$ years), which may even be comparable to the age of the universe (Larson 1977; Gott 1977). There is some observational evidence to support the idea that a substantial fraction of the star formation in disk components is relatively recent (Demarque and McClure 1977; Hardy 1976). After several billions years, the cluster perturbations have grown considerably. Figure 1 of Aarseth, Gott, and Turner (1979) graphically demonstrates that as early as 2×10^9 years after the assumed time of galaxy formation ($z = 30$), the large-scale density variations are large ($\Delta\rho/\rho \gtrsim 1$).

This discussion leads to a partial explanation of the galaxy density/morphological-type relation. If the formation of the disk component is a slower process, taking, say, several billion years, then this process will likely be interrupted by interactions among galaxies, which increase in frequency as local density increases. In only a few billion years the local density of galaxies in some regions will be substantially larger than the mean. Tidal encounters will tend to discourage the further development of the disk, and in fact, the gas will become heated as small subgroups virialize, perhaps halting the process completely (Gunn and Gott 1972). The thin disks in spirals associated with star formation may rely heavily on infall and hence may have formed over even longer time scales from lower density material. Thus a cluster like Coma, which collapsed in some 5–7 billion years, may never have included fully developed spirals, and subsequent development of spirals may have been precluded when the remaining gas was heated to $T \sim 10^8$ K during virialization.

A similar idea has been discussed in detail by Larson, Tinsley and Caldwell (1979). They suggest that accretion from a gas-rich envelope surrounding a spiral galaxy replaces gas depleted by star formation in the disk, allowing a spiral to continue star formation well beyond the typical 1–7 billion year lifetimes implied by gas consumption rates. They further speculate that S0 galaxies are spirals which have lost their gas-rich envelopes and exhausted their remaining gas by star formation. Tidal encounters and collisions between galaxies might well unbind these gas reservoirs and thus account for the increasing prevalence of S0's in regions of higher galaxy density.

While these ideas are successful in explaining the population gradients found in this study, they fail to account for the data of Figure 14 which indicate that (1) the bulges of S0 galaxies are systematically larger than their spiral counterparts, and (2) larger bulge systems are more common in denser regions.

Concerning the first point, these data show that S0 galaxies are not just systems of lower D/B, which could be explained by incomplete disk formation; they are systems with, on the average, absolutely larger bulges. It is thus necessary to explain why, at a *given* local density, the disk galaxies with the larger bulges are more likely to be S0 than spiral galaxies. One can speculate that the initial star formation rate or efficiency is higher in systems where the spheroidal component dominates, as it is, for example, in elliptical galaxies. That is, everything else being equal, there is likely to be less material left over for continuing star formation in a disk in a galaxy with a larger spheroidal component. Larger bulge systems may generate stronger shocks (Roberts, Roberts, and Shu 1975) resulting in a more rapid depletion of the remaining gas. The fact that the Sc → Sb → Sa is a sequence of both increasing bulge prominence and an ever-decreasing percentage of gas and dust is evidence for this interpretation. In addition, larger bulge disk galaxies could be, to some extent, "self-stripped" by galactic winds (Matthews and Baker 1971; Bregman 1978) as suggested by Faber and Gallagher (1976). The main point, however, is that S0 galaxies are to be interpreted as the next member of the spiral sequence, which implies a systematic decrease in D/B and gas content as one moves toward earlier Hubble types.

The second effect, if confirmed by detailed photometry, provides a greater challenge to traditional views. This is the observation that the spheroidal components are apparently larger in regions of higher galaxy density, more luminous, and presumably more massive, by a factor of 2. If formation of the spheroidal component is early and rapid, there should be little connection between the present density of a region and the luminosity of the bulge. There are, however, at least four possible ways for this to happen.

(1) Galaxies may form later ($z < 10$) when the enhancements that are to become clusters are more evolved. The higher density in regions on their way to becoming dense clusters may favor the formation of larger spheroidal systems at the expense of the formation of disks (see, e.g., Gott and Thuan 1976).

(2) The basic structures of spheroidal systems may form early, but mergers may be important for several billion years, over which time larger systems are built in regions of high galaxy density (see, e.g., Toomre and Toomre 1972; Larson and Tinsley 1978). Since overall galaxy density is higher at early epochs than it is today, inelastic collisions via dynamical friction could have resulted in the building of larger spheroidal components. The fact that the ellipticals in the present sample seem to show least of all the characteristic of larger bulges with increasing density (Fig. 14) may argue against this interpretation, suggesting rather that total mass is somehow conserved but distributed differently between disk and bulge as a function of local density.

