AGES OF S0 AND ELLIPTICAL GALAXIES IN THE COMA CLUSTER

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Received 2001 May 16; accepted 2001 August 10

ABSTRACT

The ages of stellar populations in 52 elliptical and S0 galaxies in the Coma Cluster are investigated, using a new spectroscopic sample. More than 40% of the S0’s are found to have undergone star formation in their central regions during the last ~5 Gyr, while such activity is absent in the ellipticals. Galaxies in this sample have absolute magnitudes in the range $-20.5 < M_B < -17.5$, and the fraction of S0 galaxies with recent star formation is higher at fainter luminosities. The observed luminosity range of S0 galaxies with signs of recent star formation activity is consistent with them being the descendants of typical star-forming spirals at intermediate redshift whose star formation has been halted as a consequence of the dense environment.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (Coma) — galaxies: elliptical and lenticular, cD — galaxies: evolution

1. INTRODUCTION

The formation mode and epoch of spheroids are among the most important unsolved issues in observational cosmology. These questions involve two possibly distinct aspects: when did the stars in spheroids form (i.e., their star formation history), and when were these stars assembled in a galactic structure that can be classified as a spheroid?

The bulk of stars in spheroid-dominated (early-type) galaxies are believed to be old, at least in clusters (Bower, Lucey, & Ellis 1992; Ellis et al. 1997; Kelson et al. 1997; Kodama et al. 1998; Stanford, Eisenhardt, & Dickinson 1998; Kelson et al. 2001), but the frequency and amount of later star formation activity is still a matter of debate. To discriminate among different formation scenarios, it is crucial to determine whether field spheroidal galaxies had more extended star formation histories than their cluster counterparts (for opposite views, see Bernardi et al. 1998, Menanteau et al. 1999, and Menanteau, Abraham, & Ellis 2001; also, compare Renzini 1999 with Gonzalez 1993 and Trager et al. 2000).

In most studies, early-type galaxies (ellipticals and S0’s) are treated as one class of objects because of the general similarity in their colors and their “vicinity” along the Hubble sequence. This is in spite of the fact that remarkably different formation processes have been proposed for elliptical and lenticular galaxies. In the case of ellipticals (Es), the most cited alternatives are formation at high redshift through dissipationless collapse (the so-called monolithic scenario; see, e.g., Larson 1975) and a merger of disk systems (in the framework of hierarchical galaxy formation models; see, e.g., Baugh, Cole, & Frenk 1996; Kauffmann 1996). Concerning the formation of S0 galaxies, it is a longstanding issue whether they are “primordial” objects (i.e., they formed as S0’s) or were converted from spirals that lost their gas supply by galaxy-galaxy collisions, ram pressure stripping, or gas evaporation in the hot intracluster medium, by galactic winds, or by loss of their gas-rich envelopes (Spitzer & Baade 1951; Gunn & Gott 1972; Faber & Gallagher 1976; Cowie & Songaila 1977; Burstein 1979; Dressler 1980a, 1980b).

A spiral origin for S0 galaxies seemed to be favored by the discovery of large numbers of blue (presumably spiral) galaxies in clusters at $z > 0.2$ (Butcher & Oemler 1978, 1984), coupled with the abundance of S0’s and Es in clusters in the local universe (Hubble & Humason 1931; Oemler 1974). A renewed interest in studying the stellar population ages of elliptical and S0 galaxies separately arose in recent years, when the high spatial resolution imaging achieved with the Hubble Space Telescope (HST) uncovered a strong morphological evolution taking place in rich clusters during the last few Gyr. There is an overabundance of spirals in cluster cores at $z = 0.5$, and the S0’s are proportionally (a factor 2–3) less abundant than in nearby clusters, while the fraction of ellipticals at $z = 0.5$ is the same or larger than at $z = 0$ (Dressler et al. 1997). The progression of this morphological evolution between $z = 0.5$ and now has been recently clarified by Fasano et al. (2000), who explored for the first time the intermediate-redshift range $z = 0.1–0.25$. These results strongly suggest that a large number of cluster spirals observed in distant clusters have evolved into the S0’s that dominate rich clusters today (see also Kodama & Smail 2001).

