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CLUSTER VERSUS FIELD ELLIPTICAL GALAXIES AND CLUES ON THEIR FORMATION[1]

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ABSTRACT

Using new observations for a sample of 931 early-type galaxies, we investigate whether the Mg_2-σ_0 relation shows any dependence on the local environment. The galaxies have been assigned to three different environments depending on the local overdensity (clusters, groups, and field); we used our complete redshift database to guide the assignment of galaxies. It is found that cluster, group, and field early-type galaxies follow almost identical Mg_2-σ_0 relations, with the largest Mg_2 zero-point difference (clusters minus field) being only 0.007 ± 0.002 mag. No correlation of the residuals is found with the morphological type or the bulge-to-disk ratio. Using stellar population models in a differential fashion, this small zero-point difference implies a luminosity-weighted age difference of only ∼1 Gyr between the corresponding stellar populations, with field galaxies being younger. The mass-weighted age difference could be significantly smaller if minor events of late star formation took place preferentially in field galaxies. We combine these results with the existing evidence for the bulk of stars in cluster early-type galaxies having formed at very high redshift and conclude that the bulk of stars in galactic spheroids had to form at high redshifts ($z \gtrsim 3$), no matter whether such spheroids now reside in low- or high-density regions. The cosmological implications of these findings are briefly discussed.

Subject headings: galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — galaxies: fundamental parameters — cosmology: miscellaneous

1. INTRODUCTION

Great progress has been made in recent years toward charting and modeling galaxy formation and evolution. Yet the origin of the galaxy morphologies as illustrated by the Hubble classification has so far defied a generally accepted explanation. This is especially the case for elliptical galaxies, with two quite different scenarios still confronting each other. One scenario is motivated by hierarchical clustering cosmologies, where elliptical galaxies are modeled to form through a series of merging events taking place over a major fraction of the cosmological time (e.g., Baugh, Cole, & Frenk 1996; Kauffmann 1996). The other scenario assumes instead that the whole baryonic mass of the galaxy was already assembled at early times in gaseous form, and for this reason it is sometimes qualified as *monolithic*. Early examples of this latter scenario (Larson 1974; Arimoto & Yoshii 1987) stemmed from the Milky Way collapse model of Eggen, Lynden-Bell, & Sandage (1962), and late realizations include models by Bressan, Chiosi, & Fagotto (1994) and Matteucci (1994).

Through the 1980s, much of the debate focused on the age of elliptical galaxies as derived from the integrated spectrum of their stellar populations. In general, advocates of the merger model favored an intermediate age for the bulk of stars in elliptical galaxies, but the matter remained controversial (for contrasting views, see O'Connell 1986 and Renzini 1986). A first breakthrough came from noting the very tight color-σ relation followed by elliptical galaxies in the Virgo and Coma clusters (Bower, Lucey, & Ellis 1992). This demonstrated that at least *cluster* elliptical galaxies are made of very old stars, with the bulk of them having formed at $z \gtrsim 2$. Evidence in support of this conclusion has greatly expanded over the last few years. This came from the tightness of the fundamental plane relation for elliptical galaxies in local clusters (Renzini & Ciotti 1993), from the tightness of the color-magnitude relation for elliptical galaxies in clusters up to $z \sim 1$ (e.g., Aragon-Salamanca et al. 1993; Stanford, Eisenhardt, & Dickinson 1998), and from the modest shift with increasing redshift in the zero-point of the fundamental plane, Mg_2-σ, and color-magnitude relations of cluster elliptical galaxies (e.g., Bender et al. 1998; Dickinson 1995; Ellis et al. 1997; van Dokkum et al. 1998; Pahre, Djorgovski, & de Carvalho 1997; Stanford, Eisenhardt, & Dickinson 1998; Kodama et al. 1998). All of these studies agree in concluding that most stars in elliptical galaxies formed at $z \gtrsim 3$.

However, much of this evidence is restricted to cluster elliptical galaxies. In hierarchical models, clusters form out of the highest peaks in the primordial density fluctuations, and cluster elliptical galaxies completing most of their star formation at high redshifts could be accommodated in the model (e.g., Kauffmann 1996; Kauffmann & Charlot 1998). However, in lower density, *field* environments, both star formation and merging are appreciably delayed to later times (Kauffmann 1996), which offers the opportunity for an observational test of the hierarchical merger model.

