

THE SYSTEMATIC PROPERTIES OF CLUSTERS OF GALAXIES. I. PHOTOMETRY OF 15 CLUSTERS

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ABSTRACT

Fifteen rich clusters of galaxies have been studied using a new automatic method for finding and photometering galaxies on photographic plates. It was found that their properties are such that they may be divided into three groups. Spiral-rich clusters have compositions similar to that of the field, irregular mass distributions of low density and no central concentration, and show no signs of segregation of members according to mass or morphological type. Clusters with cD galaxies are rich in ellipticals, have smooth, spherical mass distributions of high density and central concentration, have a strong deficiency of spirals in the core, and show a considerable tendency toward energy equipartition. Spiral-poor clusters, which are dominated by S0 galaxies, also show segregation by mass and morphological type, but are not as smooth, dense, or centrally condensed as the cD clusters.

The outer envelopes of all clusters have a projected density gradient of slope near 3.0. All clusters show a local minimum in the radial density distribution, the effect being strongest in the cD clusters. The mean density of clusters of all types is independent of mass. The luminosity functions of all clusters are similar, with a small dispersion in absolute magnitude. Arguments are presented that spiral-poor clusters represent a later evolutionary state of spiral-rich clusters but that cD clusters, while the most evolved, are intrinsically different.

Subject heading: galaxies, clusters of

I. INTRODUCTION

If we wish to obtain some understanding of the present characteristics and past evolution of clusters of galaxies, we need information on a sufficiently large number of objects to permit separating their systematic properties from those that are peculiar to a single cluster. Since the observations in the literature are inadequate for this purpose, a study has been made of the properties of a large group of clusters of widely varying form and richness.

The results of this study will be reported in two parts. This first paper describes observations of the static properties of clusters—namely, the positions, luminosities, and morphological types of their members—as obtained from wide-field photographic plates. Included is the description of a procedure for automatically finding and measuring galaxies on plates.

It will be shown that there are strong correlations between the various observed properties of clusters which permit them to be divided into a few fairly homogeneous groups. Arguments will be presented that the differences between these groups can be explained by different mean densities in the original protoclusters, which resulted in different rates of galaxy formation and different rates of dynamical evolution.

Paper II will deal with the dynamical properties of clusters, and with their inferred mass-luminosity ratios.

II. OBSERVATIONS

a) Choice of Objects

The objects to be studied were taken from Abell's (1958) catalog of rich clusters. Within this catalog,

those objects were selected which, of each richness class, were the nearest examples not at excessively low galactic latitude, and not in fields confused by the presence of many other clusters. Except for its richness class, the characteristics of the cluster itself were not considered in making this choice.

Some of this group were not studied because of poor plate quality or the limitations of time. Also, two clusters were later added: A2197 because of data in the literature on its internal velocity dispersion, and Zw Cl 1545.1+2104 because it had already been studied for other reasons (Oemler, Gunn, and Oke 1972). Therefore, while the original list was an unbiased sample, the final group of 15 clusters is too small and too fortuitous a selection to permit conclusions about the frequencies of clusters with various characteristics within Abell's catalog.

The final list is presented, along with the richness class, redshift, and galactic latitude of each object, in the first four columns of table 1. Unless otherwise noted, the redshifts have been taken from Noonan (1973).

b) Photometric Observations

Green and red plates were obtained of each cluster, using either the Palomar 200-inch (5-m) or the 48-inch (1.2-m) Schmidt telescope. All green exposures were made on baked IIIaJ plates behind a Wratten 4 filter. Red exposures on the 48-inch were made on 103aF, 098, and IIIaF emulsions and at the 200-inch on water-hypersensitized 098 emulsions, all behind 2.2 mm of Schott RG-1 filter. The 200-inch plates were taken by James Gunn, and two of the 48-inch plates were taken by Steven Sheckman. The 200-inch plates were 5×7

TABLE 1
CLUSTERS STUDIED

Cluster	Richness	z	(degrees)	Emulsion
Abell 194.....	0	0.0181	-43	IIIaJ
Abell 400.....	1	0.0231	-45	103aF
Abell 539.....	1	0.0267	-17	IIIaJ
Abell 665.....	5	0.183*	+35	IIIaJ
Abell 1228.....	1	0.0344	+70	103aF
Abell 1314.....	0	0.0335	+64	IIIaJ
Abell 1367.....	2	0.0205	+74	IIIaJ
Abell 1413.....	3	0.1427	+77	IIIaF
Coma cluster.....	2	0.0230	+87	098
Abell 1904.....	2	0.0719	+62	103aF
Hercules cluster.....	2	0.0360	+44	103aF
Abell 2197.....	1	0.0303	+43	IIIaJ
Abell 2199.....	2	0.0312	+43	103aF
Abell 2670.....	3	0.0753†	-69	098
Zw Cl 1545.1+2104.....	1	0.263§	+49	098

* Sargent (1973).

† Oemler (1973).

§ Oemler *et al.* (1972).

inches in size, giving a usable field of $21' \times 23'$. The 48-inch plates were either 5×7 inches ($2^\circ 0' \times 2^\circ 1'$), 10×10 inches ($4^\circ 3' \times 4^\circ 3'$), or 14×14 inches ($6^\circ 2' \times 6^\circ 2'$), depending on the angular extent of the cluster. All 10×10 inch and 14×14 inch plates had sensitometer spots placed on one corner, and one calibrated plate from the same box was developed with each batch of 5×7 inch plates. All plates were developed for 9 minutes in MWP-2 developer, using a rocker agitator to ensure even development.

Because of serious emulsion defects which rendered them unsuitable for photometry, many plates could not be used. As a consequence of this, it was impossible to measure all clusters in one color. The emulsion of the plate that was used is presented, for each cluster, in the last column of table 1. All plates were taken on the 48-inch telescope, except for those of A2670, which came from both telescopes, and those of Zw Cl 1545.1+2104.

Absolute calibration of these plates was obtained from photoelectric photometry of several galaxies in each field. Each galaxy was photometered through one large aperture, typically $40''$ in diameter for nearby objects. This was done with either the 200-inch multichannel spectrophotometer or a two-tube S20 photometer mounted on the Palomar 60-inch telescope. Filters for the 60-inch photometer were chosen to match as closely as possible the spectral response of the two photographic bands. Filters used were, in the green, 3-mm Schott BG38, 1-mm Schott GG460 and a Wratten 44; and, in the red, 3-mm Schott RG1, 3-mm Schott BG20, and 1-mm Schott BG38.

The photographic and photoelectric response curves are presented in figure 1. The green band, denoted by J , is somewhat to the blue of the V -band; and the red band, denoted by F , is similar to Sandage and Smith's (1963) R band, but is more sharply cut off at the red end. Magnitudes are defined so that, for an A0 star, $J - F = 0.0$ and $J - V = 0.0$ for the photographic bands. Both the 200-inch multichannel and 60-inch broadband photometry are tied to the absolute photometry of α Lyr (Oke and Schild 1970) through

the multichannel spectrophotometer secondary standards. J and F magnitudes of standard stars and galaxies were constructed from the multichannel scans using the photographic response functions; but because of the fairly narrow color range of the calibration objects, the errors in the photoelectric calibrations due to this are not significant for photometry of the accuracy used in this study. The photoelectric photometry showed that, for galaxies with late-type spectra, it is approximately true that

$$J = V + 0.35(B - V) \quad (1)$$

and

$$J - F = 1.1 \pm 0.10. \quad (2)$$

There were no photoelectric data on one cluster, A1413. Plates of this cluster were calibrated by using Zwicky *et al.* (1961) photometry of bright galaxies in the field. Comparison of Zwicky's photometry in other cluster fields with that done for this study showed that, for $m_p < 15.0$, the magnitudes of late-spectral-type galaxies were related by

$$m_p = m_F + 1.5 \pm 0.2. \quad (3)$$

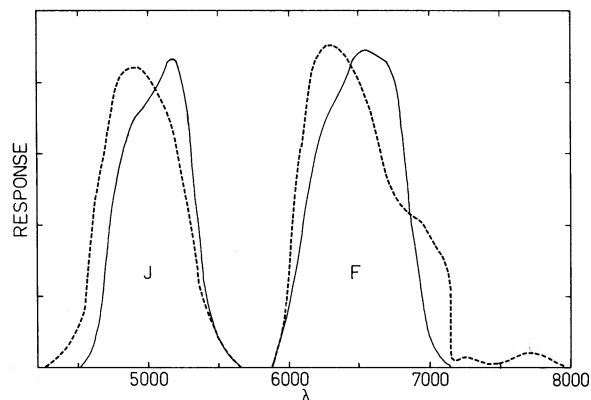


FIG. 1.—Photoelectric (dashed curves) and photographic (solid curves) response functions for the J and F bands.

c) Plate Measurement Methods

Two methods for the photometry of galaxies on photographic plates were used in this study. The first, which involves microphotometer tracings of galaxy images on a negative copy of the plate, has been described in detail elsewhere (Oemler 1973). This method was used on A1314, A539, A2670, and Zw Cl 1545.1+2104, but proved too time consuming for the very large amount of photometry which had to be done. The second method, a completely automated procedure for both finding and measuring galaxies, is based on the Caltech plate scanner. This machine is a two-axis microphotometer attached to a small computer. The computer controls carriage motion, processes the digitized output of the photometer, and writes data on magnetic tape.

The galaxy measurement process is in two parts. In the first part, the area of the plate to be studied is scanned with a long, narrow slit in a raster pattern of 256 overlapping rows. On a large computer, the data along each row are added to form 1024 overlapping boxes per row. By overlapping in each direction, we ensure that no galaxy image will be missed because it fell half in one box and half in another. On even the best of plates, the sky background density varies over the field due to variations in plate sensitivity and fog. The variation in sky density is found by an iterative procedure of ignoring the denser than average points and fitting the remainder to a low-order (3 to 5) two-dimensional least-squares polynomial fit.

Each star and galaxy in the measured field is represented by a group of points in the 256×1024 array of higher opacity than the least-squares fit to the sky. All of those groups whose peak opacity differs from that of the sky by more than some threshold value are considered as objects to be photometered, and their positions are added to a list on magnetic tape for the plate scanner. The peak opacity of each chosen point and the sky fit are saved for later use.

