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THE SPATIAL DISTRIBUTIONS AND INTRINSIC SHAPES OF DWARF ELLIPTICAL GALAXIES IN THE VIRGO AND FORNAX CLUSTERS

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ABSTRACT

Data from deep photographic surveys of the Fornax and Virgo Clusters show that the projected radial number density profile of dwarf ellipticals in these clusters depends both on luminosity and on the presence or absence of nucleation. All nucleated dE's and the nonnucleated dE's that are fainter than $M_{B_T} \sim -14.2$ are concentrated toward the centers of clusters like the giant E and S0 galaxies. In contrast, nonnucleated dE's brighter than $M_{B_T} \sim -14.2$ are distributed like the spirals and irregulars. Furthermore, the flattening distribution of *bright* nonnucleated dE's is similar to that of the dwarf irregulars, but differs from the flattening distribution of either the nucleated dwarfs (dE, N) or of the giant ellipticals. The similarity of flattenings of dE (bright, no N) and Im types removes one of the previous objections to the hypothesis that some dwarf ellipticals could be stripped Im's. However, the data are also consistent with stochastic self-propagating star-formation models of irregular galaxies.

Subject headings: galaxies: clustering — galaxies: structure

I. INTRODUCTION

Dwarf elliptical (dE) galaxies, whose absolute magnitudes are typically fainter than $M_{B_T} = -16$, are the most common type of galaxy in the universe. More than 50% of the galaxies in the Virgo Cluster brighter than $M_{B_T} = -12$ are dE's (Sandage, Binggeli, and Tammann 1985*b*, hereafter SBT85*b*), and their numbers are still increasing exponentially as they disappear into the night sky. Many dE's have compact nuclei that are similar to globular clusters in appearance but that can reach luminosities up to 100 times brighter than the most luminous globular cluster in the Milky Way. The nuclei themselves produce only a small fraction of the total galaxy luminosity (20% at most), and the envelope surrounding the nucleus is similar in appearance to the envelope of nonnucleated dE's. This similarity has led in the past to treating these two types of galaxies as a single population. However, not all dwarf ellipticals have nuclei, and in this *Letter* we present evidence from surveys of the Fornax and Virgo Clusters that the two types of galaxies differ in their spatial distributions in clusters and in their individual shapes.

II. THE SURVEYS

We have used the data obtained from deep photographic surveys of the Virgo and Fornax Clusters made with the 2.5 m du Pont telescope at the Las Campanas Observatory of the Carnegie Institution (Binggeli, Sandage, and Tammann 1985; Ferguson 1989). The catalogs include likely cluster members as faint as $B_T = 20$, and are probably complete to $B_T \sim 18$. Cluster membership for galaxies fainter than ~ 16 mag is decided primarily on the basis of morphology. Dwarf galaxies in these nearby clusters are easily distinguished by their low surface brightnesses from giant galaxies in the background.

For Virgo, we have excluded the M and W clouds and the Southern Extension, leaving a sample of 1228 likely Virgo Cluster members. The Fornax cluster sample contains 340 likely members.

The dE nuclei are typically unresolved and are in most cases easily seen against the low surface brightness envelope of the surrounding galaxies. We have excluded from our samples below the relatively small number of galaxies where the nucleation is uncertain or peculiar (classifications dE, N:, dE, N?, dE, Npec, or dE, Npec?).

III. THE SPATIAL DISTRIBUTION OF GALAXIES IN THE VIRGO AND FORNAX CLUSTERS

It is already known that nucleated and nonnucleated dE's in the Virgo Cluster have different spatial distributions. Figure 9 of Binggeli, Tammann, and Sandage (1987, hereafter BTS) shows that the nucleated dwarfs are more strongly concentrated toward the cluster center than the nonnucleated dwarfs. In a related study, Ichikawa *et al.* (1988) show that dwarf ellipticals in the central region ($r < 5°$) of the Virgo Cluster also are brighter and have larger diameters than those beyond 5°. However, because the percentage of nucleated dwarfs depends on luminosity it is not clear from these two studies whether the differing spatial distributions represent *luminosity segregation* among the dwarfs in the cluster or *segregation by morphology*.

