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Excursions into the Evolution of Early-Type Galaxies in Clusters

Omar López-Cruz

Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE) & DAUG, México

David Schade

CADC, Herzberg Institute of Astrophysics (HIA), Canada

L. Felipe Barrientos

Departamento de Astron. & Astrofís. Pontificia Universidad Católica de Chile (PUC), Chile

Michael D. Gladders & H. K. C. Yee

Department of Astronomy and Astrophysics, University of Toronto (U of T), Canada

Tadayuki Kodama

Department of Astronomy, University of Tokyo, Japan

ABSTRACT

Recent observations have revealed that early-type galaxies (ETG) in clusters comprise an old galaxy population that is evolving passively. We review some recent observations from the ground and from the HST that show that ETG have undergone a significant amount of luminosity evolution. This evolution is traced by two projections of the fundamental plane (FP): the size-magnitude relation (SMR) and the color-magnitude relation (CMR). We will briefly discuss the relevance of all these results in the context of the universality of the IMF.

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1Fulbright Visiting Scholar at the Observatories of the Carnegie Institution of Washington (OCIW)

2Carnegie Fellow, OCIW
1. Introduction

The opening line of Walter Baade’s lectures on the evolution of stars and galaxies (Baade 1963) reads: “The study of the evolution of stars and galaxies is in a stage of rapid development, and we are still at the beginning”. Almost half a century later the former statement is still timely, as advances in technology have opened new windows for the exploration of galaxy evolution. The first clue that galaxies change through cosmic time is that galaxies at high redshift \((z)\) appear systematically brighter than those at lower \(z\).

We may identify two reasons for this brightening: it could be that either the stellar content was intrinsically brighter at an earlier epoch or that galaxies appear brighter due to the properties of the space-time. We are fortunate that those issues happened to be the main running themes of this rather interesting conference. Clearly, if we want to understand the brightening of high-\(z\) galaxies, we need to understand the role of stellar evolution in galaxies as well as the propagation of light in different cosmological models. With these elements in mind let us explore the evolution of galaxy cluster ETG and its possible connections with the evolution of field ETG. We note that ETG were once considered the simplest stellar systems. Nevertheless, ETG, despite their apparently simple appearance, pose some difficult problems to models of galaxy formation and evolution. Perhaps the most remarkable is the inexistence of a comprehensive theory of stellar formation in dynamically hot systems (Silk 1999).

Clusters of galaxies provide us with probes to study the effects of the environment on the evolution of galaxies (Oemler 1974; Dressler 1984). Indeed, it has been found that clusters provide a hostile environment for some galaxies (e.g., dwarf galaxies: López-Cruz et al. 1997; Hilker 1998, and low surface brightness: Gregg & West 1998). In contrast, ETG flourish in such rich environments: this is just a paraphrase of the density-morphology relation Dressler (1980). Interestingly, the physical parameters of these galaxies, such as colors, size (e.g., the effective radius \(R\)), luminosity \((L)\), velocity dispersion \((\sigma)\), surface brightness \((I)\), etc., have the same pairwise correlations originally found for field ETG (e.g., \(L \propto \sigma^{4}\)). The correlations among these parameters are synthesized by the fundamental plane \((R \propto \sigma^{1.4 \pm 0.15} I^{-0.9 \pm 0.1}; FP; Djorgovski & Davis 1987)\). Nevertheless, the effects of the environment may be indicated by an augmented tightness in the correlations for cluster galaxies (e.g., Schade et al. 1999; Trager, Faber, & Dressler 2001).

In this review we present the results of some apparently disconnected evolutionary studies. We have explored two projections of the fundamental plane. These studies have led us to conclude that ETG in the central regions (the inner \(\approx 1 \, h_{50}^{-1} \, \text{Mpc}\))^3 of rich clusters

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3A Hubble constant of \(H_0 = 50 \, h_{50} \, \text{Mpc km}^{-1} \, \text{s}^{-1}\) is used throughout.
conform to an old population that has been evolving passively since \( z \sim 3 \). We do not intend to present a comprehensive review (see elsewhere, e.g., Kormendy & Djorgovski 1989; Buzzoni, Renzini, & Serrano 1995; Arnaboldi, Da Costa, & Saha 1996; Cepa & Carral 1998; Ellis 2001); however, we do intend to arrive at a unifying view on the evolution of ETG.