Observationally, the existence of systematic differences between the ages of stellar populations in ellipticals and lenticulars is still controversial. Neither photometry nor
spectroscopy of early-type galaxies in high-redshift clusters has been able to reveal any statistically significant difference (Ellis et al. 1997; Jones, Smail, & Couch 2000), and the same is true for other works on lower redshift clusters (Jorgensen 1997, 1999; Ziegler et al. 2001; Trager, Faber, & Dressler 2001).

However, other studies have found evidence for young and intermediate-age stellar populations in a significant fraction of lenticulars (Caldwell 1983; Dressler 1980b; Bothun & Gregor 1990; Fisher, Franx, & Illingworth 1996). Recently, two studies have uncovered a difference in the recent star formation histories of cluster S0 and E galaxies. A high-quality line strength analysis has shown that most of the (faint) lenticulars in the Fornax Cluster have lower luminosity-weighted ages than the (brighter) ellipticals (Kuntschner & Davies 1998; Kuntschner 2000). In Abell 2218, at z = 0.17, high-precision optical and near-IR photometry has found that ellipticals at all magnitudes and luminous S0’s are old and coeval, while the faintest S0’s have younger luminosity-weighted ages (Smail et al. 2001).

Both these studies find that the differences between Es and S0’s mostly stand out at faint magnitudes. The luminosity range explored by the different studies could be the key to understanding the reason for the apparently contrasting results found so far (Smail et al. 2001), but the relative roles played by mass and morphology (S0 vs. E) in driving the evolutionary history of cluster early-type galaxies is still unclear (Kuntschner & Davies 1998; Ziegler et al. 2001).

The central issue is whether recent star formation in a significant fraction of the lenticulars is a widespread phenomenon in clusters. In addition, it would be important to conclusively understand if and, eventually, why this effect is evident only in a certain luminosity range.

To address these questions, we present here a study of the spectroscopically determined ages and metallicities of ellipticals and lenticulars in what is considered the local prototype of rich clusters, the Coma Cluster. Our sample comprises 52 galaxies (19 Es and 33 S0’s), covering a broad range in luminosity ($M_B \sim 20.5$ to $M_B \sim -17.5$). We will show that the populations of S0’s and Es differ for the presence/lack of recent star formation activity in a significant fraction of these galaxies. We also discuss the luminosity dependence of these findings and its possible origin.

2. OBSERVATIONS AND ANALYSIS

This work is based on the spectroscopic survey of galaxies in the Coma Cluster presented in Mobasher et al. (2001, hereafter Paper II). Multi-fiber spectra with a resolution of 6–9 Å and a signal-to-noise ratio of ~15–19 were obtained for a random subset of galaxies from the sample of Colless & Dunn (1996) in two areas of ~1 x 1.5 Mpc toward the center and the southwest region of the cluster. A full description of the sample selection, observations, and data reduction can be found in Paper II, where it is shown that this is essentially a magnitude-limited sample with no significant bias.

In this paper we present the stellar population properties of the E and S0 galaxies. Morphological classifications from Dressler (1980b) are available for 77 galaxies in the Mobasher et al. sample, of which 19 are Es and 33 are S0’s. All except two of these galaxies are in the magnitude range $13 < R < 16$ ($-20.5 < M_B < -17.5$). Intermediate types, such as E/S0 and S0/E (two galaxies) and SB0’s (three galaxies), have been excluded from the present analysis. Dressler classified as S0’s those galaxies with a clearly recognizable non-spheroidal (disk or lens) component. When viewed face-on, they display an intensity discontinuity between the bulge and the disk. Galaxies with a smooth radial profile, with no intensity discontinuities, were classified as ellipticals. Disk galaxies with a clear spiral or outer ring pattern were classified as spirals.