The notion of field elliptical galaxies being a less homogeneous sample compared to their cluster counterparts has been widely entertained, although the direct evidence has been only rarely discussed. Visvanathan & Sandage (1977) found cluster and field elliptical galaxies to follow the same color-magnitude

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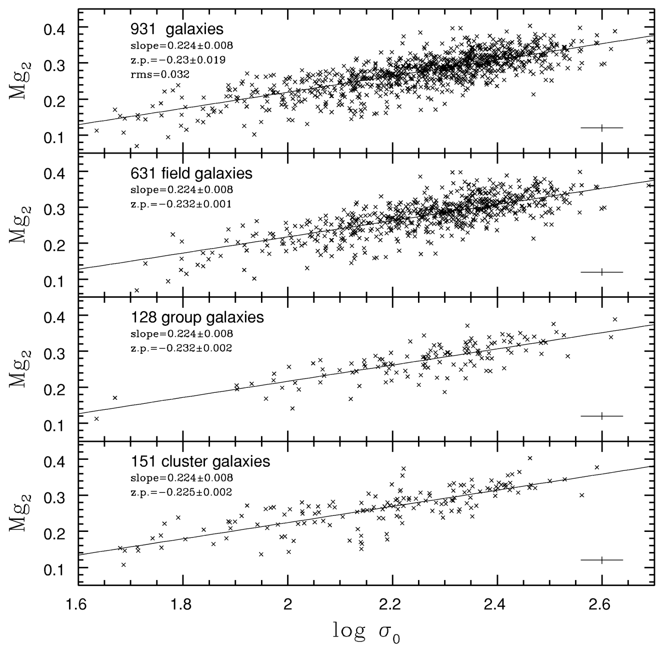

FIG. 1.—Mg_2-σ_0 relation for the total sample of early-type galaxies (*upper panel*) as well as for the field, group and cluster subsamples (*lower panels*). The corresponding number of objects, the slope, and the zero point (z.p.) are shown in the upper left-hand corner of each panel. The least-squares fits to the Mg_2-σ_0 relation are also shown. For the three subsamples, the slope as derived for the total sample was retained and only the zero point was determined. The error bars are shown in the lower right-hand corner.

relation, but Larson, Tinsley, & Caldwell (1980)—using the same database—concluded that the scatter about the mean relation is larger in the field than in clusters (see also Burstein 1977). More recently, a larger scatter in field versus cluster elliptical galaxies was also found for the fundamental plane relations by de Carvalho & Djorgovski (1992). However, at least part of the larger scatter for the field elliptical galaxies can be a mere manifestation of the distances being more uncertain, which will also affect the fundamental plane relations. Moreover, the database analyzed by de Carvalho & Djorgovki includes only ∼60 cluster galaxies and about the same number of field galaxies. One can also suspect most of the effect as being due to reddening errors (Pahre 1998).

The lack of conclusive evidence for or against systematic differences between clusters and field elliptical galaxies has prompted us to take advantage of the large database assembled for the Nearby Early-type Galaxies (ENEAR) project (da Costa et al. 1998a). The aim of the project is to create a homogeneous database for a well-defined magnitude-limited sample of early-type galaxies in order to reconstruct the peculiar velocity and mass density fields out to a distance of $cz = 7000$ km s^{-1}. Besides redshift, the measured quantities include the central velocity dispersion σ_0, the magnesium index Mg_2, and the photometric parameters D_n, R_e, and μ_e. The analysis of other absorption lines (Hβ, Fe, NaD) is currently underway. Since both σ_0 and Mg_2 are distance- and reddening-independent quantities, the comparison of the Mg_2-σ_0 relations for cluster and field elliptical galaxies offers the best available way of establishing whether intrinsic differences exist between the two populations.

This Letter is organized as follows. In § 2, the samples of cluster and field galaxies are defined and the corresponding Mg_2-σ_0 relations are presented and analyzed. In § 3, the results are interpreted and used to gather clues on the formation of early-type galaxies.

