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EVOLUTION OF CLUSTER AND FIELD ELLIPTICAL GALAXIES AT $0.2 < z < 0.6$ IN THE CNOC CLUSTER SURVEY

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ABSTRACT

Two-dimensional surface photometry has been done for 166 *early-type* galaxies (bulge/total luminosity $B/T > 0.6$) in three fields of the Canadian Network for Observational Cosmology (CNOC) cluster survey. These galaxies are either spectroscopically confirmed members of clusters at $z = 0.23$ (45 galaxies), 0.43 (22), and 0.55 (16) or field galaxies in the same redshift range. An additional 51 early-type galaxies in the rich cluster Abell 2256 at $z = 0.06$ were analyzed with the same technique. The resulting structural and surface brightness measurements show that, in the plane of absolute magnitude $M_{\rm AB}(B)$ versus $\log R_e$ (half-light radius), the locus of cluster elliptical galaxies shifts monotonically with redshift so that at redshifts of (0.23, 0.43, 0.55), galaxies of a given size are more luminous by -0.25 ± 0.10, -0.55 ± 0.12, and -0.74 ± 0.21 mag with respect to the same relation measured at $z = 0.06$ (adopting $q_0 = 0.5$). There is no evidence that early-type galaxies in the field evolve differently from those in clusters, although we emphasize that our cluster sample is dominated by galaxies far from the dense cluster core. If dynamical processes do not substantially modify the size-luminosity relation for early-type galaxies over the observed redshift range, then these galaxies have undergone significant luminosity evolution over the past half of the age of the universe. The amount of brightening is consistent with passive evolution models of old, single-burst stellar populations.

Subject headings: galaxies: evolution — galaxies: fundamental parameters

1. INTRODUCTION

Luminosity evolution of early-type galaxies has long been predicted to occur as an inevitable consequence of an aging stellar population (Tinsley 1972), but its detection has proved to be difficult. Dressler & Gunn (1990) found signs of color evolution (expected to accompany luminosity evolution) among even the reddest cluster galaxies at $z \sim 0.7$. More recent studies of distant clusters (Aragon-Salamanca et al. 1993; Rakos & Schombert 1995) report changes in color with redshift that are broadly consistent with early-forming and passively evolving elliptical galaxy models (e.g., Bruzual & Charlot 1993). Yee & Green (1987) found an apparent brightening of the characteristic magnitude of the luminosity function of cluster galaxies associated with quasars by 0.9 ± 0.5 mag at $z = 0.6$.

Observations with the *Hubble Space Telescope* (*HST*) have opened up new opportunities for morphological studies of cluster galaxies. Pahre, Djorgovski, & de Carvalho (1996) find evolution of 0.36 ± 0.14 mag in the rest-frame K band from early release observations of Dressler et al. (1994) of the cluster CL 0939+4713 (Abell 851) at $z = 0.41$. The same *HST* imaging was used by Barrientos, Schade, & López-Cruz (1996) to derive a value of 0.64 ± 0.3 mag of evolution from $z = 0.41$ to the present. These values are consistent with passively evolving models of elliptical galaxies (Tinsley 1972; Bruzual & Charlot 1993). Thus, it appears that luminosity evolution of early-type galaxies has been directly detected in one cluster. It is important to establish whether this observation is representative of the early-type population as a whole.

Although *HST* resolution (~1 kpc at $z > 0.5$) is necessary to resolve bars, dust lanes, and spiral structure in galaxies at high redshift, it has been shown (Schade et al. 1996) that ground-based imaging is capable of providing quantitative measurements of the gross morphology of distant galaxies. In particular, it was found that disk scale lengths (h) and bulge effective radii (R_e) can be measured reliably under certain conditions. Disk scale length can be usefully measured in mid- to late-type galaxies (fractional bulge luminosity $B/T < 0.5$), whereas elliptical/bulge effective radii can be reliably measured for early-type objects ($B/T > 0.7$). The fractional bulge luminosity itself was shown to be measurable with a dispersion of ~20% (Schade et al. 1996) in faint ($I_{\rm AB} \sim 22$) galaxies for high-redshift objects in the Canada-France Redshift Survey (CFRS). The typical size of CFRS galaxies is $h \sim R_e \sim 0''.35$.