2. The Size-Magnitude Relation

The work of Barrientos, Schade, & López-Cruz (1996) was the first study from a series that compared ETG in an intermediate-\( z \) cluster (CL 0939+4713 at \( z = 0.41 \), observed with the HST) with those of a nearby rich cluster (the Coma cluster at \( z = 0.023 \), observed with the KPNO 0.9m) in a bidimensional space that is defined by axes: size versus integrated magnitude. The size is defined as the core radius in a bidimensional de Vaucouleurs fit to the surface brightness distribution, and the integrated magnitude was computed by the integration of the best fit. The resulting size-magnitude relation (SMR) is expected as it conforms one of the projections of the FP (Djorgovski & Davis 1987). When the k-corrected SMR of Coma and CL 0939+4713 are compared, an offset of \( \Delta M_B = 0.72 \pm 0.24 \) is detected. This offset indicates that the galaxies in CL 0939+4713 are brighter than the ones in Coma. We can explain this result either by assuming that the size remained fixed and the change was due to the evolution of the underlying stellar population (passive evolution) or by assuming that both the size and the magnitude were changing due to mergers. Although mergers could have been important at the time of cluster formation (Schweizer 2001); the merger hypothesis is not favored because in the central regions of rich clusters the large cluster velocity dispersions (\( \sigma_{\text{cluster}} \geq 750 \text{ km s}^{-1} \)) would make merging inefficient. Moreover, the general merger rate\(^4\) is very low at \( z < 1 \). Hence, we can conclude that the observed changes are due to passive evolution. Similar amount of luminosity evolution was reported by previous observations in clusters around quasars (Yee & Green 1987).

Changes in luminosity can easily be explained with the aid of the single burst model (cf., Tinsley 1980; Buzzoni 1995; van Dokkum et al. 1998) where a burst of star formation occurs at an epoch \( t = t_0 \). It can be shown that the expected luminosity evolution is described by a power law \( L(t) \propto \left[ \frac{1}{t-t_0} \right]^\kappa \), with \( \kappa = [1.3 - 0.27(s - 1)] > 0 \) where \( x = (s - 1) \) is the slope of the IMF; it has been found that \( \kappa \) depends on the metallicity and the passband\(^5\). Hence, as

\(^4\)For example merger rate \( \propto (1 + z)^{2.3 \pm 0.7} \) (Patton et al. 2002)

\(^5\)A useful approximation valid at low \( z \) is provided by mpty universe model (\( \Omega_o = 0 \)). A simple relation results for the luminosity evolution as a function of \( z \): \( L(z) \propto \left[ \frac{(1+z)(1+z_0)}{(z_0-z)} H_0 \right]^\kappa \), where \( z_0[\approx 3] > z \) is the galaxy formation redshift.
$t$ becomes larger than $t_\circ$ the luminosity decreases, in agreement with the expected dimming in luminosity as stars evolve off the giant branch. Further studies (Schade et al. 1996b; Schade, Barrientos, & López-Cruz 1997) have included more clusters and a larger number of galaxies and have confirmed and extended the early result of Barrientos, Schade, & López-Cruz. Figure 1 taken from Schade, Barrientos, & López-Cruz (1997) summarizes the results from our previous studies. It is found that $\Delta M \propto z$, in addition the direct comparison with the models of Buzzoni (1995) has given us a constraint on $s$. The four most deviant points in this figure are produced by poor sampling. Therefore, we can safely conclude that our observations are in agreement with models with $s = 2.35$, i.e., $x = 1.35$ the Salpeter IMF (Salpeter 1955).

3. The Color-Magnitude Relation

The first pairwise relationship discovered among the physical properties of ETG was the color-magnitude relation (CMR). It was originally discovered by Baum (1959) as a trend in which the brightest galaxies are also the reddest. In the same paper Baum, with the aid of a simple population synthesis model, demonstrated that ETG were dominated by old Population I stars, contrary to the then popular belief that globular clusters and ETG had the same stellar make up. Baum’s observations and their interpretation signified a turning point in our understanding of ETG. The work of Sandage (1972), Faber (1973), and Visvanathan & Sandage (1977) showed that the CMR can be parameterized by a straight line within a luminosity interval of about 8 magnitudes. This remarkable property suggests that ETG from giants to dwarves, with the exception of some brightest cluster galaxies (BCG)\(^6\), have shared a common history of star formation, even when dwarfs and giants are structurally and dynamically different: a dwarf elliptical galaxy is not a scaled-down giant ETG (Ferguson & Binggeli 1994). This difference in dynamical behavior is further suggested by the break away of dwarves from the FP and the SMR. The other important property is the universality of the CMR at least for clusters at low redshift (e.g., Sandage & Visvanathan 1978; Bower, Lucey, & Ellis 1992; López-Cruz & Yee 2002). The CMR was first explained by Arimoto & Yoshii (1987) in terms of the combined effects of dissipative galaxy formation and metallicity.

