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A COMPREHENSIVE STUDY OF 12 VERY RICH CLUSTERS OF GALAXIES. II. DYNAMICS*

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ABSTRACT

Additional results are reported of a photographic photometry study undertaken at Lick Observatory of 12 very rich clusters of galaxies.

From the spatial distributions of the galaxies, it is concluded that the core radius may be well correlated with the overall cluster size, suggesting that the more easily determined core parameters may adequately describe the large-scale cluster characteristics. This study confirms previous results that the size of the core radius is similar among different clusters but does not agree with earlier work on the precise value of the mean core radius.

The observation that cD clusters as a whole tend to be flattened and aligned with the axes of centrally located, highly elliptical cD galaxies is briefly discussed in connection with cD formation mechanisms.

$\mathfrak{M}/L$ ratios of 100–300 for eight clusters with known velocity dispersions are consistent with other studies. $\mathfrak{M}/L$ is not found to be a function of cluster richness.

A crude scheme for the morphological classification of galaxies based on discrimination between ellipticals and nonellipticals in the clusters provides a few possible counterexamples to Oemler's three distinct population types of clusters.

Subject headings: galaxies: clusters of — galaxies: structure

I. INTRODUCTION

This is the second of two papers discussing a study undertaken at Lick Observatory of the general characteristics of 12 very rich clusters of galaxies. In Paper I (Dressler 1978), the photometric technique employed is discussed and the luminosity functions derived are investigated for differences. It is concluded that statistically significant variations do exist, in disagreement with the "universal luminosity function" model. In this paper, under the general heading of dynamics, the spatial distribution of the galaxies and the implied mass/light ratios are discussed. A small section is also included concerning the population types in the clusters.

In § II the spatial distributions of the galaxies are analyzed. Both the core radii and overall cluster size are determined, and the resulting values for the luminosity, density, and number population for the core and the cluster as a whole are calculated. Evidence is presented that the core values of these quantities are well correlated with the overall cluster values. Also included in § II is the spatial distribution of cluster galaxies as a function of absolute brightness, with an accompanying discussion of implications for models of cluster evolution. Finally, a brief discussion is included of the possible alignment of the axes of the galaxies in the cluster and the departures from spherical symmetry of the overall cluster shape.

In § III the $\mathfrak{M}/L$ ratios are derived for the clusters for which velocity dispersions are available and the data are briefly discussed. Section IV is concerned with the variation of morphological types of galaxies present in the clusters. The existence of Oemler's (1974*a*) three discrete population types of clusters is brought into question.

II. SPATIAL DISTRIBUTIONS

a) Core Parameters

In order to find a characteristic scale size for each cluster, it was decided to determine core radii in a manner similar to that of Bahcall (1975). Two techniques were used, one using the isothermal gas sphere tabulation of Zwicky (1957), who originally suggested the procedure, and the other involving the fitting of the data to a King law (Rood *et al.* 1972). This latter expression, derived by King originally for star cluster profiles, seems to fit a variety of other forms in the universe, among them the central spatial distributions of clusters of galaxies.

Determination of the core profile proceeded using the positions of those galaxies photometered on the Crossley plates ($\sim\frac{1}{2}°$ diameter) for the determination of the luminosity function. For the isothermal fits, a value of the cutoff constant $C = 0.1$ was assumed (see Bahcall 1975) and the central density and core radius were varied by computer program until a least χ^2 fit was obtained. For the King models, the expression

$$n(r) = n_0[1 + (r/R_{\rm cor})^2]^{-1} \qquad (1)$$

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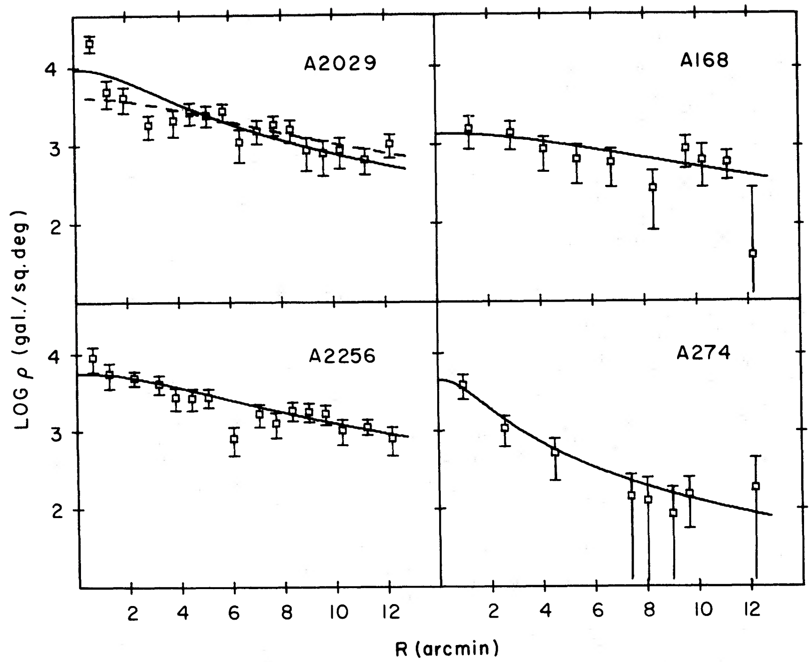

FIG. 1a

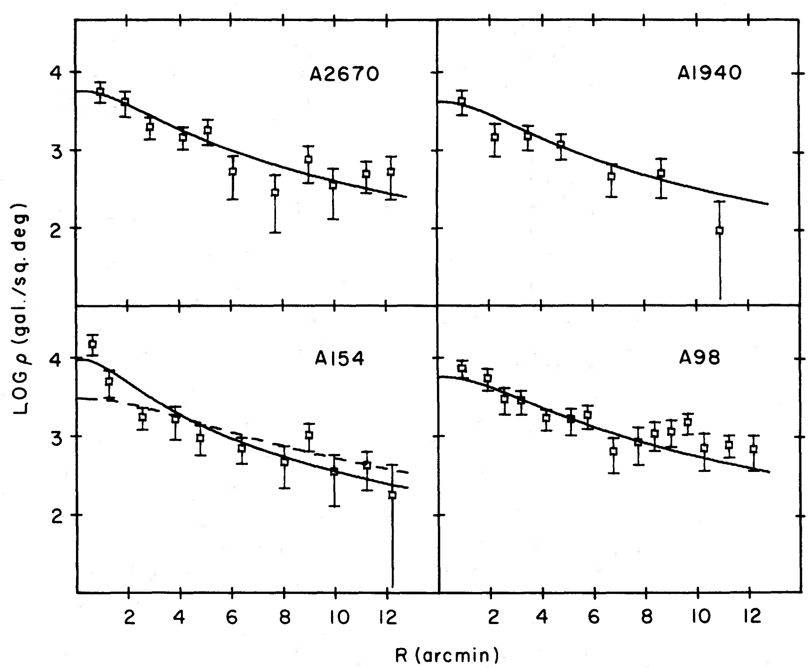

FIG. 1b

FIG. 1.—Spatial distributions of the galaxies compared with the best-fitting King models. (The core radius is defined as the point at which the density has fallen a factor of 2 below the central value.) The dashed lines in A2029 and A154 give the nucleus (center point) excluded model.

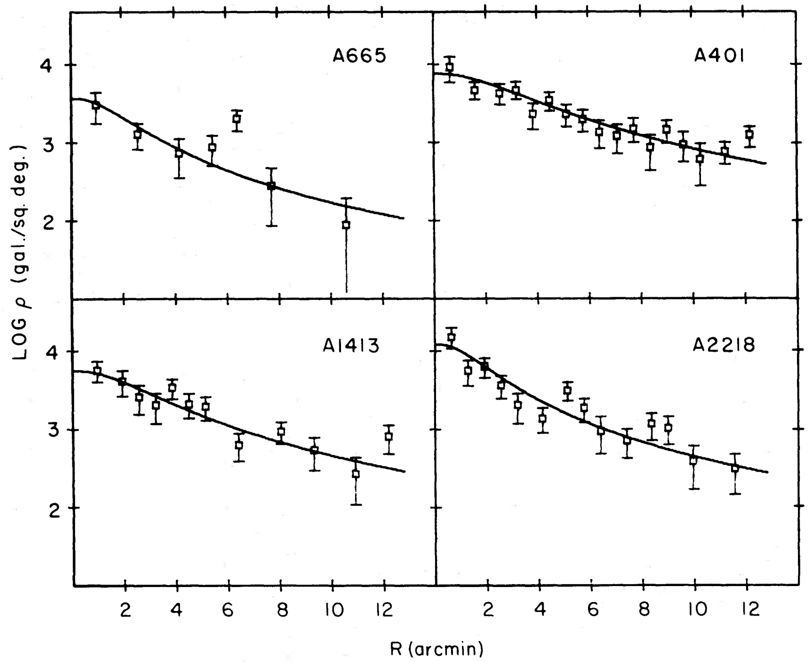

FIG. 1c

FIG. 1.—*Continued*

was substituted and n_0 and R_{cor} were subsequently determined. The core radii determined by the two techniques were found to be very similar within the uncertainties, which is not surprising when one considers that the two forms agree quite well out to several core radii. For simplicity, only the data from the King models, which had the advantage of not requiring an arbitrary cutoff parameter, are presented in this paper. R_{cor} is defined as the radius at which the projected density has dropped to half its central value. The plots of the data and of the best-fit King models are shown in Figure 1.