(3) At early epochs ($z \gtrsim 10$), the difference in density between protocluster and protofield regions is very small. But Gunn (1979) has pointed out that at this point the universe is still at nearly ρ_{crit}, the closure density, so that small density differences may translate into large differences in the amount of material bound to a given protogalaxy. Thus the spheroidal components forming in a protocluster region may be able to acquire factors of 2 more mass than their field counterparts.

(4) The low-frequency (cluster) and high-frequency (galaxy) fluctuations in the initial perturbation spectrum may be correlated. The simplifying assumption is often made that the phases of different frequency components of the perturbation spectrum in the early universe are uncorrelated, or "randomly phased" (Peebles 1974). If the initial perturbation spectrum is *not* randomly phased, then a region in which a large-amplitude, low-frequency perturbation is found, destined to collapse relatively rapidly into a dense cluster, may be dominated by large-amplitude, high-frequency perturbations as well. The larger amplitude, high-frequency perturbations grow into more concentrated galaxies, thus favoring the production of ellipticals and low D/B systems in general. (This suggestion has been made by Gott and Thuan without explicit reference to the fact that the idea of random phase has been abandoned.) If such coupling does exist between the various frequencies, this could help account for the general trend of population versus local density found in this study, i.e., that lower concentration systems (spirals and irregulars) are only common in regions of low galaxy density.

Considering our total ignorance of the nature of the initial perturbation spectrum, evidenced by the fact that the perturbations required to form galaxies are orders of magnitude larger than what is expected for the early universe, one can hardly rule out the possibility that the perturbation spectrum is not randomly phased.

Angular momentum has been ignored in the preceding discussion, but it may play a crucial role in galaxy differentiation. Apparently, ellipticals are slow rotators in comparison to the spheroidal components of disk galaxies, although they are very similar in both structure and stellar population. It is clearly, then, *unlikely* that disk galaxies are simply elliptical galaxies whose evolution continued undisturbed for a longer period of time, allowing the building of an increasingly prominent disk. This also places constraints on models of building ellipticals through mergers of disk galaxies. The rotation of the bulges of disk galaxies suggests that they formed somewhat differently than ellipticals, which adds a challenging new constraint on the modeling of the origins of galaxy angular momentum. As originally pointed out by Sandage, Freeman, and Stokes (1970), angular momentum may indeed be one of the keys to understanding galaxy formation, differentiation, and evolution.

VII. CONCLUSION

A well-defined relation exists over five orders of magnitude in density between the local density of galaxies and the proportions of different morphological types. The relationship is consistent with all previous work on populations in clusters of galaxies.

Several arguments are given *against* the interpretation that the basic reason for population gradients is the ram pressure stripping or evaporation of gas from spirals to form S0 galaxies.

(1) The population/density relation is continuous and monotonic from the low-density field to the centers of rich clusters. Thus significant ($\gtrsim 30\%$) numbers of S0's are found in regions of comparatively low density, 10^2–10^3 less dense than the regions where density-dependent processes like sweeping are thought to be important.

(2) The population/density relation is substantially the same in all types of clusters. Specifically, this seems to rule out the possibility that most S0's are produced primarily by externally driven gas removal from spirals in the dense cores of collapsed clusters.

(3) The bulges of S0's are systematically larger (brighter) than those of spiral galaxies. Likewise, the D/B ratios of spirals are much larger than those of S0 galaxies. Fading of the disks of spirals is insufficient to explain this dissimilarity, which is inconsistent with the notion that S0's are swept spirals.

Alternatively, the population gradients may be explained in the context of the longer formation times of disks as compared with spheroidal components. If the disks take at least several billion years to form completely, then the density of the local region can begin to play a role as interactions and/or virialization can halt disk formation and/or gas replenishment. In this hypothesis, the systems with the most prevalent disks, the spirals, require a substantial fraction of a Hubble time to acquire, presumably through infall, the material associated with spiral structure and present epoch star formation. They would therefore only be prevalent in low-density areas where interactions are negligible and virialization occurs very late.

Finally, there is a suggestion in the data that the spheroidal components are more massive in high-density regions, perhaps at the expense of disk mass. This might be due to (1) late galaxy formation, (2) mergers, (3) a formation mechanism that is highly sensitive to density, or (4) the coupling of low- and high-frequency perturbations in the early universe. This increase in the luminosity of spheroidal components with increasing local density may have far-reaching consequences for galaxy formation and the history of the early universe. A detailed study based on surface photometry is essential to confirm this effect.

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