Line indices of the Lick/IDS system and emission-line equivalent widths were measured from the spectra and compared with spectrophotometric models to derive luminosity-weighted ages and metallicities, as described in Poggianti et al. (2001, hereafter Paper III). The line indices used in this paper, as well as those of the whole spectroscopic sample, will be published in a later paper of the series. Great care was taken to ensure an accurate calibration onto the Lick/IDS line index system, correcting for the spectral resolution, the galaxy velocity dispersion, and any residual offset. The comparison with standard Lick stars yields an uncertainty of ±0.1 Å in our calibration of the Hβ index (see Paper III). As we will show below, this is significantly smaller than the random errors on our Hβ measurements; hence, the latter dominate the age uncertainty. Emission-line spectra were excluded from the analysis of the Lick indices, and no emission correction was applied to the index measurements.

To derive the stellar population properties, we have used the Padova version of Worthey’s models (see Paper III), which includes an accurate treatment of the horizontal branch of low-metallicity stars. The main differences between the Padova and the standard Worthey models in the Hβ-Mg$_{2}$ diagram employed below can be summarized as: (1) the standard version does not cover the range [Fe/H] $< -0.225$ for ages less than 8 Gyr, and (2) the Hβ strengths at ages 5–12 Gyr are generally lower in the Padova version, translating into age differences of typically 2 Gyr. At ages less than 4 Gyr, the difference is ~0.5 Gyr. We note that, while absolute ages are highly uncertain in this type of models, relative ages are much less affected by the model uncertainties. The current sample mostly consists of intermediate-luminosity galaxies, which do not display a high [Mg/Fe] ratio, as more luminous ellipticals do (Worthey, Faber, & Gonzalez 1992; Trager et al. 2000; Kuntschner et al. 2001; see also Paper III); therefore, no attempt has been made to vary the abundance ratios of the models.

We point out the following.

1. The spectra refer to the central 2.7’ (1.3 kpc) of each galaxy; hence, recent star formation episodes in the outer regions would not be detected.

2. The quantities derived from the spectra are luminosity-weighted ages and metallicities. Other quantities of interest—such as, for example, the mass fraction involved in the latest star formation episode—remain unknown.

3. Absolute ages/metallicities are much more uncertain than relative ages/metallicities, because of the uncertainties intrinsic to the models.

We assume a distance modulus to Coma of 35.16 ($\langle v \rangle = 7000$ km s$^{-1}$, $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$).
3. RESULTS

The main result is presented in Figure 1, showing the H/β versus Mg_b diagram of elliptical (open circles) and S0 galaxies (filled circles). The spectrum of one S0 galaxy in our sample has very strong emission lines indicative of a current starburst and has been excluded from this and the following plots.

There is a striking difference between the populations of ellipticals and S0’s. All but one of the ellipticals are consistent within the errors with ages over 9 Gyr. In contrast, 13 out of 32 S0 galaxies have luminosity-weighted ages under 5 Gyr.¹³ Hence, more than 40% of the S0’s seem to have undergone star formation at a recent epoch, while such widespread recent activity is absent in the E population. These results are corroborated by the analysis of the H/β - (Fe/Fe) diagram that provides a similar but independent method of deriving ages and metallicities.¹⁴

Inspection of Figure 1 shows that the metallicity range covered by this sample is quite wide, typically [Fe/H] = -0.7 to 0.4, i.e., abundances from 0.2 to 2.5 times solar. A metallicity spread is expected, given the broad magnitude range explored and the existence of a correlation between mean metallicity and galaxy luminosity. Es and S0’s follow a broadly similar metallicity-luminosity relation, as shown in the top panel of Figure 2. However, the relation for the ellipticals (Z = 1.850 - 0.137R, σ = 0.180) is slightly flatter and less scattered than the relation for the S0’s (Z = 5.721 - 0.400R, σ = 0.284). This could explain the finding of Fisher et al. (1996) that S0’s might have a steeper Mguesday dispersion relationship than Es.