Three constraints on the last epoch of strong galaxy formation in ETG can be derived from the study of the CMR. Bower, Lucey, & Ellis (1992) showed that the dispersion of the

\(^6\) Sometimes BCG in cooling flow clusters show very blue cores (e.g., McNamara & O’Connell 1992; López-Cruz 1997) hence, some BCG deviate from the CMR
CMR is a good indicator of the age spread in the stellar population, since newer episodes would increase the dispersion about the CMR. We have found that the dispersion is smaller than the limit of our observations for galaxies in the central regions of clusters at lower redshift (the LOCOS sample, López-Cruz 1997, 2001). The second constraint is provided by the absolute color evolution of ETG, this can be measured by changes of the zero point of the CMR (see, Stanford, Eisenhardt, & Dickinson 1998). The third constraint is provided by the slope of the CMR: in the classical scenarios (e.g., Kodama & Arimoto 1997) star formation is regulated by supernova driven winds. In these models the strongest changes in the stellar population properties occur during the first 5 Gyrs after formation. Hence if we are able to identify evolution in the slope of the CMR, we could in principle constrain the epoch of the last major starburst. We have attempted such a test using archive HST observations and LOCOS data (Gladders et al. 1998). The merit of this test is that the slope, being a ratio of colors, is independent of the calibrations and therefore we are provided by an unbiased estimator that can be readily compared with the models.

The comparison of our observed CMR slopes to a suite of four models with different formation epochs and cosmologies is presented in Figure 2. The overall slope of the red sequence seems to be consistent with passive evolution for all clusters, implying that the populations we have sampled have similar evolutionary histories and time-scales. The observed slopes of the higher redshift clusters are perfectly consistent with a high formation redshift, and a conservative limit of \( z \geq 2 \) can be set. Note that up to redshifts of \( z \approx 0.4 \), observations of the slope of the red sequence have little power to distinguish between formation epochs with \( z \geq 1.0 \). The change in slope at \( z \leq 0.4 \) is exclusively due to blue-shifting of the rest-frame band-passes. However, beyond \( z \approx 0.5 \), the expected slopes for the lowest-formation-epoch models rapidly diverge from the observed slopes. This turnover is a result of the differing metallicities in the ETG population as a function of mass; at ages younger than \( \sim 5 \) Gyr, the color evolution of the stellar population in a metal-rich ETG is significantly different from that of a metal-poorer elliptical (Kodama 1997; Kodama & Arimoto 1997). From Figure 2 it is evident that that the slope of the CMR provides a good marker on the last episode of star formation in cluster ETG that is almost independent of the cosmology.

4. Discussion & Conclusions

The two studies that have been presented here strongly suggest that ETG in clusters are evolving passively. Also Pahre, Djorgovski, & de Carvalho (1996) and Lubin & Sandage (2001) using the Tolman test have shown indirect evidence that also suggest that ETG are evolving passively.
We have used the poor-man’s approach to the FP in order to address the evolution of ETG. Can we expect to detect the same kind of evolution using the FP itself? The answer is yes: there are many FP studies for cluster galaxies at low and intermediate \( z \) that have agreed that ETG are evolving passively (e.g., Jørgensen, Franx, & Kjærgaard (1996); van Dokkum et al. (1998)).

Figure 1 also reveals that the best agreement between the models and the observations is reached with a Salpeter IMF. This is remarkable since Salpeter (1955) defined the IMF for the solar neighborhood. Field ETG at higher redshifts also reveal a Salpeter IMF (Schade et al. 1999). Star formation being such a complex physical process has all the characteristic of self-organized criticality (see, Melnick & Selman 2000). Our results along with those of Melnick & Selman further supports the universality of the IMF.

Our general conclusion, which also agrees with many other studies (see, Peebles 2002), is that cluster ETG coevally formed at \( z > 3 \) and have been evolving passively since then. Moreover, a single burst with a Salpeter IMF suffices to explain the observations presented in this review.

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Fig. 1.— The luminosity shift $\Delta M_B$ including revised results from Schade et al. (1996a) and from Barrientos, Schade, & López-Cruz (1996). Filled symbols are for clusters in the present study, open circles are cluster points from Schade et al. (1996b) (including 2 clusters in common that have been offset in redshift slightly for clarity) and open squares are field galaxies from Schade et al. (1996a). The lines are from the models of Buzzoni (1995) for IMF power-law indices of $s = 3.35$ (solid line), $s = 2.35$ (short dashed), and $s = 1.35$ (long dashed). The models assume a present-day age of 15 Gyr and we show the theoretical $\Delta M(V)$ whereas the data is in $M_B$ where the evolution would be $\sim 0.15$ mag larger by $z = 1$. 
Fig. 2.— This figure has been taken from Gladders et al. (1998). The predicted slopes for formation models (Kodama 1997, Kodama & Arimoto 1997) using three different cosmologies to map age onto redshift. Note that while the details of the turn-over in the slope for a model at a given formation redshift changes slightly in different cosmologies, the change is not significant enough to affect the conclusion that at least some clusters form at $z > 2$. 