Detection of Strong Evolution in the Population of Early-Type Galaxies

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Abstract

The standard picture holds that giant elliptical galaxies formed in a single burst at high redshift. Aging of their stellar populations subsequently caused them to fade and become redder. The Canada-France Redshift Survey provides a sample of about 125 galaxies with the luminosities and colours of passively evolving giant ellipticals and with $0.1 < z < 1$. This sample is inconsistent with the standard evolutionary picture with better than 99.9\% confidence. The standard Schmidt test gives $\langle V/V_{\text{max}} \rangle = 0.398$ when restricted to objects with no detected star formation, and $\langle V/V_{\text{max}} \rangle = 0.410$ when objects with emission lines are also included. A smaller sample of early-type galaxies selected from the Hawaii Deep Survey gives equally significant results. With increasing redshift a larger and larger fraction of the nearby elliptical and S0 population must drop out of the sample, either because the galaxies are no longer single units or because star formation alters their colours. If the remaining fraction is modelled as $F = (1 + z)^{-\gamma}$, the data imply $\gamma = 1.5 \pm 0.4$. At $z = 1$ only about one third of nearby bright E and S0 galaxies were already assembled and had the colours of old passively evolving systems. We discuss the sensitivity of these results to the incompleteness corrections and stellar population models we have adopted. We conclude that neither is uncertain enough to reconcile the observations with the standard picture. Hierarchical galaxy formation models suggest that both merging and recent star formation play a role in the strong evolution we have detected.

Keywords: galaxies:formation, evolution; galaxies: elliptical and lenticular; galaxies: stellar content
1 Introduction

In the standard model of elliptical galaxy formation first proposed by Tinsley & Gunn (1976), all stars in the galaxy form in an initial burst at high redshift and the galaxy’s luminosity subsequently evolves passively as the more massive stars evolve off the main sequence. This leads to luminosity evolution with cosmic time that can be parametrized as

\[ L(t) = L(t_0)[(t - t_f)/(t_0 - t_f)]^{-1+\theta x}, \]

where \( t_f \) is the time of formation, \( x \) is the slope of the initial mass function (\( x = 1.35 \) for a Salpeter mass function), and \( \theta \approx 0.26 \) is the slope of the mass-main sequence lifetime relation (see Phillipps 1993). Spectral synthesis techniques show that simple passive evolution models provide good fits to the colours and spectral properties of a class of galaxies conventionally called early-type, which include the ellipticals and the S0s.

With the superior imaging capability of the Hubble Space Telescope, it has recently become possible to identify early-type galaxies at high redshift purely on the basis of their morphologies (see for example Driver et al 1995, Abraham et al 1996). There is an emerging consensus that the colours and luminosities of early-type galaxies in rich clusters are consistent with simple passive evolution models and with a standard value of the IMF slope (Aragon-Salamanca et al 1993, Dickinson 1995, Bender, Ziegler & Bruzual 1996, Van Dokkum & Franx 1996, Schade et al 1996, Pahre, Djorgovski & de Carvalho 1996, Ellis et al 1996). It appears that the luminosity evolution long predicted as a consequence of stellar aging has finally been detected. These studies do not prove, however, that the early-type galaxy population as a whole formed at high redshift and evolved passively. A test of this hypothesis requires a large redshift survey of early-type galaxies that is complete to faint limiting magnitudes.

Morphological classification of early-type galaxies has been carried out to limiting magnitudes of \( I = 21 \) and \( I = 25 \) in the Medium Deep and the Hubble Deep Field surveys respectively, but redshifts for a complete sample of these galaxies are lacking at present. The Canada France Redshift Survey (CFRS) is one of the deepest large redshift surveys carried out to date (Lilly et al 1995a, Le Fèvre et al 1995, Hammer et al 1995, Crampton et al 1995, Lilly et al 1995b). As we will show, it provides a sample of about 125 I-band selected galaxies with the luminosities and colours of passively evolving giant ellipticals and with redshifts lying in the range 0.1 to 1. Morphological classifications for these objects are not yet available. The Hawaii Deep Fields Spectroscopic Survey (Cowie et al 1996) provides us with an independent K-band selected sample of 28 early-type galaxies. The great advantage of working with magnitude-limited redshift surveys is that a given evolutionary hypothesis may be tested directly in a way which is independent of the galaxy luminosity function. This was first illustrated in a seminal paper by Schmidt (1968), who introduced the so-called \( V/V_{\text{max}} \) test and used a flux-limited sample of only 33 QSOs to show that the population has evolved strongly with redshift. The test is particularly powerful in the present context because it avoids the need to assume anything about the highly uncertain local luminosity function of early-type galaxies (compare the very different results of Loveday et al (1992) and Marzke et al (1994)).