In the second part of the measurement process, the plate scanner moves in turn to each position on the list and performs a raster scan of a small square area centered on the object. The aperture size and digitizing rate are chosen so that each data point covers one resolution element on the plate. Among the objects which have been photometered, there are, typically, four times as many stars as galaxies. To separate the two groups, we make use of the fact that the images of stars are of higher surface brightness than those of galaxies. When the mean opacity is plotted against the image area for a group of objects, there is a clear separation of stars from galaxies down to that magnitude where it is becoming difficult to distinguish the two groups even by eye. By using a conservative criterion for the boundary between the two groups, virtually all normal galaxies are found, although there is undoubtedly some discrimination against very compact galaxies. A small number of objects near the dividing line are inspected by eye to remove any stars.

All stars having been eliminated, obtaining the galaxy magnitudes is a straightforward procedure. All

points in each raster scan are converted to relative surface brightnesses using the characteristic curve obtained from the sensitometer spots on each plate, then the sky background is removed by using the least-squares fit obtained earlier. The relative brightnesses are converted to absolute values by using those galaxies for which we have photoelectric photometry. Now, to obtain the isophotal luminosity of an object, we simply add the intensities of all points whose surface brightnesses are greater than that of the limiting isophote.

The final step is to determine the limit of completeness of this group of objects. First the galaxies are divided into magnitude intervals. It will be recalled that the selection criterion for objects was the peak measured opacity of their images. For each magnitude interval, we plot a histogram of the number of objects of each peak opacity, this quantity having been saved from the search routine. The result is a series of near-Gaussian curves which, with increasing magnitude, are more and more truncated by the selection limit. Assuming the distributions to be symmetrical, we can calculate, for each case, the fraction of objects which fall below the threshold, and thus find the incompleteness as a function of magnitude.

This entire procedure for finding and measuring galaxies has several great virtues. One is that, by measuring all parts of the galaxy image, it has the potential of high accuracy. Another is that it is completely automatic, requiring intervention only to specify the criterion for separating stars from galaxies. Its practical efficiency and accuracy will be discussed below.

d) Measurement of Clusters

Both the limitations of time and uncertainties in the corrections for field objects limit the depth to which a given field can be studied. In order to cover a sufficient area and a sufficient magnitude range, most clusters have been measured in two parts. First, a large field is measured over a restricted magnitude interval to survey the total extent of a cluster and obtain some measure of the galaxy background in its vicinity. Then, to obtain the faint end of the cluster luminosity function, a small field in the cluster center is measured to a much fainter limit.

A convenient measure of cluster scale is the Abell radius (Abell 1958) defined by

$$r_a = 5.15 \times 105/cz \text{ arc min.} \quad (4)$$

If we assume, as we shall throughout this paper, a Hubble constant, H_0 , of $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a deceleration parameter, q_0 , of 0.0, this is equivalent, for nearby objects, to a linear size of 3.0 Mpc. For a typical cluster, about 80 percent of the total mass is contained within the projected Abell radius.

For most of the clusters in this study, photometry of galaxies in the brightest 3-mag interval has covered an area out to 2 or 3 Abell radii. Usually, faint galaxies within 1 Abell radius have been studied, although occasionally a somewhat smaller area was covered.

The procedure of inferring the faint galaxy content of the entire cluster from a study of the center is legitimate only if there is no mass segregation due to two-body relaxation. We shall show later that this is true, in the relevant magnitude range, for all clusters.

In measuring individual galaxies, the size of the raster scan was chosen to be large enough to contain the entire galaxy out to the desired limiting isophote, but not so large that there would be a significant chance of including another object in the measured area. Scan areas used varied from 2' square for the brighter galaxies in the nearest clusters to 10" square for the fainter galaxies in the most distant clusters.

All galaxy photometry in this study was done to a limiting isophote of 24.1 mag per square second in the green and, its equivalent, 23.0 mag per square second in the red. This proved to be the faintest surface brightness which could be used without encountering problems due to plate noise and incorrect subtraction of the sky brightness.

The accuracy of the two methods of photometry has been checked in several ways. Thirty-six galaxies in 10 cluster fields were measured photoelectrically. When the galaxies, with a brightness range within each cluster of 2 mag, were used to calibrate plates of these clusters in the normal manner, the standard deviation in the calibration of individual objects was 0.10 mag, due to the combined errors in the photoelectric and in the photographic photometry.

Forty-eight objects were measured on each of two separately calibrated plates, one of very good and the other of rather poor quality, of the Coma cluster. There was no calibration difference. There was a systematic difference of 0.03 mag per magnitude in the magnitude scales, due probably to errors in the characteristic curves of the plates. The random differences between the two sets of measurements had a standard deviation of 0.13 mag, most of which can probably be attributed to the poor plate.

Twenty-seven objects were measured, with the plate scanner, on the plate of A1314 which had previously been studied using the first photometry method. Any systematic difference in the magnitude scales was below the level of the random errors. This reassures us that there are no systematic errors in photometry with the plate scanner due to inaccurate measurements of the dense centers of galaxies, since the first photometry method uses a negative of the plate on which the galaxy centers are the least dense, most easily measured part. The random errors between the two sets of measurements had a standard deviation of 0.21 mag, which, assuming $\sigma = 0.09$ for the second method, implies $\sigma = 0.18$ for the first method.

The average reliability of photometry by the two methods can be summarized thus: for the first method, calibration errors $\sigma = 0.14$, random errors $\sigma = 0.18$; for the second method, calibration errors $\sigma = 0.07$, random errors $\sigma = 0.09$.

After photometry of each cluster was completed, a finding chart was prepared of all galaxies above the limit of completeness. The IIIaJ plate of the cluster was then inspected, using this chart to see if any

galaxies were missed or stars included in the final list of objects. In general, it was found that 1–2 percent of the galaxies in the field brighter than the completeness limit had been missed for various reasons. A similar number of stars usually managed to slip through the screening processes. These omissions and inclusions were corrected.

For nearby clusters ($z \leq 0.04$), all of the galaxies in each field were classified by morphological type, using the same IIIaJ plate. Objects were classified as ellipticals, S0's, or spirals (including irregulars). Unfortunately, the classification of objects at distances of a few hundred megaparsecs on deep, small-scale photographic plates is not very satisfactory. Necessarily, one is classifying the outer features of galaxies, whereas the usual morphological types are based on the nuclear properties of the galaxies, obtained from thin, large-scale plates. Perhaps worse, the poor resolution obscures many features, making it especially difficult to distinguish S0 and spiral galaxies. A comparison of classifications of objects in the Coma cluster and A194 with those of the same objects by Rood and Baum (1967) and Zwicky and Humason (1964) using 200-inch plates shows that, while E and S0 galaxies were typed fairly reliably, there was a systematic tendency to classify many early-type spirals as S0's.

Details of individual clusters are summarized below.

Abell 194 was studied by Zwicky and Humason (1964). It is a moderately regular cluster, in which the brightest galaxies, most of which are S0's, form a long chain. The plate used was of only fair quality.

Abell 400 is a moderately regular cluster in which most of the bright galaxies are ellipticals and S0's. Only the inner part of the cluster was studied, necessitating large extrapolations in the later analysis. The plate studied was of only fair quality.

Abell 539 is similar in form and content to Abell 400. There is a short chain of bright galaxies in the center. This cluster is at low galactic latitude; there is much nearby obscuration, but the cluster itself does not seem to be obscured. A 5×7 inch plate of good quality was studied to one limiting magnitude over the entire field.

Abell 665 is the only cluster of richness class 5 in Abell's catalog. Although there is some tendency to subclustering, there is no strong evidence that this is not one cluster. The plate studied was of fair quality.

Abell 1228 is an irregular cluster dominated by spiral galaxies. The plate studied was of good quality.

Abell 1314 is a regular cluster dominated by ellipticals. There is no one galaxy of outstanding brightness. The plate studied was of good quality.

Abell 1367 has a high spiral content but is fairly compact and regular in appearance, with several bright E's and S0's in the center. The plate used was of very good quality.

Abell 1413 is a rich, regular cluster. The huge central cD galaxy was described by Morgan and Lesh (1965) as possibly the largest of all supergiant galaxies. The IIIaF plate used was deep but of poor quality.

The Coma cluster was studied on one 14×14 inch plate of rather poor quality.

Abell 1904 is a rich, regular cluster with a central cD galaxy of moderate size. A good-quality plate was photometered to a uniform depth over the entire field.

The Hercules cluster is an irregular cluster dominated by spiral galaxies. The small companion cluster Abell 2147 is located 2° to the south. A good-quality plate was used.

Abell 2197 is a somewhat irregular cluster located 1.5° north of Abell 2199. The plate used was of good quality.

Abell 2199 is a compact, regular cluster. The large central galaxy, NGC 6166, is a type example of cD galaxies (Matthews, Morgan, and Schmidt 1964). A2197 and A2199 have the same redshift and a projected separation of only 4.5 Mpc. Assuming a velocity of approach of 1000 km s^{-1} , the collapse time of this system is only 4.5 billion years. However, there is no evidence that these two clusters are not, at present, independent systems. A contour map of the number density of bright galaxies in the neighborhood of these two clusters shows that only the outermost isopleths overlap and that there is no distortion of the two clusters' inner isopleths due to interaction. Therefore, in the later analysis they will be treated as independent systems.

Abell 2670 is a compact, regular cluster with a central supergiant galaxy. It is discussed in detail in Oemler (1973).

Zw Cl 1545.1+2104 is similar in appearance, although not as rich, to A2670. See Oemler *et al.* (1972) for details.

III. DATA ANALYSIS

a) Cluster Membership

Much of the uncertainty, reflected in the literature, about the properties of clusters of galaxies is due to the difficulties of separating them from the general field of galaxies which surrounds them. Since many clusters are probably still undergoing collapse and/or infall, there are some problems with deciding which, even of the galaxies in their vicinity, should be considered cluster members. However, the most serious troubles are due to background galaxies. Fluctuations in the number density of background galaxies are strong on all scales, but particularly at those corresponding to the clustering scale of objects at a particular distance ($\sim$ apparent magnitude) (Shectman 1973, 1974). These fluctuations, plus practical limitations on the area which can be studied, make it very difficult to accurately infer the contribution of background objects to a cluster of galaxies from counts in the vicinity of the cluster.

