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THE MORPHOLOGY-DENSITY RELATION: THE GROUP CONNECTION

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ABSTRACT

We derive the relationship between galaxy morphology and local density from two complete galaxy redshift surveys. This relationship is completely consistent with the one derived by Dressler for a sample of 55 rich clusters.

The apparently universal morphology-density relation extends over six orders of magnitude in galaxy space density. There is no dependence of galaxy morphology on density in regions where the dynamical time scale is comparable with or greater than the Hubble time. At densities greater than ~ 600 galaxies Mpc^{-3}, S0's dominate the galaxy population. At these densities stripping mechanisms are likely to affect the galaxy population. At densities greater than ~ 3000 galaxies Mpc^{-3}, the fraction of elliptical galaxies rises steeply. In these regions the collapse time is short compared with typical time scales for the formation of disks.

Subject headings: galaxies: formation — galaxies: structure

I. INTRODUCTION

The morphology of galaxies is probably affected both by conditions during the epoch of galaxy formation and by subsequent environmental processes. Ram pressure stripping (Gunn and Gott 1972), tidal stripping (Gallagher and Ostriker 1972; Richstone 1976), galaxy mergers (Toomre 1977; White 1976), and galactic cannibalism (Ostriker and Tremaine 1975; Ostriker and Hausman 1977; Hausman and Ostriker 1978; Tremaine 1981) are some of the environment-dependent processes which must be considered. The importance of initial conditions may be indicated by the dissimilarity of disk-to-bulge and absolute bulge size distributions for spiral and S0 galaxies (Dressler 1980*b*). This difference argues against ram pressure stripping. Gott and Thuan (1976) suggest that spheroidal systems are produced preferentially from relatively large density perturbations where the time scale for star formation is comparable with the protogalaxy collapse time.

One of the observational constraints on models for the morphological differentiation of galaxies is the decrease in spiral population with increasing local density and the accompanying increase with density of the fraction of S0 and elliptical galaxies (Dressler 1980*b*). This morphology-density relationship for galaxies in rich clusters is continuous over four orders of magnitude in space density. Further constraints on the formation and evolution of galaxies can be obtained by extending the analysis of the morphology-density relationship to groups of galaxies in the general field.

We report a determination of the morphology-density relation for two complete galaxy redshift surveys. This project was fired in part by the apparent disagreement between two previous studies on galaxy morphology in groups (Bhavsar 1981; de Souza *et al.* 1982). Bhavsar suggests that the spiral population fraction in groups is only weakly dependent on density, in contrast to the strong dependence found by Dressler. On the other hand, de Souza *et al.* find agreement with Dressler. Our study contrasts with previous ones in (1) the determination of the morphology-density relation from galaxy surveys with complete redshift information and (2) the use of similar density estimators for both groups and clusters.

Combining the results for the galaxy surveys with the cluster results, the morphology-density relationship extends over six orders of magnitude in space density. Over two orders of magnitude, there is an overlap between the redshift survey and cluster data. In the range of overlap the morphology-density relationship for groups in the general field is the same as the relationship for the completely independent sample of rich clusters.

Section II includes a discussion of the data, a description of the method of analysis, and a survey of the previous group morphology studies. Results are in § III.

II. ANALYSIS

a) The Data

We derive a morphology-density relationship by analyzing the CfA Redshift Survey (Huchra *et al.* 1983, hereafter CfA survey) and a whole-sky catalog of 1312 galaxies brighter than $m_{B(0)} = 13.2$ (Huchra 1984, hereafter NB Survey).

The CfA survey includes 2390 galaxies with $m_{\mathrm{Zwicky}} < 14.5$ and $b > 40°$, $d > 0°$; $b < -30°$, $d > -2°.5$. Groups in the CfA survey with mean velocities less than 8000 km s^{-1} are included; in the NB survey, groups with mean velocities less than 4000 km s^{-1} are included. The velocity limits throw out groups which are poorly sampled due to the magnitude limit of the galaxy catalogs. Morphological types for most galaxies in the CfA survey are from de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter RC2) and Nilson (1973). Additional types for about 500 CfA survey galaxies have been estimated by Huchra from glass copies of the Palomar Sky Survey. Types for galaxies in the NB survey are from RC2.

Dressler's sample of 55 rich clusters (1980*a*) gives a measure of the high-density end of the morphology-density relationship. Dressler selected clusters on the basis of redshift ($z < 0.06$), richness ($N > 50$), and compactness on the sky (most cluster members lie within an area of a few square degrees). In general there are few published velocity data for the cluster sample. For the analysis, all the galaxies in a particular cluster field are assumed to lie at the "mean" redshift of the cluster. This mean is sometimes based on just two galaxies.