Since each cluster was studied to a different absolute magnitude limit, it was necessary to renormalize all the central density parameters to the same absolute magnitude limit, chosen as $M_F = -20$. When necessary, an extrapolation was made using the best-fitting Schechter luminosity function (see Paper I). It was noted in Paper I that the steep bright ends in some clusters suggest a possible overestimation of the richness when the faint end is not seen; hence the density of certain clusters (A2218, A665, A1413, and A1940) could conceivably be overestimated by as much as 50%. Since there is no way to tell with the present data whether this is the case, these luminosity functions have been applied without further comment.

With this correction and the surface to spatial density conversion (Rood *et al.* 1972), N_0, the central density of galaxies per cubic megaparsec brighter than $M_F = -20$ is obtained. By using the Schechter function again, the average luminosity per member can be obtained for each cluster, and in this way the total luminosity for galaxies brighter than -20 is derived. Finally, a correction of 20% is applied to convert the isophotal magnitudes to total luminosity (estimated with the help of Fig. 3*b* from Oemler 1974*a*), and the percentage of light contributed by galaxies fainter than $M_F = -20$ is predicted by means of the best-fitting Schechter function. The core radii, number densities, and luminosities are listed in Table 1. The core luminosity L_{cor} in Table 1 is defined as the central luminosity density multiplied by the core volume.

i) *Discussion*

Inspection of the core profiles led to the following conclusions:

1. The data are fitted reasonably well by a King model.
2. Two clusters, A2029 and A154, are unusual in that they exhibit a much higher central density than predicted by the model.
3. The core radius does seem to be relatively constant from cluster to cluster (within a factor of 2, a fact which supports its use as a standard metric).

In reference to the first point, though the χ^2 per degree of freedom is rather high in some cases, this seems to be due to departures from spherical symmetry or to subclustering. A98 is a good example of a case where a large subcluster is responsible for a significant departure from the King model (see Fig. 1). When such clumps were obvious, these points have been underweighted.

One of the more interesting results to come out of the analysis of core radii is that, while the central

TABLE 1

CLUSTER PARAMETERS

Cluster	R_{cor} (Mpc)	R_{eff} (Mpc)	Core Density N_0*	Total Density ρ*	$L_{cor}/10^{12}\ L_{\odot}$	$L_{tot}/10^{13}\ L_{\odot}$
A2256.....	0.49	2.8	141	8.0	2.2	2.7
A2029.....	0.68 (0.35)	7.0	63 (283)	1.0	2.0 (1.2)	4.4
A274......	0.30	3.5	118	1.8	0.6	1.8
A168......	0.55	5.0	30	0.7	0.8	1.4
A154......	0.44 (0.19)	3.5	77 (563)	2.0	0.8 (0.5)	1.3
A2670.....	0.31	2.3	189	7.1	0.7	1.2
A98.......	0.48	3.0	107	7.0	1.3	2.4
A1940.....	0.52	4.7	86	1.4	1.4	2.0
A1413.....	0.57	4.8	111	2.8	2.3	4.3
A665......	0.50	3.4	168	6.0	1.6	2.0
A2218.....	0.40	3.2	484	10.2	1.7	2.8
A401......	0.40	2.3	206	11.9	1.5	2.1

* In galaxies Mpc^{-3}.

density predicted by the model is quite accurate in 10 cases, the model fails badly in A2029 and A154, both of which show a central spike. Since these central data points ($r < 1'$) seriously affect the fit (see Fig. 1), the core parameters have been calculated both with and without the central point. Two pieces of evidence point to the fact that the fit made with the central value deleted is the proper one for determination of the core size. First, the fit becomes significantly better for the entire run of data if the central point is removed. Second, the good correlation of core to total cluster parameters (discussion to follow) found in the other clusters is preserved in these two cases if the "nucleus" is omitted. As a further rationalization, fitting the data with the nucleus left in is tantamount to using a bad model to fit the data, since the 2–4 σ departure is unlikely to be a statistical fluctuation from the King or isothermal model. On the other hand, since none of the models fit *all* the data within statistical uncertainties, any conclusions that can be drawn from these models must be viewed cautiously.

In the discussion to follow, the author has taken the liberty of choosing the "nucleus excluded" core parameter as the proper one. In the diagrams, however, both cases are illustrated, with the "nucleus included" value indicated by a different symbol. In Table 1 the nucleus included values are enclosed in parentheses.

Last, the universality of R_{cor} is considered. From this sample of very rich clusters it was found that $R_{cor} = 0.47 \pm 0.11$ Mpc. This small scatter is encouraging for the cosmological application; however, there is a serious discrepancy between the core radii found in this study and those of Bahcall (1975). Table 2 compares the values of the core radii found in this investigation with those of Bahcall for the three clusters studied in common. For A2029 the "nucleus included" value of ~ 0.40 is in better agreement with Bahcall; however, since most of the galaxies in this nucleus are fainter than Bahcall's limit, the "nucleus excluded" value is probably the one with which to make the comparison.

For all data Bahcall finds $R_{cor} = 0.25 \pm 0.04$ Mpc. The reason for the factor of 2 disagreement between these sets of measurements has been searched for with no success. It was thought that mass segregation might be a factor, since Bahcall's counts were made to a brighter magnitude limit. However, when the Crossley data were inspected to the same brighter magnitude level in order to duplicate the total number of objects in Bahcall's sample, no significant change in core radius was noted other than a large rise in the uncertainty of the fit.

A gross underestimation of the background (factor of 2–3) in this study would produce core radii that are too large, but the Oemler (1974*a*) data, the luminosity functions, and the fact that the radius of a given cluster should not be a strong function of magnitude (see § II*d*) rule out this possibility.

Inaccurate location of centers would tend to increase R_{cor}, but in these three cases in particular the uncertainty is much less than a core radius. (In the clusters where the center was not well defined by a high concentration of galaxies, the total luminosity in strips was calculated and the "center of light" of the distribution was used.) Determination of the center is, however, a potential problem in the study of core radii, since the bias introduced by picking a statistical fluctuation in an otherwise less-steep core could be serious.

A final suggested explanation is based on the possibility that the Bahcall (1975) data might not constitute a magnitude-limited sample. Since Bahcall had no magnitudes for the galaxies counted, a bias to select

TABLE 2

COMPARISON OF CORE RADII

Cluster	R_{cor} (Dressler) (Mpc)	R_{cor} (Bahcall) (Mpc)
A2256........	0.49	0.20
A2029........	0.68	0.27
A401.........	0.40	0.24

to a fainter magnitude limit in the central core than in the outside of the cluster might possibly have been introduced. The author estimates that only a 0.5 mag difference could reproduce this effect (owing to the steepness of the luminosity function at these bright magnitudes). It is interesting to note that the only other magnitude-limited sample subjected to core radius analysis, that by Austin and Peach (1974*a*), finds $R_{\rm cor} = 0.38 \pm 0.11$ Mpc. In particular, for A1413 Austin and Peach find $R_{\rm cor} = 0.501$ compared with 0.57 for this study.