In order to make the most of the information available, all counts of field galaxies in each color have been combined into two mean distributions. It was found that, to the limits of accuracy set by the statistics, these two distributions could themselves be combined, with a color shift of $J - F = 0.90$, into one number versus magnitude relation. All of the available data are presented in figure 2. While most of the data

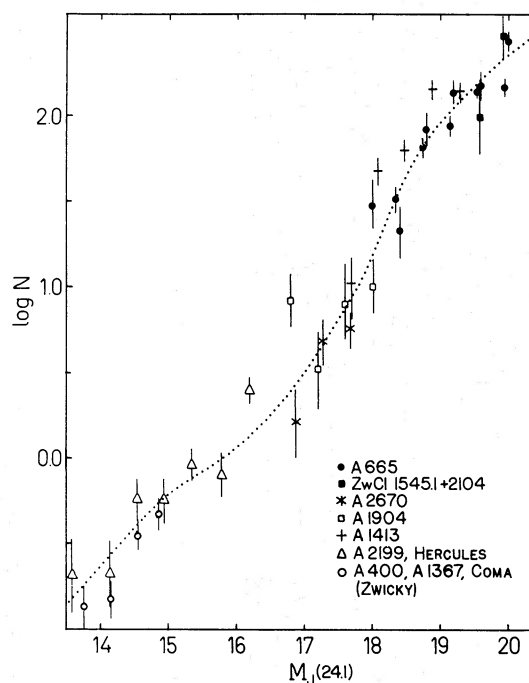


FIG. 2.—The number density of field galaxies per 0.4-mag interval in fields near the indicated clusters of galaxies. The dotted line is the adopted relation for all fields.

come from the outer parts of cluster fields photometered for this study, they have been supplemented at the bright end with counts in a few fields by Zwicky *et al.* (1961–1968) using the relation between the two photometric systems in equation (3). The dotted line in figure 2 is the adopted mean relation used for all clusters. The scatter is quite large, not only from field to field but also from point to point within one field. In all subsequent analysis, we will consider that the uncertainty in the background level is ± 50 percent.

It seems that this relation can be fit to the usual $\log N = C + 0.6m$ law over only a limited magnitude range. The falloff at the faint end is expected due to the omitted k correction; however, the increase of number with magnitude of the bright galaxies does not seem to be consistent with a constant space density.

Among those field galaxies bright enough to be classified by morphological type, there are 64 percent spirals, 23 percent S0's, and 13 percent ellipticals. It will be assumed that these proportions are correct at all magnitudes.

b) Total Magnitudes

To find the total luminosity of a galaxy, one must extrapolate beyond the isophotal luminosity obtained from photographic photometry. A semiempirical procedure for obtaining the required extrapolations has been described in detail elsewhere (Oemler 1973). We assume that the luminosity profiles of all elliptical galaxies have the same shape, differing only in their characteristic scale and surface brightness. Then, it

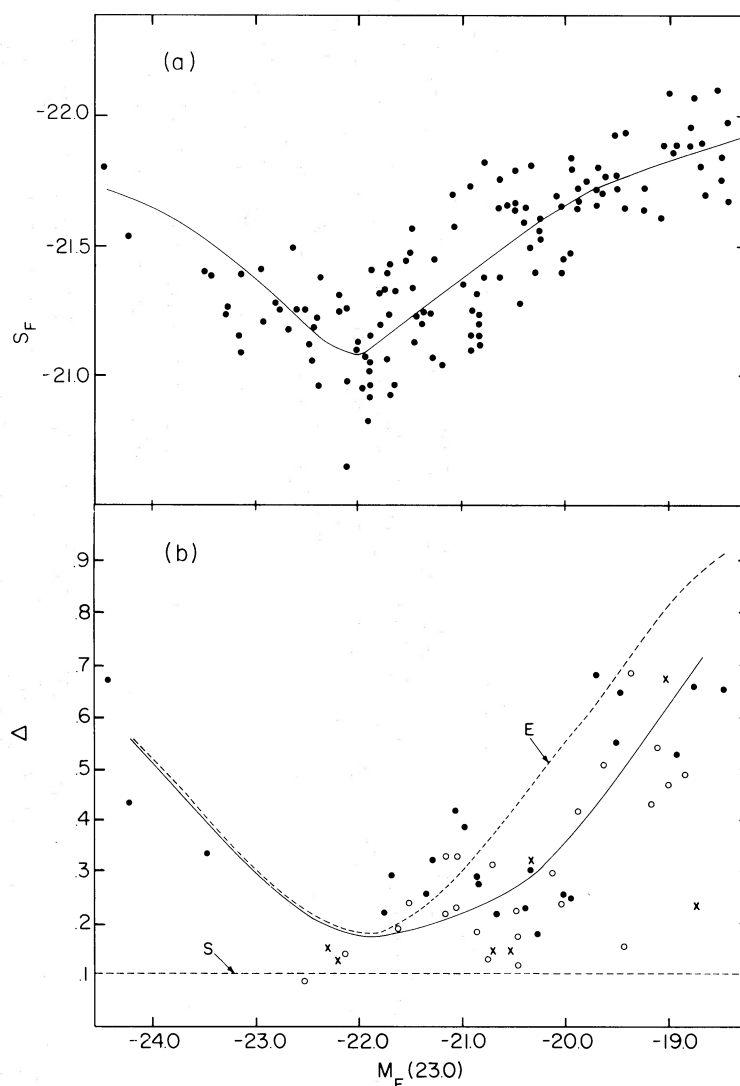


FIG. 3.—(a) Mean surface brightness versus absolute magnitude of elliptical galaxies in several clusters. The curve is the adopted mean relation. (b) The dashed lines are the calculated extrapolations to total magnitude for elliptical and S0 galaxies. The points are empirically determined extrapolations for ellipticals (filled circles), S0's (open circles), and spirals (x's). The solid line is the adopted relation for all types.

was shown, the extrapolation from isophotal to total luminosity is uniquely determined by the mean surface brightness of the galaxy within the limiting isophote.

The extrapolations were calculated from a limited amount of data on A1314 and the Coma cluster (Rood and Baum 1968) available then. The absolute calibration of the A1314 data was uncertain, and the accuracy of the Coma data has recently been questioned by Ables and Ables (1972). The calculations have therefore been repeated using some of the abundant data now available. In figure 3a, the mean red surface brightness is plotted against the isophotal magnitude for elliptical galaxies in a number of clusters. The distribution shows the same characteristic shape found in the earlier study. Most of the vertical dispersion can

be attributed to measuring errors, so the mean relation shown by the solid line will be considered as describing all elliptical galaxies.

Using the procedure described in Oemler (1973) the extrapolations for E galaxies were calculated from this curve; these are shown by the dashed line in figure 3b. Also shown by a dashed line are the extrapolations for S0 galaxies calculated in that paper from the photometry of S0 galaxies by Freeman (1970). As a check on these semiempirical determinations, the extrapolations were obtained directly for a small number of objects. Isophotometry of these objects was very carefully reduced to remove plate noise and properly subtract the sky brightness, and was then used to determine the luminosity within the $S_F = 26.0$ mag per square

second isophote, which is very close to the total luminosity. The quantity $m_F(23) - m_F(26)$ is plotted in figure 3b for these objects, with ellipticals denoted by filled circles, S0's by open circles, and spirals by $\times$'s.

There is rather good agreement between the empirical and calculated extrapolations for elliptical galaxies brighter than -21.0 . The calculations somewhat overestimate the extrapolations for fainter ellipticals, a possibility raised in the earlier study. However, there is no relation between the empirical and calculated extrapolations for S0 and spiral galaxies, implying that the assumptions in Oemler (1973) about them are not correct. Since there appear to be no great differences between the empirical extrapolations for different morphological types, the relation shown as a solid line in figure 3b will be used for all galaxies.

c) Data Reduction

The background corrections determined above were used to construct luminosity functions for all clusters. Each luminosity function was extended to that magnitude where the incompleteness of the photometry reached 25 percent or where the contribution of the background to the galaxy counts reached one-third. Before this point, the galaxy counts were corrected for the incompleteness at each magnitude calculated earlier. For those clusters which were studied in two fields of differing limiting magnitude, separate luminosity functions were constructed for each field. In the larger of the two fields, and in the single field when there was only one, the luminosity function was generally constructed from an area somewhat larger than that within one Abell radius. However, when an improved signal-to-noise ratio made it desirable, a larger or smaller area was used, so that the final luminosity functions cannot be used to directly obtain the cluster richness or the total luminosity.

In the three cases—A2197, A2199, and the Hercules cluster—where there was a neighboring cluster in the field, that quadrant of the field in the direction of the other cluster was omitted at radii greater than $30'$. The luminosity function of the large field was extended to fainter magnitudes by renormalizing the luminosity function of the smaller and deeper field so that the two agreed over the magnitude interval they had in common. In no case was there a statistically significant difference between the two curves.

The galaxy magnitudes were corrected for absorption within our own Galaxy using the prescription given by Sandage (1973) which, for this photometric system, becomes

$$A_J = A_F = 0.0 \quad (b \geq 50^\circ), \quad (5)$$

$$A_J = 0.11(\csc b - 1) \quad (b < 50^\circ), \quad (6)$$

$$A_F = 0.07(\csc b - 1) \quad (b < 50^\circ). \quad (7)$$

The only significant correction was that for A539, where $A_J = 0.27$. Apparent isophotal magnitudes were converted to absolute isophotal magnitudes using the redshifts in table 1. The k -corrections were calculated

for the more distant clusters using a scan of the central galaxy in A2670 obtained by James Gunn. The redshift of Zw Cl 1545.1+2104 is so great that the light observed in the F band was emitted at wavelengths close to the J band. Therefore, J rather than F magnitudes were calculated for this cluster. Luminosity functions for all clusters are presented in figure 4. Open circles are galaxy counts per 0.4-mag interval, and filled circles are integrated counts.

Several of these luminosity functions can be compared with results by Abell (1974). When account is taken of differences in the photometric systems and in the total areas studied, the agreement in A2199 is excellent. The two luminosity functions of the Coma cluster also match rather well, except that the results from this study do not show the very sharp break in the integrated function at $M_F \sim -21$ found by Abell.

Spherical symmetry has been assumed in determining the cluster surface-brightness profiles. This is not a very satisfactory approximation in some cases, such as A194 where the brightest galaxies form a long chain. However, circular symmetry must be assumed along the line of sight, anyway, and the number of objects is too small to adequately specify any other shape for the distribution in the plane of the sky.