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1984ApJ...281...95P

b) Density Estimators

To study the morphology-density relationship, we select a density estimator which can be used to analyze both the redshift survey and cluster data. For the redshift survey data we use a pairwise technique which identifies density enhancements in three-dimensional redshift-position space (Huchra and Geller 1982). The search algorithm finds all pairs with projected separation:

$$D_{12} = \sin(\theta/2)(V_1 + V_2)/H_0 < D_L(V_1, V_2, m_1, m_2) \quad (1)$$

and line-of-sight velocity separation:

$$V_{12} = |V_1 - V_2| < V_L(V_1, V_2, m_1, m_2) , \quad (2)$$

where V_1 and V_2 refer to the redshifts of the galaxy and its companion, m_1 and m_2 are their magnitudes, and θ is their separation. Pairs with a member in common are linked into a single group: in other words, the algorithm finds "friends of friends." The selection parameters D_L and V_L are scaled to account for the magnitude limiting of the galaxy catalog. The ratio D_L/V_L is kept fixed. The number density contour surrounding each group corresponds to a fixed number density enhancement:

$$\frac{\Delta\rho}{\rho} = \frac{3}{4\pi D_L^3}\left[\int_{-\infty}^{M_{12}} \phi(M)dM\right]^{-1} - 1 , \quad (3)$$

relative to the sample mean density. M_{12} is the limiting absolute magnitude for each galaxy pair. We use only those groups which contain three or more members.

To calculate the morphology-density relationship, we create group catalogs with limiting contours $\Delta\rho/\rho = 3$, 10, 30, 100, 300, 1000, 3000, and 10,000. For both redshift surveys the value of V_L is 400 km s^{-1} at a redshift of 1000 km s^{-1}. The word "group" is used loosely here. The galaxies inside the limiting contour are not necessarily a physical group. Especially at the lowest $\Delta\rho/\rho$ there is no reason to expect the galaxies in the region to be members of a bound or virialized system. The goal here is to measure the density in the region of each galaxy, not to identify physical groups. The higher the $\Delta\rho/\rho$, the more likely the "groups" are physical associations. Physical groups usually have $\Delta\rho/\rho > 20$. For $\Delta\rho/\rho > 20$, dynamical time scales are much less than the Hubble time. For each $\Delta\rho/\rho$, we calculate the total number of spiral, S0, and elliptical galaxies assigned to groups. The upper and lower limits of each density bin are determined by the values of $\Delta\rho/\rho$ for two consecutive group catalogs. The number of spiral galaxies in each density bin is just the difference between the total numbers of spirals assigned to groups in the two consecutive catalogs. The number of ellipticals and S0's in each density bin is also calculated by taking the difference between the populations in the catalogs which determine the edges of the bin. The space number density can be computed from $\Delta\rho/\rho$ from equation (4):

$$\rho = \rho_N(d + 1) , \quad (4)$$

where d is the number density enhancement ($\Delta\rho/\rho$) and ρ_N is the mean number density of galaxies in the survey down to some limiting absolute magnitude. We use the values $\rho_{N,\mathrm{NB}} = 0.038$ galaxies Mpc^{-3} and $\rho_{N,\mathrm{CfA}} = 0.020$ galaxies Mpc^{-3} which are the number of galaxies brighter than $M_{B(0)} = -17.5$ in each case (Huchra and Geller 1982; Geller and Huchra 1982). We take $H_0 = 100$ km s^{-1} Mpc^{-1}.

For consistency we apply a similar density estimator to Dressler's cluster sample. Here the algorithm identifies density enhancements within each cluster. Because complete redshift information is not available for this sample, galaxies in each field are assumed to be at the mean cluster redshift. The algorithm identifies surface density enhancements on the basis of positional information alone. In equation (1), $D_{12} \leq D_L =$ constant for each cluster. The surface density enhancements correspond to the range log $(\Delta\rho/\rho) = 2$ to log $(\Delta\rho/\rho) = 6$. The corresponding volume densities are obtained by assuming that the galaxies in a given surface density enhancement occupy a spherical region. Population fractions are computed for logarithmic $\Delta\rho/\rho$ intervals of 0.5. We use Dressler's morphological types. In the event of an intermediate classification (e.g., S/S0), we use the preferred type (e.g., S).

