Evolution of Elliptical Galaxies up to $z \approx 1$ *

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Abstract. We review the observational evidence showing that luminous cluster elliptical galaxies are old stellar systems, undergoing mostly passive stellar evolution up to redshift $z \approx 1$, with approximate coeval epoch of formation. This scenario is supported by observations of local early–types, collected by 2m – 4m class telescopes, and fits the recently gained high resolution imaging (given by the refurbished HST) and deep spectroscopic data coming from 4m telescopes of $z \approx 0.4$ cluster ellipticals. Up to $z \approx 1$, luminosity functions, colors and surface brightnesses provide further evidence for mild evolution of massive cluster ellipticals.

The new 8m class telescopes and in particular the VLT with its imaging and multiplex spectroscopic instruments will give further essential information on early–type galaxy evolution over the full galaxy mass–spectrum and as a function of environment, disk–to–bulge ratio and other parameters. The VLT will also allow to explore the possibility to use evolution–calibrated massive ellipticals as cosmological standard candles/rods.

1 Introduction

What was the major epoch of galaxy formation? How extended is this epoch? Are elliptical galaxies old? When did the last episodes of star formation happen in early–type galaxies? Can elliptical galaxies be used as cosmological standard candles? These are some of the most discussed questions in the last 20 years of studies of early–type galaxies. A coherent picture is now slowly emerging, which may be able to answer these questions and trace the history of star formation in these galaxies.

In Section 2 we review formation scenarios and age estimates for elliptical galaxies based on the observations of local field and cluster samples. In Section 3 we discuss the constraints on the evolution of the stellar populations of ellipticals up to redshifts $z \approx 1$ coming from the study of their colors, luminosity function, surface brightness, Fundamental Plane and Mg $- \sigma$ relation and we illustrate how cluster ellipticals can possibly be calibrated and used as standard candles. In Section 4 we highlight a number of projects which involve the study of the properties of early–type galaxies at high redshift and which will be best performed with the VLT and its imaging and spectroscopic instruments. In Section 5 we summarize our conclusions.

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The large amount of observational material accumulated over the last decade with medium-class telescopes (2m – 4m telescopes) allows one to put some important constraints on the merging and star formation (SF) history of early-type galaxies in the "local" universe.

About 1/3 of luminous nearby ellipticals show kinematically decoupled cores or otherwise peculiar kinematics. Such configurations point to formation scenarios which involve major merging events between progenitor objects with low gas–to–star ratio (see, e.g., Bender 1996, Barnes 1996). In addition, the statistics of counter–rotating gaseous disks present in E and S0 galaxies indicate that each early–type galaxy experiences accretion of a low luminosity galaxy or of intergalactic gas at least once in its life time (Bertola et al. 1992). Finally, the presence of shells, tails, x–shaped structures etc., mostly in field galaxies, is further indication for at least minor merging or accretion events taking place today in low density environments (see review by Schweizer 1990).

On the other side, the small scatter observed in the colour–velocity dispersion \((\sigma)\) and \(\mathrm{Mg}_b – \sigma\) relations indicates that the bulk of the stars of luminous cluster ellipticals must be rather old and must have an almost coeval epoch of formation, with \(\Delta t/t < 0.15\) (Bower et al. 1992; Bender, Burstein, Faber 1993), in agreement with recent calculations in the context of CDM models (Kauffmann 1996). The high \(\mathrm{Mg}_b\) absorption values and the large [Mg/Fe] ratios imply also large ages and presumably short star formation time scales for luminous Es (Matteucci 1994, Bender 1996, Greggio 1996). In addition, the small scatter observed in the mass–to–light ratio \((M/L)\) derived from the "Fundamental Plane" analysis sets tight constraints on the relative variations in dynamics, IMF and ages of the stellar populations (Renzini & Ciotti 1993). Finally, the absorption–index diagrams between \(\mathrm{H}_\beta\), \(\mathrm{Fe}\) and \(\mathrm{Mg}_b\) confirm the old age for luminous Es, but imply smaller ages or extended SF histories for low luminosity early–type galaxies (Faber, Worthey, Gonzalez 1992, Gonzalez 1993). Since most low luminosity ellipticals are likely to contain disks contributing up to 30% to the total light (Bender et al. 1989, Rix and White 1990, Scorza and Bender 1995), there is still the possibility that younger mean ages may solely be associated with extended star formation in disks while bulges may still be old. Some low luminosity Es (especially compact Es) may also be "disk–less" bulges or bulges with stirred disks (see Bender et al. 1992). Independent from this uncertainty, ellipticals in low density environments show more peculiarities and may be genuinely younger than cluster ellipticals (Schweizer et al. 1990, Kauffmann 1996, Gonzalez 1993), though the evidence is conflicting (De Calvalho & Djorgovski 1992, Lucey & Guzmán 1993, Burstein 1989).

