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THE BUTCHER-OEMLER EFFECT IN 295 CLUSTERS



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We present the study of the Butcher-Oemler effect in a sample of 295 Abell clusters. gri CCD photometry allowed the determination of the fraction of blue galaxies, and was also used to estimate photometric redshifts with an accuracy of 0.04, for those clusters without spectroscopic measurements. The resulting redshift range for the sample is $0 < z < 0.4$. Our observations show a strong Butcher-Oemler effect, with an increase in the fraction of blue galaxies, f_B, with redshift that seems to indicate that strong evolution of the cluster galaxy population can already be observed at low redshifts. We find a strong link between cluster richness and the fraction of blue galaxies, f_B. The slope of the $f_B(z)$ relation is the same for all richnesses, but at a given redshift, f_B is systematically higher for poor clusters.

1 Introduction

The Butcher-Oemler (BO) effect provided some of the first evidence for evolution of galaxies and clusters. Butcher & Oemler [1,2] found an excess of blue galaxies in high redshift clusters in comparison with the typical early-type population observed in the central region of local clusters [3]. The BO effect has also been observed in more recent studies, which indicate an even stronger evolution in the fraction of blue galaxies in clusters [4,5].

We present observations of the BO effect in a large sample of 295 Abell [6,7] clusters of all richnesses, with no further selection on the basis of morphology or X-ray luminosities. This is important because all previous works were based on samples biased toward richer clusters, with some samples being further selected according to morphology and/or X-ray luminosities, so that a combination of different selection effects could be mimicking the observed $f_B(z)$ relation. Our sample is therefore well suited for studies of cluster evolution since it should contain a more representative variety of clusters (in terms of degree of substructure, richness, and mass) at each redshift than any previous sample, and because its large size should allow a better determination of the relation.

2 Data

The data presented in this paper was primarily obtained to calibrate the POSS-II (Second Palomar Sky Survey). It comprises 295 Abell clusters imaged at the 0.9m telescope at the Cerro

Tololo Interamerican Observatory (CTIO) [5] and at the Palomar Observatory 1.5m telescope [8, 9]. The CCD images were taken in the g, r and i filters of the Thuan & Gunn [10] photometric system, with 1-σ magnitude errors of 0.12 in g, 0.10 in r, and 0.16 in i at $r = 20.0^m$. We have also observed 22 control fields in order to assess the background contribution.

3 Analysis of the Butcher-Oemler Effect

The BO effect can be measured by comparing the fraction of blue galaxies in clusters at different redshifts. The $g - r$ *vs.* r color-magnitude (CM) relation was determined by fitting a linear relation to the elliptical galaxies locus using the same prescription as in MdC00, and the sample was further divided in two according to how well defined the elliptical galaxy loci were. Galaxies were then classified as *blue* if they had $g - r$ colors 0.2^m below the linear locus in the CM relation, as originally defined by Butcher & Oemler [1, 2]. Whereas Butcher & Oemler were limited to brighter galaxies by their photographic data, our CCD sample allows us to probe significantly deeper, and we selected galaxies with r magnitude between $M^* - 1$ and $M^* + 2$ (where $M_r^* = -20.16$ [11]), inside a region of radius 0.7 Mpc around the cluster. We assume a cosmology with $H_\circ = 67$ Km s^{-1} Mpc^{-1}, and $q_\circ = 0.1$.

The final fractions of blue galaxies for the entire sample are shown in the upper panel of Figure 1. For those clusters with multiple observations, we have used the observation with smaller σ_{f_B}. Clusters with spectroscopic and photometric redshift measurements are indicated by solid and open circles respectively. The individual error bars are not presented to avoid confusion in the plot, but the median σ_{f_B} is 0.071. The lower panel presents only clusters that have: (1) $\sigma_{f_B} < 0.071$, (2) spectroscopic redshift measurements, and (3) a well-defined CM relation. The 1-σ_{f_B} errors are indicated for these clusters. In both panels, the solid lines indicates a linear fit derived from the clusters with $z \leq 0.25$ ($f_B = 1.24z - 0.01$, with an rms scatter of 0.1 for the entire sample shown in the upper panel, and $f_B = 1.34z - 0.03$, with an rms of 0.07 for the sample shown in the lower panel). The dashed line indicates the rms scatter around the fit, and while the upper panel shows a larger scatter, the two derived relations are the same within the errors. A clear trend of strong evolution with redshift is seen.

Richness is a natural second parameter which might cause the range in f_B at given redshift. Figure 2 shows the $f_B(z)$ diagram with marker sizes scaled by N, the number of galaxies between $M^* - 1$ and $M^* + 2$, inside 0.7 Mpc, after background correction. Only clusters from the central panel in Figure 1 and at redshifts between 0.1 and 0.2, where no corrections needed to be applied to compute f_B, are presented in this figure. The solid line is the best-fit linear $f_B(z)$ relation for the 26 clusters shown, and the dashed lines indicate the relations obtained when the sample is subdivided in two 13 cluster samples according to richness (red for rich, and blue for poor clusters). The rate of evolution is approximately the same for all richnesses, and there is clearly an effect, with richer clusters tending to lower f_B. The suggestion that the observed increase of f_B with redshift is caused by missing poor clusters at higher redshift [12] is therefore no longer tenable, because any such selection effects would serve to *decrease* the redshift evolution of f_B. The evolution in f_B is real, and takes place in all richness classes.

