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THE EVOLUTION OF GALAXIES IN CLUSTERS. V. A STUDY OF POPULATIONS SINCE $z \sim 0.5$

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ABSTRACT

In this paper we analyze photometry of 33 clusters of galaxies, with redshifts between 0.003 (the Virgo Cluster) and 0.54 (Cl 0016+16) to search for evolution of the colors of cluster populations. In each cluster we select those galaxies brighter than $M_v = -20$ which are within the circular area containing the inner 30% of the total cluster population. From the distribution of these galaxies in the color-magnitude plane, we determine the fraction of galaxies whose rest-frame $B-V$ colors are at least 0.2 mag bluer than the ridge line of the early type galaxies at that magnitude. We define this to be the blue galaxy population, f_B, and find it to have the following characteristics in compact, concentrated clusters: (1) For $z \lesssim 0.1, f_B \sim 0.03 \pm 0.01$ in all clusters. (2) For $z \gtrsim 0.1, f_B$ increases with redshift, reaching $f_B \sim 0.25$ at $z = 0.5$. (3) The values of f_B seen in clusters at a particular redshift are mostly consistent with clusters being random samples of one homogeneous galaxy population, but there is some evidence that processes within individual clusters may also affect the galaxy content.

At the present epoch, open, irregular clusters have as many spiral galaxies as the field, but these spirals are much redder than those in the field. From a sample of three nearby open clusters and one high-redshift open cluster, it appears that f_B in such clusters increases with z at a rate similar to that in compact clusters.

Most of the data are consistent with the hypothesis that, in some fraction (~25%) of galaxies, the rate of star formation has decayed rapidly with epoch, *independent of the galaxy's environment*. One possible cause is simply a general depletion of gas in at least some regions of the universe.

Subject headings: cosmology — galaxies: clustering — galaxies: evolution — galaxies: photometry

I. INTRODUCTION

Some time ago, we published photometry of two distant clusters of galaxies, Cl 0024+1654, at a redshift of 0.39, and the cluster surrounding 3C 295, at a redshift of 0.46 (Butcher and Oemler 1978*a*, hereafter BO I). We found that these clusters contained significant populations of blue galaxies, which were tentatively identified as spirals. In contrast, nearby clusters of similar compactness and central concentration have few spirals (Butcher and Oemler 1978*b*, hereafter BO II). This difference suggested that there has been strong, recent evolution of galaxies in clusters.

These observations were received with interest but also with some skepticism, since such strong recent evolution was not predicted by conventional models of galactic evolution. There have been a number of theoretical attempts to understand these results. There have also been claims that our conclusions were incorrect, because of errors in the data, their analysis, or their interpretation. Of these claims, three are particularly significant. Mathieu and Spinrad (1981) have restudied the 3C 295 cluster, and have found a smaller fraction of blue galaxies, a difference which they attribute to an underestimate of the field galaxy contamination in our analysis. This is a real possibility, because of the indirect way in which we determined the density of field galaxies. Dressler and Gunn (1982, 1983) have measured redshifts of a number of our blue galaxies in Cl 0024+1654 and 3C 295. They find that most of the objects in the Cl 0024+1654 field are cluster members, but that there is substantial contamination of the 3C 295 sample by foreground objects, in agreement with Mathieu and Spinrad. Wirth and Gallagher (1980) have used plate material sensitive to very weak structural features to search for spirals in two nearby clusters. They find that the fraction of spirals is much higher than previously estimated, thereby decreasing or eliminating the difference between nearby and distant clusters.

It is clear that more data are needed. We would like to resolve the doubts which have been raised about the 3C 295 data. Also, information on many more than two clusters, at a wide range of redshifts, is needed to properly elucidate the evolution of galaxy populations in clusters. Finally, the Wirth and Gallagher results illustrate the importance of studying evolution using a uniform measure of galaxy properties, rather than by comparing the colors of distant galaxies with the morphology of nearby ones. For the past five years, we have been gathering such data. We have obtained photometry in two bands of 17 additional intermediate and high redshift clusters (Butcher, Oemler, and Wells 1983, hereafter BOW III) and of 10 nearby clusters (Butcher and Oemler 1984*a*, hereafter BO IV). With the addition of published photometry of several other clusters, these observations cover 33 clusters, ranging in redshift from $z = 0.0033$ to $z = 0.54$.

In this paper we study the evolution of the colors of cluster galaxies since $z \sim 0.5$. We shall show that our original conclusions were substantially correct: there has been strong recent evolution of galaxy populations in clusters.

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II. OBSERVATIONS AND ANALYSIS

a) *The Data*

The clusters and their redshifts are listed in the first two columns of Table 1. Redshifts of Abell clusters are taken from Sarazin, Rood, and Struble (1982); redshifts of others are taken from the sources of the photometry. Photometry of most of the clusters is taken from BO I, BOW III, and BO IV. These data are from three sources. Four clusters, Cl 0949+4409, Cl 1446+2619, Cl 0024+1654, and 3C 295, were photometered in the V and R bands using the video camera on the KPNO 2.1 m telescope. The photometry covers a field of about 6.2 sq. arcmin. One of the four, Cl 0949+4409, proved to be too poor to work with, and has not been used. Fifteen other intermediate and high redshift ($z > 0.15$) clusters were photometered from IIIa-J and IIIa-F (or, in one case, IV N) photographic plates obtained on the KPNO and CTIO 4 m telescopes. The photometry covers areas of 55 sq. arcmin centered on the clusters, and field areas of the same size located elsewhere on the same plate. A few bright galaxies in this data set, which have no measured colors, were incorrectly assigned colors of 0.00 in BOW III. These are noted below, in the discussion of individual clusters. Ten nearby clusters ($z < 0.10$) were photometered from IIIa-J, 098 and 103a-F plates obtained on the Palomar 1.2 m Schmidt telescope. Photometry in these clusters extends to a radius of 1.5 Mpc (assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$) from the cluster centers. More details of the photometry may be found in BO I, BWO III, and BO IV.

TABLE 1

THE CLUSTER SAMPLE

Cluster	z	C	R_{30}	f_B	N30
Field	$\le$ 0.04	–	–	.41±.10	–
Virgo	0.0033	0.36	120'	.04	21
Abell 262	0.0164	0.28	27'	.02±.03	22
Abell 1367	0.0213	0.33	16'	.19±.03	20
Abell 400	0.0232	0.48	17'	.05±.04	30
Coma	0.0235	0.53	22'	.03±.01	94
Abell 2199	0.0305	0.53	18'	.04±.01	57
Abell 2634	0.0322	(0.5)	(30')	.02±.04	60
Hercules	0.0371	0.32	14'	.14±.02	29
Abell 2256	0.0601	0.51	11'	.03±.01	116
Abell 1904	0.0714	0.53	9.4	.02±.02	68
Abell 401	0.0748	0.60	10.7	.02±.02	92
Abell 2670	0.0749	0.50	4.9	.04±.01	51
Cl 0004.8-3450	0.114	(0.50)	(5'.9)	.07±.04	60
Abell 2218	0.171	0.59	5'.8	.11±.04	114
Abell 1689	0.1747	0.55	5'.8	.09±.03	124
Abell 520	0.203	0.38	4'.5	.07±.07	126
Abell 963	0.206	0.60	3'.6	.19±.05	88
Abell 223	0.207	(0.50)	(3'.2)	.10±.06	67
Abell 222	0.211	(0.50)	(1'.6)	.06±.04	45
Abell 1942	0.224	0.56	2'.8	.17±.05	57
Abell 2397	0.224	0.48	2'.0	-.04±.04	23
Abell 777	0.226	0.39	1'.4	.05±.08	15
Abell 2111	0.229	0.40	4'.1	.16±.03	155
Abell 1963	(0.23)	0.50	1'.5	.10±.04	38
Abell 1961	0.232	0.50	3'.4	.10±.05	88
Abell 2645	0.246	0.38	1'.4	.03±.05	35
Abell 2125	0.2472	0.49	2'.3	.19±.03	62
Abell 1758	0.2800	0.49	2'.4	.09±.04	91
Cl 1446+2619	0.369	0.30	0'.9	.36±.05	42
Abell 370	0.373	0.59	2'.2	.21±.05	107
Cl 0024+1654	0.39	0.53	1'.1	.16±.02	87
3C295	0.465	0.58	1'.0	.22±.05*	45
Cl 0016+16	0.541	0.49	1'.0	.02±07	65

* Average of 2 methods. See text.