c) Potential Biases and Some Corrections

Magnitude-limited surveys require correction for the variation in sampling of the galaxy luminosity function at different redshifts. In making this correction, we assume that the luminosity function is independent of distance and position. Detailed discussions of the sampling correction are given in Dressler (1980*a*) and Huchra and Geller (1982). The space number density must be multiplied by the factor:

$$R = \int_{-\infty}^{M_{\mathrm{lim}}} \phi(M)dM \Big/ \int_{-\infty}^{M_T} \phi(M)dM , \quad (5)$$

where M_{lim} is the absolute magnitude limit to which we refer all densities, M_T is the absolute magnitude limit for a group or cluster in the surveys, and $\phi(M)$ is the luminosity function, which we assume has the Schechter form with $M_{B(0)}^* = -19.40$ and $\alpha = -1.30$ for the CfA survey and $M_{B(0)}^* = -19.06$ and $\alpha = -1.02$ for the NB survey. This correction ensures that number densities for groups and clusters at different redshifts refer to the same limiting absolute magnitude. All space number densities are computed for $M_{B(0)} < -17.5$, the limit used by Dressler. The corrections are typically a factor of 2 or 3 for both the redshift survey and cluster data.

The sampling corrections are based on $B(0)$ magnitudes. Dressler's cluster samples are V-magnitude limited surveys. Because elliptical and S0 galaxies are redder ($B-V \sim 0.9$) than spiral galaxies ($B-V \sim 0.7$), an additional correction to the cluster population fractions is needed to compensate for the fainter effective $B(0)$ magnitude limit (M_{lim}) for elliptical and S0 galaxies. Specifically, we make an average correction where the number of spiral galaxies in each density range is multiplied by a factor:

$$A = \int_{-\infty}^{M_{\mathrm{EL,lim}}} \phi(M)dM \Big/ \int_{-\infty}^{M_{\mathrm{SP,lim}}} \phi(M)dM , \quad (6)$$

where $M_{\mathrm{EL,lim}}$ is the $B(0)$ magnitude limit for ellipticals at a fiducial redshift of $z = 0.04$ and $M_{\mathrm{SP,lim}}$ is the analogous magnitude limit for spirals. For the luminosity function parameters derived from the CfA and NB surveys, the value of A is approximately 1.2. We assume that the form of the luminosity function is independent of morphological type. Davis and Huchra (1982) and Huchra (1983) have shown that variations in the Schechter function parameters for different morphological types in the CfA redshift survey are not large ($|M_{\mathrm{EL}}^* - M_{\mathrm{SP}}^*| = 0.5$ mag; $|\alpha_{\mathrm{EL}} - \alpha_{\mathrm{SP}}| = 0.08$). We estimate that the variation in a typical sampling correction due to the morphology dependence of the CfA luminosity function is less than 20%. If f_{S}, f_{S0}, and f_{E} are the uncorrected cluster population

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1984ApJ...281...95P

fractions at a given density, then for spirals, S0's, and ellipticals, respectively, the color-corrected population fractions are:

$$f_{C,S} = Af_S/B \quad f_{C,S0} = f_{S0}/B \quad f_{C,E} = f_E/B \tag{7}$$

where B is $f_S(A - 1) + 1$. The cluster data are corrected appropriately to match the redshift surveys.

d) Comments on Previous Studies

Bhavsar (1981) and de Souza *et al.* (1982) reach different conclusions about the morphology-density relationship for groups of galaxies. Bhavsar finds inconsistencies between the morphology-density relationships for groups and clusters; de Souza *et al.* find that the relations for groups and clusters are completely consistent. Here we examine some of the sources of disagreement.

Neither Bhavsar nor de Souza *et al.* correct their group data to a limiting magnitude consistent with the cluster data. Without this sampling correction, a direct comparison to Dressler's data is inappropriate. Neither study includes the appropriate color correction from V to $B(0)$. Bhavsar's observation that the S0 fraction in the field appears less than the S0 fraction in clusters is merely a consequence of the color difference for the group and cluster surveys.

Bhavsar's groups are surface density enhancements selected from a $B(0)$ magnitude limited galaxy survey. In galaxy surveys, the survey depth is much greater than the size of the detected groups and a surface density enhancement translates to a wide range of volume density enhancements. This effect is much less important when analyzing rich cluster samples because the galaxies are mostly at similar distances; there is a tighter relationship between volume and surface density. The absence of sampling corrections and the lack of redshift information are responsible for Bhavsar's relatively flat morphology-density relationship.