Summarizing, the above observational facts suggest the following conclusion. Luminous cluster ellipticals formed rapidly in early merging events. Luminous field ellipticals may be younger and could be late mergers. Faint ellipticals and S0 galaxies may have had extended SF histories.
3 4m Science + HST: redshift evolution of elliptical galaxies

Confirmation and even tighter constraints on stellar population ages in early–
type galaxies come from the combined use of 4m (spectroscopic) telescopes and
the imaging capabilities of the refurbished HST. In order of increasing accuracy,
the following tests of the evolutionary history of early–type galaxies can be listed.

The median colours of cluster E galaxies evolve only slowly with redshift,
consistent with mostly passive evolution up to $z \approx 1$ (Aragon–Salamanca et
al. 1993, Stanford et al. 1995). The galaxy counts, divided as a function of
morphological type, show that the number density of E/S0 galaxies does not
evolve with redshift within current errors (Driver et al. 1996). The luminosity
function of red galaxies and K–band selected galaxies changes only very weakly
with redshift up to $z \approx 1$ (Glazebrook et al. 1995, Lilly et al. 1996, Ellis et al.
1996).

The surface brightnesses of E/S0s decrease with redshift following closely the
Tolman relation ($I \approx (1 + z)^{-4}$) and passive evolution models (Franx 1993, 1995;
Dickinson 1995, Pahre et al. 1996), up to redshifts $z \approx 1$.

More recently, pushing to the limit the current generation of 4m telescopes
and instrumentation, it has been possible to investigate problems that will be
best tackled with the future 8m telescopes. The evolution of the Fundamental
Plane (and the related $M/L$) has been followed up to $z \approx 0.4$. It is consistent
with mostly passive evolution, but smaller SF events cannot be excluded (Franx
1993, 1995, see also this conference).

On the same line of research, the evolution of the Mg − $\sigma$ relation (Bender,
Ziegler, Bruzual 1996) demonstrates that luminous cluster ellipticals are very
old. Figure 1 shows the Mg$_b$ − $\sigma$ relation for the clusters A370 and MS1512+36,
at redshift $z \approx 0.375$, together with the local ellipticals of the Virgo and Coma
cluster. An aperture correction has been applied to put the two samples on the
same scale. Distant ellipticals also show a correlation between Mg$_b$ and $\sigma$ as local
ellipticals do. However, there is clear evidence for evolution: at any given $\sigma$, the
mean Mg$_b$ of Es at $z = 0.375$ is lower than at $z = 0$. The evolution is very small
for massive Es and likely stronger for faint Es, on average it is about 0.3 Å. Using
Worthey’s (1994) population synthesis models, the Mg$_b$ weakening at a given $\sigma$
can be translated into a relative age difference. This results in the conclusion
that the bulk of the stars in the luminous cluster ellipticals must have formed at
redshifts $z > 2$. Moreover, the same models can be used to translate the observed
Mg$_b$ weakening into a ~0.4 mag change of the B–band luminosity, assuming a
Salpeter IMF. The fact that the slope of the Mg$_b$ − $\sigma$ relation at $z = 0.375$
appears to be slightly steeper than today indicates that less luminous ellipticals
may be generally younger (consistent with Faber et al. 1992 local H$_\beta$ − Mg−Fe
measurements, see previous section). Note that, in contrast to luminosity and
surface brightness evolution tests, the Mg$_b$ − $\sigma$ test is independent of the slope
of the IMF in elliptical galaxies (see discussion in Bender et al. 1996).

We have imaged some of the ellipticals observed spectroscopically by Bender
et al. (1996) with HST and determined the structural parameters $R_e$ (the half–
luminosity radius) and $\langle SB_e \rangle$ (the effective average surface brightness) in the F675W filter, using the two-component fitting algorithm developed by Saglia et al. (1996), with HST psf convolution tables. The surface brightness term has been transformed to rest–frame B–band, corrected for cosmological dimming ($(1+z)^4$) and for passive evolution using the $M_{g_b} - \sigma$ relation described above. Figure 2 shows the Fundamental Plane of the clusters A370 and MS 1512+36 (filled/open squares before/after evolution correction) together with the data points of the Coma ellipticals (open circles), all having $\sigma > 150$ km/s. The distances are computed using $H_0 = 50$ km/s/Mpc and $q_0 = 0.25$. The figure shows that the passive evolution correction fully explains the observed luminosity evolution and allows for $q_0$ values in the range $0 - 0.5$.