Usable data on several other clusters have been obtained from the literature. For the Virgo Cluster, we have used the $(B-V)_T$ colors reported in the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976). Newell and Couch (1976), as part of a large study similar to this one, have photometered Abell 1689 using AAT telescope plates. Koo (1981) and White, Silk, and Henry (1981) have studied the very distant cluster Cl 0016+16, using 4 m telescope plates. Carter (1980) has studied the cluster Cl 0004.8−3450, using AAT and SRC Schmidt telescope plates. Finally, Dressler (1978) has photometered Abell 2256 from plates taken with the Lick Observatory Crossley telescope. Although only photometry in the F band is published, he has very kindly provided us with unpublished $B-V$ colors of the cluster members. These are the only clusters with suitable published photometry. Although photometry of galaxies in some other clusters does exist, we judge it to be insufficient in accuracy, depth or completeness for our purposes.

In addition to photometry of the galaxies, we shall need radial surface density profiles of the clusters. For the clusters with redshifts $z < 0.10$, we take these from Oemler and West (1984). Profiles of Cl 0024+1654 and 3C 295 come from BO I, that of Cl 0016+16 comes from White, Silk, and Henry (1981), and that of A1689 from Newell and Couch (1976). We have obtained profiles of most of the clusters in BOW III by counting galaxies on prints enlarged from one of the plates from which the photometry was obtained. Similarly, the profile of Cl 1446+2619 was obtained from an enlargement of a 4 m telescope plate. These profiles were supplemented in the cores with profiles obtained from a magnitude limited subset of the galaxy data in BOW III.

The resulting profiles are presented in Figure 1. The smooth curves are a smoothed representation of the data, extrapolated to larger radii using the theoretical cluster profiles in Figure 1 of BO II. From these smoothed profiles we obtain the structural parameters described below. We have, throughout, assumed circular symmetry in determining the galaxy distributions in our clusters. While that is a reasonable approximation for most clusters, its application to A222 and A223, which together form one very elongated S shaped structure, is unacceptable. However, to analyze these clusters in a way consistent with the others, we must obtain structural parameters for them which are at least roughly comparable to those of the other clusters. To do this, we have derived core profiles from the photometric data, as for the other clusters, and have compared these to the core profiles of the other clusters. By matching the core profiles of A223 and A222 to the most similar of the others, we have estimated structural parameters for them. We have no profile for Cl 0004.8−3450. We have estimated its structural parameters from those of the other clusters of similar appearance and richness.

b) *Data Analysis*

In BO I and BO II we tried to deduce the spiral galaxy populations of two distant clusters, using the observed colors of the cluster galaxies and what we knew about the colors of nearby spirals. For reasons already discussed, this is not a satisfactory approach. We wish, instead, to use a method of analysis which is uniform, unbiased with redshift, and makes the fewest possible assumptions about the galaxies. We describe below such a method, the final product of which is the

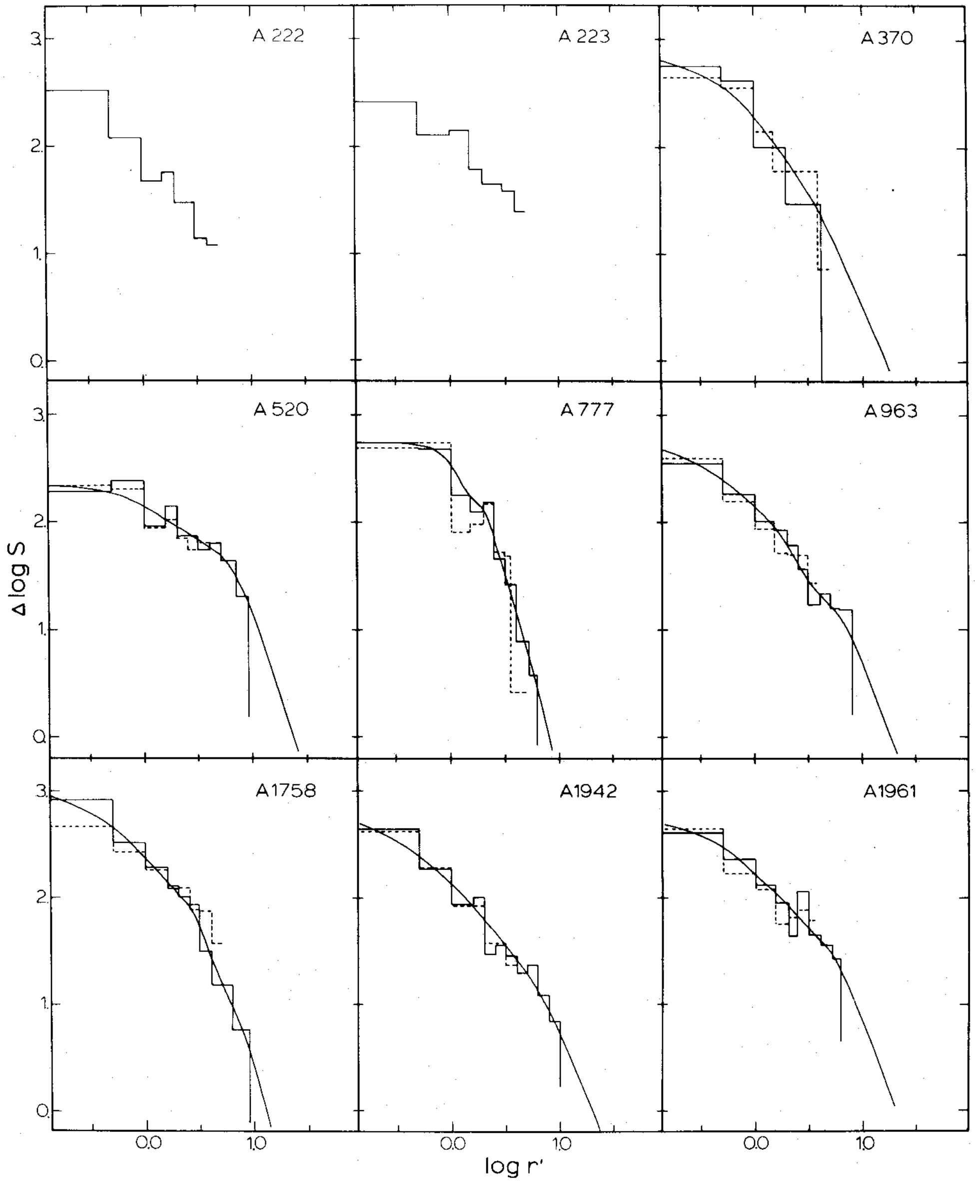

FIG. 1*a*

FIG. 1.—Cluster surface density profiles. *Solid line*, eye counts; *dashed line*, counts from photometric sample; *smooth curve*, smoothed profile. The vertical normalizations are arbitrary.

fraction of blue galaxies (defined in a particular manner) in a cluster. It is very important to note that, because the definition of the samples and of "blue galaxy" differ significantly from those used elsewhere, *these numbers cannot be directly compared with those obtained in previous papers by ourselves or others.*

Part of the analysis parallels that of BO III. We classify clusters according to their degree of central concentration. If R_n is the radius of the circle containing n% of the cluster's projected galaxy distribution, we define the *concentration index*,

$$C \equiv \log(R_{60}/R_{20}) \,. \qquad (1)$$

In BO II we showed that clusters whose density distributions approximate those of uniform-density spheres have $C \approx 0.3$ and, at the present epoch, have large populations of spiral galaxies. We call such objects open or irregular clusters. Clusters with centrally concentrated galaxy distributions have $C \gtrsim 0.4$ and, at present, contain few spirals in their cores; we call these compact or concentrated clusters. Values of C for our clusters, derived from the profiles, are presented in the third column of Table 1; those in parentheses are estimates.

The fraction of galaxies in a cluster of a particular morphological type varies with radius and limiting magnitude. To obtain a uniform population sample we select in each cluster those galaxies with projected distances from the cluster center less than R_{30}, and with absolute visual magnitudes $M_v \leq -20$. Values of R_{30}, obtained from the profiles, are presented in the fourth column of Table 1; those within parentheses are estimates.