The disagreement among the results of Bahcall (1975), Austin and Peach (1974*a*), and this study deserves more attention because of the encouragingly small scatter found in all three investigations.

b) *Total Cluster Parameters*

It was deemed desirable to compare these core values with their counterparts for the entire cluster. This determination is subject to greater uncertainty than is the core modeling, since the total cluster size is difficult to assess. However, a reasonable estimate was made using the scheme followed by Rood *et al.* (1972), in which de Vaucouleurs's (1948) expression was fitted to the large-scale cluster distribution.

The fields of the Crossley plates alone were not large enough to completely cover many of the clusters; in these cases the Crossley data were supplemented by Shane-Wirtanen counts in the following way: the number of galaxies counted by Shane-Wirtanen in the cluster over an area equivalent to the Crossley plates was determined from the unpublished 10′ counts. The luminosity function was then inspected in order to determine the magnitude limit of the Shane-Wirtanen data. The Crossley data to these brighter magnitude limits ($m_F \approx 17.3$–17.5) were then combined with the Shane-Wirtanen counts, using the background correction determined from the latter. The results are shown in Figure 2. For some of the clusters there are no Shane-Wirtanen data because of the faintness of the high-redshift clusters. Fortunately, much of the cluster in these cases is contained on the Crossley plate, so that a reasonable estimate of overall cluster size may still be made.

The data were then fitted by computer program to de Vaucouleurs's curve to obtain an estimate of $R_{\rm eff}$. Once the effective radius has been estimated, it is a simple matter to obtain the total cluster population (number) and luminosity. Again, a magnitude limit of $M_F = -20$ was adopted as a standard, the luminosity function was extrapolated where necessary, and a table was consulted to correct for the amount of the cluster outside the area covered by the Crossley plate. This latter correction amounted to a factor of about 2–5, an enormous correction and one which may be too large if the cluster falls off more steeply as, for example, Oemler (1974*a*) assumed. At the present time there are insufficient data to accurately model cluster profiles at great distances from the cluster center. It is not even clear whether the profile varies from cluster to cluster. If one assumes, however, that such variations are small, then applying the same model to all the clusters, though it might lead to systematically incorrect richness and luminosity, should not affect the relative values of these quantities and thus should not affect the conclusions within the confines of this project.

As a final note to this section, no convincing cases of "bumps"—i.e., local maxima or minima—in the radial cluster profiles, similar to those found by Oemler (1974*a*), were found, save those which could be attributed to obvious subclustering. To confirm their existence, the clusters in which such features are found should be analyzed in angular as well as radial dependence in order to eliminate the possibility of a contaminating subcluster or adjacent cluster. Also, certain kinds of departure from spherical symmetry could play a role. Assuming the scale size for clustering and the low density where these "bumps" occur, even a minor perturbation could frequently make itself felt.

c) *Discussion*

i) *Comparison of Core to Total Cluster Parameters*

A comparison of the parameters obtained for the cores of the clusters and their counterparts for the entire cluster is an aid in judging the reliability of each analysis. Figures 3–6 show the results of comparison of $R_{\rm cor}$ to $R_{\rm eff}$, $N_{\rm cor}$ to $N_{\rm tot}$, $L_{\rm cor}$ to $L_{\rm tot}$, and N_0 to $\rho_{\rm tot}$. In every case the correlation was much better than had been expected, which implies that the errors have been overestimated. In each diagram the use of the "nucleus omitted" fits for A2029 and A154 brings these clusters into agreement with the trend of the data.

It should be reemphasized that, in most cases, the Shane-Wirtanen counts were the critical factor in the estimation of the total cluster size and that these counts were not included in the core radius determinations. Even for the few clusters where the same data were used in both analyses, the fitting procedure tended to weight the data rather differently, with the innermost points determining $R_{\rm cor}$ and the other points determining $R_{\rm eff}$. The two quantities are then, in most cases, rather independent.

The agreement of the core and total cluster parameters is significant because it implies that the core parameters, which are more easily and reliably obtained than the total cluster parameters, are good estimates of the gross cluster characteristics. Furthermore, the correlation between these two sets of data implies a coherence of the large- and small-scale behavior of the clusters, certainly a helpful concept for the understanding of cluster evolution.

When one considers the errors in estimating these quantities, particularly the total cluster parameters where background and other cluster contamination are a serious problem, the data are consistent with a perfect correlation between the two sets of data. An inverse correlation of these two radii, such as was found by Austin and Peach (1974*a*) for $R_{\rm cor}$ and R, does not appear to be consistent with these data.

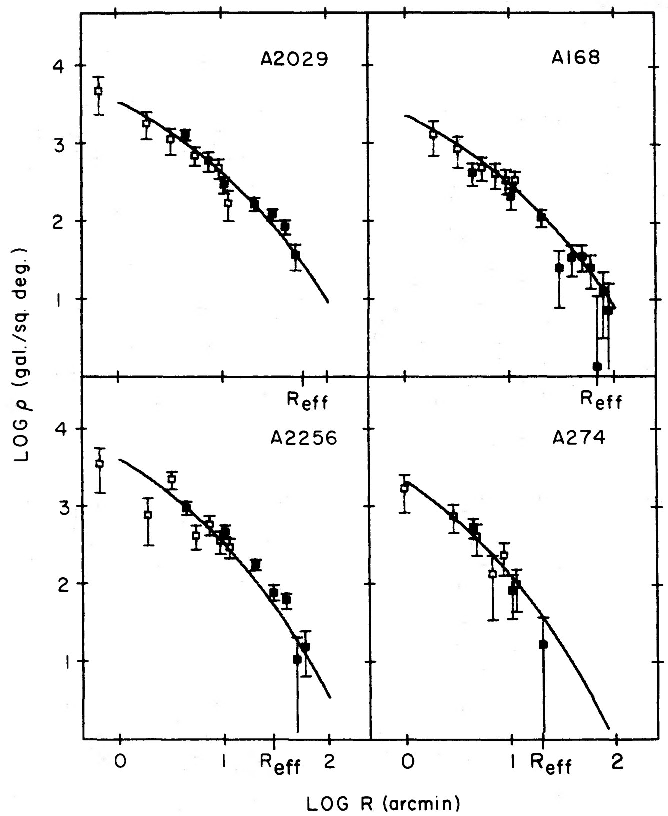

FIG. 2*a*

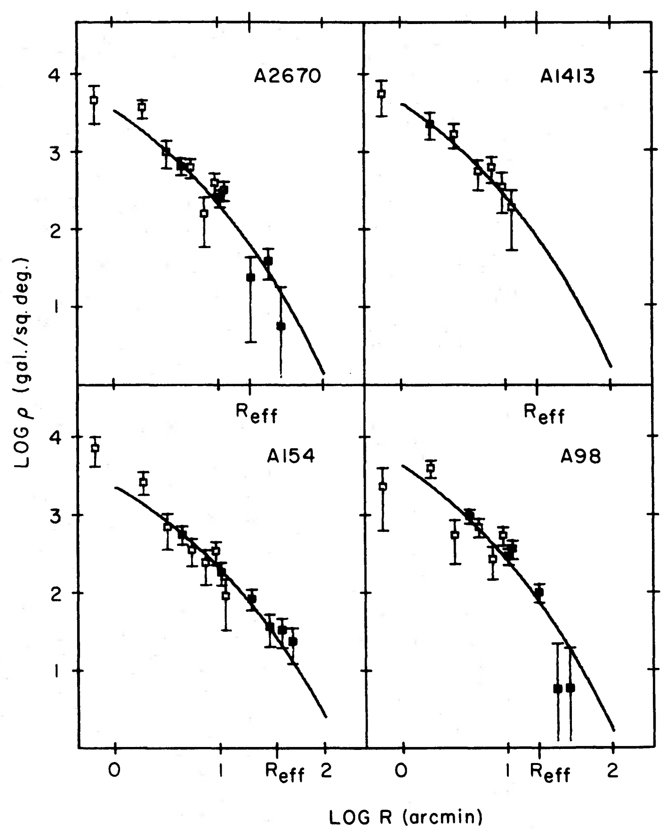

FIG. 2*b*

FIG. 2.—Total cluster profile, showing both the Crossley counts (*open squares*) and the Shane-Wirtanen data (*solid squares*). The appropriate de Vaucouleurs model is plotted, and $R_{\rm eff}$ is indicated.