In each cluster, the center was determined from a plot of the positions of the brighter galaxies. It is estimated that in the worst cases the uncertainty in this position is 0.25 Mpc and for most clusters is much smaller. Since this uncertainty is inversely proportional to the central gradient in galaxy density, its effect on the derived profiles should be minimal. Using the largest field studied of each cluster, whose depths ranged from 2.5 to 4 mag beyond the brightest member, the surface brightness due to galaxies was calculated in a series of concentric rings. Then the surface brightness due to background objects, calculated from figure 2, was subtracted from this profile and a series of corrections made. The effect of galactic absorption was removed using equations (6) and (7). Extrapolations from isophotal to total magnitude were made using the relation in figure 3b. The additional luminosity in galaxies beyond the completeness limit of the large field was added using the cluster luminosity function, extrapolated to infinite magnitude by

$$\log N = C + 0.15m. \quad (8)$$

The luminosities were converted to the visual band using $J - V = 0.3$ and $J - F = 1.1$ for spiral-poor clusters or $J - F = 0.9$ for spiral-rich clusters (A1228, A1367, A2197, and the Hercules cluster). The former relation is taken from equation (2) and the latter relation from the mean color for field galaxies found in § IIIa. The surface brightnesses of distant clusters are corrected for the effect of the k factor and the (redshift, angular diameter)-relation for $q_0 = 0.0$.

The final results are presented in figure 5. The horizontal scale is in megaparsecs and the vertical scale in units of 20 mag per square arc minute, which is equivalent to $9.62 \times 10^{10} L_\odot \text{ Mpc}^{-2}$. The error bars

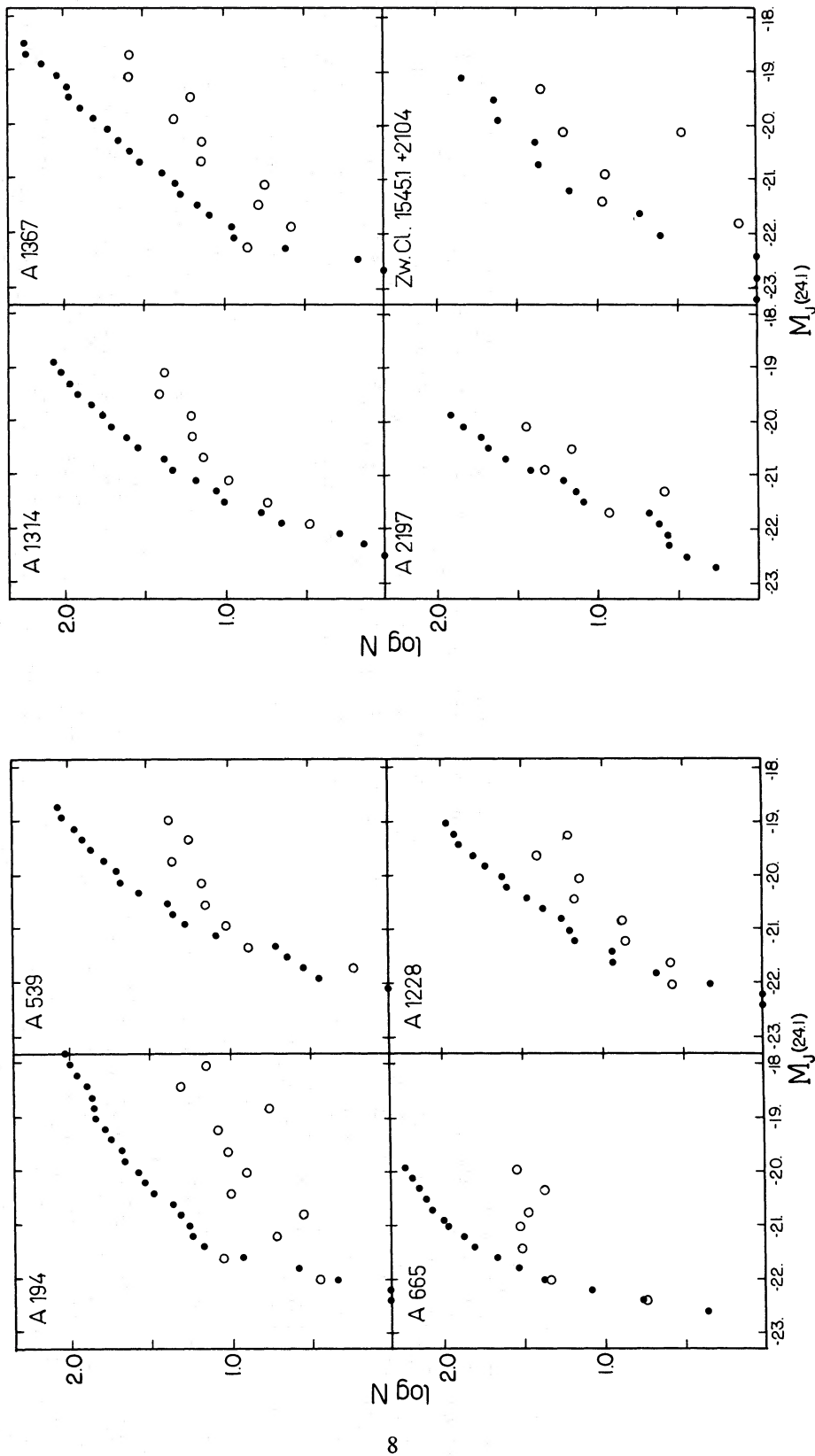


FIG. 4a

FIG. 4b

FIG. 4.—The cluster luminosity functions. Open circles are galaxy counts per 0.4-mag interval, and filled circles are integrated counts.