The results presented here are not to be directly compared with fractions of blue galaxies as originally defined [2]. The most important reason for differences is the magnitude range used to calculate f_B. It is believed that the number of *blue* galaxies increases at fainter magnitudes and it is therefore natural that our f_B measurements are in general higher. Also, the usage of a rigid physical scale for all clusters, instead of regions determined individually for each cluster according to its density profile, should yield different f_B estimates. When f_B is computed using the same absolute magnitude range used by Butcher & Oemler [2], we find signs of evolution consistent with recent studies [4, 5]. Limiting our sample at brighter absolute magnitudes however increases the σ_{f_B} because of the smaller galaxy count statistics, and probes a smaller fraction

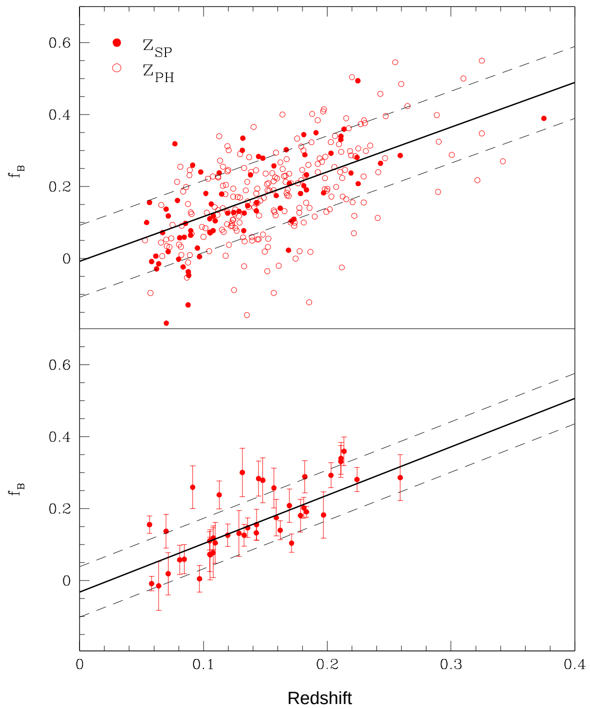

Figure 1: Fraction of blue galaxies in the magnitude range between $M^{*}-1$ and $M^{*}+2$, and within 0.7 Mpc from the center of the cluster. The entire 295 cluster sample is shown in the upper panel, and only clusters with (1) $\sigma_{f_B} < 0.071$, (2) spectroscopic redshift measurements, and (3) well-defined CM relation are presented in the lower panel. In each panel the solid line indicate a linear $f_B(z)$ fit derived from the clusters with $z \leq 0.25$, and the dashed line represents the rms scatter of the clusters around the fit.

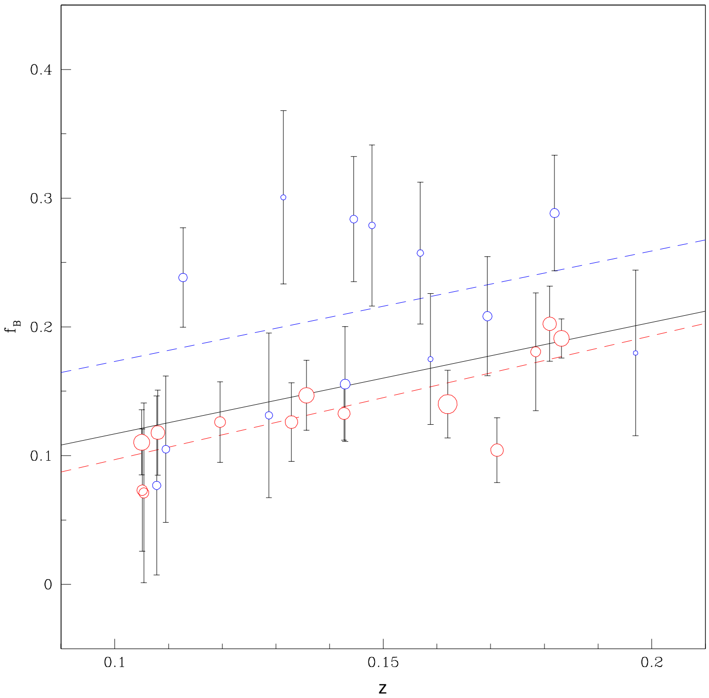

Figure 2: Subsample of clusters with $0.1 \leq z \leq 0.2$ from the lower panel in Figure 1. The solid line represents the best-fit to the entire sample; the dashed red line indicates the linear fit for the subsample of rich clusters; and the dashed blue line indicates the fit for the poorest ones.

of the cluster population.

4 Summary

This is the first sample large enough to allow the study of the f_B variations at a given redshift. We investigate the richness dependence of the Butcher-Oemler effect, and find a strong correlation between f_B and galaxy counts in the sense that poorer clusters tend to have larger f_B than richer clusters at the same redshift. The inclusion of poor clusters tends therefore to increase the slope of the $f_B(z)$ relation, and is another factor (together with the inclusion of fainter galaxies) responsible for the stronger evolution observed in this sample when compared to previous works based mostly on rich clusters.

A more complete analysis of the BO effect and of its richness dependence will be presented in a paper recently submitted to *ApJL* [13].

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