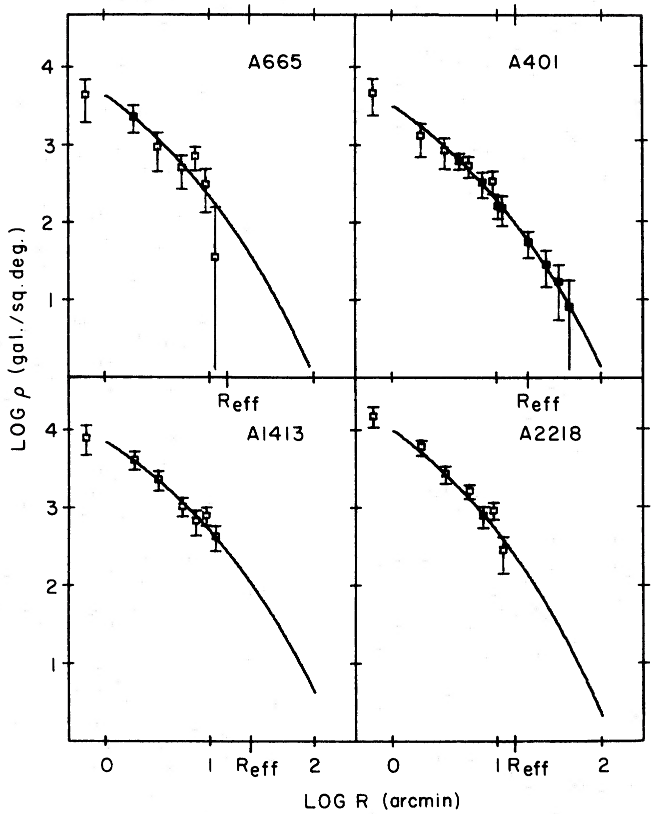

FIG. 2c

FIG. 2.—*Continued*

ii) *The Richness Parameter*

Abell's (1958) criterion for estimating richness was based on the number of galaxies within a 2 mag interval fainter than the third brightest member. As such, it contained the assumption that the luminosity function was essentially universal, since a change in the slope of the bright end from cluster to cluster could enhance or detract from a cluster's "richness" even though its total population might be unchanged. This and the unfortunate lack of photometric data to establish such a magnitude interval give richness determinations that are, on the whole, consistent but that occasionally give a poor estimation of the total cluster population. These limitations notwithstanding, the value of Abell's work cannot be overestimated.

The most natural richness criterion is based on the total number of galaxies, a rather difficult number to estimate. Inspection of Figure 4 indicates, however,

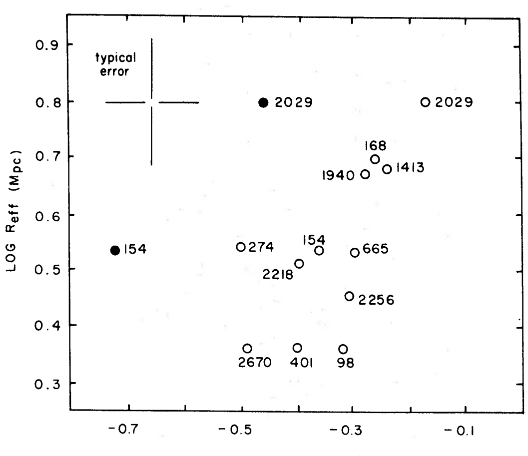

FIG. 3.—Radius of the core versus "total radius," R_{eff}. In Figs. 3–6, the solid points indicate the values for the nucleus included model.

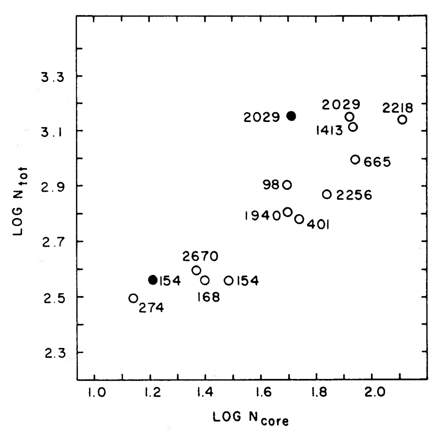

FIG. 4.—Number of galaxies in the core versus total number (as estimated from de Vaucouleurs's expression).

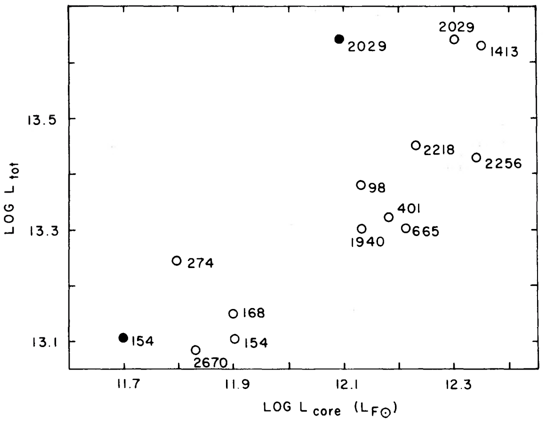

FIG. 5.—Luminosity of the core galaxies as compared with the total luminosity of the cluster.

that N_{cor}, the central density multiplied by the core volume, gives a reliable estimate of N_{tot}. A system that seems to make even more sense in light of the variations in the luminosity functions is the estimation of the total or core luminosity. This should be converted to mass using $\mathfrak{M}/L$ ratios, but because of the uncertainties involved in this area, no attempt has been made to do so. These quantities have been normalized in the following way. The cluster with the highest N_{cor}, for example, has been assigned a richness of 5 in this category. The other clusters have been assigned values from 0 to 5 in direct proportion to their comparison with the "richest" cluster. Table 3 compares these four measures (N_{cor}, N_{tot}, L_{cor}, L_{tot}) of richness with the Abell parameter. The table shows a good correlation of the various parameters which might be used to indicate richness, although, in fairness, it should be pointed out that they are not totally independent measures. An average of the four parameters, given in column (6), has been adopted as the richness measure in this study.

The table also demonstrates that Abell's richness classes may be unreliable when the clusters become very rich. For example, A2029 is extremely rich and was probably underestimated at richness class 2 by Abell because of its lack of very bright galaxies. A274 is classified by Abell as richness 3, but it is one of the poorest in this sample despite its abundance of very bright galaxies. A665, the richest cluster in Abell's catalog according to him, is actually surpassed by three clusters in this sample alone, one each of richness classes 2, 3, and 4. From the data from Rood *et al.* (1972), the value for the Coma Cluster on this richness scale is 2.9 as compared to 4.5 for A1413, the richest cluster in this study. Apparently, there are relatively few clusters in the Abell catalog that are richer than Coma, and these may be only about a factor of 2 richer at most.

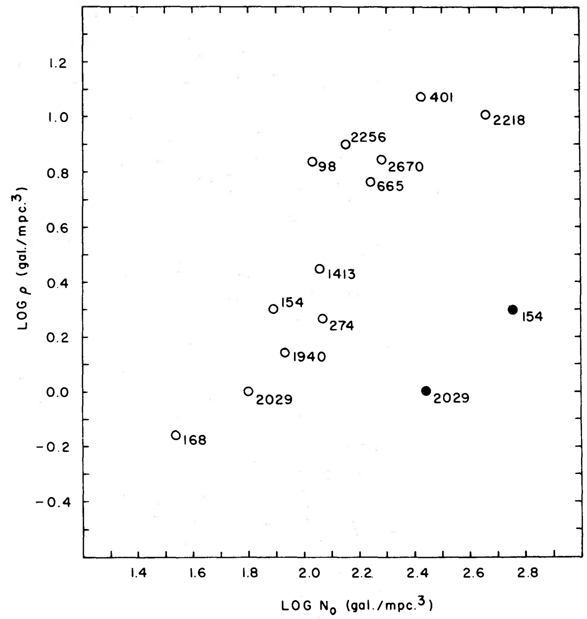

FIG. 6.—Central density of galaxies versus overall average density.