The Canadian Network for Observational Cosmology (CNOC) cluster survey (Carlberg et al. 1994; Yee, Ellingson, & Carlberg 1996) provides a unique data set for the study of the evolution of cluster and field galaxies. In addition to good redshift coverage (16 clusters with $0.2 < z < 0.6$), the CNOC survey contains redshifts for 2600 galaxies all the way from the cluster core ($R_c < 0.5$ Mpc) to the low-density outer regions ($R_c \sim 3$ Mpc) and into the field. Abraham et al. (1996) exploited this wide range in environments in a study of the

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galaxy populations in A2390. Particularly relevant to the present work is the fact that directly comparable samples of field galaxies at each redshift are available to complement the cluster samples. The typical galaxy size (disk scale length or bulge effective radius) in the present work is ~0″.7, so that the ratio of typical size to seeing (FWHM) is 0.7, compared to a ratio of 0.5 in Schade et al. (1996) for CFRS ground-based imaging.

This Letter concentrates on the morphological analysis of 124 cluster and 66 field *early-type* galaxies at $0.06 < z < 0.55$, representing the first phase of a comprehensive study of the evolution of cluster galaxies and cluster/field differential evolution. Observations and the analysis procedure are described in § 2. The relations between size and luminosity or surface brightness are presented in § 3, and the results are discussed in § 4. It is assumed throughout this paper that $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

2. OBSERVATIONS AND PROCEDURE

Imaging was obtained in 1993 June and October using the Canada-France-Hawaii Telescope Multiobject Spectrograph (MOS). Gunn *r*-band imaging was used to fit the two-dimensional luminosity distributions in this analysis. Integration times were 900 s for A2390 (Yee et. al. 1996) and MS 1621+26 (Ellingson et al. 1996) and 1200 s for MS 0016+16. These three clusters were chosen to yield a good range in redshift (0.228, 0.427, and 0.547) and to contain reasonably large numbers of spectroscopically confirmed cluster members (174, 98, and 47, respectively). The MOS image quality was fairly good for these clusters, with seeing of 0″.93 ± 0″.06 and 0″.97 ± 0″.04 (FWHM) for the central and inner east fields in A2390, 1″.04 ± 0″.04 and 1″.2 ± 0″.04 for the two fields in MS 1621 (central and south), and 1″.00 ± 0″.04 in MS 0015. These dispersions are from Gaussian fits to azimuthally averaged stellar profiles and represent the variation of the point-spread function (PSF) *core* over the regions of the frame where fitted galaxies are located. An empirical PSF for each frame was constructed using DAOPHOT routines (Stetson 1987).

The analysis procedure was identical to that described by Schade et al. (1995). Galaxy parameters (size, surface brightness, and fractional bulge luminosity, B/T) were estimated by constructing "symmetrized" images of the galaxies (see Schade et al. 1995) in the Gunn *r*-band. The use of images that are symmetric by construction minimizes the effects of nearby companions and other irregular structure. These images were fitted with two-dimensional galaxy models integrated over each pixel and convolved with the empirical point-spread functions. The two components used are an exponential disk and a deVaucouleurs ($R^{1/4}$) law. The majority of local galaxies have luminosity distributions that are well described by some combination of these components (Kormendy 1977; Kent 1985; Kodaira, Watanabe, & Okamura 1986), and *HST* work confirms that this is also true for high-redshift galaxies (Schade et al. 1995; Barrientos et al. 1996).

A set of 561 galaxies in these three CNOC fields with velocities, regardless of cluster membership or color, were subjected to the two-dimensional fitting procedure. Fitting failed to converge for 22 of the galaxies (4%), usually because of close neighbors and image defects. Failures were discarded.

In addition to the CNOC clusters, fits were done on 100 bright galaxies on an 1800 s B image of the cluster A2256 from the López-Cruz & Yee survey (López-Cruz 1996) obtained with the Kitt Peak 0.9 m telescope. These galaxies were chosen to be within ±0.1 mag in $B - R$ of the tight red cluster galaxy sequence in the color-magnitude diagram, thus ensuring a high probability of both cluster membership and early-type morphology. Fits were done using an identical procedure to that used for the CNOC galaxies.

