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THE RANGE OF $V - R$ COLORS FOR A CLUSTER OF E AND S0 GALAXIES AS A FUNCTION OF REDSHIFT

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ABSTRACT

The expected $(V - R)$ color distribution for a centrally condensed, relaxed cluster of E and S0 galaxies has been calculated as a function of redshift. Because of the differences in the ultraviolet spectra of E and S0 galaxies, which are correlated with absolute magnitude, the spread in $(V - R)$ colors for such a cluster becomes increasingly wide for increasing redshift. This effect becomes pronounced for redshifts of 0.4 and beyond. Thus evidence for the color evolution of cluster galaxies will be seen as an additional broadening of the color distribution.
Subject headings: galaxies: clusters of — galaxies: photometry — galaxies: redshifts

I. INTRODUCTION

The expected distribution of colors in a cluster of galaxies is of general interest in the study of galactic evolution. Clearly it is necessary to know in detail the expected color distribution of galactic colors in a cluster before any broadening due to evolutionary effects can be deduced.

The $(B - V)$ and $(V - R)$ colors of nearby E and S0 galaxies show little color dispersion (e.g., Butcher and Oemler 1978). The $(U - B)$ color, on the other hand, shows a strong correlation with the absolute magnitude of the galaxy (e.g., Lasker 1970; Visvanathan and Sandage 1977). As the redshift increases the B, V, and R photometric bands successively are occupied by the luminosity-sensitive rest wavelength ultraviolet spectrum.

We have calculated the expected $(V - R)$ colors of E and S0 galaxies of differing absolute magnitude for redshifts up to 0.5. We then applied these colors to the luminosity function of a centrally condensed, relaxed cluster consisting almost entirely of E and S0 galaxies. Because of the differences in the ultraviolet region of the energy distribution the spread in colors of such a cluster widens for increasing redshifts, first becoming pronounced at about $z = 0.4$.

II. THE CALCULATION

Absolute spectral energy distributions for E and S0 galaxies of different absolute magnitudes in the Virgo cluster were obtained from Visvanathan and Sandage (1977). The distributions merge and end at about λ6200, and so were extended further into the red using the data of Wells (1978).

Using the V filter transmission function for zero air mass given by Matthews and Sandage (1963) and the R filter transmission function for zero air mass given by Oke and Sandage (1968), we calculated the $(V - R)$ colors for the cluster galaxies of different absolute magnitude using a Simpson's integration. The zero point of the color was determined using the absolute spectral energy distribution for Vega given by Hayes and Latham (1975). The calculations were repeated for redshifts up to 0.5; K-corrections for the various energy distributions were calculated at each redshift.

The results of these calculations allowed us to construct magnitude-color relations for each redshift. In these diagrams both the magnitudes and colors are corrected for the instrumental effects of the redshift.

In order to convert the magnitude-color relation to an expected number distribution of color we require a luminosity function. Coma was chosen as a representative cluster since it is centrally condensed and relaxed and consists almost entirely of E and S0 galaxies. Godwin and Peach (1977) have tabulated the luminosity functions for the Coma cluster for two areas symmetric about the cluster center, one 1.22 square degrees and the other $R \leq 16'$. For the larger-area sample the spirals, when identified, were removed. The galaxies in the smaller-area sample were tabulated as unclassified so all were assumed to be E and S0 galaxies. This is reasonable since the percentage of spiral and irregular galaxies is very small.

We chose to have our sample span an observed interval of 4.5 mag. The Godwin and Peach luminosity function is complete to much deeper limiting magnitudes. Since the K-corrections for the V filter vary with the absolute magnitude of a galaxy, the fainter galaxies become systematically less faint with respect to the brightest galaxy in a cluster at higher redshifts. Thus there are more galaxies in a 4.5 mag interval at higher redshifts. Table 1 contains the actual number of galaxies used in each sample.