In this Letter, we apply the Schmidt \( V/V_{\text{max}} \) test to early-type galaxies selected by colour from the CFRS and Hawaii surveys. We show that these samples are both inconsistent with the simple passive evolution picture with better than 99.7% confidence.
2 Selecting Early-type Galaxies in the CFRS

Ellipticals and S0s are the reddest objects in the local Universe. To define a colour threshold for separating early from late-type galaxies, we make use of new population synthesis models by Bruzual & Charlot (1996), which include the effects of metallicity (see also Charlot 1996). For our standard model, we assume that all early-type galaxies form in a single burst of duration 0.1 Gyr at \( z = 5 \) and have a Salpeter IMF with upper and lower cutoffs at \( 100 M_\odot \) and \( 0.1 M_\odot \).

Ideally, our adopted colour boundary should be blue enough to include all elliptical and S0 galaxies, yet red enough to exclude spiral galaxies of type Sa or later. In practice galaxies of given type show a substantial spread in colour, so no perfect boundary exists. We adopt a colour threshold corresponding to a passively evolving model with 50% solar metallicity. We have chosen this model because it gives the best separation between early and late-type galaxies in local photometric surveys. We find that under this criterion, 88% of the galaxies in the Bower, Lucey & Ellis (1992) sample of 66 ellipticals and S0s in the Coma and Virgo clusters would be included in our sample, while 84% of the galaxies in the Visvanathan (1992) survey of 177 luminous Sa-Sc spirals towards the Great Attractor region would be rejected.

Figure 1 shows the resulting \((V-I)_{AB}\) redshift relation superposed on the CFRS data. We identify 98 early-type galaxies down to a limiting magnitude of \( I = 22.5 \), 17% of the total sample of 591 galaxies with secure redshifts. In the Hawaii Survey, galaxies are selected according to \( B-K \) colour. We identify 23 early-type galaxies to \( K = 19.5 \), again about one fifth of the total sample. Note that these fractions agree rather well with the 20−25% of galaxies brighter than \( I = 22.5 \) in the HST Medium Deep Survey which have early-type morphology according to Driver et al (1995) and Abraham et al (1996).

In addition to information about colours, magnitudes and redshifts, the CFRS catalogue contains a list of the main features seen in the spectrum of each galaxy. Evidence for ongoing star formation is provided by the detection of O[II] emission at 3727 Å. Such emission is almost never seen in nearby E/S0 galaxies. If we exclude galaxies with detected O[II], our sample is reduced to 72 galaxies. In figure 2, we plot redshift and absolute magnitude histograms for these samples. Note that the absolute magnitudes are present-day values, assuming that each galaxy evolves passively from the time of detection until the present day. Galaxies with detectable O[II] emission tend to lie at higher redshift and to be intrinsically fainter than those with no such emission. However, almost all objects in the sample have absolute magnitudes typical of giant ellipticals.

It is important to realise that the CFRS survey is only just over 80% complete. The Hawaii Survey is 87% complete to \( K = 19.5 \). Omission of the galaxies without secure redshifts would introduce significant bias into our analysis, since many of them are red and lie close to the magnitude limit of the survey. It is thus important that we correct for incompleteness as well as possible and investigate the uncertainties which this correction introduces.

Our “standard” correction procedure is as follows and is similar to one described by Lilly et al (1995b). We assume that each galaxy without a measured redshift has the same distribution in \( z \) as galaxies of the same apparent magnitude and colour which do have secure redshifts. In practice, we define intervals in \( I \) and \( V-I \) (or \( K \) and \( B-K \)) centred on the galaxy and adjust them so that they contain 20 galaxies with redshifts. We randomly select one of these galaxies and assign its redshift to our candidate. If the galaxy then falls above the colour threshold
Figure 1: The division of the CFRS galaxies into early and late-types according to the colour-redshift criterion discussed in the text. Solid circles represent the ellipticals and S0s and stars represent the spirals and irregulars.
shown in figure 1, it is classified as early-type. As shown in figure 2 for the CFRS data, this procedure adds about 28 objects to the sample, about 20% of all the galaxies without secure redshifts. Most lie close to \( I = 22.5 \) and are redder than the majority of galaxies of the same apparent magnitude which do have secure redshifts. Their redshift and absolute magnitude distributions are thus biased towards higher values of \( z \) and somewhat fainter luminosities.