The bottom panel of Figure 2 presents the luminosity-weighted ages as a function of magnitude. The population of S0’s with young luminosity-weighted ages is clearly visible in the region of the plot below the dotted line. Only four of the 13 S0 galaxies with luminosity-weighted ages less than 5 Gyr are brighter than R = 14.5 (M_b = -19). In general, the luminosity distributions of Es and S0’s are different, with the S0 distribution being more skewed toward fainter magnitudes. In fact, the E:S0 number ratio changes from 5:6 at 13 < R < 14 to 9:12 at 14 < R < 15 and 5:13 at 15 < R < 16.

13 We note that only one of these—the galaxy with the luminosity-weighted age ~ 1.5 Gyr at H/β = 3.15—is classified as a “k+a” galaxy (= “E+A”) according to the MORPHs classification scheme of Dressler et al. (1999). Another three S0’s with luminosity-weighted ages less than 5 Gyr were classified as k/k+a (marginal k+a cases). There is an excellent agreement between the MORPHs classification and the results based on the Lick indices for the strongest Balmer line cases. As expected, the MORPHs classification is able to identify those galaxies with luminosity-weighted ages less than 2 Gyr regardless of metallicity but—because of the line strength thresholds adopted—it is insensitive to older episodes of star formation which, instead, can be still detected in the Lick system.

14 During the course of this work, another spectroscopic survey of Coma galaxies has been presented (Castander et al. 2001). These authors investigate the star formation history of these galaxies using different methods, comparing with the spectral energy distributions of synthetic models. While a direct comparison of the ages derived would be meaningless—because of the different meaning of the word “age” between our analysis and theirs—it is interesting to note that in the great majority of cases the two studies agree in identifying galaxies with and without recent star formation: among the 21 galaxies in common (10 Es and 11 S0’s), both studies assign “old” ages (lack of recent star formation) to 15 galaxies, identify one emission-line galaxy in common, and detect recent star formation (~ 3 Gyr or less) in three galaxies with absorption-line spectra. There is only one discrepant case of a galaxy in which we detect a recent activity not reported in their work and another case where the results agree within the errors.

It is therefore important to assess how luminosity effects come into play. This is better exemplified in Figure 3, where the age distributions of Es and S0’s are shown for the whole sample and for galaxies brighter and fainter than R = 14.5 (M_b = -19) separately. The total age distributions of lenticulars and ellipticals differ significantly (with a 93.3% probability, according to a Kolmogorov-Smirnov test). A higher proportion of “young” S0’s in the faint subsample, compared with the bright subsample, is clearly visible in the middle panel of Figure 3, and the difference between the age distributions of Es and S0’s is more conspicuous at faint magnitudes.

This luminosity dependence of the evolutionary histories of S0 galaxies is naturally explained if a fraction of the S0’s were previously star-forming spiral galaxies. We computed the luminosity evolution of a galaxy whose star formation was truncated at some time between 2 and 5 Gyr ago. For galaxies with a star formation history (before truncation) typical of Sa, Sb, Sc, and Sd galaxies (Barbaro & Poggianti 1997), we find that the B-band luminosity fades by 0.5–1.5 mag, depending on the truncation epoch and galaxy type. In the event of a starburst before truncation, the luminosity evolution would be greater. Cluster spirals at intermediate redshift have M_V ~ -21 (Smail et al. 1997) in the cosmology adopted here; thus, even in the most conservative scenario (only truncation, no starburst, B – V = 0.4),¹⁵ the passive descendants of spirals are expected to be typically fainter than M_b = -20/19, corresponding to R = 13.5/14.5 in our Coma sample.