2. THE Mg_2-σ_0 RELATION IN CLUSTERS AND IN THE FIELD

The ENEAR database includes over 2000 early-type galaxies with $m_{B(0)} \leq 14.5$ and $cz \leq 7000$ km s^{-1} and galaxies in well-known nearby clusters, which are used to derive distance relations (for a full description of the database, see da Costa et al. 1998a). While part of the ENEAR database consists of data assembled from the literature, in the present analysis we restrict ourselves to the sample of 931 galaxies so far observed specifically for the ENEAR project (Bernardi et al. 1998a; Wegner et al. 1998). Among them, 232 galaxies have $T = -5$ (E type), 189 have $T = -3$ (E-S0 type), and the remaining 510 have $T = -2$ (S0 type) according to the morphological classification of Lauberts & Valentijn (1989). The vast majority of these galaxies have disk-to-bulge ratios (D/B's) less than 1 (Alonso et al. 1998; Bernardi et al. 1998a). The spectra come from a variety of telescopes (European Southern Observatory 1.52 m, Michigan-Dartmouth-MIT Observatory 2.4 m and 1.3 m, and Complejo Astronomico El Leoncito 2.15 m) and instrumental setups. Special care was taken to cross-calibrate against each other the Mg_2 and σ_0 measurements of spectra obtained with different setups (see Bernardi et al. 1998a for details). After bringing the various measurements to a uniform system, the calibration to the Lick system (Worthey et al. 1994) was enforced using galaxies in common with the updated 7 Samurai (7S) sample (D. Burstein 1998, private communication). Typical internal errors (as well as differences with other data sets, e.g., Jorgensen, Franx, & Kjaergaard 1996) are 5%–13% for σ_0 and 0.005–0.011 mag for Mg_2.

We were especially careful in assigning galaxies to cluster, group, and field environments. We used the known clusters to obtain a combined D_n-σ_0 relation (Bernardi et al. 1998b), which was used to estimate galaxy distances. Clusters were defined as those aggregates containing at least 20 galaxies and groups as those including at least two and less than 20 members in the group catalogs of Ramella, Pisani, & Geller (1997) and Ramella et al. (1998), which correspond to overdensities of $\delta\rho/\rho \geq 80$. These catalogs were derived from complete redshift surveys (CfA2, Geller & Huchra 1989; Southern Sky Redshift Survey 2, da Costa et al. 1998b). Assignment to a cluster or group was then made for our early-type galaxies fulfilling the following criteria: $d_i \leq 1.5R_p$ and $c|z_i - z_{\rm cl}| \leq 1.5\sigma_{\rm cl}$, where d_i and cz_i are the distance from the cluster center and the radial velocity of the galaxy, respectively, R_p is the pair radius (Ramella, Geller, & Huchra 1989), and $cz_{\rm cl}$ and $\sigma_{\rm cl}$ are respectively the radial velocity and velocity dispersion of the cluster. When applying these criteria, a few galaxies originally assigned to the clusters (and used to derive the D_n-σ_0 relation) dropped out of the sample, while a few new ones were included. The D_n-σ_0 relation was then adjusted iteratively until convergence was reached. In this way, 151 and 128 galaxies have been finally assigned to clusters and groups, respectively. All of the remaining galaxies were assigned to the field (631 objects), after having excluded a few close pairs and those in the outskirts of clusters with $d_i \leq 3R_p$ and $c|z_i - z_{\rm cl}| \leq 3\sigma_{\rm cl}$, whose assignment was ambiguous.