### 3 The Schmidt Test

The ratio \( V/V_{\text{max}} \) is a measure of the position of a source within the total volume \( V_{\text{max}} \) where it could have been included in the sample. To determine \( V_{\text{max}} \), one must know the intrinsic luminosity of the source, and hence the distance at which it would fall below the limiting magnitude of the survey, assuming that it evolves in luminosity according to the passive evolution model described in section 2. When applied to the CFRS data, one must also take account of the fact that no galaxies brighter than \( I = 17.5 \) are included in the survey. If passive evolution is the correct model, \( V/V_{\text{max}} \) should be uniformly distributed between 0 and 1 and \( \langle V/V_{\text{max}} \rangle \) should scatter around 0.5, with a variance only dependent on sample size. In this Letter, we calculate all magnitudes and volumes assuming that \( q_0 = 0.5 \) and \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \). We have checked that changing \( q_0 \) has almost no effect on our results.

In figure 3, we show the \( V/V_{\text{max}} \) distribution for early-type galaxies selected by colour from the CFRS catalogue. The solid histogram shows the result obtained if galaxies with \( \text{O}[\text{II}] \) emission are excluded from the sample, while the hatched area shows the contribution from galaxies with such \( \text{O}[\text{II}] \) emission. Finally, the unfilled area shows the \( V/V_{\text{max}} \) distribution of the galaxies included by the incompleteness correction of section 2.

The \( V/V_{\text{max}} \) distribution is clearly skewed to values less than 0.5. We obtain \( \langle V/V_{\text{max}} \rangle = 0.398 \) when objects with detected star formation are excluded and \( \langle V/V_{\text{max}} \rangle = 0.410 \) when they are included. For a uniform distribution, the expected standard deviations in \( \langle V/V_{\text{max}} \rangle \) for samples of these sizes are 0.029 and 0.026 respectively. The observational data are thus inconsistent with the standard model of passive evolution with better than 99.9% confidence. It seems that with increasing redshift, a larger and larger fraction of the nearby elliptical/S0 population must drop out of the sample, either because the galaxies are no longer single units or because star formation alters their colours. We can parametrize the evolution of the remaining fraction as \( F = (1 + z)^{-\gamma} \) and determine the value of \( \gamma \) required for the \( V/V_{\text{max}} \) distribution to come out uniform. We find that \( \gamma = 1.7 \pm 0.4 \) for the sample without \( \text{O}[\text{II}] \) emission and that \( \gamma = 1.5 \pm 0.4 \) for the full sample (see the lower panel of figure 3). This density evolution is quite dramatic! It implies that at \( z = 1 \) only about one third of nearby bright E and S0 galaxies were already assembled and had the colours of old, passively evolving stellar systems.

For the 23 early-type galaxies identified in the Hawaii data, we obtain \( \langle V/V_{\text{max}} \rangle = 0.317 \). The expected variance for this sample is 0.060. Thus even though this sample is much smaller, the deviation of \( \langle V/V_{\text{max}} \rangle \) from 0.5 is almost as significant as in the CFRS data. The smaller value of \( \langle V/V_{\text{max}} \rangle \) reflects the fact that passively evolving galaxies could in principle be detected to higher redshift at \( K \), but are not in fact found. This sample gives \( \gamma = 2.0 \pm 0.7 \), quite consistent with the values from the CFRS.

It should be noted that a very similar calculation was carried out by Lilly et al (1995b).
Figure 2: Redshift and absolute magnitude histograms for early-type galaxies selected from the CFRS catalogue. The solid area is for galaxies with no detected O[II] emission and the hatched area for galaxies with O[II] emission. The unfilled area represents galaxies included by the incompleteness correction described in section 2.
They found that $\langle V/V_{\text{max}} \rangle$ for colour-selected ellipticals was not significantly below 0.5, but for a non-evolving model. As mentioned previously, however, passive evolution has now been observationally established for cluster ellipticals, so a non-evolving model does not represent a viable physical picture.

4 Sensitivity of the Results to Stellar Models, Sample Selection, Incompleteness and Photometric Error

In this section, we describe a series of tests carried out to explore the sensitivity of our results to the various modelling and sample selection procedures that we have adopted.

- **Stellar Population Models.** The standard model of passive evolution adopted in this paper is a single star formation burst of duration 0.1 Gyr at redshift $z_f = 5$ with a Salpeter IMF ($x = 1.35$ in equation 1). Higher formation redshifts or a longer duration (up to 1 Gyr) of the initial starburst lead to nearly identical predictions. If a more recent formation epoch is assumed, the passive evolution model is even more strongly ruled out since galaxies then fade more rapidly between $z = 1$ and $z = 0$ (this more than compensates for the fact that high $z$ galaxies are also somewhat bluer in such a model). The results are also only weakly sensitive to changes in the IMF slope. Increasing $x$ leads to slower luminosity evolution because low-mass stars evolve less rapidly than high-mass stars (see equation 1). However, even for an extreme slope of $x = 2.5$, we find that $\langle V/V_{\text{max}} \rangle$ only increases by 1.6% to 0.417. Finally, we note that using alternative population synthesis models by Worthey (1994) or Tantalo et al. (1996) would lead to results similar to those presented here.