Consequently, the great majority of galaxies that evolved from the spiral into the S0 class should not be found at the bright end of the luminosity function. The luminous side of the S0 luminosity function could be filled up by another population of S0’s that did not evolve from spirals (or evolved from brighter spirals at higher redshifts). If the morphological transformation spiral = S0 is accompanied by a conversion of a star-forming galaxy into a passive one, it is not surprising that those S0’s with signs of recent star formation are preferentially lower luminosity galaxies. This could be the reason why many previous studies—concentrating primarily on the most luminous galaxies—have not found significant differences between the evolutionary histories of S0 and E galaxies.

A question of great importance is whether it is mass, morphology, or environment that plays the dominant role in determining the evolutionary history of early-type galaxies (Kuntschner & Davies 1998; Kuntschner 2000; Smail et al. 2001; Ziegler et al. 2001). The results presented here indicate that the distinction between an S0 and an E (i.e., the presence of a disk/lens, according to Dressler’s classification) is able to separate classes of galaxies with different star formation histories. These differences are noticeable between E and S0 galaxies of similar luminosity. Hence, morphology seems to be the galactic property best correlated with the presence of recent episodes of star formation, at least in clusters like Coma. However, we have discussed how the differences between S0’s and Es can only be appreciated at M_b > –20 and become more and more evident going toward fainter magnitudes. In this respect, our findings for the Coma Cluster are similar to those by Kuntschner & Davies (1998) for the Fornax Cluster and by Smail et al.

¹⁵ B – V ~ 0.4 for a very late type spiral, ~ 0.9 for an early-type galaxy.
(2001) for Abell 2218. As far as galaxy metallicity is concerned, galaxy luminosity (i.e., mass) seems to be the primary parameter controlling it (see Paper III).

While the effects of the cluster environment may be a viable mechanism to make spirals evolve into S0’s, the existence of field lenticulars clearly proves that this cannot be the only mechanism of S0 production. Two (or more) formation processes might be at work, of which one could be effective only in clusters and would be responsible for the formation of a fraction of the faint S0’s. If this is the case and if a large proportion of cluster S0’s were spirals at higher redshift, as suggested by the HST studies (Dressler et al. 1997), then the luminosity function of S0’s in distant clusters could be significantly different from the present-day luminosity function, likely with a lower number ratio of faint to bright S0’s at high z. For the same reason, the field and cluster S0 luminosity functions at z = 0 would also be expected to differ. Studies of both the luminosity and the age distributions of S0’s in different environments would be very valuable in placing constraints on acceptable evolutionary scenarios.

![Diagram](image-url)

**Fig. 1.** — Hβ vs. Mg2 index strength for Es (open circles) and S0’s (filled circles). Overplotted are models from Paper III (see text). Random errors in the index measurements, taking into account the variance in each pixel and the statistical propagation of errors (see Paper III), are shown.

**Fig. 2.** — Luminosity-weighted metallicities (top) and ages (bottom) of Es (open circles) and S0’s (filled circles) as a function of R-band magnitude. Absolute B magnitudes shown on top of the plot have been found for $B - R = 1.6$. The observed R-band magnitudes are aperture magnitudes over a radius 3 times the Kron radius and are taken from Paper II (see also Komiyama et al. 2001). Data points falling outside (on the right-hand side) of the model grid in Fig. 1 have been arbitrarily assigned a $Z$ of 3 in this plot. Similarly, an age of 30 Gyr was recorded when the data points lay below the model grid (see Paper III for a discussion of the mismatch between the observations and the model grid). The metallicity-luminosity relation in the top panel for all galaxies in this sample (Es and S0’s) is $Z = 4.555 - 0.318R$, $\sigma = 0.238$ (excluding the points lying at $Z = 3$).