The resulting Mg_2-σ_0 relations are shown in Figure 1 for the whole sample as well as separately for the field, group, and cluster samples. Also shown are linear least-squares fits to the data ($Mg_2 = a \log \sigma_0 + b$), where a is the slope and b is the zero point. For each subsample, the slope obtained for the whole sample was retained, and only the zero point was derived. As is evident from the figure, field, group, and cluster elliptical galaxies all follow basically the same relation. The zero-point offset between cluster and field galaxies is 0.007 ± 0.002 mag, with field galaxies having lower values of Mg_2—a statistically significant, yet very small difference. This is in excellent agreement with the offset of 0.009 ± 0.002 mag, obtained by Jorgensen (1997) using 100 field and 143 cluster galaxies from the *old* 7S sample (Faber et al. 1989). Our own redetermination using the revised 7S sample (D. Burstein 1998, private communication) yields a marginally lower value, i.e., 0.005 ± 0.002 mag. Figure 2 shows a histogram of the residuals for the ENEAR sample. The rms of the field sample is 0.032 mag, virtually identical to that of the cluster sample (0.030 mag). This is appreciably larger than our estimated internal errors, indicating that most of the scatter is indeed intrinsic (see Colless et al. 1998).

Subsamples of the cluster and field galaxies have been analyzed in search of possible correlations. No significant correlations of the residuals were found with morphology or with *D*/*B* ratios. In practice, we recover here the result that elliptical galaxies and spiral bulges are alike (Jablonka, Martin, & Arimoto 1996). Marginally significant differences are instead found when dividing about the median each of the samples into high- and low-velocity dispersion subsamples (at $\log \sigma_0 = 2.15$) and high- and low-luminosity subsamples (at $M_{B_0} = -18.5$). (The subsamples are highly correlated given the Faber-Jackson relation.) When keeping the slope constant, the zero-point difference between the high-velocity/high-luminosity cluster and field subsamples is 0.005 ± 0.004 mag. The difference between the low-luminosity/low-velocity subsamples is instead 0.011 ± 0.006 mag. If anything, it appears that bright/massive galaxies form a more homogeneous population with a smaller difference in their Mg_2-σ_0 relation between cluster and field objects compared to subsamples of intrinsically smaller galaxies. Finally, it is worth noting that no correlation seems to exist between the zero point of the Mg_2-σ_0 relation for cluster elliptical galaxies in the EFAR sample (Wenger et al. 1996) and cluster richness as measured by cluster X-ray luminosity, temperature of the intercluster medium or σ_{cl} (Colless et al. 1998). The present study extends this (lack of) trend to the lowest density regions inhabited by early-type galaxies.

3. DISCUSSION AND CONCLUSIONS

As is well known, the Mg_2 index of a stellar population depends on both age and metallicity. When dealing with real galaxies, it will also depend on the detailed *distribution* of stellar ages and metallicities within a given galaxy (Greggio 1997). Here, we set this complication aside (although it may help explaining the intrinsic scatter of the Mg_2-σ_0 relation) and use simple stellar population models to set constraints on an indicative *age difference* between cluster and field elliptical galaxies. As is widely appreciated, population models are still affected by several limitations, which makes it unwise to use them to determine the absolute age of galaxies. However, here we use the models only in a *differential* fashion, so our conclusions should be less prone to systematic errors that may affect such models. For solar composition and an age in excess of 10 Gyr, the time derivative $(\partial Mg_2/\partial t)$ is 0.0060, 0.0034, and 0.0077 mag Gyr^{-1} in the models of Buzzoni, Gariboldi, & Mantegazza (1992), Worthey (1994), and Weiss, Peletier, & Matteucci (1995), respectively. A straight average gives $(\partial Mg_2/\partial t) \simeq 0.0057$ mag Gyr^{-1}, or $\Delta t(\mathrm{Gyr}) \simeq 175\ \Delta Mg_2$. Therefore, the zero-point offset between cluster and field galaxies suggests an average age difference between the two samples of $\sim 1.2 \pm 0.35$ Gyr. This roughly corresponds to a luminosity-weighted age, while the actual, mass-weighted age difference can be substantially smaller. To produce the observed offset, it is indeed sufficient that some galaxies have undergone a minor star formation event a few Gyr ago and that this has taken place preferentially among field galaxies (this effect may have been already detected among Hubble Deep Field elliptical galaxies; see Abraham et al. 1998). Therefore, this ~1 Gyr age difference should be regarded as an upper limit to the intrinsic, mass-averaged age of stars in field and cluster elliptical galaxies. Of course, given the age/metallicity degeneracy affecting spectroscopic indices such as Mg_2, one can claim that the age difference may be larger than the above limit but is almost precisely compensated by field galaxies being more metal rich at any given value of σ_0. We find this alternative interpretation very contrived and hence unattractive.