It is particularly important that the galaxies be selected by their absolute magnitude in some rest frame band (we have

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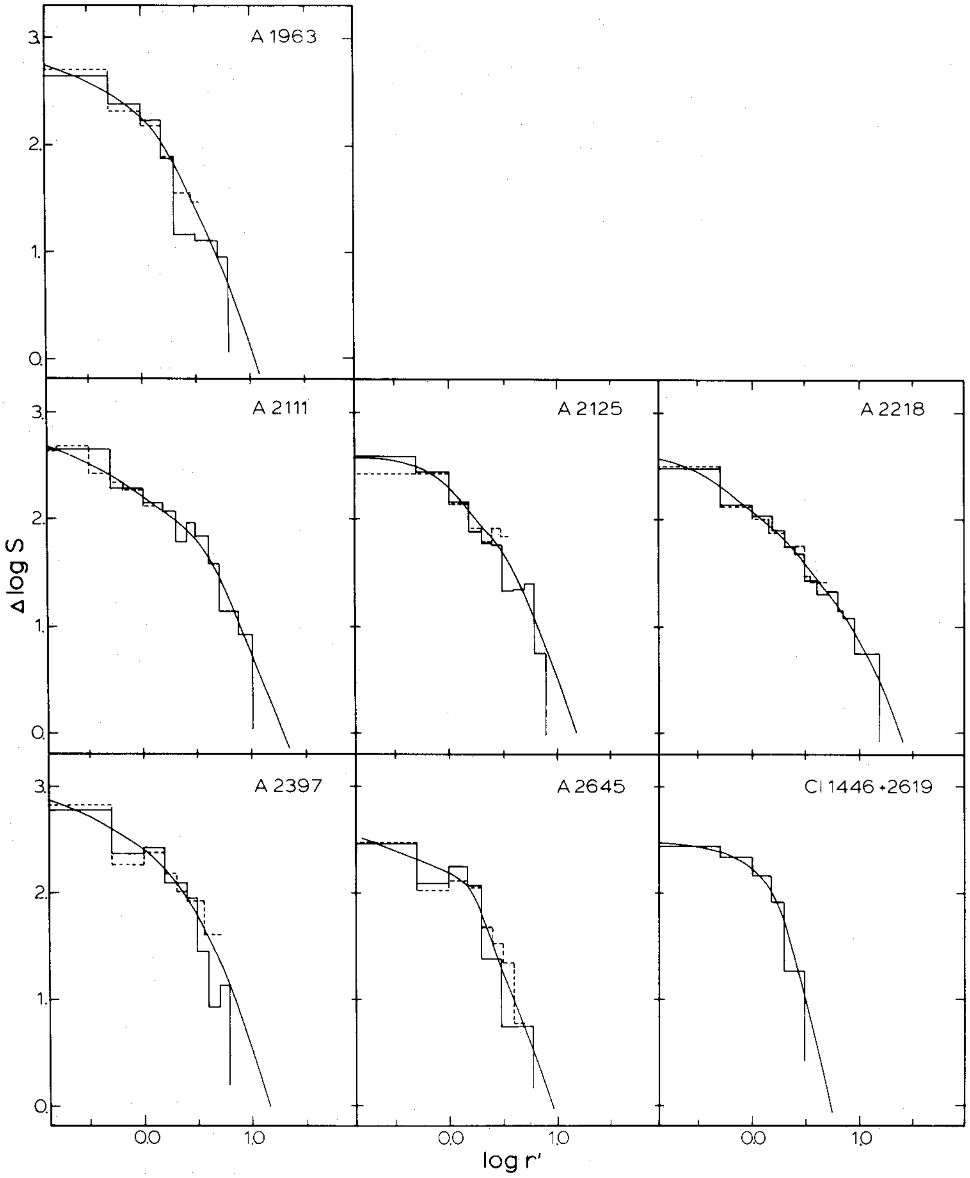

FIG. 1*b*.—Same as Fig. 1*a*

chosen *V*) independent of color and redshift. In general this will imply that, except for zero-redshift clusters observed in the *V* band, the apparent magnitude limit will be a function of color. Failure to take this effect into account will lead to a strong selection bias for or against blue galaxies. Absolute visual magnitudes were calculated from the magnitudes and colors using Pence's (1976) *k*-corrections, the mean of the galactic extinction relations of Sandage (1973) and de Vaucouleurs, de Vaucouleurs, and Corwin (1976), and assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$. Conversion between photometric systems was done using equations (1)-(5) of BOW III. A limiting magnitude of -20 was chosen because it is approximately the faintest accessible in all of the clusters. In a few clusters, the data do not quite extend to the radial or magnitude limits. These cases are noted below in the discussion of individual clusters.

The selection procedure described above produces a uniform sample of the color-magnitude distribution of the galaxies in each cluster. Ideally, one would like to extract all of the information contained in this two-dimensional distribution. This was not a practical approach with these data, and we shall only analyze the marginal distributions, particularly the distribution in color. However, there is one piece of information contained in the two-dimensional distribution which it is important not to ignore: the color-magnitude (C-M) effect in E and S0 galaxies. Unless corrected for, it will produce a broadened and skewed marginal color distribution even if the distribution of colors at one magnitude is infinitely narrow. Although not all of the galaxies in our samples are E's and S0's, we shall correct all of the data—including the background fields—for the C-M effect. The resulting marginal color distribution will represent the distribution of the colors of galaxies relative to the color of the early-type galaxies of the same magnitude. For most clusters, we were able to estimate the slope of the C-M relation directly from the data. The slopes obtained usually agreed rather well with those predicted in

Figure 2 of Sandage and Visvanathan (1977): exceptions are noted below. In those cases where the C-M slope could not be determined from the photometry—usually because of too large a spread of colors—the latter predicted values were used.

The most important correction to be made to the observed cluster distributions is for contamination by foreground and background galaxies. Since these tend to be bluer than most cluster members, an incorrect accounting for their presence can seriously affect the inferred blue galaxy population of a cluster. No background correction was needed for the Virgo Cluster. All other clusters with $z \leq 0.12$ were corrected using the mean background galaxy densities given in BO IV. Although less precise than background determinations made in the neighborhood of each cluster, they should be adequate since the contamination of these low-redshift clusters is generally small. With three exceptions, the high-redshift clusters all have their own background density determinations, obtained near each cluster. The exceptions are the three clusters with video camera