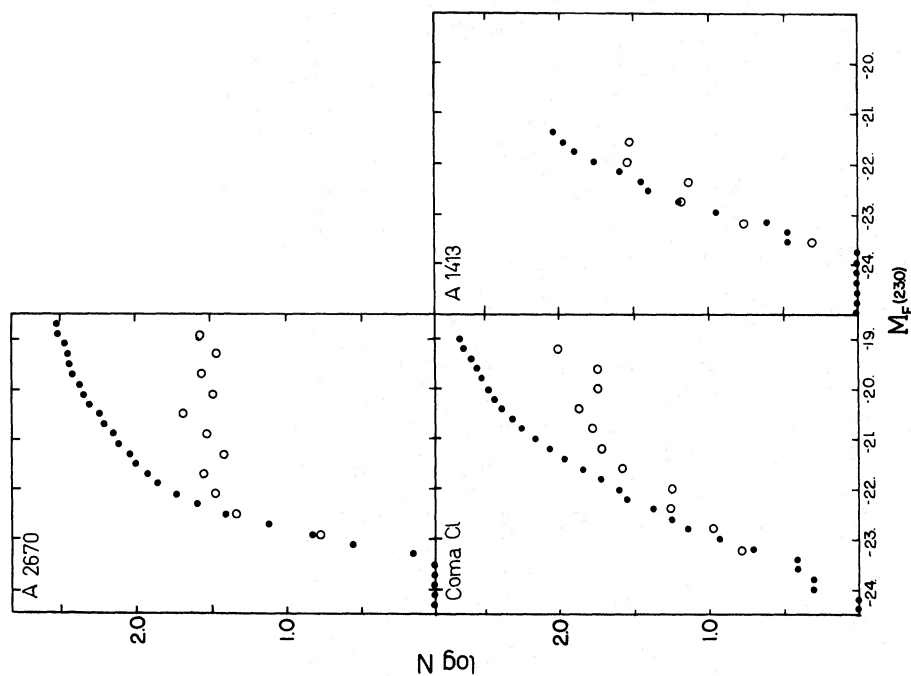


FIG. 4d

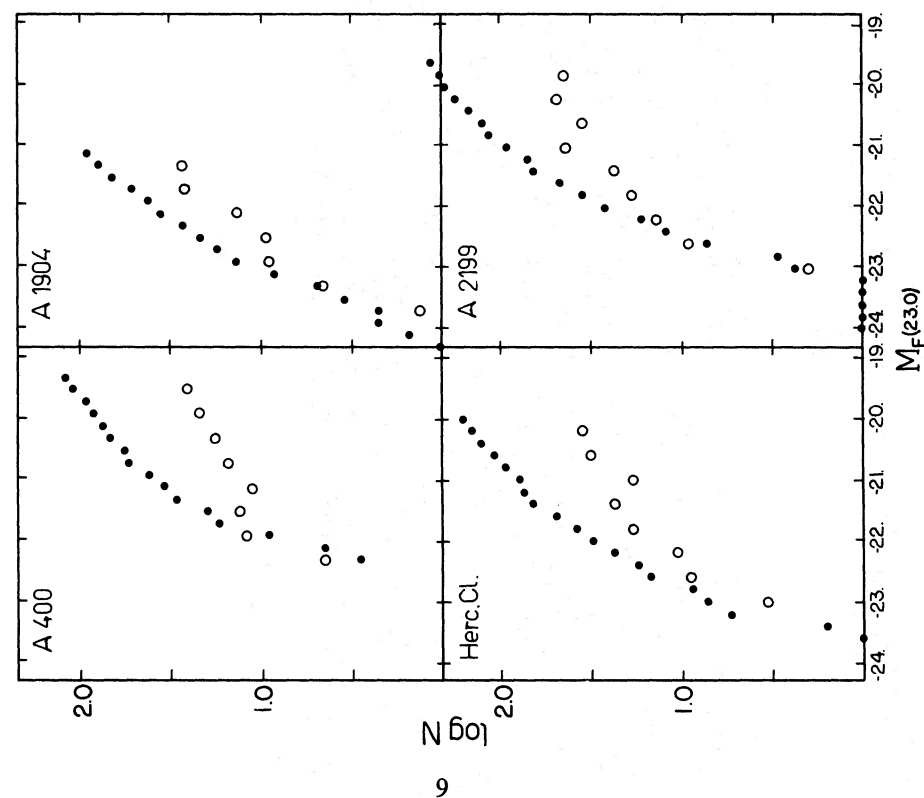


FIG. 4c

FIG. 4.—Continued

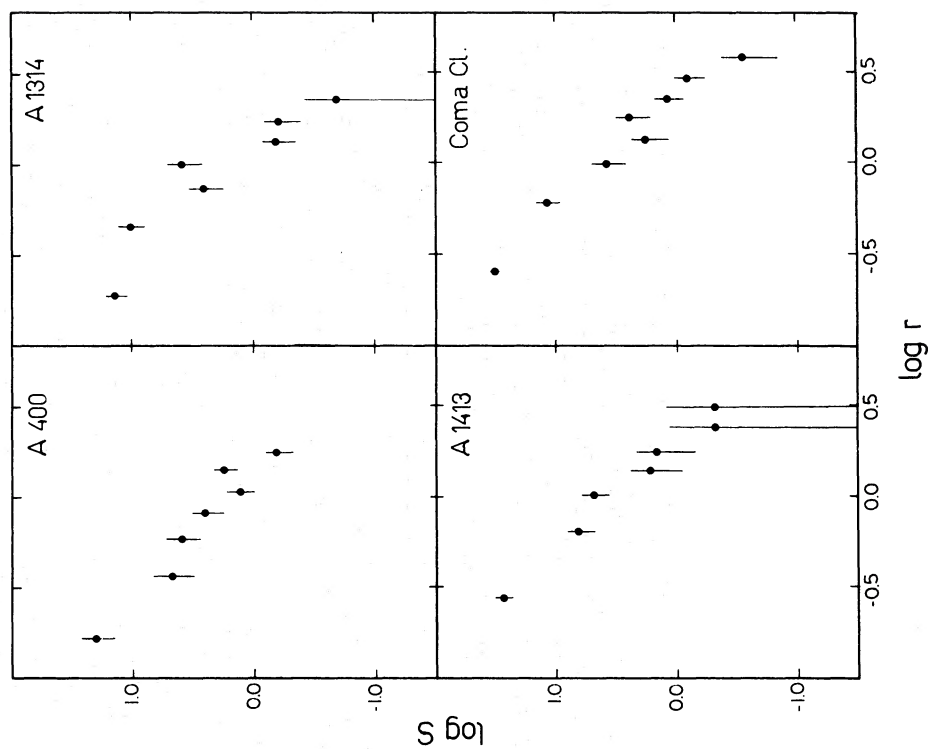


FIG. 5b

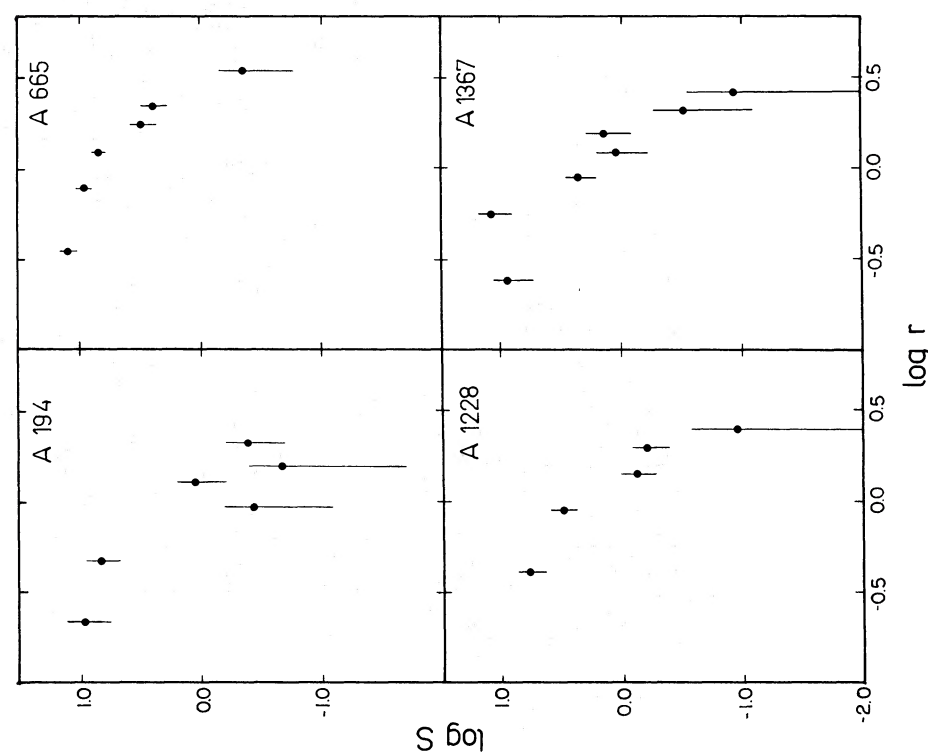


FIG. 5a

FIG. 5.—Cluster surface brightness profiles, where r is in megaparsecs and S in units of 20 mag per square minute in the V -band

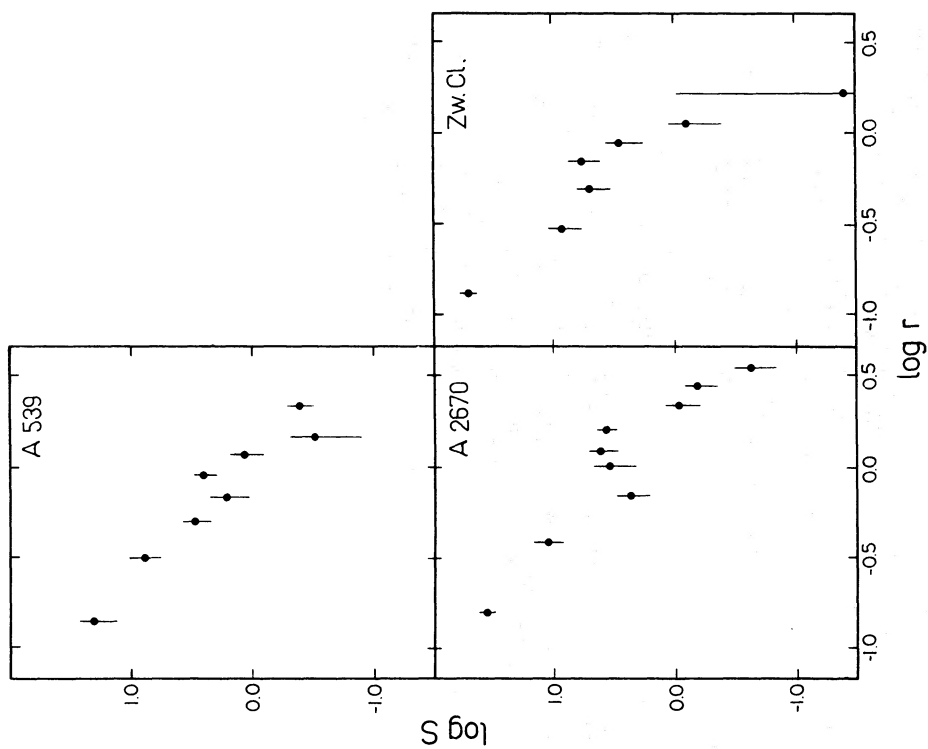


FIG. 5d

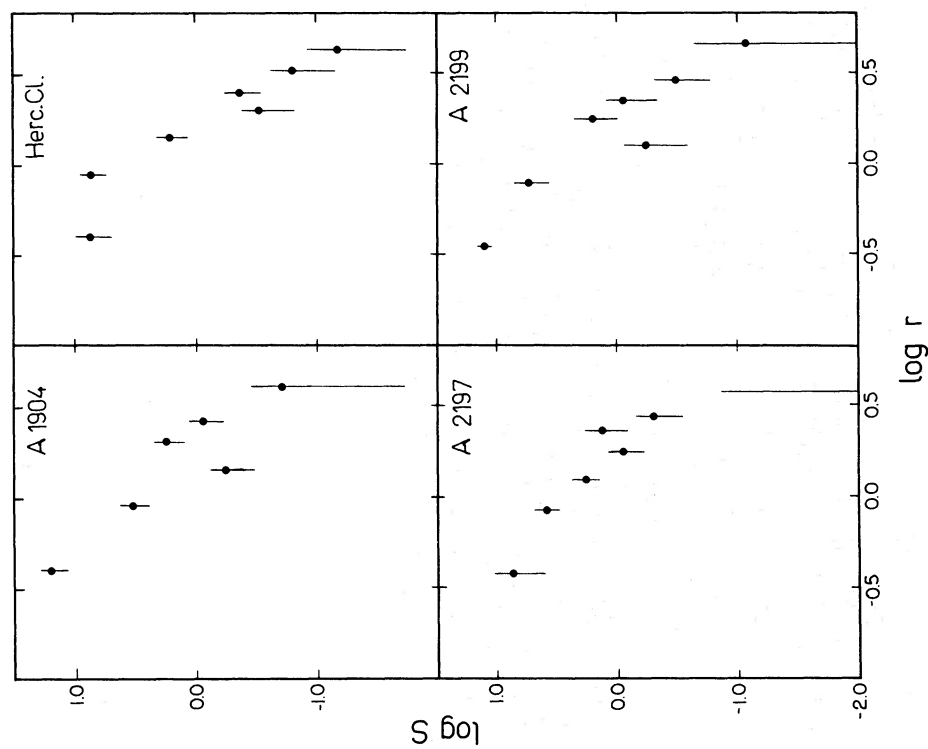


FIG. 5c

FIG. 5.—Continued

TABLE 2
CLUSTER PARAMETERS

Cluster	L ($10^{12} L_{\odot}$)	R_G (Mpc)	%E	%S0	%Sp
Abell 194.....	1.8	2.6	18	56	26
Abell 400.....	3.5	3.3	15	56	29
Abell 539.....	2.6	2.7	19	53	28
Abell 665.....	17.0	5.6	...	...	...
Abell 1228.....	2.9	3.7	14	25	63
Abell 1314.....	3.1	2.8	38	43	19
Abell 1367.....	3.3	2.9	17	40	43
Abell 1413.....	8.2	3.4	...	...	...
Coma cluster.....	9.4	3.9	35	47	18
Abell 1904.....	7.8	4.0	...	...	...
Hercules cluster.....	3.6	4.0	14	36	50
Abell 2197.....	4.2	4.1	19	36	45
Abell 2199.....	5.7	3.7	35	41	24
Abell 2670.....	5.5	3.7	...	...	...
Zw Cl 1545.1+2104.....	2.6	2.6	...	...	...

are the sum of the uncertainties due to Poisson statistics and the assumed 50 percent uncertainty in the background.

The accuracy of these profiles deteriorates rapidly at large radii, where the background galaxies are dominant. Rather than relying on individual points in analyzing these profiles, the outer parts have been fitted to a power law $s \sim r^{-3.0}$, which is the best fit to the sum of all the profiles. Using this curve and a smooth fit to the inner points, the total luminosity was calculated for each cluster. To make the results for A2670 comparable with those for the other clusters, the diffuse background light, amounting to one-third the entire cluster luminosity (Oemler 1973), has been omitted.

Then, using von Zeipel's inversion to obtain the three-dimensional mass distribution, the binding energy can be calculated for a given mass-luminosity ratio. In the second and third columns of table 2 are listed, for each cluster, the total luminosity (in solar units), and the gravitational radius R_G (in megaparsecs), the latter being defined by

$$E_{\text{grav}} = -GM^2/R_G. \quad (9)$$

For those clusters in which the morphological types of the galaxies were classified, the fractional composition of each type has been calculated for those galaxies within R_G and within 3 mag of the brightest member. These percentages are listed in the next three columns of table 2.