TABLE 3

RELATIVE RICHNESS CRITERIA

Cluster (1)	N_{cor} (2)	N_{tot} (3)	L_{cor} (4)	L_{tot} (5)	Average Richness (6)	Abell Richness (7)
A2256.............	2.7	2.6	4.8	3.1	3.3	2
A2029.............	3.2	5.0	4.4	5.0	4.4	2
A274.............	0.5	1.1	1.4	2.0	1.3	3
A168.............	0.9	1.3	1.8	1.5	1.4	2
A154.............	1.1	1.3	1.8	1.5	1.4	1
A2670.............	0.9	1.3	1.5	1.4	1.4	3
A98.............	1.9	2.8	3.0	2.7	2.6	3
A1940.............	2.0	2.2	3.0	2.3	2.4	3
A1413.............	3.3	4.6	5.0	4.9	4.5	3
A665.............	3.4	3.5	3.6	2.3	3.2	5
A2218.............	5.0	5.0	3.8	3.2	4.3	4
A401.............	2.1	2.2	3.4	2.4	2.5	2
A1656 (Coma)*.....	2.0	3.3	2.6	3.5	2.9	2

* Data from Rood *et al.* 1972.

d) *Evidence for Equipartition*

It is generally believed that the process of equipartition is far from complete in clusters of galaxies because of the lack of sufficient time for the process. Oemler's (1974*a*) data suggested that equipartition had proceeded to the point where the brightest cluster members were noticeably affected. As the process continues, the massive galaxies lose energy to the less massive ones; consequently, the massive ones fall toward the center of the cluster. Therefore, equipartition will result in a segregation of mass or, in this case, luminosity. Specifically, Oemler found that, for the average of his data, the brightest 2 mag of the cluster population were systematically closer to the cluster center than were the fainter members.

In order to check the progress of equipartition in each cluster in the present sample, the average radius was determined for galaxies brighter than $M_F = -21$ in four intervals of brightness. The advantage of studying very rich clusters was again apparent, since statistically significant results could be derived for each cluster rather than only for the data sample as a whole. These average radii are plotted in Figure 7, where the error bars represent the standard deviation of the mean.

In the clusters which show some evidence for equipartition, A274, A2256, and A2218, the results are in agreement with Oemler's (1974*a*) contention that there is no indication of the process fainter than $M_F = -22$. A154, A1940, and A665 show unusually "noisy" distributions, but it is difficult to assess the significance of this result without an interpretation.

The most interesting result to come out of this analysis is the lack of evidence for equipartition in the cD clusters (A2029, A2670, A1413, A2218, A401). If Oemler's (1974*a*) and Hickson's (1976) view that cD clusters are the most evolved distributions of galaxies is correct, one would naively expect the segregation effect to be the most pronounced in these clusters. However, in only one of the five cD clusters, A2218, is there any evidence at all that the brighter galaxies are more concentrated toward the cluster center. In fact, if one excludes A2218, the data for the cD clusters are consistent with the statement that the brightest galaxies are less concentrated than the fainter ones.

These data could be interpreted as evidence for the destruction of bright galaxies in the core by the cD galaxy. (For this reason, the cD galaxies themselves have not been included in analyzing the average radii.) If, for example, the dynamical friction mechanism of Ostriker and Tremaine (1976) (discussed in Paper I) were at work, then there would be perhaps three types of distributions one would expect to see in a diagram like Figure 7. In the first stage, insufficient cluster age would have prevented significant equipartition from occurring, and no mass segregation would have occurred. Presumably A168 and A98 would be examples of this stage. With sufficient time the cluster should show the brighter members at systematically smaller radii from the cluster center. A2256, A274, and A2218 are perhaps the only clear examples in

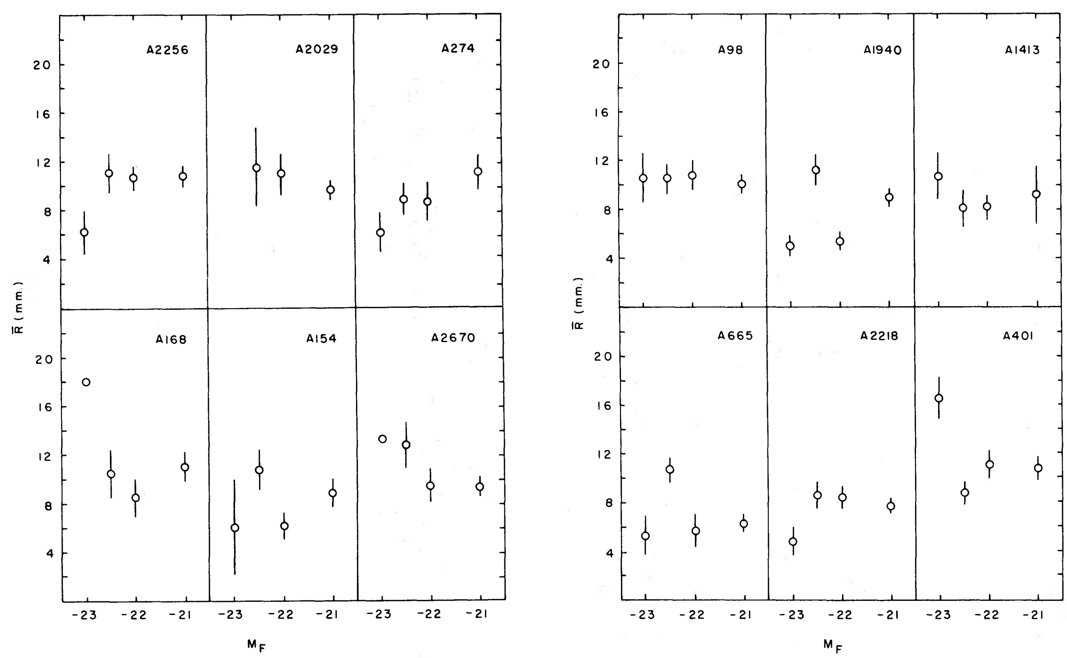

FIG. 7*a* FIG. 7*b*

FIG. 7.—Average radial distance from the center of the cluster for galaxies of different brightness. The galaxies have been grouped as follows: $M_F \leq -23.0$, $-23.0 < M_F \leq -22.5$, $-22.5 < M_F \leq -22.0$, $-22.0 < M_F \leq -21.0$. Four of the five cD clusters (A2029, A2670, A1413, A401) show no signs of equipartition and in fact, show possible decentralization of the brightest galaxies.

these data, although Oemler's (1974*a*) result for the average of his data is good evidence. In the final stage, however, the brighter galaxies which have taken up residence in the core of a cD cluster could begin to lose their identities as tidal stripping would reduce their luminosities, and they might be completely disrupted if they spiraled into the center as a result of dynamical friction. Thus a hole in the bright galaxy distribution might develop. The only remaining bright galaxies in the cluster might be the ones too far from the core of the cD cluster to suffer the interactive effects, and thus the bright galaxies would appear less concentrated toward the cluster center than would the faint ones. Presumably it would also be possible to have a combination of the second and third possibilities, such that the effect of equipartition would be compensated for by the destruction of the bright galaxies.

The galaxy distributions in four of the five cD clusters are consistent with this third possibility, and it is particularly interesting that these are the only clusters which are. The only exception is A2218, and the galaxies here could be in the process of being disrupted, as indicated by their proximity to the cD. Certainly, a larger sample of cD clusters should be investigated for evidence of the lack of apparent equipartition, but the data in this study are quite suggestive.

e) *Alignment Properties*

There are two types of alignment one might expect in clusters of galaxies: (1) the alignment of an elongated cluster as a whole to an elongated giant galaxy or chain of galaxies and (2) the alignment of the member galaxies with each other or to the cluster core or center.

It has long been known that certain clusters containing cD galaxies exhibit the first type of alignment. In 1964, Matthews, Morgan, and Schmidt pointed out that A2029 and A401 both exhibited alignment of the cluster to the central highly elongated cD galaxy. Sastry (1968) confirmed this claim and added other examples, among them A2199. A1413 was found by Sastry not to show such an effect, but Sastry was limited to the brightest 30 members, and Austin and Peach (1974*b*) later found significant alignment in this cluster for the fainter members. The only other cD clusters in the present study not mentioned by these authors are A2218 and A2670. A2218 shows a significant elongation of the central region of the cluster along the axis of the cD. A2670 shows no elongation of the cluster, but the cD in this cluster is also circular. It is interesting to note that none of the seven non-cD clusters in this sample displayed a significant flattening of the galaxy distribution.

Of the five giant cD galaxies in this sample, which represent the brightest in their class, all but one are highly elliptical and all but that one lie in clusters which are noticeably flattened and aligned with the cD. Furthermore, the cD galaxies seem to increase in ellipticity with increasing radius, as evidenced by A2029 (see Fig. 8), so that the ellipticity of the cD becomes comparable to that of the surrounding galaxy distribution.