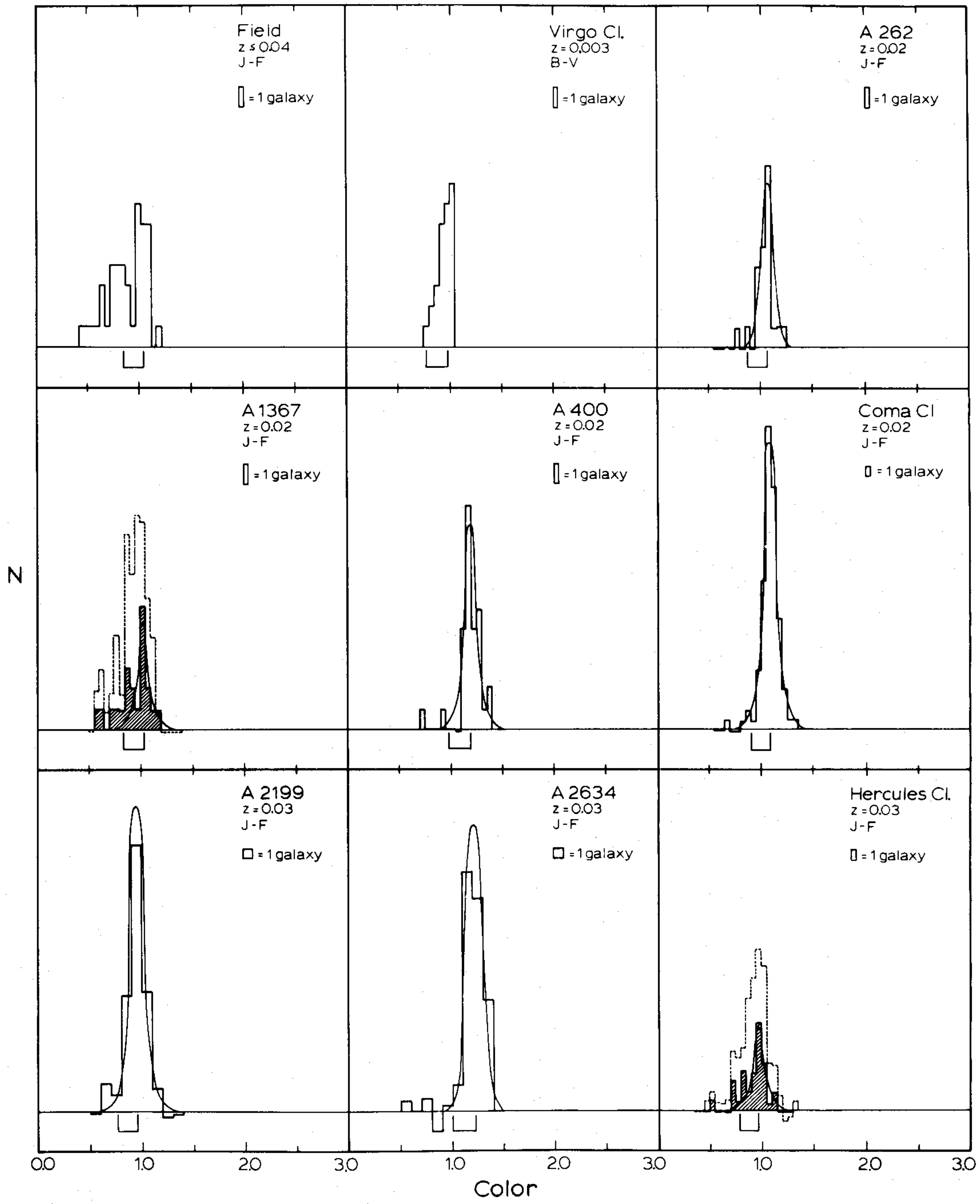

FIG. 2*a*

FIG. 2.—Cluster color distributions. *Solid* or *shaded histogram*, uniform sample; *dotted histogram*, larger sample (see text); *smooth curve*, expected color distribution of E/S0's. The brackets at the bottom represent a color difference of $\Delta(B-V) = 0.2$ in the rest frame of the cluster.

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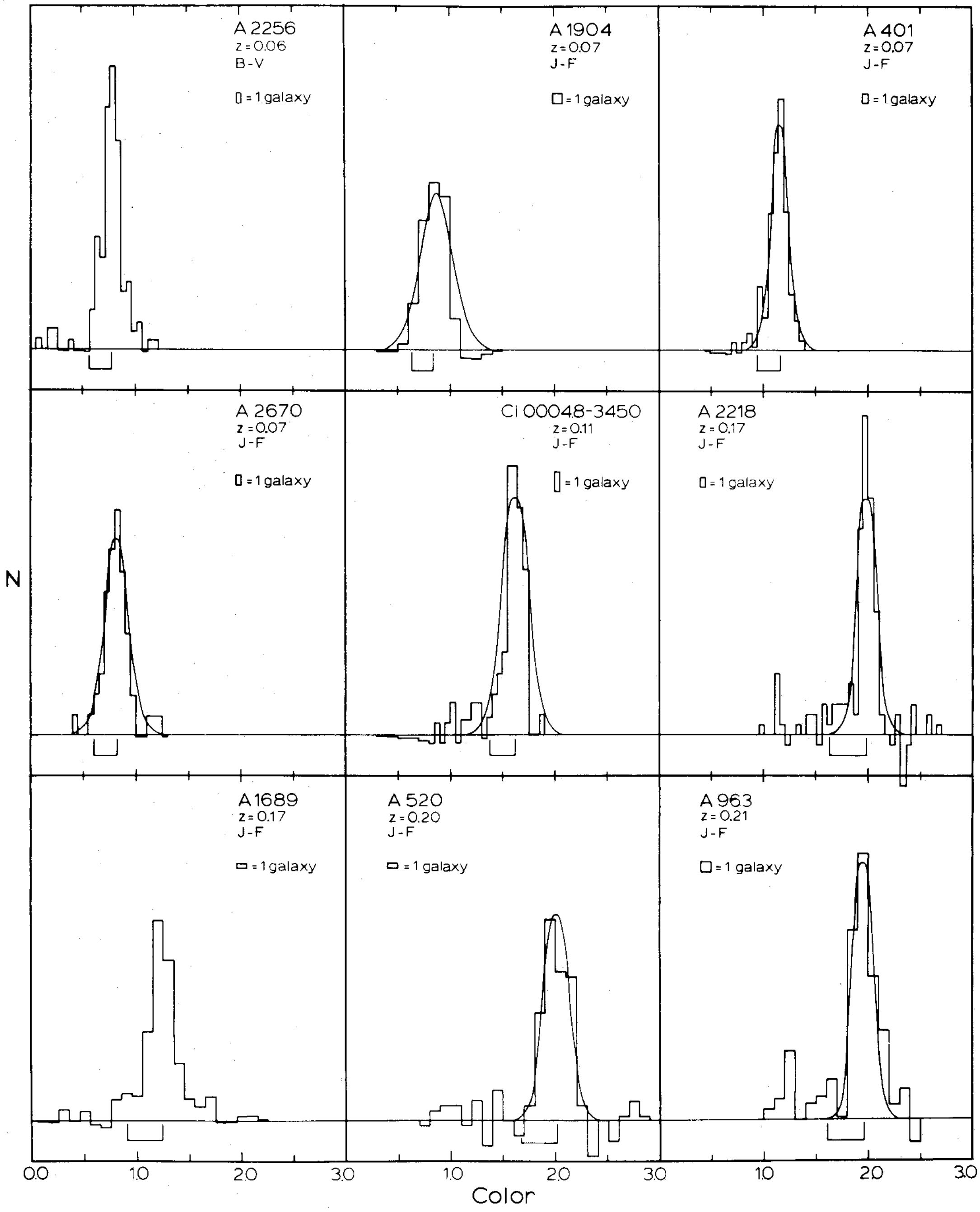

FIG. 2*b*.—Same as Fig. 2*a*

photometry: Cl 1446+2619, Cl 0024+1654, and 3C 295. For these we have used the mean of the galaxy counts in the blank field regions next to A963, A1758, A1961, A2111, and A2645, these clusters being the only high-latitude clusters in BOW III with good calibrations. Conversion between the *JF* and *VR* bands was performed using equation (1-5) of BOW III. We shall return to discuss the reliability of these corrections later.

The resulting color distributions, corrected for the C-M effect and field galaxy contamination, are presented in Figure 2. It should be noted that, because of the way that the C-M effect has been removed, the color zero points of these distributions are arbitrary to a few tenths of a magnitude. The solid (or shaded) histograms show, in each case, the distribution of the uniform sample constructed as described above. In many cases, because of the application of the criteria described above, this sample includes only a small fraction of the available data, and for some clusters we also show, as a dotted histogram, the color distribution of a larger sample whose details are described below. Also shown, as a smooth curve, for those clusters in which we understand the photometric errors, is the expected color distribution of a population consisting of only E and S0 galaxies. The width of this distribution is the product of the photometric errors and the intrinsic spread about the C-M relation of E's and S0's. The work of Sandage and Visvanathan