V. ANALYSIS OF THE RESULTS

One of the most immediate points which can be made about the data presented above is that, while the clusters show an almost continuous range of properties, they can be divided into clear types. Clusters of galaxies have been classified in the past by a number of systems, using several of their observed properties; one of the most natural and objective methods is by their galaxy content. Inspection of table 2 and the descriptions in § II*d* shows that they divide into three

groups. The cD clusters have one (or two, in the case of Coma) unique and dominant member and have E:S0:Sp ratios of about 3:4:2; this group includes A1413, the Coma cluster, A1904, A2199, A2670, and Zw Cl 1545.1+2104. The spiral-rich clusters have an E:S0:Sp ratio of about 1:2:3, not too dissimilar from that of the field, and include A1228, A1367, the Hercules cluster, and A2197. The remaining clusters, which may be called spiral-poor, have E:S0:Sp ratios of about 1:2:1 and include A194, A400, A539, A1314, and A665. The classification of A665 is uncertain because of its distance, but its appearance suggests that it belongs to the third rather than the second class. With the exception of A1314, whose proportions of galaxy types resemble those of the cD clusters, there is no ambiguity in the typing of any of these clusters. This classification scheme is most closely related to that of Morgan (1962), although the dividing lines between types do not precisely coincide.

As has been pointed out by Abell (1974), there is a strong correlation between groupings by galaxy content and the general appearance of the clusters. Spiral-rich clusters tend to be irregular in shape, with no symmetry and no apparent gradient in density toward the center. On the other hand, the cD clusters tend to resemble globular star clusters, being rather circular, with a well-defined center toward which the mass is highly concentrated. The spiral-poor clusters fall midway between these two types, being more regular than the spiral-rich clusters but less regular than the cD clusters.

Some of these correlations of galaxy content with other properties can be expressed in a more quantitative fashion. One measure of the compactness of a cluster is its gravitational radius, which is a mass-weighted harmonic mean of the distances between cluster members. The gravitational radius of each cluster, in megaparsecs, is plotted against its total luminosity, in solar units, in figure 6. Spiral rich clusters are denoted by $\times$'s, spiral-poor clusters by open circles, and cD clusters by filled circles. Superposed on the mean trend of size with luminosity is a

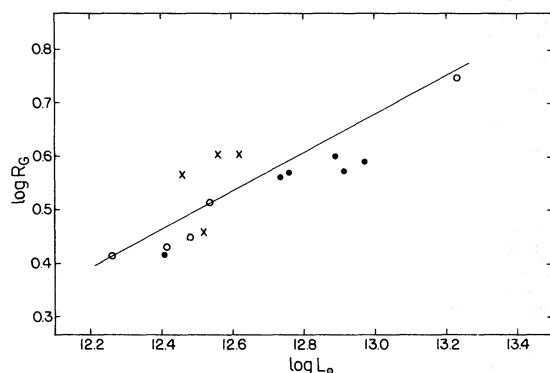


FIG. 6.—Gravitational radius, in megaparsecs, versus total luminosity, in solar units, for all clusters. Spiral-rich clusters are designated by $\times$'s; spiral-poor clusters, by open circles; and cD clusters, by filled circles. The solid line is the fit to the data.

systematic tendency for the spiral-rich clusters to be larger and the cD clusters smaller than average, as expected from their appearance.

Because of this variation of size with type, and because the various types are not distributed evenly with L , a single fit to all the data would be misleading. Instead, one straight line with a slope of 0.30 was fitted by least squares to the cD clusters, and a separate line of slope 0.37 was fitted to the rest of the data. The mean of these two lines, weighted by the number of clusters represented by each, is shown as a solid line in figure 6. Its slope of 0.34 ± 0.05 is essentially equal to $1/3$; in other words, in the mean all clusters have the same density, independent of mass.

Using this mean relation, the systematic trend of size with type is illustrated in figure 7. Plotted for each cluster is the deviation of $\log R_g$ from the mean line versus its E:Sp ratio; A2670 has been plotted, using an E:Sp ratio typical of cD clusters. With the exception of A1367, which on plates is noticeably compact for a spiral-rich cluster, there is a quite tight relation between compactness and galaxy content.

The detailed distribution of luminosity within clusters of each type is illustrated in figure 8. Each set

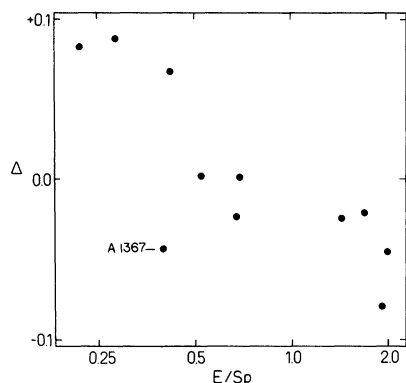


FIG. 7.—The deviation of $\log R_g$ of a cluster from the mean line in fig. 6 versus its elliptical to spiral ratio.

of points is the composite of several clusters, namely, A1228, A1367, and the Hercules cluster for the spiral-rich profile; A400, A539, and A1314 for the spiral-poor profile; and A1904, the Coma cluster, A2199, and A2670 for the cD cluster profile. Each cluster was scaled by R_g^{-1} to equalize their size. The errors are the sum of those due to Poisson statistics and the assumed 50 percent uncertainty in the background.

Three points can be made about these profiles. The outer envelopes all have steep slopes consistent with 3.0, similar to that predicted by the numerical models of Peebles (1970) and others and much steeper than that of 1.0 given by a projected isothermal sphere. The spiral-rich clusters have a flat central density gradient and little central concentration. As one moves to the spiral-poor and then to the cD clusters, the central concentration and density gradient increase, although the latter never becomes as high as that of the envelope.

Midway in the profiles is a plateau or local minimum at about $0.4R_g$ which grows in importance as one moves from spiral-rich to spiral-poor to cD clusters. It is more prominent in some of the individual cD cluster profiles, such as A1904, A2199, and A2670.

The significance of this feature becomes even stronger in the three-dimensional mass profiles. The dotted curves in figure 8 are typical three-dimensional mass distributions obtained by inverting a smooth curve through the points. These are only typical curves; one could easily draw a projected curve through the cD profile which would make the space density zero in some shell.

This feature has been seen by other investigators and cannot be easily explained away. Bahcall (1971) has shown that it is not due to measuring errors or to the presence of subclustering. It is seen in both the luminosity distribution and number counts (Clark 1968). Since both of these depend on the brightness of the galaxies, one might wish to reconcile the observed profile with a smooth mass distribution by invoking a discontinuity in the mass-to-light ratio. This could be accomplished either by giving the galaxies in the core a higher mass-luminosity ratio or by removing mass from their outer envelopes into a diffuse sea of stars, where it would not be observed with the techniques used. It is known that such a component of diffuse light exists in some clusters (Oemler 1973), but it is probably not massive enough. Also, a comparison of galaxies in the Coma cluster inside the feature (but excluding the very center) with those outside shows no difference in either their surface brightness or mean magnitude greater than 0.02 mag. From the information now available, we must conclude that this is a real feature, in the mass, as well as the light, distribution in clusters.

The composite cluster profiles have been broken down by the morphological types of the galaxies in figure 9. These graphs are in the same format as figure 8 except that the vertical axis represents number density rather than surface brightness. Although the uncertainties are large, the different galaxy types seem to have almost the same distribution, with one major exception: in the spiral-poor and cD clusters, the

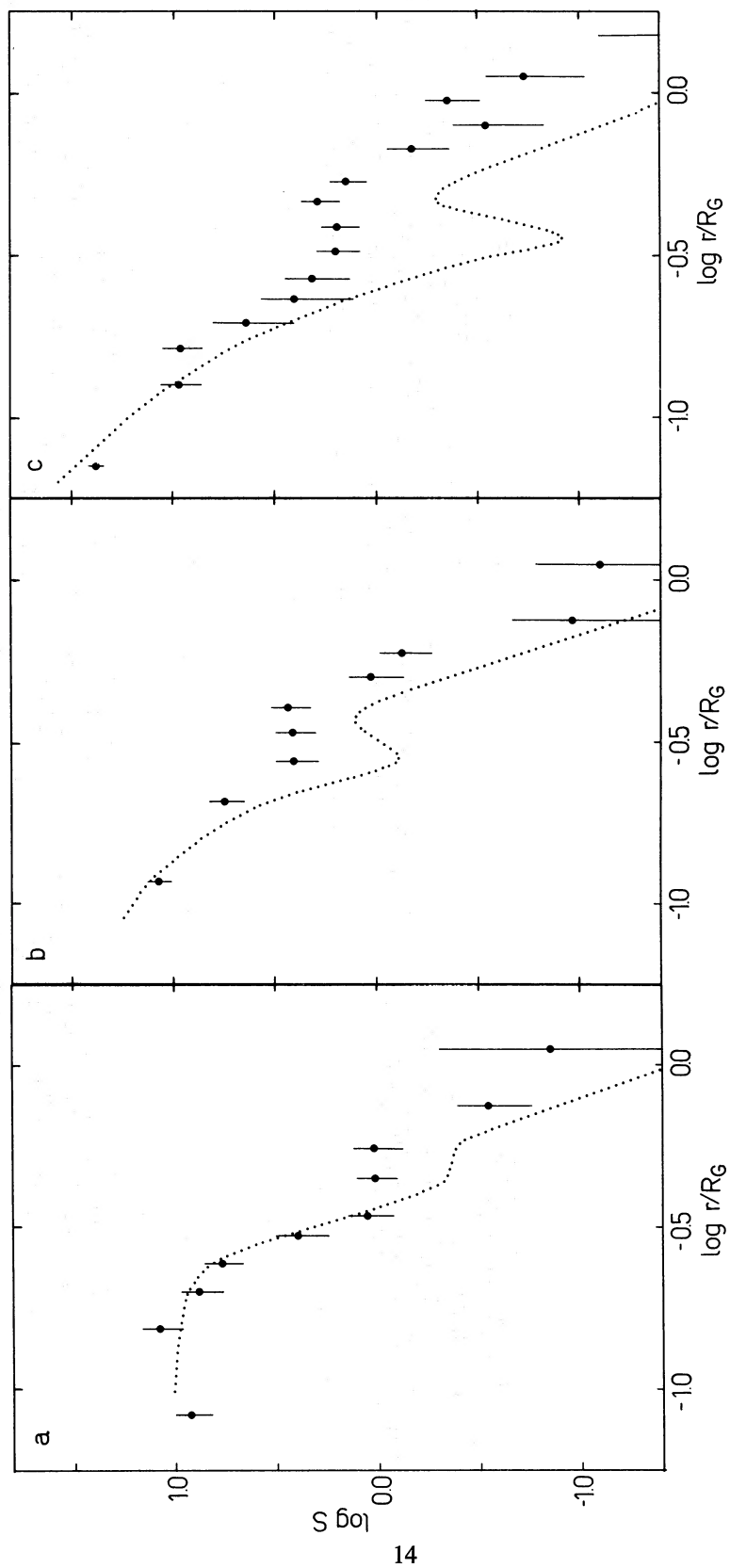


FIG. 8.—Composite surface brightness profiles for spiral rich (a), spiral-poor (b), and cD clusters (c). The dotted lines are typical three-dimensional density distributions obtained from a smooth curve through the points.