Those objects with a bulge fraction $B/T > 0.6$ as measured from the best-fit two-dimensional models were defined as early-type galaxies. After applying this selection criterion, the median values of B/T for the clusters A2256, A2390, MS 1621+26, and MS 0016+16 are 0.81, 0.83, 0.83, and 0.94, respectively. The CNOC field samples had similar median B/T values. The numbers of early-type galaxies for these clusters are respectively, 51, 45, 22, and 16. In all cases, the pure-bulge model-fit values of $M_{\rm AB}(B)$ and R_e were adopted because this choice results in a slightly smaller dispersion in the M_B-log R_e relation. The observed Gunn g and r magnitudes and colors were converted to rest-frame $M_{\rm AB}(B)$ luminosities and $(U - V)_{\rm AB}$ colors $[(U - V)_{\rm AB} = (U - V) + 0.7]$ based on interpolation among the spectral energy distributions of Coleman, Wu, & Weedman (1980) as described by Lilly et al. (1995). The galaxies in A2256 were also K-corrected according to Coleman et al. (1980).

3. RESULTS

Figure 1 shows the relation between R_e (half-light radius) and luminosity for cluster and field *early-type* galaxies at $0.06 < z < 0.55$. We measure the change in the galaxy loci with redshift assuming they can be represented simply by shifts along the luminosity axis. The similarity of the slopes in the individual panels tends to support this approach, but no physical interpretation is necessarily implied. A slope of $\Delta M/\Delta \log R_e = -3.33$ (the mean of fits to the cluster and field galaxy loci individually, including the Coma fit from Barrientos et al. 1996) was adopted for the cluster and field galaxies. The magnitude shifts ΔM were estimated using a constrained linear fit using this fixed slope, and the errors are given by $s/(n-1)^{1/2}$, where s is the estimated dispersion and n is the number of data points.

Superposed on Figure 1 are the best-fit lines to the galaxy loci for each cluster, and these *cluster* loci are plotted on the field galaxy panels (these are *not* the best-fit field galaxy lines). The best-fit shifts in luminosity for the clusters and field, along with their uncertainties, are given in Table 1. The data in Figure 1 and Table 1 show that cluster galaxies of a given size grow progressively more luminous with increasing redshift. The corresponding amount of brightening in the field galaxy sample is consistent with that in the clusters at similar redshift. The galaxy luminosity enhancement is well described by $\Delta M_B = -1.35z$, and this is equivalent to an increase in surface brightness (at a given size) by this amount.

The effect of cosmology on this result is indicated by the arrows in the lower left of each cluster panel. These show the change in size and luminosity that result from changing $q_0 = 0.5$ to $q_0 = 0.1$. The net effect on the computed magnitude shifts relative to the cluster A2256 is an increased evolution by −0.02, −0.05, and −0.09 for the clusters at $z = 0.23$, 0.43, and 0.55, respectively.

4. DISCUSSION

Two conclusions follow from the present observations. First, the relationship between M_B and log R_e for early-type cluster