Since the color-magnitude relation of Visvanathan and Sandage was calibrated for the Virgo cluster, the magnitudes were shifted to correspond to those in the Coma cluster by the observed Δm of +3.89 mag. We then matched the number of Coma cluster galaxies per 0.02 mag interval to the calculated $(V - R)$ color for that magnitude.

Figures 1 and 2 are histograms of the number of galaxies per expected $(V - R)$ magnitude for the larger and smaller area, respectively. It appears that the spread in $(V - R)$ colors in a cluster consisting solely of E and S0 galaxies increases with redshift, becoming most noticeable starting at about $z = 0.4$.

III. COMPARISON WITH OBSERVATIONS

In order to compare our theoretical colors with observation at least two sources of error had to be taken into account. Both the cosmic scatter in the color-magnitude relation and observational error will tend to broaden the distribution of colors in a cluster. So before comparing our distributions with observation, we convolved the distributions with normal error functions whose widths were the errors from these two sources.

TABLE 1

NUMBER OF GALAXIES IN EACH 4.5 MAGNITUDE INTERVAL SAMPLE

	z				
SAMPLE	0.1	0.2	0.3	0.4	0.5
Area 1°22 square.....	241	241	241	268	302
Area $R \leq 16'$..........	100	100	100	109	118

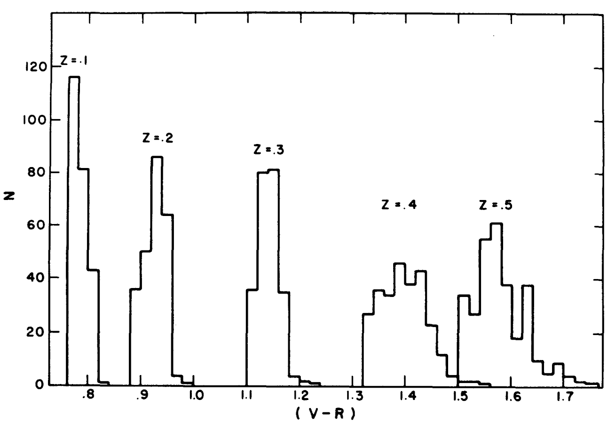

FIG. 1.—Histogram of the number of galaxies per expected $(V - R)$ magnitude calculated for redshifts up to $z = 0.5$ for our larger sample of galaxies. The sample covers an area of 1.22 square degrees at the center of the Coma cluster. The cosmic dispersion of the color-magnitude relation has not been taken into account.

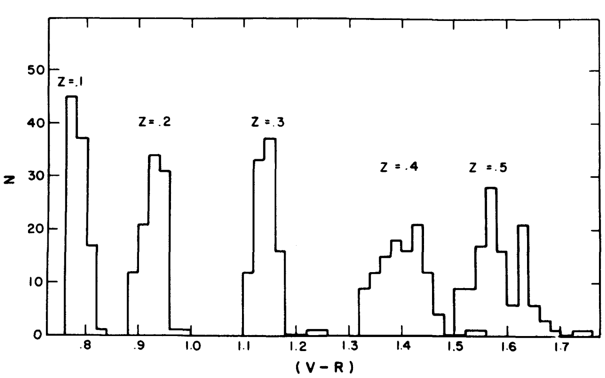

FIG. 2.—Histogram of the number of galaxies per expected $(V - R)$ magnitude calculated for redshifts up to $z = 0.5$ for our smaller sample of galaxies. This is the core sample for $R \leq 16'$ in the Coma cluster. The cosmic dispersion of the color-magnitude relation has not been taken into account.

For high redshifts, the $(V - R)$ color of a galaxy is comparable to its unshifted $(u - b)$ color. Since Visvanathan and Sandage did not present a $(u - b)$ color-magnitude relation, we related the cosmic scatter in their $(u - V)$ relation to the expected scatter for the $(V - R)$ relation. We took as the uncertainty for our $(V - R)$ color-magnitude relation that quoted for the $(u - V)$ relation multiplied by the ratio of the slopes of our $(V - R)$ relation and their $(u - V)$ relation. Thus the cosmic scatter for the $(V - R)$ color-magnitude relation was taken as $\pm 0.059 \times 0.52 \approx \pm 0.031$ mag.