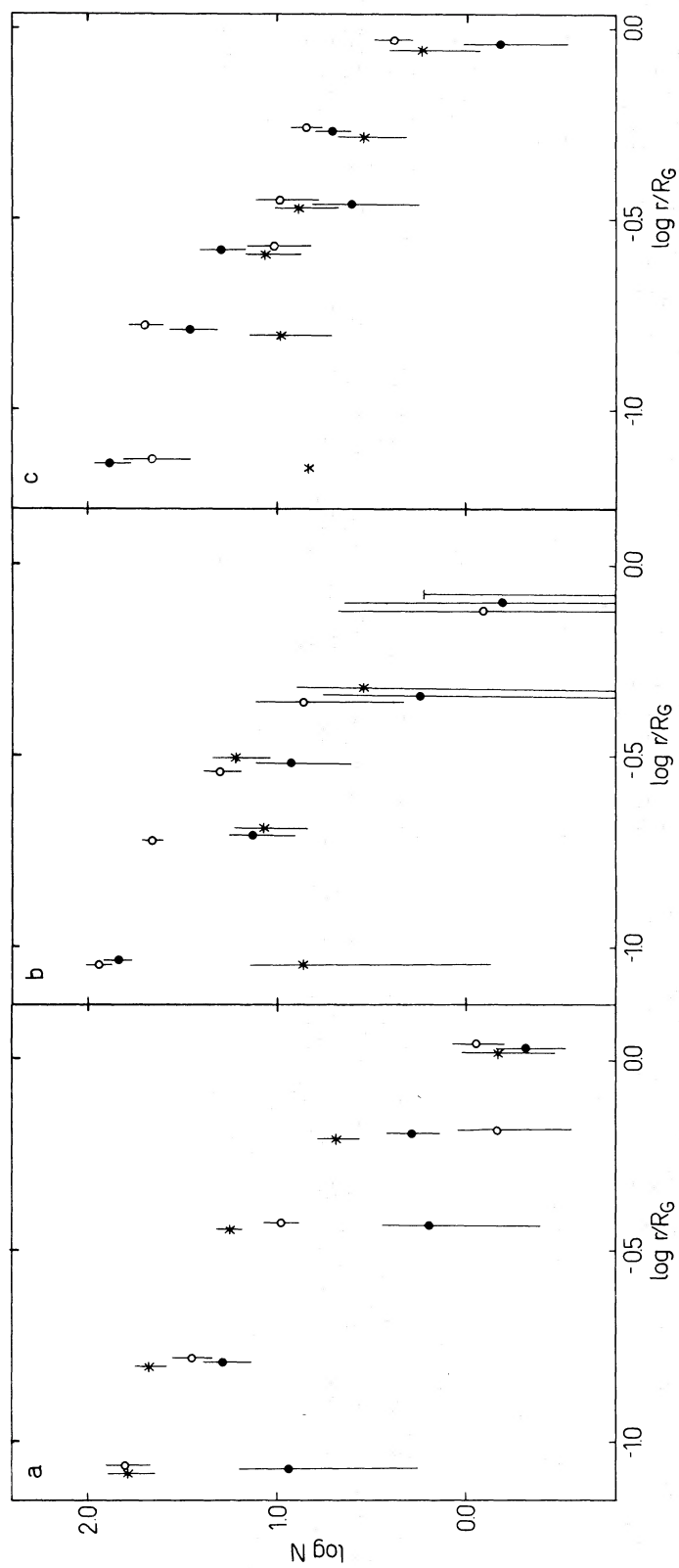


FIG. 9.—Composite projected number density profiles for spiral-rich (a), spiral-poor (b), and cD clusters (c). Spirals are denoted by stars; S0's, by open circles; and ellipticals, by filled circles.

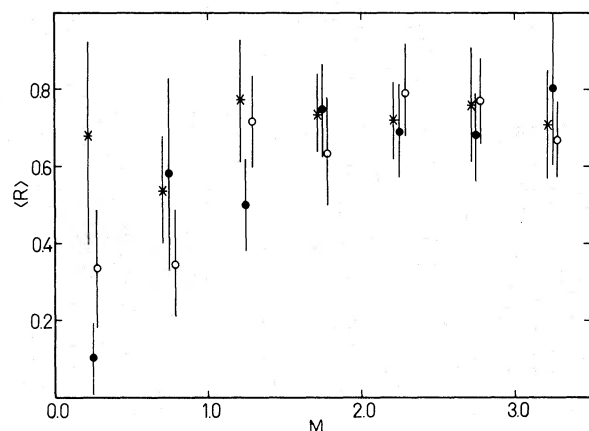


FIG. 10.—The mean radius as a function of magnitude of galaxies within the projected gravitational radius in spiral-rich (stars), spiral-poor (open circles), and cD (filled circles) clusters.

projected density of spiral galaxies decreases toward the center; in fact, the decrease is steep enough to make the space density of spirals zero in the core. There is some suggestion, in the cD clusters, that the gradient of the elliptical density in the envelope is greater than the mean and that of spirals less than the mean, but the statistical significance of this is rather low and could easily be due to slight errors in the background corrections. Also in the cD profile, the ellipticals seem to participate the most, and the spirals the least, in the feature at $0.5R_g$.

There has been some controversy in the past over whether clusters of galaxies show mass segregation due to the approach to energy equipartition by two-body interactions. Presented in figure 10 is the mean radius of galaxies within the projected gravitational radius in different magnitude ranges in spiral-rich (stars), spiral-poor (open circles), and cD (filled circles) clusters.

The spiral-rich clusters show no evidence of mass segregation. In the spiral-poor and cD clusters, there is marginally significant evidence for differential mass segregation in the first few magnitude intervals but none more than 2 mag below the brightest member. The shape of these latter two curves is that expected in a system which has partially evolved toward energy equipartition. The time scale for the large galaxies to lose energy to the smaller objects is short, and these large galaxies have moved inward. The smaller galaxies have gained energy from the large objects and moved outward; however, because of the long time scale, they have not had time to exchange energy among themselves and therefore still have similar distributions. This latter observation justifies our procedure of inferring the faint galaxy content of an entire cluster from photometry of the core only.

The luminosity functions of the clusters can be treated in the same way that we have treated their galaxy distributions. Since the clusters were classified by their galaxy content, one might expect to see substantial differences in the luminosity functions of the different type clusters. Composite differential

luminosity functions for the same groups of clusters as in figure 8 are presented in figure 11. The differences between these three curves are quite small. The spiral-poor and cD luminosity functions are identical to within the errors except for the outstandingly bright first-ranked member typical of the latter. The spiral-rich function appears to be slightly different, but the difference is of only marginal significance. The shape of these luminosity functions is quite similar to that predicted theoretically by Press and Schechter (1974) but differs markedly from that predicted by Icke (1973). The approximation of two straight lines suggested by Abell (1962) seems to be an oversimplification.

That the cutoff at the bright end of the spiral-rich luminosity function occurs at the same absolute magnitude as in the spiral-poor and cD functions, coupled with the observation that even in spiral-rich clusters the first-ranked galaxy is usually an S0 or elliptical, is a significant point. If, as is commonly thought, the mass-luminosity ratio of spirals is considerably lower than those of E and S0 galaxies, this observation implies that the mass function of spirals must cut off at a significantly lower mass than those of the other two types.

A comparison of the composite luminosity functions with those of the individual clusters shows no significant differences with the exception of those of A665 and A2670, both of which rapidly level off at the faint end. Although both are distant objects, it is unlikely that this effect is due to photometry or reduction errors. Abell (1962) has asserted that there is a universal luminosity function characterized by the same absolute magnitude for all clusters. Constructing a mean luminosity function from the composite functions and fitting by eye to the individual functions produces a dispersion in absolute magnitude (assuming $J - F = 1.1$) of 0.24 mag. This is not much larger than would be expected from uncertainty in the fitting alone, since the normalization in absolute magnitude depends on the small number of galaxies at the bright end of the luminosity function.

VI. CONCLUSIONS

The properties of clusters of galaxies found from this study may be summarized as follows. Although clusters display a wide range of characteristics, most of their gross features may be accounted for by dividing them into three groups. One group, labeled above as spiral-rich, has compositions similar to that of the field, with a high proportion of spiral galaxies. They are irregular in appearance, have a low mean density and no tendency to central concentration. They are fairly homogeneous in composition, with no perceptible segregation by morphological type, and show no evidence of relaxation by two-body encounters.

