Detection of strong evolution in the population of early-type galaxies

Guinevere Kauffmann,1 Stéphane Charlot2 and Simon D. M. White1

1Max-Planck Institut für Astrophysik, D-85740 Garching, Germany
2Institut d’Astrophysique du CNRS, 98 bis Boulevard Arago, F-75014 Paris, France

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ABSTRACT
The standard picture holds that giant elliptical galaxies formed in a single burst at high redshift. Ageing 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 early-type galaxies and with 0.1 < z < 1. This sample is inconsistent with the standard evolutionary picture for elliptical galaxies with better than 99.9 per cent 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 that \( \gamma = 1.5 \pm 0.4 \). 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 that we have adopted. We conclude that neither the corrections nor the models are 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 that we have detected.

Key words: galaxies: formation – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: stellar content.

1 INTRODUCTION
In the standard model of elliptical galaxy formation proposed by Tinsley & Gunn (1976), all stars in the galaxy form in an initial burst at high redshift, and the luminosity of the galaxy 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

\[
L(t) = L(t_0)[(t - t_i)/(t_0 - t_i)]^{-1 + \alpha_x},
\]

where \( t_i \) is the time of formation, \( x \) is the slope of the initial mass function (IMF) (\( x = 1.35 \) for a Salpeter mass function), and \( \alpha_x \approx 0.26 \) 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 (HST), 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 ageing 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,b; Le Fèvre et al. 1995; Hammer et al. 1995; Crampton et al. 1995). As we will show, it provides a sample of about 125 $I$-band-selected galaxies with the luminosities and colours of passively evolving early-type galaxies 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 the Hawaii Survey. We show that these samples are both inconsistent with the simple passive evolution picture with better than 99.7 per cent 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 (in preparation), 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 cut-offs at 100 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 per cent 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 per cent 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 per cent of the galaxies in the Visvanathan (1992)

![Fig. 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 three-pointed stars represent the spirals and irregulars.](https://academic.oup.com/mnras/article-abstract/283/4/L117/1071236/1)}
correct for incompleteness as well as possible and investigate the uncertainties that 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 that 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 shown in Fig. 1, it is classified as early-type. As shown in Fig. 2 for the CFRS data, this procedure adds about 28 objects to the sample, about 20 per cent 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 that 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 $VV_{\text{max}}$ 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, $VV_{\text{max}}$ should be uniformly distributed between 0 and 1 and $\langle VV_{\text{max}} \rangle$ should scatter around 0.5, with a variance that is only dependent on sample size. In this Letter, we calculate all magnitudes and volumes assuming that $q_0=0.5$ and $H_0=50$ km s$^{-1}$ Mpc$^{-1}$. We have checked that changing $q_0$ has almost no effect on our results.

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

The $VV_{\text{max}}$ distribution is clearly skewed to values less than 0.5. We obtain $\langle VV_{\text{max}} \rangle=0.398$ when objects with detected star formation are excluded, and $\langle VV_{\text{max}} \rangle=0.410$ when they are included. For a uniform distribution, the expected standard deviations in $VV_{\text{max}}$ 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 per cent 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 $F=(1+z)^{-t}$, and determine the value of $t$ required for the $VV_{\text{max}}$ distribution to come out as uniform. We find that $t=1.7 \pm 0.4$ for the sample without [O II] emission and that $t=1.5 \pm 0.4$ for the full sample (see the lower panel of Fig. 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). 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.

4.1 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 \( z_t = 5 \) with a Salpeter IMF \( (x = 1.35 \text{ in equation } 1) \). 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 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 per cent 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.

4.2 The colour threshold

The 50 per cent 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/SOs and spirals included in the sample quite substantially, the derived values of \( \langle V/V_{\text{max}} \rangle \) vary very little. It is therefore highly unlikely that a bluing of a contaminating disc population can explain the low value of \( V/V_{\text{max}} \) that we derive.

4.3 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 analyse separately each of the five fields that make up the CFRS survey. These fields are well enough separated 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.

4.4 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 \( I \)-bandphotometry is available for all galaxies, even 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 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 of 2 decrease in the number density of early-type galaxies by redshift 1, rather than a factor of 3.

4.5 \( V/V_{\text{max}} \) 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

<table>
<thead>
<tr>
<th>Model</th>
<th>% E/S0 included</th>
<th>% Sp rejected</th>
<th>% E/S0 (CFRS)</th>
<th>\langle V/V_{\text{max}} \rangle (CFRS)</th>
<th>% E/S0 (Hawaii)</th>
<th>\langle V/V_{\text{max}} \rangle (Hawaii)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 ( Z_\odot )</td>
<td>98</td>
<td>65</td>
<td>21</td>
<td>0.413 ± 0.023</td>
<td>34</td>
<td>0.343 ± 0.045</td>
</tr>
<tr>
<td>0.4 ( Z_\odot )</td>
<td>97</td>
<td>78</td>
<td>19</td>
<td>0.408 ± 0.025</td>
<td>26</td>
<td>0.356 ± 0.052</td>
</tr>
<tr>
<td>0.5 ( Z_\odot )</td>
<td>88</td>
<td>84</td>
<td>17</td>
<td>0.410 ± 0.026</td>
<td>19</td>
<td>0.317 ± 0.060</td>
</tr>
<tr>
<td>0.6 ( Z_\odot )</td>
<td>79</td>
<td>92</td>
<td>14</td>
<td>0.409 ± 0.028</td>
<td>13</td>
<td>0.326 ± 0.075</td>
</tr>
<tr>
<td>0.7 ( Z_\odot )</td>
<td>65</td>
<td>94</td>
<td>12</td>
<td>0.434 ± 0.031</td>
<td>11</td>
<td>0.274 ± 0.080</td>
</tr>
</tbody>
</table>


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adds only four extra objects. This sample gives $\gamma = 1.2 \pm 0.6$, in good agreement with the results for the fainter sample.

### 4.6 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 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 that are too faint to be included in the sample. This evolution may apply exclusively to the elliptical galaxy population, or exclusively to the S0 galaxy population, or to both populations equally.

We cannot use colour alone to separate ellipticals from S0s.

It should be noted that this result is indirectly evident in the studies of the evolution of the luminosity function of red galaxies with redshift by Lilly et al. (1995b). Simple passive evolution would require the luminosity function to shift 1 mag brighter by $z = 1$, whereas in fact the luminosity function is found not to evolve with redshift.

In recent hierarchical models of galaxy formation (Kauffmann, White & Guiderdoni 1993; Baugh, Cole & Frenk 1996), galaxy discs form as gas cools and condenses at the centres of dark matter haloes, while elliptical galaxies form when two disc galaxies merge. If no further gas cools on to the elliptical, its stellar population will fade and it will evolve passively until the present day. In such models, elliptical 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 $b = 1/\sigma_8$). 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' cold dark matter (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 of 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 of 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 to 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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