The large ellipticities of these galaxies are remarkable, especially when one considers that random orientations of elliptical galaxies make them appear, on the average, less elliptical than they actually are. In comparison with the distribution of eccentricities of normal giant elliptical galaxies (Thompson 1976), these cD galaxies are noticeably flatter. For example, Thompson finds the "average" elliptical to be E1.5 on the Hubble system as compared to an average of E2.5 for these five cD galaxies. A qualitative investigation by the author of the type cD clusters studied by Matthews *et al.* indicates that, of the 10 examples, four contain very elliptical cD galaxies, four are more moderate, and only two are roughly circular.

The obvious implication of this alignment between highly elliptical cD's and their clusters is that the cD is a function of its environment, either from birth or from evolution. Such a correlation of the cluster and cD orientation could suggest a mechanism of alignment operating at the time of formation of the cluster. The most likely explanation is rotation of the cluster and the giant cD, although a nonrotating system of elliptical orbits is also possible. It is difficult to see

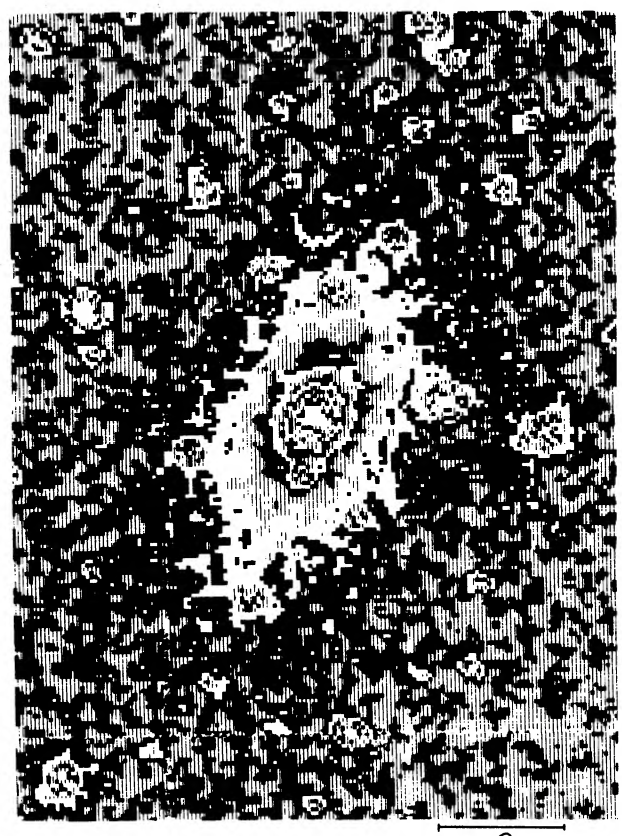

FIG. 8.—Central cD galaxy in A2029 (scanned by D. Burstein with the UC Berkeley PDS system), showing the increasing ellipticity of the outer isophotes.

why rotation would favor the formation or the evolution of a cD galaxy, since rotation at the time of formation might tend to discourage the collection of a large mass at the center and since the higher angular momentum of the system should make close encounters of the other cluster members with the cD less likely. On the other hand, a flattened distribution might imply highly elliptical orbits, which could favor the interaction of galaxies with the cD by more frequent crossings of the cluster core. Accretion of cluster material by the cD provides a natural explanation for the correlation of cluster and cD shape and orientation. These flattened galaxy distributions and their highly elliptical cD's may therefore be valuable clues in explaining the existence of cD galaxies.

In the course of the data reductions, the ellipticities and orientations of all noticeably flattened galaxies were recorded. These data were analyzed with a method similar to that of Thompson in order to search for the alignment of the projected major axes of the galaxies in a given direction or along radial vectors to the center of the cluster. Thompson's work includes a summary of the various mechanisms for galaxy alignment, including the torques exerted on galaxies by neighbors or by the core of the cluster, and the results of a collapsing asymmetrical cloud.

Owing to the graininess of the images of these distant galaxies, only 20%–50% were flattened enough to be recognized as such by the program. However, because of the richness of these clusters, this amounted to 50–100 members in most cases.

The computer program assigned only rough position angles to the galaxies, each bin being 22.°5 wide. The majority of clusters showed no alignment whatsoever, so it was assumed that the program had negligible built-in bias. For the clusters where a significant alignment was found, however, the computer's determinations were checked by the less reliable but more skeptical eye of the author. About 90% of the computer's identifications were easily verifiable.

Those distributions which departed from random distributions by more than 3 σ are presented in histogram form in Figure 9. A2029, A2670, and A2218 were found to show alignment of the galaxies along a given axis. Only A2218 showed a significant radial alignment; this would be expected, since the alignment along an axis took place in a flattened distribution.

Only in the case of A2218 does the observed alignment of the galaxies match the orientation of the cD; because this result is based on only two plates, both of which could have elongated images due to imperfect guiding, this result is uncertain. A2029 seems to have alignment perpendicular to the cD, and so might A2670 if the cD is elongated along the line of sight. Since no mechanism has been proposed, to the author's knowledge, which might account for such perpendicular alignment, this result is merely presented without further discussion.

In summary, the data collected in this and other studies indicate that cD clusters and cD galaxies are flattened systems, which may be the result of rotation of the cluster or the remnant of an initially flat distribution. The possible alignment of galaxies in A2218, if confirmed, would support the rotation hypothesis. How either of these possibilities might be related to the cD phenomenon is an open question, but the cD galaxies themselves seem significantly more flattened than normal giant ellipticals, suggesting that they have been formed with material from a flattened system.

III. MASS/LIGHT RATIOS

The treatment of the dynamics followed that of Rood *et al.* (1972), where the King model was used to obtain $\mathfrak{M}/L$ for the cluster core and the total cluster $\mathfrak{M}/L$ was estimated using de Vaucouleurs's (1948) curve to describe the cluster profile.

The radial velocities of the galaxies were obtained with the image-dissector scanner at the Cassegrain focus of the Lick 3 m reflector; the method of reduction is described in detail in Faber and Dressler (1977). Because of the difficulty in obtaining redshifts for such faint galaxies, the velocity dispersion is usually based on only 10–20 galaxies, so that the error in the velocity dispersion can be quite large (~20%). Six velocity dispersions were obtained, which, in addition to the result for A2670 by Oemler (1973) and the dispersion for A401 by Hintzen, Scott, and Tarenghi (1977), brings the total to eight of the 12 clusters (see Paper I, Table 1).

The velocity dispersion for A2029 provided the only serious ambiguity, since the value of 1514 km s^{-1} for the line-of-sight dispersion included three objects of questionable membership (see Faber and Dressler). Without these three galaxies the velocity dispersion is only 788 km s^{-1}. In the following discussion the use of the lower velocity dispersion is indicated in the tables by quantities in square brackets and in the figures by square symbols. Until additional redshifts are available it will have to be assumed that the true

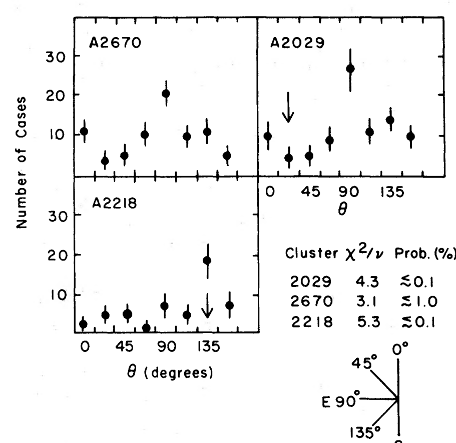

FIG. 9.—Alignment of axes of galaxies in three clusters. The χ^2 per degree of freedom is given, as well as the probability of such a distribution. Presence of an arrow indicates the orientation of a cD galaxy.

TABLE 4

$\mathfrak{M}/L_F$*

Cluster	ΔV	$\mathfrak{M}/L_{\rm cor}$	$\mathfrak{M}/L_{\rm tot}$
A2556	1274	270	293
A2029	1414 [788]	580 [157]	639 [174][ ] → lower σ
A274	...	(350)	(411)
A168	576	174	207
A154	829	282	323
A2760	890[1]	267	269
A98	786	162	134
A1940	715	145	210
A1413	...	(185)	(192)
A665	...	(226)	(298)
A2218	...	(172)	(200)
A401	1390[2]	369	370
Coma	861[3]	174[3]	176[3]

NOTE.—( ) → $\sigma \equiv 1000$.