At the other extreme are those clusters dominated by central supergiant galaxies. They are deficient in spirals and contain a much higher proportion of ellipticals than the other cluster types. These cD clusters are dense, centrally concentrated, and spherical in

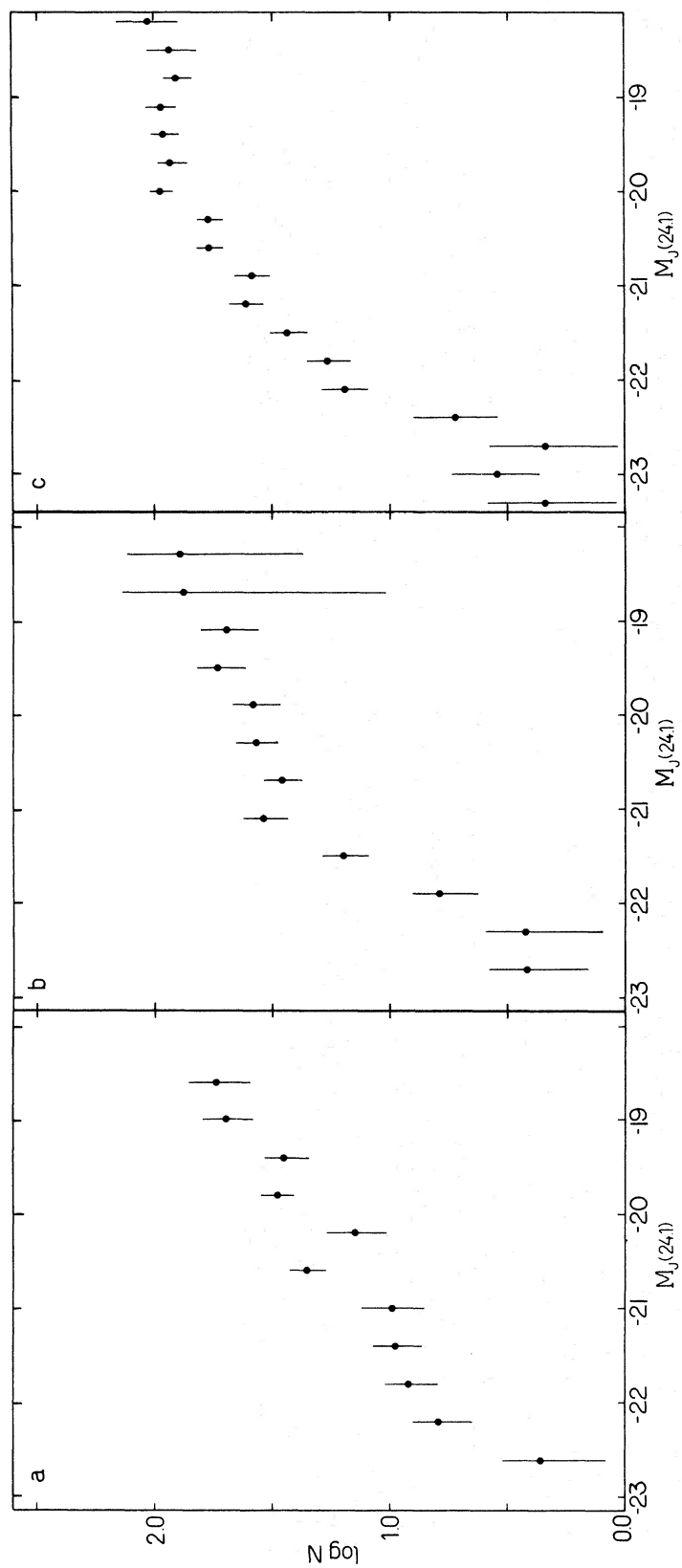


FIG. 11.—Composite differential luminosity functions for spiral-rich (a), spiral-poor (b), and cD clusters (c)

appearance. Their low overall proportion of spiral galaxies is due to a complete absence of spirals in their cores. They show evidence of considerable differential two-body relaxation among the brighter members.

Somewhat intermediate between these two types are the spiral-poor clusters, whose composition is dominated by S0 galaxies. Like the cD clusters, they show segregation by mass and morphological type, but they are not quite as regular, compact, or centrally condensed as the former.

Even without any dynamical information, we can make some tentative attempts at a theoretical explanation of these facts. Let us assume, following the conventional idea, that clusters of galaxies began as regions of higher than average density in the early expanding universe. With time, these areas lagged behind the general Hubble expansion until they reached a point of maximum expansion and then collapsed.

If one follows the evolution of a bound system of particles, initially at rest, through its collapse and until it reaches a state of quasi-equilibrium, its qualitative behavior can be characterized by a constant increase in regularity and spherical symmetry, and by the growth of a dense core. With this in mind, it is tempting to regard the morphological sequence of spiral-rich, spiral-poor, and cD clusters as a sequence in dynamical evolution.

Gunn and Gott (1972) first suggested that the differences between what are here called spiral-rich clusters and the other types could be explained if the former had not collapsed, while the others had. The morphological evidence for this is quite strong. The low densities of the spiral-rich clusters imply a long collapse time. Their irregular mass distributions could not survive the phase mixing and violent relaxation which occur during collapse, and the lack of mass segregation also suggests that little dynamical evolution has occurred. Finally, their homogeneous composition, resembling that of the field, shows their affinity to the general field of unbound galaxies.

Conversely, the spiral-poor and cD clusters show the characteristics expected of systems in a steady state. They have smooth mass distributions, are centrally condensed, and show the effects of a considerable period of two-body relaxation processes. Their luminosity profiles are in good qualitative agreement with the predictions of numerical models of collapsed clusters.

Most important for Gunn and Gott's argument for the relation between these types of clusters is the composition of the spiral-poor and cD clusters. Will spiral-rich clusters like the Hercules cluster eventually become typical spiral-poor clusters? As we have seen, the necessary dynamical evolution should occur on collapse, and there only remains the problem of changing the galaxy content. The galaxy content of the two cluster types is such that the transmutation of some fraction of the spiral galaxies into S0's will change the spiral-rich cluster content into that of a spiral-poor cluster. Gunn and Gott showed how this might be done by the interaction of the gas content of a spiral galaxy with a hot intergalactic medium in

the core of a collapsed cluster, and this theory provides the most natural—although not the only possible—explanation for the decrease in the density of spirals toward the center of spiral-poor and cD clusters seen in figure 9.

There is no equivalent mechanism for the transmuting of S0 into elliptical galaxies, and so the relation between the two types of collapsed clusters—spiral-poor and cD—is not so clear. The direct collision of two stellar systems in which the dynamical time is comparable with the collision time tends to be inelastic (Aarseth and Hills 1972; Toomre 1973), and thus the disks of two colliding S0 galaxies are likely to be sufficiently disrupted to make the final system elliptical in appearance. However, the frequency of direct collisions in a cluster is too low (Gunn and Gott 1972), and it is doubtful whether the tidal interaction in near encounters would be sufficiently strong.

Therefore, while the greater regularity and symmetry of the cD clusters, together with their slightly steeper central profiles, would suggest that they are dynamically older than the spiral-poor clusters, their greater proportion of ellipticals seems to rule out the idea that they have evolved from the spiral-poor clusters. These cluster types are, then, intrinsically different. If they are the dynamically oldest, and therefore have evolved the fastest, the cD clusters must have begun as the densest fluctuations in the early universe. One could speculate, then, that their higher abundance of ellipticals is due to a birthrate of elliptical galaxies which increases with density relative to the other galaxy types.

At the present time, then, we only see three of what were originally four types of clusters. The spiral-rich clusters are the precursors of the spiral-poor clusters; but, because of their short collapse times, the elliptical-rich precursors of the cD clusters have all evolved into the latter.

We therefore have two reasons for the tight relation between compactness and galaxy content seen in figure 7. The relative importance of initial rates of galaxy creation and later evolution cannot be very precisely determined from the present data. Inspection of the outer parts of the profiles in figure 9 where the transmutation of spirals into S0's has, presumably, not been important, suggests differences in the initial proportions of all galaxy types, but the data are very poor.

Thus, we can begin to develop a consistent picture of the structure and evolution of clusters of galaxies. One observation which cannot be explained at present is the peculiar feature in the radial mass distributions. If we believe the small bump in the spiral-rich profile, it would seem that this feature must be due to the initial distribution of mass in the cluster's vicinity, since these clusters have presumably not undergone any significant dynamical evolution. It is true that any irregularity in the initial mass distribution will grow with time as the cluster collapses, but it is difficult to understand why all clusters should start with the same irregularity at almost the same radius. Also, it is surprising that the violent relaxation during collapse

seems to amplify rather than smooth out this feature. Although this particular problem has not been studied, Aarseth and Hills (1972) have shown that irregularities in the form of subclustering are smoothed out during collapse. Clearly, more theoretical work needs to be done.

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REFERENCES

- Aarseth, S. J., and Hills, J. G. 1972, *Astr. and Ap.*, **21**, 255.
 Abell, G. O. 1958, *Ap. J. Suppl.*, **3**, 211.
 ———. 1962, in *Problems of Extragalactic Research*, ed. G. C. McVittie (New York: Macmillan).
 ———. 1974, in *Stars and Stellar Systems*, Vol. **9**, ed. A. and M. Sandage and J. Kristian (Chicago: University of Chicago Press) (in press).
 Ables, H. D., and Ables, P. G. 1972, *AAS Photo-Bulletin*, No. 2.
 Bahcall, N. A. 1971, *A.J.*, **76**, 995.
 Clark, E. E. 1968, *A.J.*, **73**, 1011.
 Freeman, K. C. 1970, *Ap. J.*, **160**, 811.
 Gunn, J. E., and Gott, J. R. 1972, *Ap. J.*, **176**, 1.
 Icke, V. 1973, *Astr. and Ap.*, **27**, 1.
 Matthews, T. A., Morgan, W. W., and Schmidt, M. 1964, *Ap. J.*, **140**, 35.
 Morgan, W. W. 1962, *Ap. J.*, **135**, 1.
 Morgan, W. W., and Lesh, J. R. 1965, *Ap. J.*, **142**, 1364.
 Noonan, T. W. 1973, *A.J.*, **78**, 26.
 Oemler, A. 1973, *Ap. J.*, **180**, 11.
 Oemler, A., Gunn, J. E., and Oke, J. B. 1972, *Ap. J. (Letters)*, **176**, L47.
 Oke, J. B., and Schild, R. E. 1970, *Ap. J.*, **161**, 1015.
 Peebles, P. J. E. 1970, *A.J.*, **75**, 13.
 Press, W. H., and Schechter, P. 1974, *Ap. J.*, **187**, 425.
 Rood, H. J., and Baum, W. A. 1967, *A.J.*, **72**, 398.
 ———. 1968, *ibid.*, **73**, 442.
 Sandage, A. 1973, *Ap. J.*, **183**, 711.
 Sandage, A., and Smith, L. L. 1963, *Ap. J.*, **137**, 1057.
 Sargent, W. L. W. 1973, *Pub. A.S.P.*, **85**, 281.
 Sheckman, S. A. 1973, *Ap. J.*, **179**, 681.
 ———. 1974, *ibid.*, **188**, 233.
 Toomre, A. 1973, *IAU Symposium No. 58*.
 Zwicky, F., Herzog, E., Wild, P., Karpowicz, M., and Kowal, C. T. 1961–1968, *Catalogue of Galaxies and Clusters of Galaxies* (Pasadena: California Institute of Technology).
 Zwicky, F., and Humason, M. L. 1964, *Ap. J.*, **139**, 269.

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