To investigate this question, we have divided the dE's into three samples: nonnucleated dE's fainter than $M_{B_T} = -13.3$, nonnucleated dE's brighter than $M_{B_T} = -14.2$, and nucleated dE's brighter than $M_{B_T} = -14.2$ (there are very few nucleated dE's fainter than this limit). The gap between the "bright" and "faint" subsets serves to separate the two samples more cleanly. Distance moduli $m - M = 31.7$ and 31.9 for the Virgo and Fornax Clusters, respectively, have been assumed. The projected number densities of various types of galaxies as a function of radius in the two clusters are plotted in Figures 1 and 2. The centers of the clusters are taken to be $12^h25^m.3$,

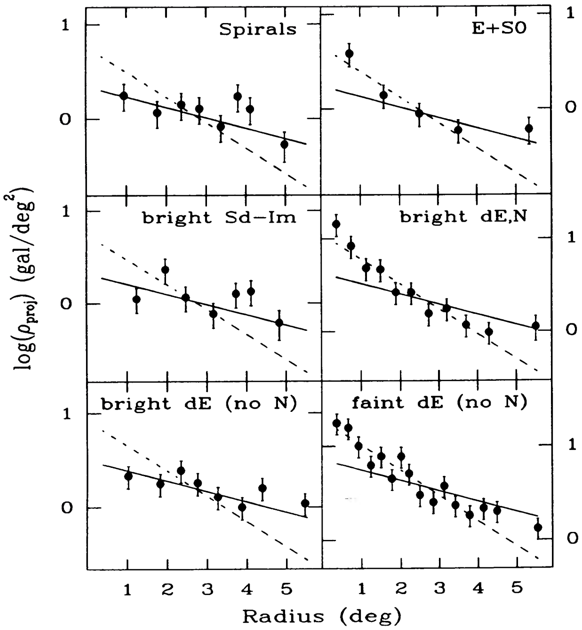

FIG. 1

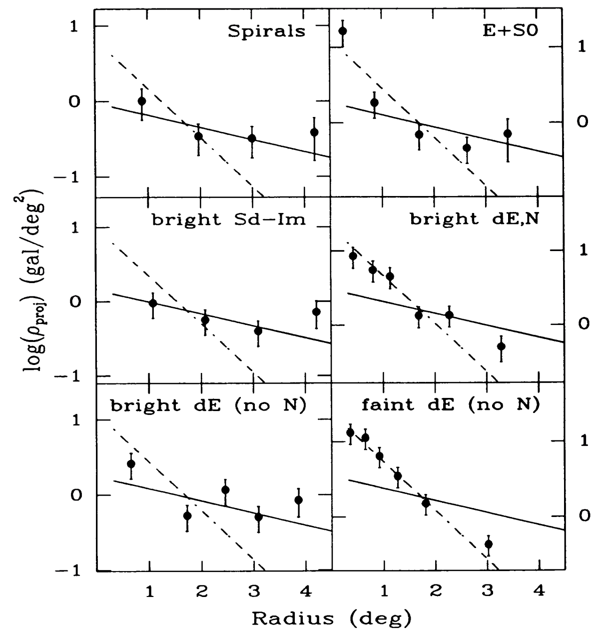

FIG. 2

FIG. 1.—The projected density of galaxies as a function of radius in the Virgo Cluster. The solid line shows the best-fit exponential to the bright nonnucleated dE distribution; the dotted line shows the best fit to the faint nonnucleated dE distribution. Both fits are normalized to the number of galaxies in each sample. The bright samples contain likely cluster members down to $M_{B_T} = -14.2$ ($B_T = 17.5$). The faint dE sample contains galaxies fainter than $M_{B_T} = -13.3$.

