PHOTOMETRY OF REMOTE GALAXY CLUSTERS

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ABSTRACT

New data on the colors of galaxies in distant, rich clusters of galaxies are presented. Of seven clusters examined having $z>0.20$, all exhibit color distributions indicating that a significant proportion of the member galaxies are undergoing star formation. The one cluster studied with $z<0.20$ clearly shows a reduced fraction of such galaxies.

I. INTRODUCTION

Several years ago, two-color photometry of the member galaxies in two rich, centrally concentrated clusters at $z\tilde{=}0.4$ indicated the presence of an anomalously large population of blue objects (Butcher and Oemler 1978a,b). The natural inference was that these blue objects are galaxies in the process of forming stars, and that probably we are observing spiral galaxies before they somehow lost their interstellar matter and turned into S0's. If this hypothesis is correct, then we are witnessing a rather great deal of evolution of galactic morphological types in clusters in the very recent cosmological past--so recent, in fact, as to be entirely unexpected. If these two clusters turn out to be representative of all concentrated, relaxed clusters at such redshifts, then we will need to confront the fact that all or nearly all of the giant clusters changed in an important way rather abruptly some 2-3 billion years ago. For if cluster spirals stopped forming stars any later, we would find today that S0's are distinguishable from ellipticals by their colors, which they are not (Sandage and Visvanathan 1978), and if they did so much earlier, then these two clusters must be quite unrepresentative for some reason.

To address this question of how representative the first two clusters really are, and at the same time to see if we might be able to study the conversion process as it actually occurs, we have begun a program of photometry of additional remote clusters. To date, we have obtained two-color data on nearly two dozen distant ($z\gtrsim0.2$), rich (richness class ≥3) clusters for the analysis, and at present, we are

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in the process of examining this material. While not all the clusters, for one reason or another (but mostly because of background and foreground contamination problems), are found to be suitable for the study, we should soon be able to say something concrete about the galaxy cluster population between about 2 and 5 billion years ago. The purpose of the present report is to give some of the early, preliminary results of this study.

II. OBSERVATIONS AND REDUCTIONS

Recall that our technique is the very simple one of constructing the distribution of broad band colors for all galaxies in the core regions of the clusters. We then identify the peak in this distribution due to the cluster members with classical elliptical galaxy-type colors, and attempt to use the size of this peak to estimate the fraction of spiral galaxies in the cluster. Note that we are unabashedly injecting into the discussion our biases concerning the nature of the blue objects. It is not yet certain that they are spirals, but we are supposing that they are, and at least for the moment, we will continue to refer to them as such.

Specifically, the data mostly comprise either ISIT vidicon observations in the V and R passbands, or IIIaJ+GG385 and IIIaF+RG610 4-m prime focus plates. The vidicon data have been reduced by the methods described in Butcher and Oemler (1978a), and the photographic data by a new, automatic computer code which detects and measures all objects within a specified area.

We have tried to pay close attention to several effects which might compromise our final results. First, we have used metric diameters for both our measurement apertures and the radii in the clusters for inclusion in the final color distribution determination. Specifically, we have assumed $q_o = 0.05$, and have used an aperture of 6 arcsec diameter and cluster radius of 1.24 arcmin at $z = 0.40$, and then scaled these quantities to the redshift of each cluster before measurement. Similarly, we have assumed that our completeness limit occurs with R = constant at $z = 0.40$, and then varied the completeness limit as a function of color at each redshift in such a manner as to account approximately for the known effects of differing K-corrections for the different types and colors of galaxies. The depth in the luminosity function to which we go has not been maintained precisely constant, but in nearly all cases it is close to 4 magnitudes below the brightest cluster member. Finally, in our estimate of the fraction of classical E and SO type galaxies in each cluster (and, hence, also the fraction of spirals), we have tried to account approximately for the effects of the color vs. magnitude relation for nearby E/So's, as given by Visvanathan and Sandage (1977).