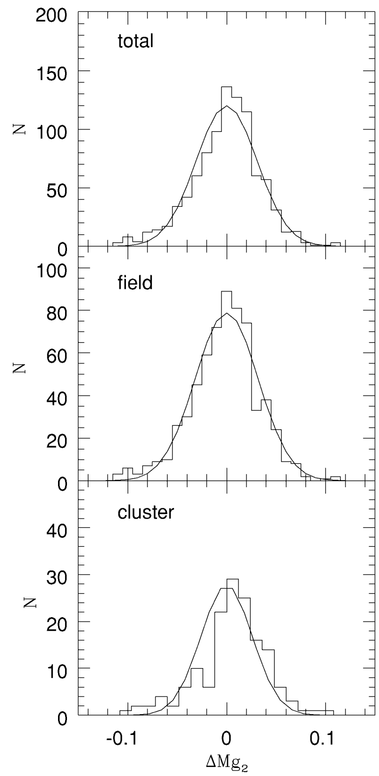

FIG. 2.—Distribution of the Mg_2 residuals relative to the least-squares fit obtained for the total sample in Fig. 1 are shown for the total, field, and cluster data sets. The Gaussian that best fits the residuals for the total sample is overplotted in each panel.

We are now in a position to compare with theoretical simulations. In the hierarchical merger model of Kauffmann (1996), the luminosity-weighted age of stars in bright elliptical galaxies that reside in low-density environments is about 4 Gyr less than that of cluster galaxies of similar luminosity. This would correspond to a difference $\Delta Mg_2 \simeq 0.023$ mag, which our data exclude at the 4.6 σ level. Indeed, in the hierarchical merger model, the brightest field elliptical galaxies form last (as expected), while smaller ones are instead more coeval to cluster galaxies. The evidence presented in § 2 suggests the opposite: brighter field galaxies appear to be more similar to their cluster counterparts than the fainter ones. We should warn that the specific model with which we are comparing refers to a standard cold dark matter model, i.e., $\Omega = 1$. Hierarchical models for low Ω (and, even more so, Λ models) may produce more homogeneous populations of elliptical and spheroid galaxies. It remains to be seen whether such models can produce cluster and field galaxies following the same Mg_2-σ_0 relations.

The present results do not necessarily invalidate the hierarchical merging paradigm but tend to push the action back to an earlier cosmological epoch, favoring a scenario in which merging takes place at high redshifts among still mostly gaseous components in which the merging itself promotes widespread starburst activity. The natural observational counterparts of these events is represented by the Lyman-break galaxies at $z \gtrsim 3$ (Steidel et al. 1996), in which star formation rates can reach values as high as $\sim 1000\ M_{\odot}\ \mathrm{yr}^{-1}$ (Dickinson 1998).

Combining the evidence mentioned in § 1 of this Letter with the close similarity of cluster and field early-type galaxies documented here, one can conclude that the bulk of stellar populations in galactic spheroids formed at high redshift ($z \gtrsim 3$), no matter whether such spheroids now reside in high- or low-density regions. Additional direct evidence supporting this conclusion also comes from stellar color-magnitude diagrams of globular clusters and fields in the bulge of our own Galaxy, which indicate a uniform old age for the Galactic spheroid (Ortolani et al. 1995). With spheroids containing at least 30% of all stars in the local universe (Schechter & Dressler 1987; Persic & Salucci 1992) or even more (Fukujita, Hogan, & Peebles 1998), one can conclude that at least 30% of all stars and metals have formed at $z \gtrsim 3$ (Renzini 1998; see also Dressler & Gunn 1990). This is several times more than is suggested by a conservative interpretation of the early attempt at tracing the cosmic history of star formation, either empirically (Madau et al. 1996) or from theoretical simulations (e.g., Baugh et al. 1996). Yet, it is more in line with recent direct estimates from the spectroscopy of Lyman-break galaxies (Steidel et al. 1998).

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