FIG. 2.—The projected density of galaxies as a function of radius in the Fornax cluster. The solid line shows the best-fit exponential to the bright nonnucleated dE distribution; the dotted line shows the best fit to the faint nonnucleated dE distribution.

13°18′.0 for Virgo and $3^h35^m.15$, −35°43′.6 for Fornax. Galaxies below 9° declination have been excluded for Virgo, to reduce the influence of the secondary cluster centered on NGC 4472 (BTS); however, the contribution from this secondary cluster above 9° declination does slightly contaminate the density profiles beyond ∼4°. Figures 1 and 2 show that luminosity segregation has not taken place in the Fornax and Virgo Clusters. The faint dE's have the same radial surface-density profile, to within the errors, as the bright nucleated dE's and the luminous E and S0 galaxies. Furthermore, all of these early-type galaxies (E, S0, dE, N, and faint dE's) are much more centrally concentrated than the bright *nonnucleated* dE's, *which, in turn, have the same radial profile in the clusters as the spiral and Im galaxies.*

Kolmogorov-Smirnov (K-S) tests on the radial distributions indicate a probability of 0.1% in the Virgo Cluster and 0.03% in the Fornax Cluster that the bright dE and dE, N galaxies are drawn from the same population. The K-S test also rejects the hypothesis that the bright and faint nonnucleated dE's are drawn from the same population (0.09% probability for Virgo, less than 0.001% for Fornax). On the other hand, the K-S test indicates that the radial distributions of the E+S0's; dE, N's and faint dE's are not significantly different, given the number of galaxies in each sample. Similarly, the radial distributions of the bright spirals, irregulars, and bright dE's are indistinguishable via the K-S test.

Tables 1 and 2 show the results of fitting exponentials of the form $N(r) \sim e^{-\alpha r}$ to the observed density profiles. Fitting was carried out using a maximum-likelihood technique on the unbinned data. Confidence intervals were determined from

TABLE 1

TYPE-DEPENDENT GALAXY DENSITY PROFILES IN THE VIRGO CLUSTER

				70% CONFIDENCE		99% CONFIDENCE	
SAMPLE	M_{B_T} RANGE	N	BEST-FIT $1/\alpha$	Minimum	Maximum	Minimum	Maximum
E + S0	...	62	1°61	1°4	2°0	1°1	2°8
Sa + Sb + Sc	...	78	3.08	2.4	4.2	1.9	9.1
Sd-Im	≤ −14.2	74	3.77	2.9	5.6	2.1	22.2
Faint dE (no N)	> −13.3	256	1.72	1.6	1.9	1.4	2.2
Bright dE (no N)	≤ −14.2	112	3.90	3.1	5.6	2.3	12.5
dE, N	≤ −14.2	151	1.61	1.5	1.8	1.3	2.2
dE (no N)	> −12.4	105	1.62	1.4	1.9	1.2	2.4
	−13.1 to −12.4	104	1.82	1.6	2.1	1.3	2.8
	−13.7 to −13.1	99	1.67	1.5	1.9	1.3	2.5
	−14.7 to −13.7	98	2.44	2.0	3.2	1.6	4.6
	≤ −14.7	104	7.55	4.6	22.2	2.8	> 50.0

TABLE 2

TYPE-DEPENDENT GALAXY DENSITY PROFILES IN THE FORNAX CLUSTER

Sample	M_{B_T} Range	N	Best-fit $1/\alpha$	70% Confidence Minimum	70% Confidence Maximum	99% Confidence Minimum	99% Confidence Maximum
E + S0	...	31	0°87	0°7	1°1	0°6	1°4
Sa + Sb + Sc	...	18	2.46	1.6	5.3	1.0	>50.0
Sd-Im	≤ −14.2	27	4.08	2.4	14.3	1.5	>50.0
Faint dE (no N)	> −13.3	66	0.67	0.6	0.7	0.5	0.9
Bright dE (no N)	≤ −14.2	34	2.69	1.9	4.6	1.3	>50.0
dE, N	≤ −14.2	57	0.87	0.8	1.0	0.6	1.3

Avni's (1976) prescription for one "interesting parameter." The results indicate that the distributions of nucleated and non-nucleated dE's have significantly different scale radii. In the Virgo Cluster, the bright non-nucleated dE's have a scale radius that is a factor of 2.4 larger than that of the dE, N's; in the Fornax cluster, the scale radii differ by a factor of 4.2.