De Souza *et al.* base their analysis on groups from Sandage (1975), Sandage and Tammann (1975), and de Vaucouleurs (1975). Taken together, these group samples do not comprise a consistent data set because the selection criteria are not identical. The de Vaucouleurs group members are selected partly by similarity in morphology. Because of this selection bias, the spiral population fraction for the de Vaucouleurs groups as given in de Souza *et al.* is virtually independent of density. A Kolmogorov-Smirnov test rejects, at the 95% confidence level, consistency between this relationship and the steeper one found by Dressler. The agreement between de Souza *et al.* and Dressler is coincidental: it is a consequence of failure to make sampling corrections and of a fortuitous combination of the de Vaucouleurs sample with the Sandage-Tammann sample which has an even steeper population-density relationship than the one found by Dressler.

III. RESULTS

Figures 1 and 2 show the morphology-density relationships for the CfA and NB samples, respectively. The error bars are one formal standard deviation. Errors for the S0 and elliptical data are omitted for the sake of clarity. The morphology-density relationships in Figures 1 and 2 are based on the study of "groups" which contain at least three members and cluster enhancements which contain at least 10 members. Our relationship for clusters reproduces the relationship found by Dressler. The results are insensitive to the minimum membership size of the groups or cluster enhancements studied, pro-

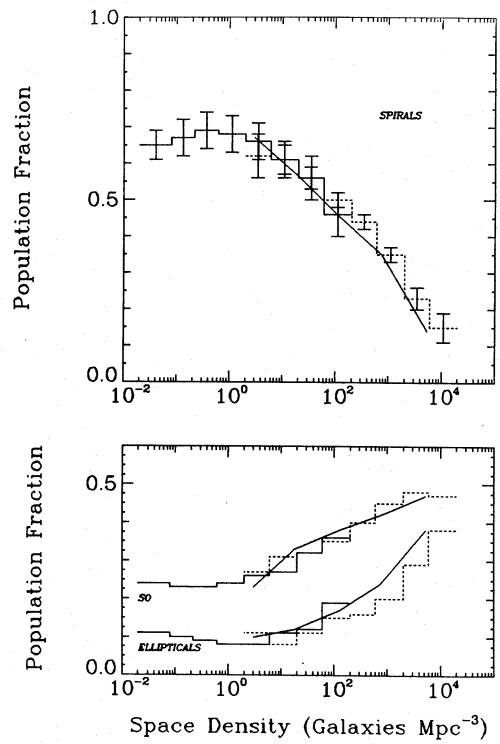

FIG. 1.—Population fraction as a function of space density for the CfA sample. The group contribution to the morphology-density relation is indicated by the solid histograms; the cluster contribution, by the dashed histograms. Dressler's morphology-density relation is indicated by the solid curves which are color corrected and shifted to correspond to $H_0 = 100$ km s^{-1} Mpc^{-1}.

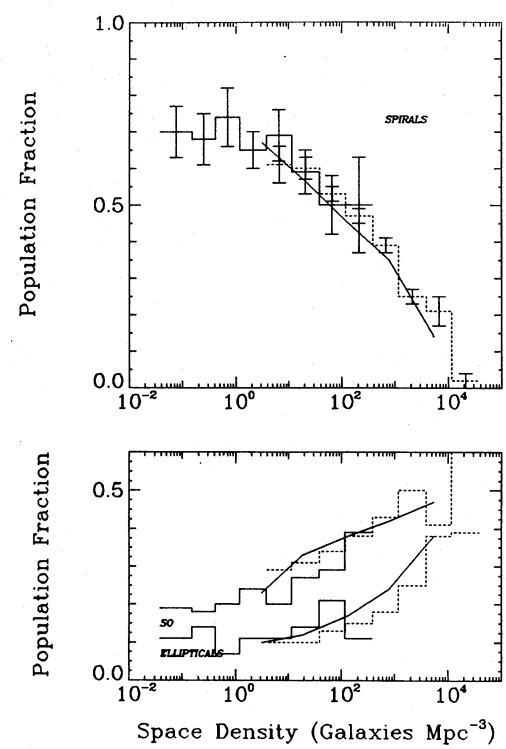

FIG. 2.—Population fraction as a function of space density for the NB sample.

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1984ApJ...281...95P

vided extreme values are avoided. If the minimum group size is increased to five galaxies and/or the minimum cluster enhancement size is decreased to five galaxies, the maximum variation in population fraction due to the change in membership is less than 20%. If the minimum cluster size is less than five galaxies, edge effects become important.

There is complete agreement between the group and cluster morphology-density relationships in the density range ~ 2 to ~ 200 galaxies Mpc^{-3} ($100 \leq \Delta\rho/\rho \leq 10{,}000$). Because the group and cluster samples are completely independent, this result suggests that the observed relationship is universal.