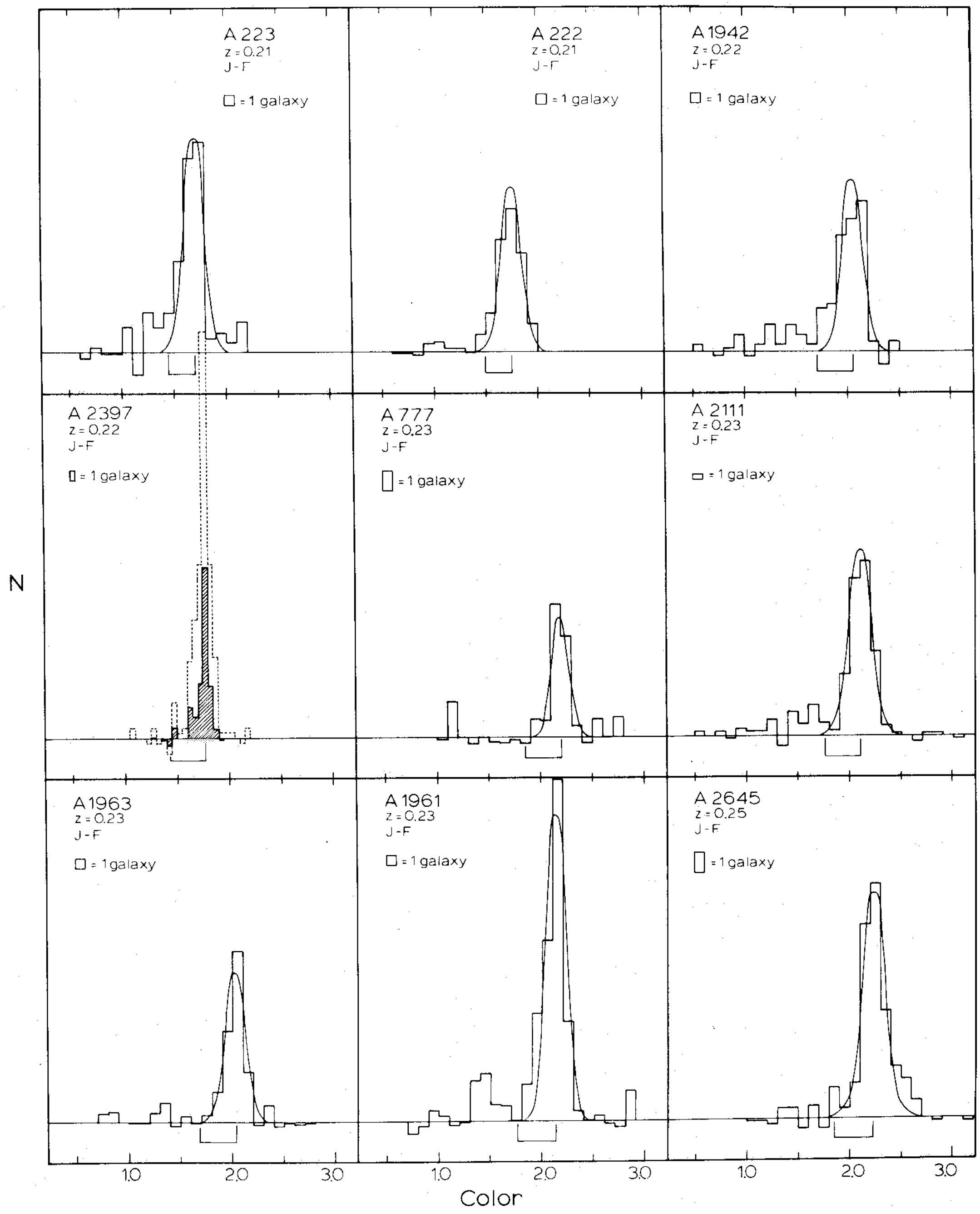

FIG. 2*c*.—Same as Fig. 2*a*

(1978) suggests that the standard deviation of the colors of E's and S0's about the C-M relation is about equal to that relation's slope per magnitude. The photometric errors of the data presented in BO I, BOW III, and BO IV are well understood and are described in those papers. The errors in the photometry of Cl 0004.8 − 3450 were determined from the scatter in Figure 8 of Carter (1980). The errors in the photometry of the remaining clusters are unknown. Inspection of the color distributions in Figure 2 show that there always exists a well defined peak, at a color which is consistent with that expected for early-type galaxies at the redshift of the cluster. The predicted E/S0 color distribution, calculated as described above, has been shifted in color and normalized in area to best agree with that peak. As can be seen, the fit is usually excellent, suggesting that our error estimates are reliable. Also indicated in Figure 2, for each cluster, are the photometric bands in which the data are obtained. However, because of the proliferation of bands with the same name (e.g., *J*) the reader should consult the original source of the photometry for an exact specification of the bands.

The total net number of galaxies in each uniform sample, after correction for field contamination, should equal 30% of the total number of cluster members brighter than $M_v = -20$, and is thus a measure of the cluster richness. This number,

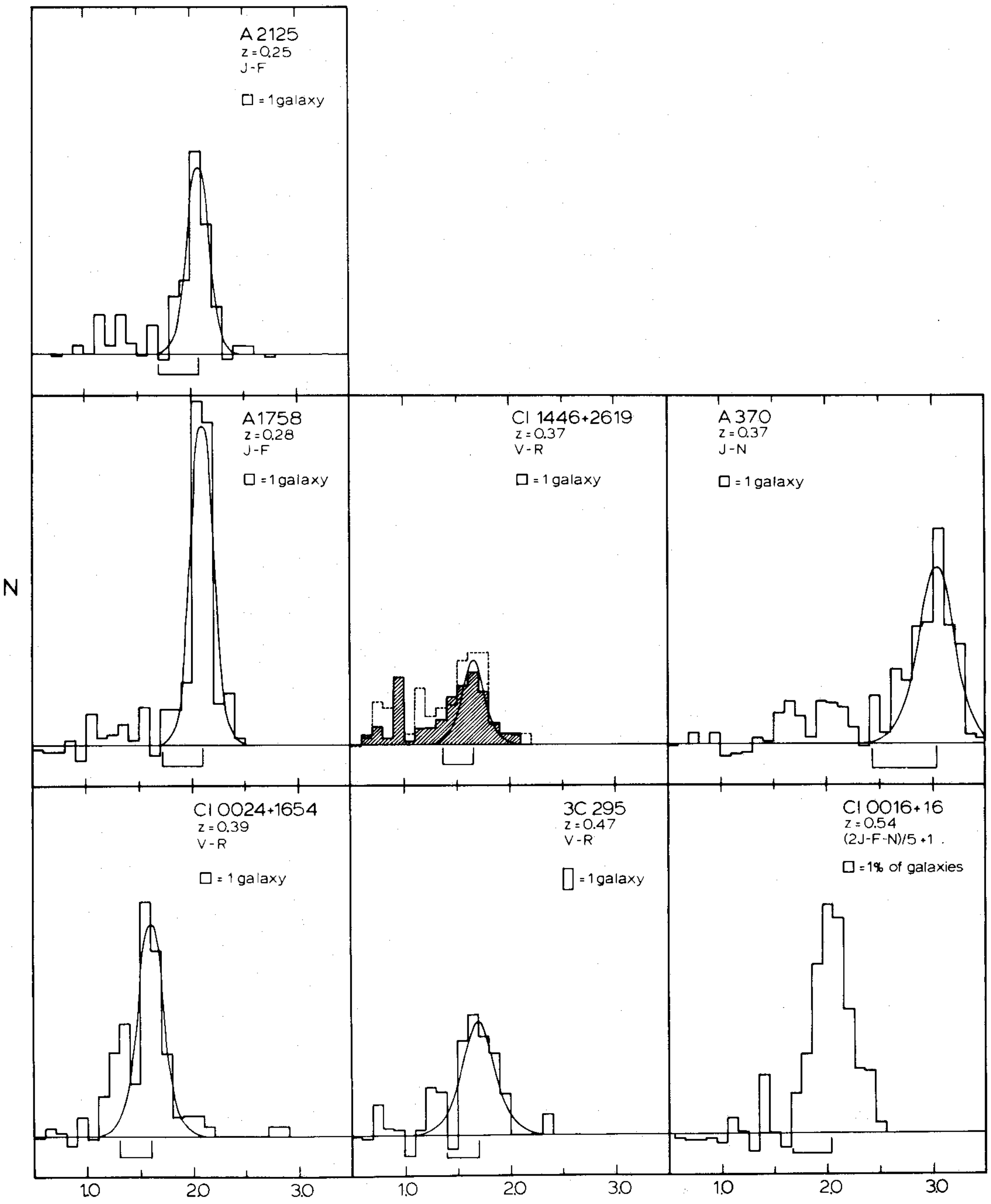

FIG. 2*d*.—Same as Fig. 2*a*

denoted N_{30}, is presented in the last column of Table 1. In those few cases where, as noted below, the sample does not reach the magnitude or radial limits, N_{30} has been calculated by extrapolation, using the cluster profile and/or an assumed luminosity function.

It is of interest to compare the galaxy populations in clusters with the general galaxy population of the nearby universe (which we shall, somewhat loosely, call the "field"). For this we use the galaxy sample of Kirshner *et al.* (1983). From that sample we extract a volume limited subset, complete to $M_v = -20$. We analyze this sample, which extends to $z \sim 0.04$, in the same manner as the cluster samples; the results are included in Figure 2 and Table 1.

Some of the particulars of individual clusters are described below.

Virgo Cluster.—In order to obtain a large enough sample, all galaxies brighter than $M_v = -19.5$ were used. N_{30} was calculated using only those brighter than $M_v = -20$.

Abell 1367.—The larger sample consists of all galaxies with $M_v \leq -19.25$, $R < 24'$. For this sample, as for the smaller one, $f_B = 0.19$.

Abell 400.—The galaxies in this cluster are very red, suggesting that galactic extinction in its direction is much higher than predicted by the cosecant law which we use. We have assumed an additional extinction $\Delta A_J = 0.20$.

Abell 2199.—As can be seen in BO IV, the color-magnitude distribution shows a break at $M_v \sim -21$. It can also be seen in the data of Strom and Strom (1978) and may therefore be real. We use $d(J-F)/dm = 0.0$ for $J < 16$, $d(J-F)/dm = -0.09$ for $J \geq 16$.