Fig. 1. The $M_{g_b} - \sigma$ relation for ellipticals in the clusters A370 and MS1512+36 at redshift $z = 0.375$ (filled squares), compared to the one of Coma Cluster ellipticals (small filled circles).
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Fig. 2. The Fundamental Plane at redshift $z = 0.375$ for the same elliptical galaxies as in Figure 1 (filled/open squares: before/after correction for luminosity evolution). The filled small circles show the position of Coma Cluster ellipticals. We used $H_0 = 50$ km/s/Mpc and $q_0 = 0.25$.

In contrast to cluster ellipticals, blue members and E+A galaxies are known to show strong evolution (Butcher and Oemler 1978, Dressler and Gunn 1983). However, these objects are unlikely to end as ellipticals. Hubble Space Telescope imaging of blue and E+A galaxies indicates that presumably most of them are infalling spirals experiencing tidal shaking or ‘harrassment’ (Moore, Katz, Lake 1996) with only a small percentage undergoing merging events. Since the outer parts of the disks are stripped during these processes and/or star formation is likely to enhance the central stellar densities, large disk-to-bulge ratios are transformed into low disk-to-bulge ratios. The end products of this process are therefore likely to resemble S0 galaxies or disky ellipticals. In fact, S0s, and not ellipticals, are the dominant galaxy population in clusters at lower redshifts (e.g., Saglia et al. 1993, Jørgensen et al. 1994).

Summarizing, the conclusions based on the redshift evolution of elliptical
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galaxies are in full agreement with the analysis of the properties of local samples of ellipticals (see Section 2).

4 8m Science (+HST)

Following the discussion of the previous sections, it is natural to highlight a few tasks that the VLT (and other 8m telescopes) will be able to perform (the list is of course very incomplete).

The search for the oldest ellipticals at high redshifts is connected to the determination of the epoch of first star formation, a crucial test of cosmological models. Some of these objects may have been found already (see Giavalisco, this conference), but larger statistics and better information about these objects is still needed. As preparatory work to the spectroscopic observations with the VLT, a (photometric) survey of distant clusters \((z \gtrsim 0.6)\) in the southern hemisphere of the kind described by Da Costa et al. (1996) is needed.

An extremely powerful test of cosmological models of structure formation is the determination of the evolution of the potential function (or dispersion function) of E, S0 and spiral galaxies via the measurement of their internal kinematics as a function of redshift. This will allow to follow the evolution of the potential depth of dark matter halos directly, bypassing the uncertain steps related to the ill-known processes of star formation needed to compute the luminosity function.

The VLT, in combination with HST photometry, can allow the accurate determination of the redshift evolution of the luminosities, stellar population parameters, internal kinematics and structural parameters of galaxies. This will be the essential information to test galaxy formation models in detail, i.e., beyond dark halo evolution. In addition, this information can possibly be used to calibrate elliptical galaxies as standard candles and cosmological tools, to be used to constrain \(q_0\) via the Fundamental Plane relations and the Volume test.

Spectroscopic instruments with multiplex capabilities and low/medium resolution in the optical and near infrared spectral range such as FORS, ISAAC, NIRMOS/VIRMOS will play a decisive role in the above outlined projects. The imaging capabilities offered by FORS and especially CONICA plus Adaptive Optics in the NIR will complement the HST high resolution with the power of collected flux.

5 Conclusions

Observations of local massive ellipticals obtained with 2m – 4m class telescopes over the last decade demonstrated that these objects, though most likely being formed in mergers, exhibit only small scatter in color/line–strengths vs. velocity–dispersion diagrams and in mass-to-light ratios (from ‘fundamental plane’ analysis). The small amplitude of the scatter indicates approximately coeval formation of massive ellipticals at high redshift. Further support for this conclusion comes
Evolution of Elliptical Galaxies up to $z \approx 1$ from $H_\beta$ vs. metal–linestrength analysis and from the high overabundance of light elements relative to iron (indicating short star formation time scales). Age and formation constraints on lower luminosity early–type galaxies and also field ellipticals are less tight and lower mean ages or extended star formation histories are possible.

Observations of redshifted luminous cluster ellipticals with 4m–class telescopes and the Hubble Space Telescope up to $z \approx 1$ confirm this picture. Luminosities, surface brightnesses and mass–to–light ratios, as well as the fundamental plane relation evolve only slowly with redshift $z$. The most reliable measurements show a rest–frame B–band evolution following the simple relation $\Delta B(z) \approx -z$. Again, our information on low luminosity ellipticals and field ellipticals at higher redshift is much more uncertain.

These results put strong constraints on the formation of luminous cluster ellipticals and may further offer a route to calibrate these objects as cosmological standard candles or standard rods.

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