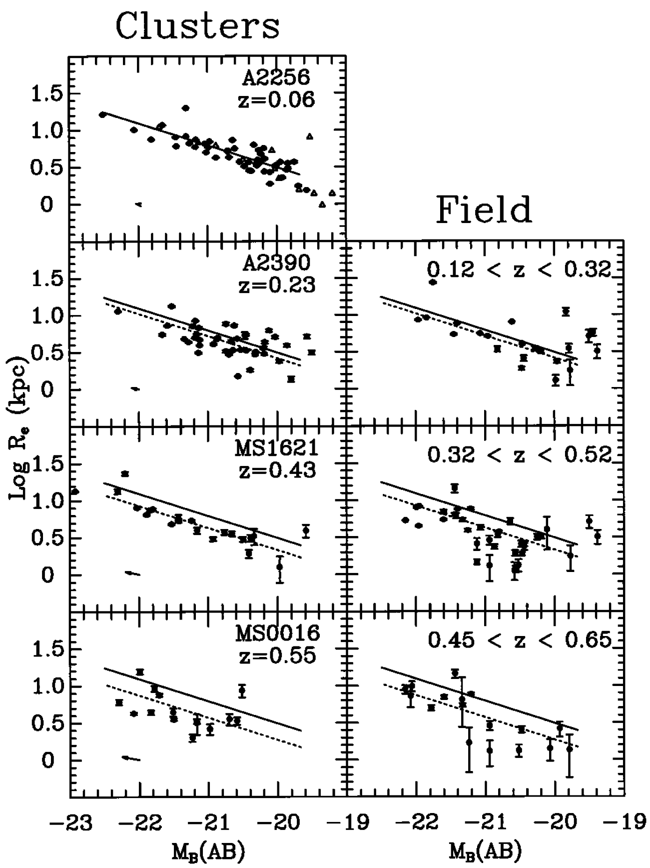

FIG. 1.—Relation between $M_{AB}(B)$ and $\log R_e$ (half-light radius in kiloparsecs) for early-type galaxies (measured $B/T > 0.6$). Clusters are shown in the left panels and corresponding field samples on the right. The best-fit fixed-slope relation from the cluster A2256 is superposed (*solid line*) on each of the panels. The best-fit relation for each cluster is also plotted (*dotted lines*), and this *cluster* line is superposed on the corresponding field galaxy panel. All fits were restricted to $M_{AB}(B) < -20$. The differences between the best-fit cluster and field relations are not statistically significant.

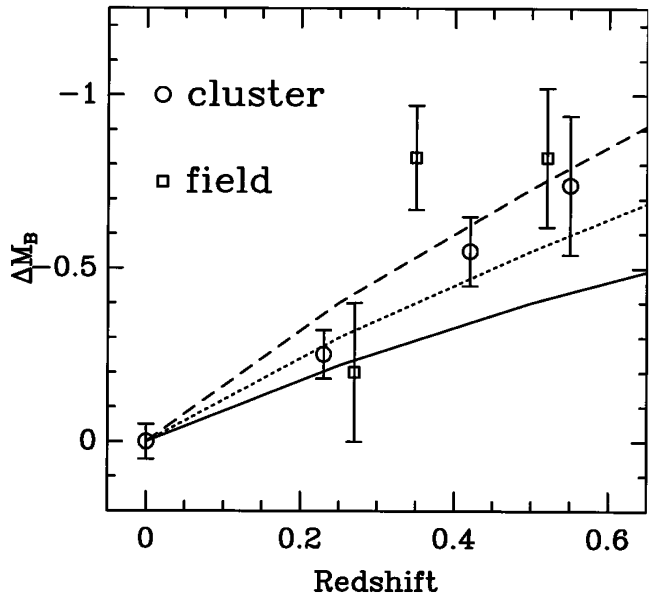

FIG. 2.—Luminosity shift ΔM from the M_B -log R_e relation is plotted against redshift. Also shown are the theoretical tracks for the passive evolution of a single-burst stellar population formed 15 Gyr before the present time (with $q_0 = 0.5$) from Buzzoni (1995) for three values (s = 1.35, 2.35, and 3.35) of the power-law index s of a Salpeter IMF. The giant-rich IMF (s = 1.35) produces the largest amount of evolution. The models of Bruzual & Charlot (1993) predict a flatter slope and larger amount of evolution at $0 < z < 0.3$ but are also consistent with these observations.

galaxies shifts progressively with redshift such that by $z = 0.55$ a galaxy of a given size is more luminous by -0.74 ± 0.21 mag than its counterpart at $z = 0.06$. In other words, the surface brightness has increased by this amount. Second, evolution of the M_B-log R_e relation for the early-type population in the field is also observed (see Table 1), and the amount of brightening is consistent with that observed in clusters at similar redshift. Thus, there is no indication from this study that early-type galaxies in clusters evolve differently than those in the field environment. It is important to note, however, that our sample of cluster galaxies is dominated by those far (up to several megaparsecs) from the high-density cluster core. Many of these galaxies may have recently fallen into the cluster, in which case their similarity to the field population would not be surprising.