For space densities greater than ~ 5 galaxies Mpc^{-3}, there is a dramatic decrease in the spiral population fraction accompanied by an increase in the S0 and elliptical population fractions. For space densities less than ~ 5 galaxies Mpc^{-3} ($\Delta\rho/\rho \leq 100$), all population fractions show little density dependence and take on the "field" values for the redshift survey samples (see Figs. 1 and 2). The "field" values for the CfA survey are 65% spirals, 23% S0's, and 12% ellipticals; the values for the NB survey are 70% spirals, 19% S0's, and 11% ellipticals. For comparison, the field values for the Revised Shapley-Ames catalog are 71% spirals, 15% S0's, and 14% ellipticals (Sandage and Tammann 1981). These values refer to $B(0)$ magnitude-limited samples. Distance limited samples derived from these catalogs have similar morphological fractions. This similarity is further evidence for the insensitivity of this analysis to variations in the luminosity function with morphological type.

Morphological information on the fainter galaxies in the CfA survey is somewhat less reliable than for the brighter CfA galaxies or for galaxies in the NB survey. However, there are no apparent classification biases. The NB and CfA morphology-density relationships are consistent with each other. Furthermore, the complete agreement between the group and cluster data rules out any important discrepancies between the morphological classifications in the two redshift surveys and those in Dressler's cluster sample. One possible source of error in the relation is incompleteness in the cluster samples near the magnitude limit (Shectman 1983).

IV. DISCUSSION

The comparison between the redshift surveys and data on rich clusters shows that there is a universal relationship between galaxy morphology and local density. The crucial distinction between this work and earlier studies is the use of redshift information. Sampling and color corrections have a smaller effect on the analysis but do explain some earlier inconsistencies.

The universality of the relation is somewhat puzzling. Many clusters show significant substructure in their galaxy distribution (Geller and Beers 1983). N-body simulations indicate that in the course of cluster evolution these clumps of galaxies merge (White 1976). It is difficult to understand how the morphology-density relationship is maintained in these mergers. However, some features of the morphology-density relation have a qualitative physical basis. There are three density ranges of particular interest: for densities less than ~ 5 galaxies Mpc^{-3} the population fractions are independent of density; at a density of ~ 600 galaxies Mpc^{-3}, the fraction of S0 galaxies becomes greater than the fraction of spiral galaxies; for densities greater than ~ 3000 galaxies Mpc^{-3} the elliptical fraction rises steeply.

The dynamical time scale of interest for gaining physical insight into the morphology-density relation is, as suggested by Dressler, the collapse time,

$$t_c = 1.43/(G\rho)^{0.5} \tag{8}$$

(Gunn and Gott 1972). Here ρ is the mean mass density of the region at the present epoch. For this discussion, we compute mass densities by adopting a typical $M/L_B = 350\ M_\odot/L_\odot$. We convert number densities to luminosity densities using the luminosity function parameters given in § II. The collapse times at 5, 600, and 3000 galaxies Mpc^{-3} ($4.2 \times 10^{12}\ M_\odot\ \mathrm{Mpc}^{-3}$, $4.8 \times 10^{14}\ M_\odot\ \mathrm{Mpc}^{-3}$, and $2.4 \times 10^{15}\ M_\odot\ \mathrm{Mpc}^{-3}$) are 10^{10} years, 10^9 years, and 4×10^8 years, respectively.

In the range where there is no density dependence of the population fraction, the dynamical time scale is roughly the Hubble time. The importance of the environment is reflected in the dependence of morphology on density when the dynamical time scale is less than a Hubble time. At densities where ellipticals outnumber spirals, the collapse time is shorter than 4×10^8 years. This time scale is shorter than the few billion year time scale required for disk formation. The collision time is of the same order as the collapse time, making disk formation difficult.

The morphology-density relation suggests that S0 galaxies are not a population of homogeneous origin. At densities where S0's dominate the galaxy population, stripping mechanisms are likely to operate (Gunn and Gott 1972; Pryor and Geller 1984). The observed dissimilarity of the disk-to-bulge ratios and bulge distributions for S0's and spirals makes it very unlikely that all or even most S0's are stripped spirals. However, there are large disk-to-bulge S0's in the core of the Coma Cluster (Bothun, Schommer, and Sullivan 1983). The density at the core of the Coma cluster is greater than 500 galaxies Mpc^{-3}. These observations of Coma give some support to this interpretation of the morphology-density relation.

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