**Fig. 3.** — Luminosity-weighted age distributions of Es and S0’s (left). In the middle and right panels the brightest ($R < 14.5$) and faintest ($R > 14.5$) subsets are plotted separately.
In distant clusters, a large population of poststarburst/post-star-forming galaxies in which star formation stopped some time during the previous 1.5 Gyr has long been known to be present (Dressler & Gunn 1983; Couch & Sharples 1987; Dressler & Gunn 1992; Barger et al. 1998; Dressler et al. 1999 [MORPHs collaboration] and references therein). It has been suggested that these are recently infallen field galaxies whose star formation has been suppressed by the cluster environment. Furthermore, since most of these post-star-forming galaxies have spiral morphologies at $z = 0.5$, it has been proposed that at least some of these spirals are going to evolve into S0’s at a later time and that the timescale for morphological transformation (from spiral to S0) must be longer than the duration of the observational signature of the cessation of star formation (1.5 Gyr; Poggianti et al. 1999). These poststarburst/post-star-forming spirals would be an intermediate step between star-forming spirals and passive S0’s. In this scenario, the fact that in Coma we find a number of S0’s with “recent” star formation could seem to be at odds with the results found at $z = 0.5$, where the poststarburst/post-star-forming galaxies are mostly spirals. This apparent inconsistency is resolved if one considers that the Lick system employed here also allows an exploration of luminosity-weighted ages between 2 and 5 Gyr, so the times elapsed since the halting of the star formation that we can detect in this work are much longer than the poststarburst timescales that have been identified in distant clusters (1.5–2 Gyr at most). The S0’s with recent star formation observed here could be a later evolutionary stage of the poststarburst/post-star-forming spirals observed at $z = 0.5$, but not as advanced as passive S0’s observed in Coma and other clusters at $z = 0$.

Finally, it is interesting to examine the distribution in the sky of galaxies of different Hubble types and ages (Fig. 4). In our sample, the phenomenon of recent star formation in some lenticulars (filled circles) is not preferentially observed in the southwest region around NGC 4839. This seems to be in contrast with the findings of Caldwell et al. (1993) and Caldwell & Rose (1997), who argued for a higher incidence of galaxies with recent star formation in the southwest area than toward the central region and proposed that this phenomenon could be mostly related to the (possibly infalling) NGC 4839 group. Again, it is possible that the current study is sensitive to a wider luminosity-weighted age range than the studies by Caldwell and collaborators and therefore also identifies star formation episodes that temporally preceded the last activity detected by these authors. The different epochs of activity could be associated with groups of galaxies in different regions of the cluster.

Figure 4 also shows that S0 galaxies with luminosity-weighted ages less than 5 Gyr have an asymmetric distribution with respect to the center of Coma, being preferentially located in a region east-northeast of NGC 4874 (identified by the letter A in Fig. 4). Instead, older S0 galaxies and Es (triangles and circles with a central dot, respectively) are found to be spread out both north and south of NGC 4874. This perception by eye of a difference in the spatial distribution of “young” and “old” S0’s is not confirmed by a two-dimensional Kolmogorov-Smirnov test, which turns out to be inconclusive (the probability is only 32.8%). Clearly, larger samples are needed for reaching statistically significant conclusions. The possibly higher level of clumpiness of the S0’s with recent star formation could be due to the presence of substructure in Coma (Biviano et al. 1996; Colless & Dunn 1996; Zabludoff & Franx 1993) found an apparently bimodal or trimodal velocity distribution for Coma S0’s, possibly being related to the NGC 4889 merger event. At least some of the “young” S0’s in the east-northeast region could be part of the same group, could have accreted onto the cluster approximately at the same epoch, and consequently could have had their star formation halted by the effects of the cluster on similar timescales, as suggested by the fact they have comparable luminosity-weighted ages (see Fig. 1).

We are grateful to Matthew Colless, Ian Smail, and Andrea Biviano for their comments and useful discussions regarding this work.

\[^{16}\text{See also Caldwell & Rose (1998), who found a similar result in their sample of low-luminosity early-type galaxies in Coma.}\]
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