* $\mathfrak{M}/L_v \approx 1.15\,(\mathfrak{M}/L_F)$.

REFERENCES.—(1) Oemler 1973. (2) Hintzen *et al.* 1977. (3) Rood *et al.* 1972.

velocity dispersion could lie at either extreme (or less likely in between).

Since the velocities were chiefly from galaxies in the brightest 3 mag of the cluster, the core radius was reexamined at this somewhat higher magnitude limit. No significant systematic differences were found in this subset of the data, so the value obtained for the entire sample was adopted. $R_{\rm eff}$ was automatically determined in the proper magnitude range from the use of the Shane-Wirtanen counts.

One final correction was made to the velocity dispersions before the $\mathfrak{M}/L$ ratios were calculated. The velocities were generally from a region of about 2–3 $R_{\rm cor}$, so that they were not directly applicable to the dynamics of the smaller core and larger cluster as a whole. Models by van Albada (1961) and Peebles (1970) suggest that the velocity dispersion of a cluster should decrease with radius, and Rood *et al.* (1972) compare the data for the Coma cluster with the prediction made for a King model and find reasonable agreement. In accordance with Figure 7 of Rood *et al.* (1972), the velocity dispersions have been decreased by 10% for use in the total cluster $\mathfrak{M}/L$ determination and increased by 10% for application to the core. The values of 1031 km s^{-1} for the core and 861 km s^{-1} for the entire cluster derived by Rood *et al.* for the Coma cluster are in good agreement with this correction.

From relations given in Rood *et al.* (1972) it is a simple matter to obtain the core mass density from the core radius and the velocity dispersion:

$$\rho_0 = 1.74 \times 10^8 \frac{\sigma^2\,(\text{km s}^{-1})^2}{R_{\rm cor}{}^2\ \text{Mpc}^2}\,\mathfrak{M}_\odot\ \text{Mpc}^{-3}\,. \quad (2)$$

The core luminosity density is calculated by multiplying the core density N_0 of the best-fitting King model by the average luminosity per galaxy, and then correcting for the amount of unseen cluster luminosity in (1) the outer envelopes of galaxies and (2) the galaxies fainter than $M_F = -20$. The results for the core mass/light ratios are presented in Table 4. In the four clusters for which velocity dispersions were unavailable, $\mathfrak{M}/L$ has been calculated using $\sigma = 1000$ km s^{-1} and the values thus obtained are enclosed by parentheses.

The calculation of $\mathfrak{M}/L$ for the entire cluster is equally straightforward. The mass of the cluster has been determined using equation (8) from Rood *et al.* (1972), with the value $R_{\rm eff}$ determined from the cluster profile and the total luminosity of the cluster as derived in § II*b*.

Figure 10 shows the comparison between $\mathfrak{M}/L_{\rm cor}$ and $\mathfrak{M}/L_{\rm tot}$. Open circles in Figure 10 represent clusters where σ was assumed to be 1000 km s^{-1}. The correlation is good, as it must be, because of the good correlation between radius and luminosity. The $\mathfrak{M}/L$ values for the cluster as a whole seem to be systematically 10% higher than the core values. This could imply that the total radii have been systematically underestimated or that the velocity dispersion has been incorrectly adjusted for the core or outer regions.

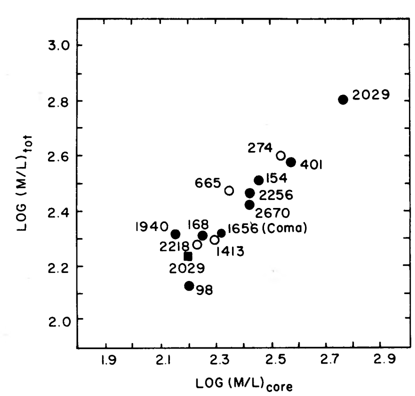

FIG. 10.—$\mathfrak{M}/L$ ratios derived for the core of the clusters as compared with $\mathfrak{M}/L$ for the entire cluster. (The square symbol for A2029 refers to the lower velocity dispersion.) Open circles represent clusters where σ was assumed to be 1000 km s^{-1}.

Figure 10 also includes the values for Coma from Rood *et al.* (1972).

The values found in this study are comparable with $\mathfrak{M}/L_v = 250$ for Virgo (van den Bergh 1977), $\mathfrak{M}/L_v = 200$ for Coma (Rood *et al.* 1972), and $\mathfrak{M}/L_v = 350$ for Perseus (Bahcall 1974, corrected for $H_0 = 50$), all obtained for the core parameters. Reasonable agreement also exists between the $\mathfrak{M}/L$ ratios for this study and the average for the eight clusters studied by Oemler (1974*b*), $\mathfrak{M}/L_v = 200$.

The mass/light ratio depends on richness, cluster size R, and velocity dispersion σ in the following way:

$$\frac{\mathfrak{M}}{L} \propto \frac{R\sigma^2}{\text{richness}} . \tag{3}$$

Figure 11 shows an apparent lack of dependence of $\mathfrak{M}/L$ on cluster richness. Oemler (1974*a*) displayed a correlation of R_G with L_{tot} (and thus richness) in his data, but the data in this study do not confirm his result (Figs. 12*a* and 12*b*). Similarly, the data from this study do not confirm a correlation of $\mathfrak{M}/L$ with radius, as reported by Rood, Rothman, and Turnrose (1970). There is also no indication in the data from this study that the velocity dispersions increase with increasing cluster richness. The large scatter in these two relationships apparently results in the absence of a correlation between $\mathfrak{M}/L$ and cluster richness.

However, there is another interesting parameter which has been omitted. The clusters which are known X-ray emitters (Kellogg *et al.* 1973) probably contain intracluster gas. Tarter and Silk (1974) predict an amount of gas on the order of 15% of the virial mass for the Coma cluster. Though this amount of gas is insufficient to bind the cluster, there is, apparently, as much matter in the form of gas as in the luminous galaxies. This means that the observed $\mathfrak{M}/L$ ratios for the strong X-ray emitters could be too high by a factor of 2 or so. Of the data in this sample, two of the clusters are among the strongest X-ray emitters, A2256 and A401, and their $\mathfrak{M}/L$ ratios are 270 and 369, respectively. Perseus has a rather high $\mathfrak{M}/L$ of 350, and the value for Coma is 174. If all these were reduced by a factor of 2, they would be in better agreement with the values of the other very rich clusters, A98, A1940, and A2029 (assuming the lower velocity dispersion in this case), of about 100–200. To make matters even more complicated, however, while most of the poorer clusters are close enough for detection as strong X-ray sources, a cluster like A1413 or A1940 would have to be a very strong emitter to be detected with present instrumentation. Therefore, some of these richer distant clusters may have even lower $\mathfrak{M}/L$ values because of unseen intracluster gas. Hence it is possible that a trend of lower $\mathfrak{M}/L$ with richness is hidden in Figure 11.

In summary, the data are consistent with no dependence of $\mathfrak{M}/L$ on richness or perhaps with declining $\mathfrak{M}/L$ in the richest examples. The possibility that a significant amount of nonluminous material is present in the very rich clusters means that it is quite possible the $\mathfrak{M}/L_v$ ratios of these clusters all lie between 100 and 200. When one considers the results of Turner's (1976) treatment of binary systems and Gott and Turner's (1977) study of small groups of galaxies, where in both cases $\mathfrak{M}/L_v \approx 100$ was found for ellipticals and $\mathfrak{M}/L_v \approx 50$ for spirals, it seems that

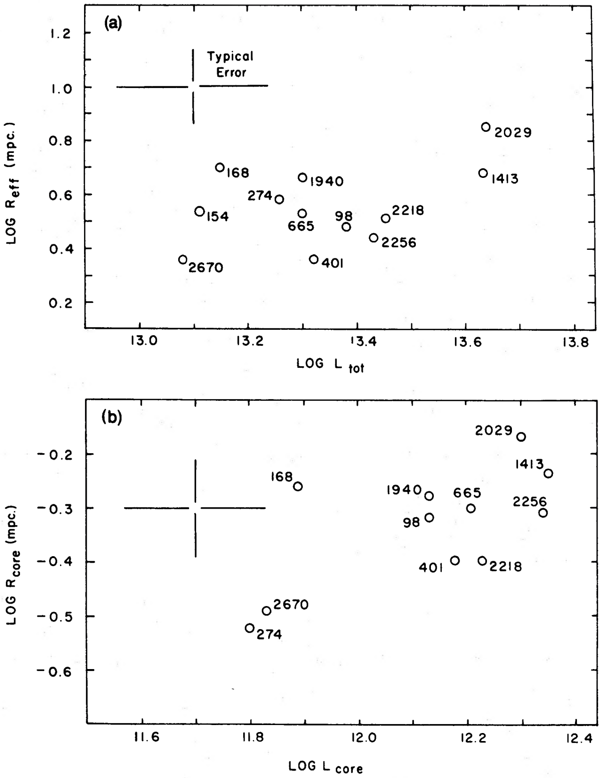

FIG. 12.—(*a*) The total luminosity versus effective radius, and (*b*) core luminosity versus core radius.