- **The Colour Threshold.** The 50% solar model is our canonical boundary for separating early from late-type galaxies. For comparison, Table 1 shows how our results are affected if redder or bluer boundaries are adopted. Although changing the colour threshold alters the relative fractions of elliptical/S0s and spirals included in the sample quite substantially, the derived values of $\langle V/V_{\text{max}} \rangle$ vary very little.

- **Field-to-Field Variations.** Large-scale structures such as voids or great walls can cause significant fluctuations in the number of galaxies in certain redshift bins. This might cause us to underestimate the sampling variance of $\langle V/V_{\text{max}} \rangle$. To test for this effect, we analyze separately each of the 5 fields that make up the CFRS survey. These fields are well enough separated so that structure should not correlate between them. The field-to-field fluctuations in $\langle V/V_{\text{max}} \rangle$ scatter about the mean with $\chi^2 = 6.54$ for four degrees of freedom, showing that any effect is small.

- **Incompleteness.** So far we have quoted results for samples corrected for incompleteness as described in section 2. We have also experimented with an alternative procedure that takes into account the possibility that the surveys may be systematically biased against including early-type galaxies at redshifts close to 1, simply because at $z > 0.7 - 0.8$ it becomes substantially more difficult to determine redshifts in the absence of strong emission lines. Since $V$ and $I$-band photometry are available for all galaxies, even
Figure 3: upper panel: The $V/V_{\text{max}}$ distribution for early-type galaxies selected from the CFRS catalogue. Explanations of the histogram shadings are as in figure 2. lower panel: The resulting $V/V_{\text{max}}$ distribution when density evolution of the form $F = (1 + z)^{-1.5}$ is applied to the full (incompleteness corrected) sample of 150 early-type galaxies.
those without redshifts, one can evaluate the maximum redshift $z_{\text{max}}$ for which each “unidentified” galaxy would still lie above our colour threshold and be classified as early-type. If $z_{\text{max}} > 0.7$, we assign $z_{\text{max}}$ to be the redshift of the unidentified galaxy. If $z_{\text{max}} < 0.7$, we assign a redshift as before. In practice, what this means is that all unidentified galaxies that could be early-type galaxies at redshifts greater than 0.7 are assigned their maximum possible value of $V/V_{\text{max}}$. Even this extreme procedure only raises $\langle V/V_{\text{max}} \rangle$ to 0.451 for the full CFRS sample, implying $\gamma = 1.0 \pm 0.3$ and a factor 2 decrease in the number density of early-type galaxies by redshift 1, rather than a factor 3.

- $V/V_{\text{max}}$ for early-type galaxies limited at $I=21.5$. As a further check, we repeat our analysis for the subsample of early-type galaxies limited at $I = 21.5$. There are then 76 galaxies with redshifts and the incompleteness correction adds only 4 extra objects. This sample gives $\gamma = 1.2 \pm 0.6$, in good agreement with the results for the fainter sample.

- The Effect of Photometric Errors. We model the effect of photometric errors on our results by introducing a random error in the $V$ and $I$ magnitudes that increases for galaxies with fainter apparent magnitudes. If the maximum errors are less than 0.4 mag, there is no significant change in the results. If the photometric errors are bigger than this, $\langle V/V_{\text{max}} \rangle$ rises above its true value. This is because of the number of blue galaxies increases at fainter apparent magnitudes, so photometric errors have the net effect of scattering more faint galaxies into the early-type colour window than out of it. The low values of $\langle V/V_{\text{max}} \rangle$ which we obtain for the CFRS and Hawaii data are thus overestimates of the true values if photometric errors are significant.

## 5 Conclusions

We conclude that uncertainties in the stellar population models, sample selection and incompleteness corrections are insufficient to reconcile the observations with the standard picture. Early-type galaxies selected from the Canada France Redshift Survey according to $V - I$ colour have a luminosity and redshift distribution that is inconsistent with the hypothesis that they have all been evolving passively since a redshift of 1. It appears that by $z = 1$, two thirds of nearby early-type galaxies have dropped out of the sample, either because they are star-forming and no longer have colours consistent with an old stellar population, or because they have broken up into several pieces too faint to be included in the sample. This evolution may apply exclusively to the elliptical galaxy population, exclusively to the S0 galaxy population, or to both populations equally. We cannot use colour alone to separate ellipticals from S0s.