Butcher and Oemler (1978) found the $(V - R)$ color distribution of galaxies for the Coma-like cluster Cl 0024+1654, $z = 0.39$. Their samples of galaxies covered approximately a four-magnitude interval, and linear diameters (assuming $q_0 = 0$) close to those covered by the Coma luminosity functions of Godwin and Peach. They estimated the observational error to be about ± 0.08 mag in their determination of $(V - R)$ colors. Therefore the total uncertainty applied to our calculations was assumed to include both this observational error and the cosmic scatter calculated previously, or $[(0.031)^2 + (0.08)^2]^{1/2} = 0.086$ mag.

Our color distribution for $z = 0.4$ was then convolved with a Gaussian error function with a σ of 0.086 mag and compared to the distribution in Figure 13 of Butcher and Oemler. For this comparison we normalized the number of galaxies in our sample to the number in theirs. Figure 3 is the comparison of the distributions for both the entire samples (our 1.22 square degrees sample and their $R \leq 1'.5$) and the core samples (our $R \leq 16'$ and their $R \leq 0'.5$). The distributions are in very good agreement for the core sample. The large-area sample shows a tail of galaxies toward blue colors. From our calculations we see that only galaxies bluer than $(V - R) < 1.2$ require explanation as other than E or S0 galaxies. For $(V - R) < 1.2$ the observed number of galaxies for the three areas $R < 0'.5$, $1'.0$, and $1'.5$ are respectively 3, 20, and 43 galaxies. We note that these numbers are in nearly precisely the ratios expected for galaxies distributed uniformly across the field. Although Butcher and Oemler have estimated the expected number of field galaxies and found it too small to explain the observed tail of blue galaxies, we feel that this peculiarity of spatial distribution raises serious doubts about those field galaxy corrections.

IV. CONCLUSION

Because of the differences in spectral distribution in the ultraviolet, a spread in the $(V - R)$ colors of E and S0 galaxies of different absolute magnitudes is expected at high redshifts. The currently available observations of the $(V - R)$ colors in distant galaxy clusters are not inconsistent with the expected effect. There is not yet clear-cut evidence for an evolving color distribution.

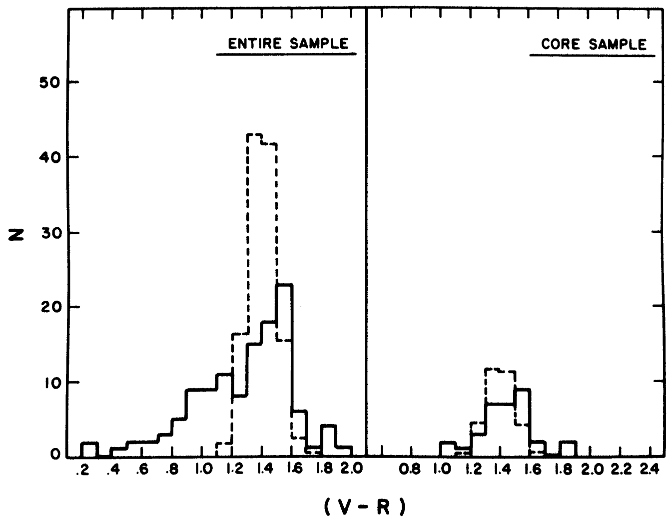

FIG. 3.—The solid lines are the distributions given by Butcher and Oemler for their entire sample for $R \leq 1'.5$ and core sample of $R \leq 0'.5$ in the cluster Cl 0024 + 1654, $z = 0.39$. The dashed lines are our calculated distributions for $z = 0.4$ convolved with the cosmic scatter in the color-magnitude relation and Butcher and Oemler's observational error. Our samples, taken from the Coma cluster, are of 1.22 square degrees for the entire sample and for $R \leq 16'$ for the core sample.

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