Abell 2634.—Poorly determined profile. R_{30} and C are uncertain.

Hercules Cluster.—Our data require a color magnitude slope, $d(J-F)/dm = -0.04$, considerably larger than expected. Here, as in other clusters mentioned below where the C-M slope is different from that expected, we do not know whether the difference is real or due to a scale error in the photometry. For the purposes of this paper, the correct explanation is unimportant.

A1904.—The data show a C-M slope of -0.10, much greater than predicted.

A401.—The data from BO IV do not reach $M_v = -20$. We use $M_{\lim} = -20.24$.

A2670.—The data do not reach $M_v = -20$. We use $M_{\lim} = -20.30$.

Cl 0004.8−3450.—The values of C and R_{30} are estimates. The colors have been corrected for the systematic color error shown in Figure 8 of Carter (1980). Even so, the C-M slope is 0.1, higher than expected. Carter's Figure 8 has also been used to determine the random photometric errors.

A2218.—The photometered field is too small to include the entire area within R_{30}. Because of the general gradient of blue galaxy content with radius which we shall demonstrate, the deduced blue galaxy content of A2218 is probably an underestimate.

A1689.—The color distribution has been taken from Figure 4 of Newell and Couch (1976), zones I and II. The sample covers an area slightly smaller than that within R_{30} and goes somewhat too deep ($M_{\lim} \sim -19.2$). The C-M effect has not been removed but is small.

A250.—The photometered field is slightly smaller than the area within R_{30}. The effect on the derived galaxy content is probably slight.

A963.—Objects 15 and 26 incorrectly given colors of 0.00 in BOW III. Colors unknown.

A223.—Objects 1 and 2; colors unknown, not 0.0 as stated in BOW III.

A222.—Object 3: color is unknown, not 0.0 as stated in BOW III.

A2397.—The larger sample includes all objects for which $M_v < -19$, $R \leq 3'$. For this sample, $f_B = 0.01 \pm 0.03$. Object 5 in BOW III is a star.

Cl 1446+2619.—The larger sample includes galaxies in the entire field brighter than $M_v = -20$.

3C 295.—$M_{\lim} = -21.13$; f_B is probably underestimated.

Cl 0016+16.—As with A1689, only the color distribution of the galaxies is available. It is uncorrected for the C-M effect, and the radial and magnitude limits of the sample are quite different from ours. The effect of this on the results is discussed in § III.

Our goal is to determine what fraction of the galaxies in a cluster do not have the colors of E's and S0's. Rather than decompose the red peak of the color distributions into those objects with E/S0 colors and those which are slightly different, as we tried to do in BO I, we here ask instead which galaxies have colors *significantly* different from those of the E/S0's. At the bottom of each color distribution in Figure 2 is a bracket which spans a color difference of 0.2 mag in the rest-frame $B-V$ color of the cluster galaxies. Inspection of Figure 2 shows that this is about the minimum color difference which is significant in all of the clusters. We therefore define the fraction of blue galaxies in a cluster, f_B, to be the fraction of the total net cluster population with rest-frame $B-V$ colors at least 0.2 mag bluer than those of the early-type galaxies. The values of f_B are given in column (5) of Table 1. The quoted uncertainties are solely those due to the statistical uncertainties in the background correction. It should be noted that these values of f_B, derived from the unbinned data, are in some cases slightly different from those one would deduce from the histograms in Figure 2.

c) The 3C 295 Cluster

We find that, in the 3C 295 cluster, the fraction of blue galaxies $f_B = 0.23$, similar to that of other high-redshift clusters and much higher, as we shall show, than that of nearby compact clusters. However, as noted earlier, there have been two significant published claims that the 3C 295 cluster does not have many more blue galaxies than nearby clusters. Mathieu and Spinrad (1981) have claimed that our deduction of a large blue galaxy population was due to a serious underestimate of the field galaxy contamination. However, we demonstrated in BOW III that this claim was based on an incorrect transformation between photometric systems and that, while our old background estimate was somewhat lower than that of Mathieu and Spinrad, and somewhat lower than that which we are now using, the difference has only a moderate effect on the derived cluster population. In fact, although the import of their paper was that the findings of BO I were incorrect, their final estimate for the blue galaxy content, for a sample of similar radial and magnitude limits to that considered here, was 25%, slightly *higher* than our present determination and only a little lower than our original estimate (31%). (However, note, as stressed before, that these numbers can only be very roughly compared. To make a better comparison, their value must be adjusted for two competing effects, both of which are the result of the fact that their sample is limited by a J-magnitude, which in the rest frame of the cluster is very far to the blue ($\lambda_{\text{eff}} \approx 3200$ Å). On the one hand, such a selection will strongly favor blue cluster members, thus raising the inferred blue population. On the other hand, it also favors blue field galaxies, thus greatly increasing the field galaxy contamination. The net blue cluster population is a small difference between two large numbers and is very sensitive to errors in field corrections. There is reason to think that Mathieu and Spinrad have overcorrected for background contamination. The cluster luminosity function shown in their Figure 5 drops at faint magnitudes, unlike that of any other known rich cluster. The obvious inference is that they have subtracted too many field galaxies. Such an overcorrection would lower the inferred blue cluster population. It is difficult to estimate the relative importance of these two competing effects. The only safe conclusion is that the Mathieu and Spinrad results are not inconsistent with our own.)

Determining cluster populations by correction for field contamination is an indirect and statistical method which can never be completely error free. Much more satisfactory is to directly determine which galaxies are cluster members from their radial velocities. Dressler and Gunn (1983) have measured redshifts of 23 galaxies in the field of the 3C 295 cluster, and find significant contamination by field galaxies. From this they conclude that Mathieu and Spinrad are correct and 3C 295 does not have an excess of blue galaxies. However, an

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analysis of the data shows them not to be inconsistent with our results. Within the uniform sample in the cluster, as defined earlier, there are 33 galaxies—22 red and 11 blue (as we define them). Of these, Dressler and Gunn have obtained redshifts of three red galaxies, all of which are members, and eight blue galaxies, four of which are members. From this we infer that 50% of the blue galaxies, or 5.5 ± 1.4, are cluster members. From background counts, we predict that one of the red galaxies should be a field object. We therefore obtain, using the redshift data,

$$f_B = \frac{5.5 \pm 1.4}{5.5 + 21} = 0.21 \times 0.05 ,$$

entirely consistent with our result. The value quoted in Table 1 is the mean of this number and our determination.

Why, given the virtual identity of the results of Dressler and Gunn, of Mathieu and Spinrad, and of this paper, was there such an apparent conflict between the conclusions of first two groups and those of BO I and BO II? The blame, it appears, lies about equally on each side. We did underestimate the field galaxy contamination in BO I, resulting in an inferred blue galaxy content of about 30% instead of 20% within $R_{30} = 1'$. On the other hand, Mathieu and Spinrad exaggerated the discrepancy between their result and our own by comparing their blue galaxy content of 25% within $R = 1'$, not with our value within the same radius (31%), but with our larger value (40%) within $R = 1\farcm5$. Then, both groups *minimized* the difference between nearby clusters and 3C 295, Dressler and Gunn by comparing the *blue* galaxy content of 3C 295 with the *spiral* galaxy content of nearby clusters, with no attempt to account for red spirals, and both groups by exaggerating our estimates of the typical spiral fraction of nearby clusters.

Most of these confusions are consequences of the limited data originally available, which resulted in errors in the determination of galaxy content, and in improper comparisons between different data sets. Our present data should be sufficiently complete and uniform to eliminate these problems. Finally, it is worth remarking that, although our original estimate of the blue galaxy population of 3C 295 (and *only* of 3C 295: there has never been any question about Cl 0024+1654) has been lowered a bit, the contrast between it and nearby clusters has not because, as we shall see, the blue galaxy content of nearby clusters is also lower than we originally estimated.

d) *Accuracy of the Field Corrections*

The reliability of the results of this paper rest entirely on the reliability of the correction for foreground and background contamination of the cluster samples. The two questions which have been most asked about this work are: Is it possible that the contamination has been systematically underestimated? And is it possible that the distant, anomolously blue clusters are actually each the superposition of two clusters along the line of sight? The latter objects would, of course, have a wider range of colors than would a single cluster.