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III. RESULTS AND DISCUSSION

As for the clusters discussed in Butcher and Oemler (1978b), our final results for each cluster consist of an estimate of the percentage of spirals in the cluster, and a concentration index to characterize the dynamical state of the cluster. The latter quantity is defined as the logarithm of the ratio of two projected radii: that containing 60% of all cluster members, and that containing 20%. Its definition is more or less arbitrary, but it does seem to quantify the well-known relation between cluster concentration and spiral galaxy content in the nearby clusters. For reference, a uniformly filled sphere has an index of 0.26.

The results available at this time are given in the table and in Figure 1. The filled circles in the Figure are for the sample of nearby clusters discussed by Butcher and Oemler (1978b), and the open circles containing redshift values are for the sample in the table.

TABLE 1. Results for 8 Remote Clusters

Cluster	Redshift	Concentration	% Spirals
A2218	0.18	0.53	30
A2111	0.23	0.38	53
A2645	0.25	0.32	58
A1758	0.28	0.48	61
A370	0.37	0.44	59
Cℓ1446+26	0.38	0.30	64
Cℓ0024+16	0.39	0.50	50
3C295	0.46	0.58	59

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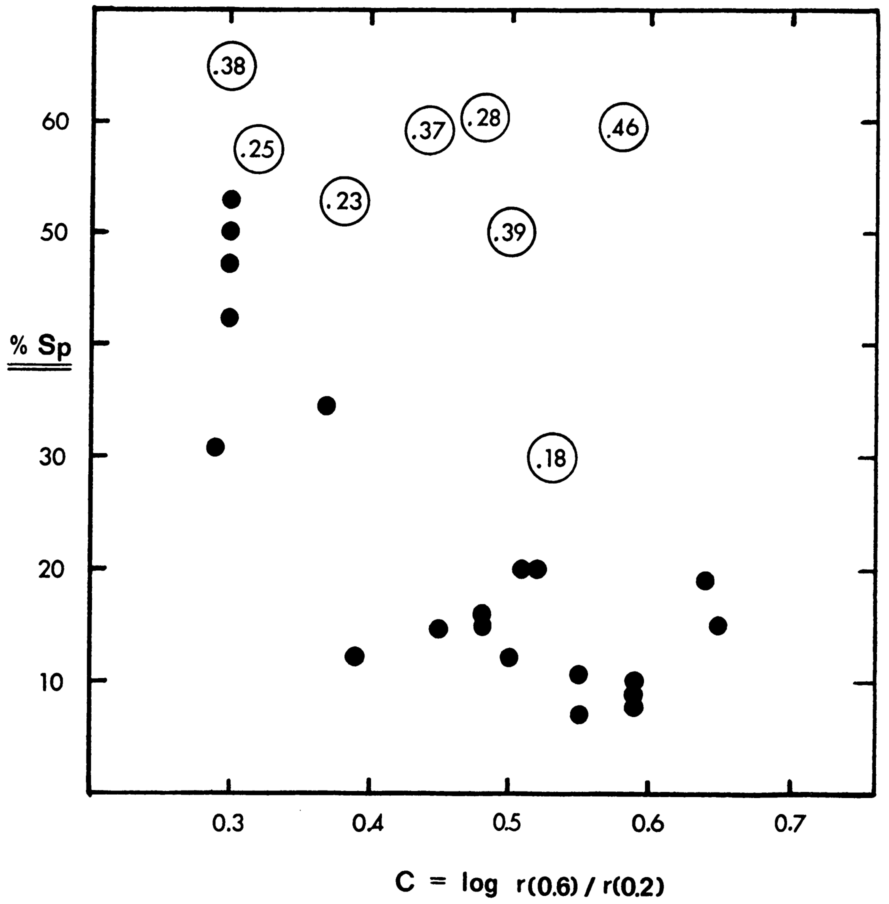

Figure 1. Spiral content vs. cluster concentration, for nearby clusters (filled circles) and the present sample of remote clusters (open circles with redshifts indicated).

It is immediately evident that seven of the distant clusters have essentially the same spiral content, some 50-60%, regardless of their concentration indices. The sole exception, Abell 2218, has the lowest redshift in the sample, and would seem to lie closer to the sample of nearby, concentrated clusters than to the set of distant ones.

Apparently, then, it is not uncommon in giant clusters with $z \gtrsim 0.2$ for there to be a significant population of blue cluster members independent of cluster morphology. There also already seems to be some suggestion that the observed quenching of star formation may be a phenomenon related not only to the dynamical age of the clusters, but also to the particular cosmological epoch near $z \approx 0.2$.