Where does the transition between the centrally concentrated and the more extended population of dE's occur? The end of Table 1 shows the results of fitting exponentials to smaller subsets of the Virgo data. The extended population of nonnucleated dE's begins to dominate the sample brighter than $M_{B_T} \sim -14.2$. This does not correspond to any readily apparent feature in the composite dE luminosity function (SBT85*b*; Ferguson and Sandage 1988).

IV. THE DISTRIBUTION OF AXIAL RATIOS OF DWARF GALAXIES

A key test for a possible evolutionary connection between dE's and Im's is whether these types of galaxies have the same intrinsic shapes. The flattening distributions of dE's and Im's have been compared by Caldwell (1983), Sandage, Binggeli, and Tammann (1985*a*), Okamura (1985), Ichikawa, Wakamatsu, and Okamura (1986), Feitsinger and Galinski (1986), and Ichikawa (1989). While there is general agreement that the dE's are not flattened disk systems such as spirals and S0's, there is disagreement over whether they have the same shapes as the giant ellipticals or the dwarf irregulars. Because of this inconsistency in the literature, the flattening distributions have been used to argue both for (Kormendy 1986) and against (SBT85*a*; Binggeli 1986) the hypothesis that dwarf ellipticals are stripped irregulars. However, none of the investigations to date have separated the dwarf samples by nucleation or luminosity.

In Figure 3 the distribution of axial ratios for dE's and Im's are plotted based on eye estimates from the du Pont plates of the Virgo and Fornax Clusters. The axial ratios have not been measured at a fixed isophote, only eye-estimated, and can be uncertain by ~20%. Nevertheless, Figure 3 suggests that bright nonnucleated dE's are somewhat flattened systems similar to the Im's and distinct from the nucleated dE's, which have axial ratios similar to the giant E's (compare Fig. 3 [*right*] with Fig. 1 of Sandage, Freeman, and Stokes 1970). Neither the dE's nor the Im's, however, show the flattening distribution expected from a pure disk system observed at a random distribution of angles. A physical explanation for this effect suggested by Binney and de Vaucouleurs (1981) and Kormendy (1986) is that the stellar random velocities in dwarf galaxies are comparable to their rotation velocities, leading to a more isotropic velocity distribution than in more massive galaxies.

V. DISCUSSION

To summarize, giant E, dE, N galaxies and faint dE(no N) galaxies are similar in their spatial distributions in the Virgo and Fornax Clusters. The faint dE's may thus be more closely related to the dE, N galaxies than to the bright dE(no N) galaxies. (It is possible that many of the faint dE's contain nuclei that are too faint to be seen on our plates.) Nonnucleated dE galaxies brighter than $M_{B_T} \sim -14.2$ are similar to Im galaxies in their spatial distributions in the clusters and in their flattening distributions. This extended population of dE's may plausibly be explained as the remnants of dwarf irregulars that have been stripped of their gas by passage through the cluster core or alternatively as dwarf irregulars that are in a quiescent phase between star formation bursts, as predicted by stochastic self-propagating star formation (SSPSF) models (Gerola, Seiden, and Schulman 1980; Tyson and Scalo 1988).