If the size-luminosity relation in clusters and in the field is universal (so that the comparison done here between high-redshift and local galaxies is valid), and if dynamical evolution does not significantly change the structure of early-type galaxies over this redshift range (i.e., the sizes remain constant), then we are seeing luminosity evolution of individual galaxies. A similar amount of evolution ($\Delta M^* = -0.2$, -0.5, and -0.5 at z = 0.2, 0.4, and 0.6, respectively) was detected in the luminosity function of galaxies in clusters associated with quasars by Yee & Green (1987) and is consistent with preliminary results of an analysis of the CNOC cluster luminosity function (Yee et al. 1996). Barrientos et al. (1996) found evolution of $\Delta M_B = -0.6 \pm 0.3$ mag in the cluster CL 0939+4713, and Bender, Ziegler, & Bruzual (1996) derived a similar amount of evolution (~0.5 mag) from velocity dispersions and Mg absorption-line strengths for 16 elliptical galaxies in the cluster MS 1512+36 at $z \sim 0.37$ (part of the CNOC survey).

The M_B-log R_e relation is a projection of the fundamental plane of elliptical galaxies (Djorgovski & Davis 1987), whose properties have been found to vary between cluster and field

TABLE 1

EVOLUTION OF THE M_B-log R_e RELATION FOR CNOC GALAXIES

Cluster	z	ΔM_B	N	Field	ΔM_B	N
Abell 2390	0.228	-0.25 ± 0.10	40	$0.12 < z < 0.32$	-0.2 ± 0.2	14
MS 1621+26	0.427	-0.55 ± 0.12	19	$0.32 < z < 0.52$	-0.8 ± 0.2	33
MS 0016+16	0.547	-0.74 ± 0.21	16	$0.45 < z < 0.65$	-0.8 ± 0.2	15

NOTE.—N gives the number of galaxies with M_B(AB) < -20 that were used to derive the values of ΔM_B given in this table. These results assume $q_0 = 0.5$, and the effect of cosmology appears in the text.

samples (de Carvalho & Djorgovski 1992) in a number of respects, with field elliptical galaxies representing a less homogeneous population than those in clusters. Although we see no sign of that effect in the present sample, we cannot exclude it and it is important to consider this issue in detail in future work. Dynamical evolution of elliptical galaxies could complicate the interpretation of morphological results such as those presented here, although simulations (Capelato, de Carvalho, & Carlberg 1995) indicate that dynamical evolution may simply change an object's position on the fundamental plane rather than modifying the position of the plane itself. In this case, no evolution of the fundamental plane would occur with redshift except that due to the evolution of the stellar populations themselves.

If interpreted as luminosity evolution of individual galaxies, the amount of brightening measured in the present study is consistent with that expected for a single-burst stellar population formed at high redshift (see Fig. 2). Models published by Bruzual & Charlot (1993) and Buzzoni (1995) predict a brightening of $\Delta M_B = -0.6$ to -1.2 mag between $z = 0$ and $z = 0.6$ for a single-burst population with an age of 15 Gyr, very similar to the results of Tinsley (1972). The exact amount of brightening depends strongly on the initial mass function (IMF) and less strongly on the age and metallicity of the population and cosmology. Taken at face value, the data presented here agree better with models based on IMFs with proportionally more high-mass stars and flatter power-law mass functions than the standard Salpeter (power-law index 2.35) initial mass function.

This work represents the first phase of a comprehensive analysis of the cluster and field populations in the CNOC survey. A number of questions that are beyond the scope of the present work clearly need to be answered. For example, Figure 1 shows a range of scatter about the mean relation. The cluster MS 1621+26 has a much smaller scatter than the other clusters, and it is important to know whether this is due to observational error or is a reflection of intrinsic differences between clusters. A complete analysis of the variation of galaxy properties with distance from the cluster core and with redshift is the fundamental goal of the CNOC morphology project. It is also important to reconcile these results with analyses of the luminosity functions in this survey (Yee et al. 1996; Lin et al. 1996) and in other surveys (Lilly et al. 1995). A comparative study of the disk galaxy population in clusters and the field, similar to that done here for elliptical galaxies, is clearly important.

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