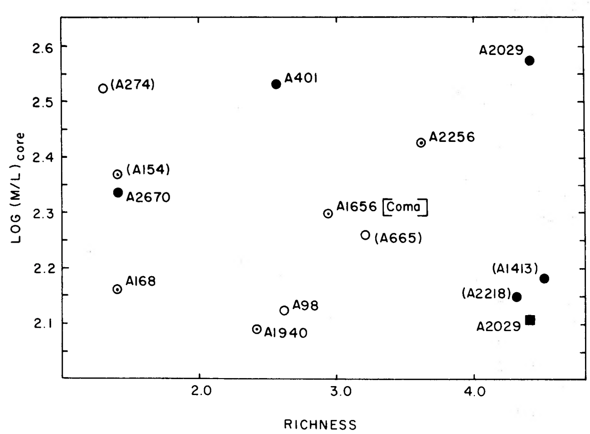

FIG. 11.—Log $(\mathfrak{M}/L)_{\text{cor}}$ versus richness. *Solid circles*, Bautz-Morgan I; *circles with dots*, Bautz-Morgan II; *open circles*, Bautz-Morgan III. Square symbol for A2029 indicates use of lower ΔV. Numbers in parentheses represent cases where σ was assumed to be 1000 km s^{-1}.

all the data from binary systems to very rich clusters give the same $\mathfrak{M}/L$ within the errors.

The mass discrepancy problem seems to have settled into one nagging issue. Within a galaxy, rotation curves and velocity dispersions (e.g., Faber *et al.* 1977; Faber and Jackson 1976) give $\mathfrak{M}/L \lesssim 10$. Immediately outside the realm of the galaxy (whether in binary groups or large clusters), the $\mathfrak{M}/L$ jumps a factor of 5–20. As has been the case for some 40 years, the answer to this problem awaits more data and more inspiration, not necessarily in that order.

IV. POPULATION INFORMATION

Oemler (1974*a*) suggested that the population variation in clusters of galaxies breaks down into three distinct groups: spiral-rich, spiral-poor, and cD clusters. Though a complete check of this contention is desirable, the greater distances of the clusters in the present study, compared to the 10 clusters Oemler used to form his conclusions, made accurate morphological classifications impossible, even with the somewhat better plate scale available for this study.

As a compromise, a cruder classification scheme was adopted, in which the author decided by eye whether a galaxy was an "elliptical" or "nonelliptical." Galaxies typed were usually brighter than $m_F \approx 17.5$ for the closer clusters, and $m_F \approx 18.0$ in the more distant ones.

The nonelliptical class included any highly flattened galaxy (disk systems, including S0's) and any galaxy with irregular wisps, tails, or distinguishing marks. The elliptical category was defined simply by the lack of departure from a smooth, elliptical profile. It was thought that the increasing redshift would seriously hamper the effort to distinguish the nonelliptical members, but surprisingly, even at $z = 0.18$ for A665, a majority of members inspected showed signs of being nonelliptical.

The percentages of ellipticals/nonellipticals for Oemler's three types are 33%/77% for cD clusters, 17%/83% for spiral-rich clusters, and 25%/75% for spiral-poor clusters.

If we assume that $\frac{1}{3}$ of the S0's are misidentified as ellipticals from the difficulty in recognizing disks seen face-on, the percentages of observed ellipticals/nonellipticals become 48%/52%, 28%/72%, and 42%/58% for the cD, spiral-rich, and spiral-poor clusters, respectively. Table 5 compares these predictions with the actual data for the 12 clusters. The average of all five cD clusters does indeed show the proper proportions of galaxy types, but the difference between A401 and A2670, both cD clusters, seems too large to be due to identification errors. Of the other seven clusters, only A98 seems to be deviant. It is the second richest in ellipticals of the 12 clusters and yet is not a cD cluster.

The uncertainty in these data is very great, and the ability to distinguish between the Oemler (1974*a*) types is poor; yet these three clusters seem to cast some doubt as to the reality of the discrete groups suggested by Oemler. In view of the significance of quantized population groups, more data are needed to verify the discrete or continuous nature of these distributions. Richer clusters offer a better vehicle because of better statistics, but they suffer the serious disadvantage of requiring higher plate scale and thus larger-aperture telescopes.

TABLE 5

CLUSTER POPULATION

Cluster	% Ellipticals	% Nonellipticals	Remarks
A2256	42	58	
A2029	47	53	cD
A274	32	68	
A168	39	51	
A154	35	65	
A2670	37	63	cD
A98	53	47	
A1940	38	62	
A1413	49	51	cD
A665	39	61	
A2218	48	52	cD
A401	57	43	cD
Predictions			
cD	48	52	
Spiral-rich	28	72	
Spiral-poor	42	58	

V. CONCLUSIONS

Because of the small number of clusters analyzed in this work, conclusions drawn must be considered tentative and await confirmation by more extensive studies. The following discussion summarizes the major findings contained in Paper II and outlines some possibilities for future investigations.

1. The small-scale (i.e., core) and large-scale (e.g., radius, density, and luminosity) characteristics in a given cluster seem well correlated. The limitations imposed by the background severely hamper detailed modeling of the entire cluster and make it particularly difficult to determine how steep the cluster profile becomes in the low-density outskirts. Furthermore, adding individual profiles to form a composite may be unjustifiable if spatial distributions differ from cluster to cluster, as will be the case, for example, if the galaxy distributions are subject to evolutionary change. For these reasons, it is important to know if the more easily determined core parameters adequately describe the entire cluster, as is indicated here.

2. The cD galaxies appear preferentially in "flattened" clusters, and the cD's themselves are more eccentric than normal ellipticals. Furthermore, the alignment of these flat distributions of galaxies with the axis of the cD is common, suggesting that a cD's formation is linked to its environment.

Luminosity functions like that of A2029, a cluster with an enormous cD and few other bright galaxies, suggest that cD's may grow by accretion of their neighbors (see Paper I). Further support for this view in Paper II is the presence of a density spike in excess of the normal cluster profile in the "nuclear region" of A2029. These numerous companions may be the remnants of brighter galaxies accreted by the cD. On the other hand, the short time scale for accretion by dynamical friction (~one crossing time) indicates that one would not expect to see several galaxies undergoing this process simultaneously. If such density enhancements are to be explained by dynamical friction, some mechanism must halt the effectiveness of the process when the companions draw sufficiently close to the accreting body.

The distribution of bright galaxies in cD clusters may also give support to the dynamical friction model. Little, if any, tendency toward equipartition is shown by cD clusters, presumably the most dynamically evolved clusters. Indeed, many seem to show decentralization of bright galaxies, which is again suggestive of a scheme where bright galaxies are accreted by the cD when they enter its domain.

3. The mass/light ratios of 100–300 in these clusters are found to agree with results from previous studies of galaxy associations of all richnesses. No significant correlations of $\mathfrak{M}/L$ with other cluster characteristics have been found here.

4. Populations of ellipticals/nonellipticals in these clusters seem to provide possible counterexamples to Oemler's (1974*a*) discrete population types. Particularly, two cD clusters show a large discrepancy in each direction from the proportion of E's/non-E's expected in Oemler's cD-type clusters.

Such an unusual phenomenon as discrete population types deserves a more detailed and statistically sound analysis. If such groups are real, a natural question to ask is whether they represent initial or evolutionary conditions. If an evolutionary scheme is correct, is age the only important parameter, or do other factors (e.g., initial gas density or intracluster medium) help determine the evolving population of a cluster?

It is hoped that answers to these questions lie not far ahead in the infant study of clusters of galaxies.

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