A consideration of the data shows that it is unlikely that the contamination has, in general, been underestimated. All but three of our moderate and high redshift clusters have field galaxy determinations made in the immediate proximity of the cluster. The field regions were analysed in an identical manner to the cluster regions. A systematic error in the background correction is, therefore, quite implausible.

An even stronger case can be made for the three clusters without their own background estimates, Cl 1446+2619, Cl 0024+1654, and 3C 295. Redshift surveys have been made of all three. Cl 1446 has been studied by Butcher and Oemler (1984*b*). Cl 0024 has been observed by Dressler and Gunn (1982), and we have additional, partially reduced observations of this cluster. The 3C 295 cluster was, of course, observed by Dressler and Gunn (1983). Table 2 compares estimates of field contamination of the blue galaxy sample by our photometric method with direct determinations using redshifts. We take as our sample those blue galaxies within R_{30} and brighter than $M_v = -21$, that being roughly the completeness limit of the redshift surveys. Columns (1)–(3) list the clusters and the fraction of blue galaxies determined to be field contaminants using the two methods. It is clear that we have, if anything, overestimated the degree of contamination.

The redshift surveys also demonstrate that at least these three clusters are not superpositions of pairs of clusters (there is a small group at $z \sim 0.28$ in front of 3C 295, but Table 2 shows that its total population is no greater than the expected field contamination). The available redshift data on more than 60 nearby clusters also show few such superpositions. It is easy to demonstrate that this is in accord with expectations. Let us assume that two clusters must be separated by more than 3 Mpc to be considered separate clusters, and must have a projected separation of less than 3 Mpc to be confused on the sky. The chance of a superposition is, then, the mean number of clusters in a cone of angle $\theta \sim 3$ Mpc/D (where D is the cluster distance) and of length of the order of D but with a hole of radius 3 Mpc at the position of the cluster. Most of our intermediate redshift clusters are among Abell's (1958) distance class 5 and 6 sample. Using the mean surface density and the spatial convariance function of such clusters determined by Bahcall and Soneira (1983), we calculate that expected number of superpositions per cluster

$$N \sim 0.013 \text{ clusters} .$$

Now, among richness class 1 to 3 clusters in the Abell catalog, the ratio of the number of clusters of population $2N$ to that of population N is about 0.14. Thus, the fraction of population $2N$ clusters which are actually chance superpositions of 2 population N clusters,

$$f = \frac{0.013}{0.14} = 0.09 ,$$

too small to be responsible for our results.

III. RESULTS

The fraction of blue galaxies within each cluster is plotted against the cluster's redshift in Figure 3. Two points are immediately obvious: the fraction of blue galaxies in clusters gener-

TABLE 2

ESTIMATES OF CONTAMINATION OF BLUE GALAXIES

	CONTAMINATION	
CLUSTER	Photometry	Spectra
Cl 1446+2619	1.7/7 = 24%	1/6 = 17%
Cl 0024+1654	2.5/8 = 31%	0/3 = 0% (0/7 = 0%)[a]
3C 295	5.8/10 = 58%	4/8 = 50%

[a] $R \leq 1\farcm5 = 1.36 R_{30}$.

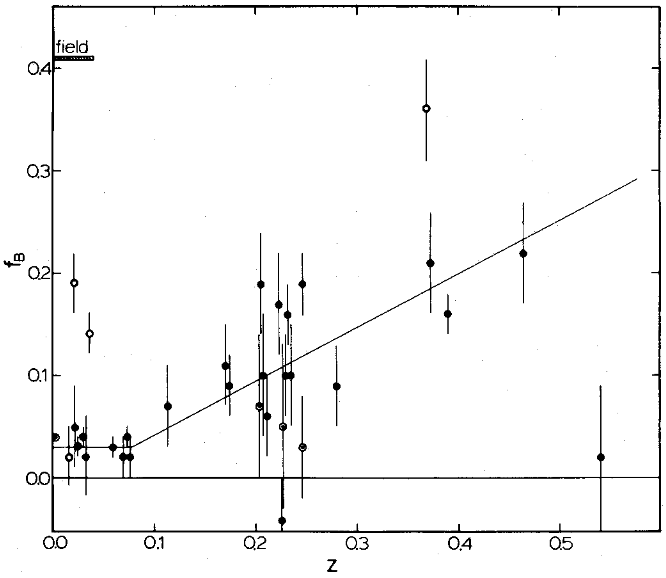

FIG. 3.—Blue galaxy fraction versus redshift. *Filled circles*, compact clusters ($C \geq 0.40$); *open circles*, irregular clusters ($C < 0.35$); *dotted circles*, intermediate clusters ($0.35 \leq C < 0.40$).

ally increases with redshift; and, at every redshift, open clusters contain more blue galaxies than compact ones (a fact known since Zwicky). It also appears that the intermediate-concentration clusters have galaxy populations (at least with R_{30}) like the compact ones, and we shall include them with the latter in all subsequent discussion.

An interesting fact now apparent about low-redshift clusters is that the fraction of blue galaxies is much smaller than the fraction of spirals. This may be easily seen by comparing the fraction of spirals in nearby clusters, as reported in Table 1 of BO II, with the values of f_B in Table 1 of this paper. A typical ratio is 4:1 in both compact and open clusters. In contrast, the ratio among field galaxies is 4:3. In one way this is surprising since the galaxy populations of, at least, open clusters look very much like that of the field. However, this result is at least qualitatively consistent with observations which show that the gas content (and therefore perhaps the star formation rate) of cluster spirals is, on average, lower than that of field galaxies of the same morphological type (see Giovanelli, Chincarini, and Haynes 1981 and references, and Giovanelli and Haynes 1983; but see Bothun, Schommer, and Sullivan 1982 for a contrary opinion). This finding is directly opposite to the conclusion which we drew from the field and cluster galaxy photometry in Figure 3 of BO II. However, that figure was based on the very limited set of photometry available at the time, and was heavily weighted toward the outer parts of the Virgo Cluster, which are not, it appears, very representative of cluster populations.

Compact clusters with redshift $z \leq 0.075$ appear to have very similar, and very red, galaxy populations. Beyond $z \sim 0.1$, the blue galaxy content begins to rise, approaching $f_B \sim 0.25$ at $z = 0.5$. Superposed on the obvious trend, however, is considerable scatter. The most discrepant cluster is the most distant, Cl 0016+16, which has a color distribution indistinguishable from that of nearby compact clusters. The cluster A2397 also shows no evidence of blue galaxies. How significant are these variations? The straight lines in Figure 3 represents one reasonable eye fit to the mean trend. We wish to test whether the observed distribution of f_B is consistent with each cluster being a random sample drawn from a population with f_B represented by the line. In Figure 4 we present the distribution of the values of Δ/σ of those clusters with $z > 0.1$, where Δ is the deviation of f_B of the cluster from the mean line and σ is the expected error, a combination of the quoted uncertainty in f_B and the expected fluctuation in the true value of f_B in a sample of size N_{30}. The smooth curve represents a normal distribution of unit variance, and is the expected distribution if the clusters are random samples. The agreement is very good except for Cl 0016+16. The probability of one cluster in 20 having so large a deviation is 0.09; its discrepancy, therefore, is interesting but not highly significant. This significance may, however, have been underestimated, for two reasons. The area of the cluster from which the published data were obtained is larger than our standard area, and, as we shall show, blue populations increase outward. Furthermore, the data sample is limited by F magnitude, a band rather far to the blue of the rest frame V band, again favoring blue galaxies. For both reasons, the expected observed f_B for Cl 0016+16 is probably somewhat higher than that represented by the mean line in Figure 3, which increases the discrepancy with the observed low value.

On the other hand, the outskirts of Cl 0016+16 are very blue indeed. Among those galaxies which Koo (1981) studied within a 6′ × 6′ field but beyond $R = 1\farcm5$, corresponding to a range of R/R_{30} of 1.5 to 4.5, $f_B = 0.55$. Although we have little photometry of nearby clusters in this range of radii with which to compare this number, it is certainly a much higher value than would be seen in the outskirts of clusters at the present epoch. The other anomolous cluster is A2397, for which $\Delta/\sigma = 1.8$. This discrepancy is not particularly significant; indeed, inspection of Figure 4 shows that we expect one such object. If we use the larger sample whose color distribution is shown in Figure 2, we increase the discrepancy to $\Delta/\sigma \sim 2.3$, an unimportant change.