In recent hierarchical models of galaxy formation (Kauffmann, White & Guiderdoni 1993, Baugh et al 1996), galaxy disks form as gas cools and condenses at the centres of dark matter halos, while elliptical galaxies form when two disk galaxies merge. If no further gas cools onto the elliptical, its stellar population will fade and it will evolve passively until the present day. In such models, ellipticals form by mergers at all redshifts. The typical formation redshift of an elliptical is higher in a rich cluster than in the field, simply because galaxy-
sized perturbations collapse earlier in dense environments. The typical formation redshift of ellipticals also depends sensitively on the cosmological parameters, in particular on the density parameter $\Omega$ and the normalization parameter $\sigma_8$ (sometimes referred to as $b \equiv 1/\sigma_8$). Studies of the evolution of elliptical galaxies can thus provide important constraints on these models.

In recent work, Kauffmann (1996) has shown that a “standard” CDM model with $\Omega = 1$ and $\sigma_8 = 0.7$ can explain the observed spread in the colours of elliptical galaxies in clusters at redshifts between 0 and 0.6, as well as the apparent passive evolution of the colours of cluster ellipticals. It is interesting that this model predicts that the global number density of bright ellipticals should decrease by a factor 2-3 by redshift 1, in rather good agreement with our results from the CFRS. By contrast, if a lower normalization of $\sigma_8 = 0.4$ is adopted, as would be appropriate for a COBE-normalized CDM model with a “shape”-parameter $\Gamma = 0.2$, one obtains much more rapid evolution, with the number density of ellipticals decreasing by a factor 25 by redshift 1.

There is also considerable spectroscopic evidence that many elliptical galaxies have undergone recent episodes of star formation. Charlot & Silk (1994) attempt to quantify this using signatures of intermediate-age stars in the spectra of ellipticals in clusters at redshifts between 0 and 0.4. They find that the Balmer absorption line strengths increase with redshift and they interpret this in terms of an increasing contribution of younger stars to the total light (see also Barger et al 1996). It is not possible, however, to determine from the spectra the star formation history of the elliptical prior to its last burst, or to assess what physical mechanism was responsible for triggering the star formation. In future, morphological information will be available to complement the colours and redshifts from the Canada-France survey. The combination of morphologies, colours and redshifts will help decide whether merging, star formation, or both, are responsible for loss of early-type galaxies at high redshift. Hierarchical formation models suggest that the answer will be both.

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Table 1: Variation in $\langle V/V_{\text{max}} \rangle$ for the CFRS and Hawaii surveys as the colour threshold is changed.

| Model $Z_\odot$ | % E/S0 included (Bower et al) | % Sp rejected (Visvanathan) | % E/S0 (CFRS) | $\langle V/V_{\text{max}} \rangle$ (CFRS) | % E/S0 (Hawaii) | $\langle V/V_{\text{max}} \rangle$ (Hawaii) |
|-----------------|-------------------------------|-----------------------------|---------------|------------------------------------------|----------------|------------------------------------------|
| 0.3             | 98                            | 65                          | 21            | 0.413 ± .023                             | 34             | 0.343 ± .045                             |
| 0.4             | 97                            | 78                          | 19            | 0.408 ± .025                             | 26             | 0.356 ± .052                             |
| 0.5             | 88                            | 84                          | 17            | 0.410 ± .026                             | 19             | 0.317 ± .060                             |
| 0.6             | 79                            | 92                          | 14            | 0.409 ± .028                             | 13             | 0.326 ± .075                             |
| 0.7             | 65                            | 94                          | 12            | 0.434 ± .031                             | 11             | 0.274 ± .080                             |
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Figure Captions

**Figure 1:** The division of the CFRS galaxies into early and late-types according to the colour-redshift criterion discussed in the text. Solid circles represent the ellipticals and S0s and stars represent the spirals and irregulars.

**Figure 2:** Redshift and absolute magnitude histograms for early-type galaxies selected from the CFRS catalogue. The solid area is for galaxies with no detected O[II] emission and the hatched area for galaxies with O[II] emission. The unfilled area represents galaxies included by the incompleteness correction described in section 2.

**Figure 3:** upper panel: The $V/V_{\text{max}}$ distribution for early-type galaxies selected from the CFRS catalogue. Explanations of the histogram shadings are as in figure 2. lower panel: The resulting $V/V_{\text{max}}$ distribution when density evolution of the form $F = (1 + z)^{-1.5}$ is applied to the full (incompleteness corrected) sample of 150 early-type galaxies.