Many of the arguments against stripping (SBT85*a*; Binggeli 1986; Bothun *et al.* 1986) rely on a comparison of the properties of Im galaxies to the properties of dE galaxies *in general.*

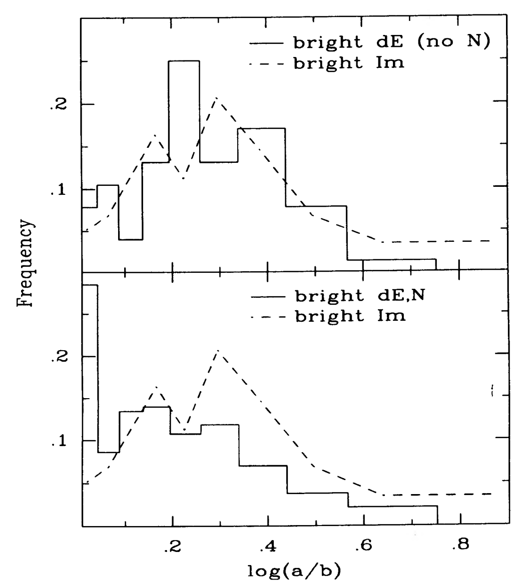

FIG. 3.—The distribution of axial ratios for bright nucleated and nonnucleated dE galaxies, and dwarf irregulars. The samples include likely members of the Virgo and Fornax Clusters brighter than $M_{B_T} = -14.7$. The Im sample includes 117 Sd, Sdm, Sm, and Im galaxies. The dE, N sample includes 186 galaxies, and the nonnucleated dE sample includes 79 galaxies. The bins in axial ratio are those used by Sandage, Freeman, and Stokes (1970).

Specifically, dE galaxies appear to be too round, to have surface brightnesses that are too high, scale radii that are too small, and metallicities that are too high to have been produced simply by removing the gas from Im's. However, these arguments do not rule out the possibility that a *subset* of the dE's, specifically the bright, nonnucleated dE's, could be the stripped remnants of irregulars.

The idea that the Im's are affected by the cluster environment finds observational support in the apparent deficit of Im's toward the center of the Virgo and Fornax Clusters (BTS, Fig. 10d; Caldwell and Bothun 1987, Fig. 4). However, this deficit barely shows up in the radial distributions shown in Figures 1 and 2 and is not highly significant statistically. The similarity of spatial distributions of the Im's and the bright nonnucleated dE's argues *against* a stripping hypothesis if the orbits of the Im's are distributed isotropically. However, the similar spatial distributions can be understood if the dwarf irregulars are predominantly on radial orbits that take them through the cluster core and then back out to large distances. This is consistent with the idea put forth by Tully and Shaya (1984) that late-type galaxies originally formed outside of galaxy clusters and slowly accrete onto them as the universe evolves, an idea that has gained recent support from the observation that late-type galaxies have significantly higher velocity dispersions in clusters than early-type galaxies (Sodré *et al.* 1989).

In the SSPSF models, low-mass galaxies undergo irregular intermittent episodes of star formation, with dormant periods in between. During the dormant periods, the more massive irregular galaxies are expected to have properties similar to the bright nonnucleated dE's. In particular, they should be flattened, low surface brightness, nonnucleated galaxies with the same spatial distribution in the cluster as the star-forming irregulars. If these galaxies really are dwarf irregulars in their dormant state, then most of them should be rich in neutral hydrogen (see Fig. 7 of Gerola, Seiden, and Schulman 1980). Impey, Bothun, and Malin (1988) observed 32 low surface brightness dwarfs with Arecibo, five of which were classified as nonnucleated dE's brighter than $M_{B_T} = -14.2$ in the Virgo Cluster Catalog. None were detected to a limit of 3–5 $\times 10^6$ $M_\odot$. However, given the small sample, these limits probably do not rule out the SSPSF model. The key test will clearly be to observe a larger sample of nonnucleated dE galaxies at 21 cm.

Finally, it is possible that the nonnucleated dE's are unrelated to the Im's, and that the similarity in their spatial distributions in the clusters is simply a coincidence. The difference in the flattening distributions of the nucleated and nonnucleated galaxies can perhaps be explained by dynamical arguments (Norman, May, and van Albada 1985). The problem that remains is then to explain why the fraction of dE's with nuclei increases toward the centers of clusters.

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