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These new results also provide some hope that the detailed shapes of the various color distributions can provide us with clues to the progress of the transformation in each cluster at the time of observation. We find, for example, that the color distributions in Cℓ0024+16, A2645, and A370 are characterized by an elliptical color peak and a blueward tail stretching all the way to colors typical of the bluest known Sc galaxies. Such a distribution is similar to that in the field near zero redshift. On the other hand, A2111 and possibly also A2218 show only short, stubby blue tails, barely reaching into Sc type colors at all. Finally, Cℓ1446+26 and probably A1758 seem to exhibit color distributions at the opposite extreme, with perhaps half of the spirals showing the colors expected from typical Sc galaxies.

If this last sort of color distribution turns out to be real and not too infrequent, then we may want to begin thinking in terms of galaxy-cluster interactions having a significant effect on the evolution of cluster spirals. One might imagine, for example, that the act of cluster collapse could enhance star formation in member spirals for a brief period, perhaps even driving star formation close enough to completion for one or another of the various gas removal mechanisms to become important.

While such speculation is probably somewhat premature, we do get the impression from these early results that the study of the giant galaxy clusters as a function of redshift is likely to become a rich and rewarding field, one which may help us understand both the details of cluster evolution and certain aspects of the processes governing star formation in individual galaxies.

We wish to thank Jack Jewell for his help in shepherding our data through the KPNO CDC 6400 computer.

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DISCUSSION

Silk: Would you comment on the spatial distribution of the blue galaxies in the distant clusters that you have observed?

Butcher: Generally, the clusters do show a gradient in the ratio of red-to-blue objects with radius, in the sense of an increasing fraction of blue galaxies with increasing radius. We try to minimize the effects of such gradients by scaling the apparent size of the region we include in our color distributions with redshift.

Segal: There appears to be a very simple explanation for the large proportion of blue galaxies that are apparently members of clusters at redshift ~ 0.5. In fact, the chronometric cosmology preducts that for a cluster defined by apparent magnitude limits in part, as is practice, a relatively large proportion of blue galaxies is likely to be cluster members. This arises from the fact that a magnitude dimming of ~ 0.4 mag corresponds in the chronometric theory to a displacement from z = 0.5 to z = 1, although in a Friedmann model, the dimming is ~ 1.5 mag. Consequently, a large proportion of the objects in a cluster defined (partially) by conventional magnitude limits would be likely to be at redshifts > 0.5, quite possibly ~ 1, with consequent shifting of the spectrum towards the blue. Would you not agree that the hypothesis that the redshifts of your cluster members are not ~ 0.5, but considerably greater, could explain your observation of an otherwise anomalously large proportion of blue galaxies?

Butcher: It certainly is a possibility we have not considered carefully.

M. Burbidge: Is anything known about X-ray emission from any of these clusters?

Butcher: Yes, the Einstein Observatory satellite has detected X-rays from the 3C295 cluster, as well as other clusters near z ~ 0.4. Hence, one can probably infer the presence of a substantial intracluster medium in such clusters, present at the same time as these blue galaxies are seen.

N. Bahcall: From one of the z ~ 0.4 clusters for which you find evidence for a large fraction of blue (spiral?) galaxies, 3C295, the Einstein observations have recently detected a rather strong source of extended X-ray emission, similar to those found in the compact

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nearby clusters. Since most of the hot intracluster gas is believed, in general, to have originated in the galaxies (due to the solar iron abundance found in the X-ray emitting gas), not too many normal spiral galaxies would be expected to be present in this cluster. Further observations, both in optical and X-rays, are needed in order to clarify this apparent "conflict," and better understand the relation between the X-rays, intracluster medium, and the galaxy type.

Koo: The color distribution of field galaxies resembles that of the fainter clusters. Would you comment on the possible contamination by the background?

Butcher: All of our clusters have been chosen to have richness classes of 3 or greater. Hence, they are at least a factor of 5, and often a factor of 10, above background. For each cluster we have determined the local background and subtracted it, but in most cases this step is of academic interest only and of little practical consequence.

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