The reason for the peculiarity of Cl 0016+16 is not obvious. It is not atypical in structure or richness. Among all of the compact clusters, we have not been able to find any optical property of clusters which is significantly correlated with f_B, although there is some tendency for the poorer and less concentrated clusters to be redder. This lack of correlation is not unexpected, given the fact that Figure 4 shows that the distribution of Δ of most clusters is entirely attributable to sampling errors. However, Henry and Lea (1984), who have made X-ray observations of many of our clusters, have apparently

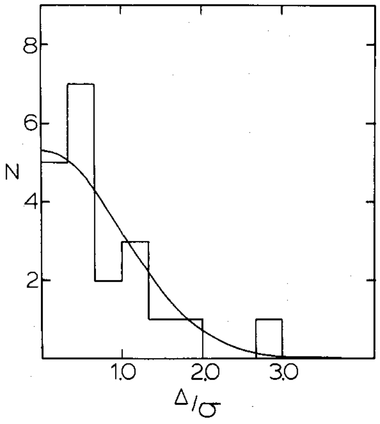

FIG. 4.—A comparison of the scatter in f_B with that expected from sampling errors. See text.

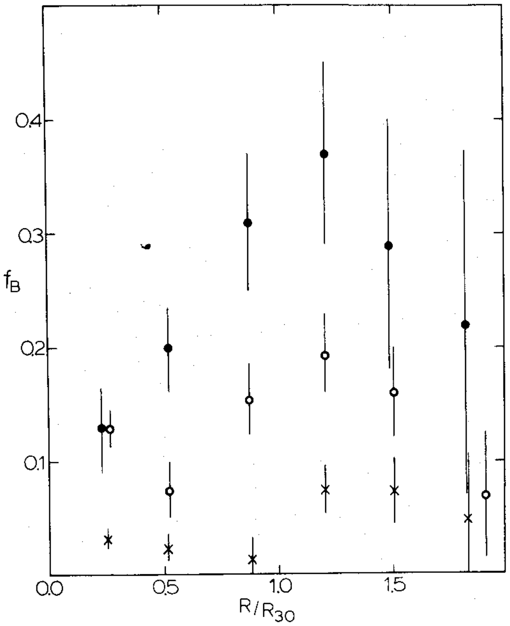

FIG. 5.—Variation of f_B with radius in nearby clusters (*crosses*), intermediate-redshift clusters (*open circles*), and high-redshift clusters (*filled circles*).

found a strong correlation of f_B with X-ray temperature, in the sense that hotter clusters have fewer blue galaxies. This is particularly intriguing because Cl 0016+16 is a very hot cluster with only a lower limit known for its X-ray temperature (White, Silk, and Henry 1981). The significance of this result is not yet clear.

Another view of the distribution and evolution of the blue galaxy population is presented in Figure 5, which plots f_B versus radius in nearby ($z < 0.08$), intermediate redshift ($0.2 < z < 0.25$) and high-redshift ($0.35 < z < 0.5$) clusters. Again, the evolution with redshift is very obvious, as is the general tendency for f_B to increase outward. The fact that f_B always seems to reach a maximum at $R/R_{30} \sim 1.3$ is intriguing but hardly statistically significant.

Some idea of the relative luminosity functions of blue and red galaxies may be obtained from Figure 6, which plots f_B versus magnitude in the sum of four clusters (A963, A2111, A2125, and A370). The tendency for the very brightest galaxies to be red confirms the impression obtained from the color-magnitude arrays of cluster members (q.v. BO I, BOW III) which tend to be quite narrow at the bright end and quickly spread to the blue as one goes fainter.

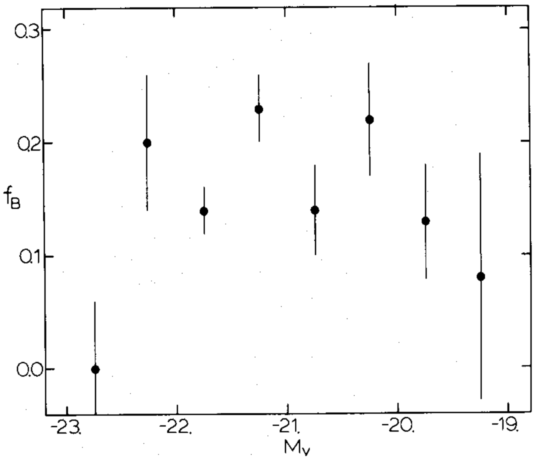

FIG. 6.—The variation of f_B with absolute magnitude in four clusters.

Finally, we must comment on the few irregular clusters in our sample. The only high redshift open cluster, Cl 1446+2619, has, particularly in the larger sample shown in Figure 1, a remarkable population, being much more skewed toward the blue than even the nearby field sample. In fact, the large fraction of very blue galaxies is uncharacteristic of any nearby population of which we are aware. The redshift measurements summarized in Table 2 show that most of the blue galaxies are indeed cluster members. Although based on very few clusters, the data are consistent with an evolution with redshift of the blue galaxy fraction of irregular clusters which is parallel to that of the compact clusters.

IV. DISCUSSION

The results of this study may be summarized as follows: (*a*) Low-redshift compact clusters form a very homogeneous group of objects, with cores essentially devoid of blue galaxies. (*b*) At redshifts $z > 0.1$, compact clusters have significant numbers of blue galaxies, the fraction increasing with redshift. (*c*) Although redshift is the most important determinant of cluster content, there are suggestions that processes within individual clusters may also affect it. (*d*) There is some evidence that the color evolution of galaxies in irregular clusters parallels that of galaxies in compact clusters. (*e*) The colors of spiral galaxies in the cores of nearby clusters tend to be redder than those of spirals in the field.

What can we make of these observations? First, it is clear that there has been strong recent evolution of some cluster galaxies. There is also in the results the compelling suggestion that this evolution is not primarily due to the cluster environment, but rather proceeds at a similar rate regardless of environment. This would not be an unreasonable discovery in an evolving universe, but confirmation of the possibility will require much more data on the evolution of galaxies in open clusters, in the outskirts of compact clusters, and in the field than are now available.

Are the data consistent with the observed evolution being due to the gradual fading of star formation in normal spiral galaxies? We have noted that nearby clusters contain significant numbers of red spirals, and that Wirth and Gallagher (1980) find many other cluster members to show very weak spiral structure. The suggestion clearly is that today's compact clusters contain large numbers of dead and dying spirals, which may have been bluer in the past. Larson, Tinsley, and Caldwell (1980) have argued that most spiral galaxies are rapidly exhausting their gas supplies. They suggested that this supply is usually replenished by infalling extragalactic material. But this material has proved very difficult to find, and, if it does not exist, spiral galaxies may have total lifetimes comparable to the present age of the universe, and today's blue spirals may be the remnant of a once larger population.

Based on their own data on the 3C 295 and Cl 0024+1654 clusters, Dressler and Gunn (1982, 1983) have expressed the view that many of the distant blue cluster members have higher, more centrally concentrated surface brightnesses and very different spectra from nearby spirals. The nearby type of object resembling most closely the proposed Dressler-Gunn blue cluster member is the class of blue S0's discussed by

Sparke, Kormendy, and Spinrad (1980). If these objects are indeed the correct analogs for the distant blue cluster members, then one should not think of cluster S0's and red spirals as having originated from classical spiral galaxies. In our view, however, as yet too few high-quality spectra of the distant blue galaxies, and too few of the various possible nearby comparison objects, are available to be certain that there really are important differences between normal spirals, seen either today or at earlier epochs, and the blue cluster members.

Finally, if our suggested parallel evolution for galaxies in irregular clusters is ultimately confirmed, and especially if it is shown also to occur in distant galaxies not in rich clusters, then the identification of the epoch in question as a very special one will be inescapable. We cannot help but note in passing, that the observed evolution of active galactic nuclei and QSOs also occurs over much the same time scale and epoch. Both phenomena are thought to involve the consumption of gas, and both will naturally decline with the removal or dispersal of that gas. The observed evolution of blue and of active galaxies may both be signs of the exhaustion of gas in the universe.

We cannot end this discussion without noting that, as usual, Zwicky was here first. In *Morphological Astronomy* (Zwicky 1957) he states: "From cursory inspection of 100-inch and 200-inch plates it appears that δC [the color range of cluster galaxies] is increasing with distance of the clusters. Many interpretations of this observation are possible such as . . . intergalactic obscuration, the Stebbins-Whitford effect, or some systematic evolutionary phenomena".

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Note added in proof.—Dr. Richard Ellis reports that Cl 0016+16 is actually the superposition of two clusters at very different redshifts. If so, its apparently anomalous galaxy content must be considered suspect.

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