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Evolution of Early-type Galaxies in Clusters

MARIJN FRANX
Leiden Observatory

Abstract

Early-type galaxies dominate rich clusters, and their formation and evolution are intimately related to the formation of the clusters themselves. They form a very homogeneous class at low redshift, and they evolve slowly to higher redshifts. Here we review the evolution of these galaxies, and compare them to early-type galaxies in the field. Furthermore, we discuss recent results on galaxies at $z > 2$, which are likely the progenitors of early-type galaxies at low redshift.

1.1 A Working Definition

Early-type galaxies encompass both elliptical galaxies and S0 galaxies. The distinction between those classes is not very sharp. Whereas ellipticals were originally thought to be axisymmetric or triaxial systems without disks or other substructure, it became clear after the first high signal-to-noise ratio imaging with CCDs that elliptical galaxies contain substantial substructure (e.g., Jedrzejewski 1987; Bender, Döbereiner, & Möllenhoff 1988; Franx, Illingworth, & Heckman 1989). The most convenient observable is the distortion of the isophotes, measured by c_4 (or a_4). If positive, the deviation is "disky" (i.e., similar to the distortion caused by a disk); if negative, it is "boxy." Many L_* ellipticals have disky isophotes, with c_4 at a level of a few percent. The first modeling of these results showed that the disky ellipticals contain substantial disks, and can be thought to form one class with S0s (Rix & White 1990). If these galaxies are viewed edge-on, they are classified as S0s; if they are viewed face-on, they are classified as ellipticals. Hence, the relative contribution of the disks in disky ellipticals is much higher than the values of c_4, and can be on the order of 50%.

Modeling of the isophotal shapes of early-type galaxies in Coma indicated that the L_* ellipticals and S0s were consistent with forming a single "class" with bulge-to-total light ratios homogeneously distributed between 0 and 1 (Jørgensen & Franx 1994). No "diskless" class was necessary to reproduce the observations, except at the high-luminosity end of the luminosity function.

Given these results, we have to conclude that the classes of L_* ellipticals and S0s are overlapping, a galaxy classified as S0 can be classified as elliptical at another viewing angle, and *vice versa*. To avoid the complications, we do not treat them as separate classes below.

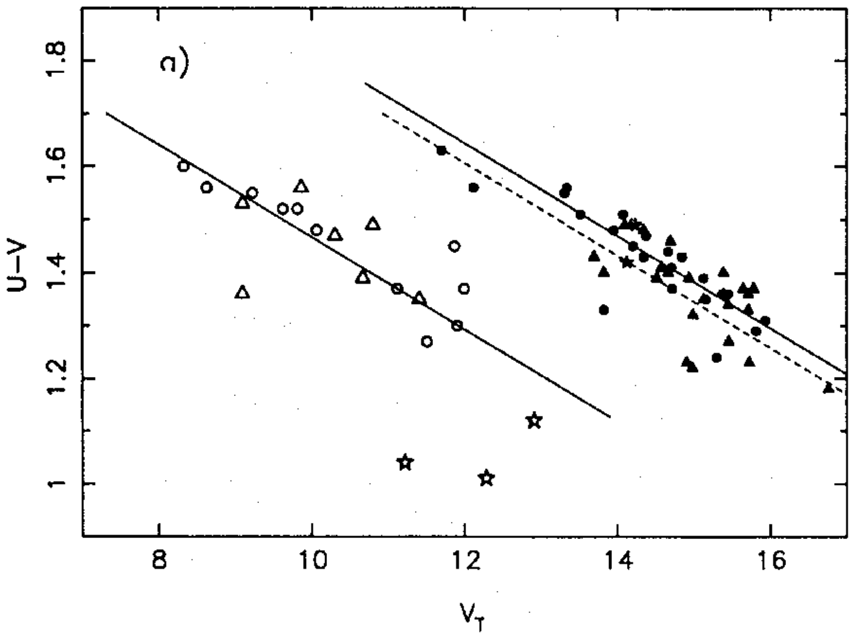

Fig. 1.1. The color magnitude relation of Virgo and Coma, measured by Bower et al. (1992). Open symbols are Virgo galaxies, closed symbols are Coma galaxies. The solid lines show fits to the relation. Open circles and triangles are ellipticals and S0s, and stars are later types. The scatter around the fit is very low for the ellipticals and S0s: 0.05 mag. (From Bower et al. 1992.)

1.2 Homogeneity at Low Redshift

Early-type galaxies in low-redshift clusters form an extremely homogeneous class. It has been known for a long time that early-type galaxies form a tight sequence in the color-magnitude diagram (e.g., Sandage & Visvanathan 1978). Since the colors of stellar populations evolve with age, the width of the color-magnitude relation puts a strong constraint on the age scatter at a given magnitude. Bower, Lucey, & Ellis (1992) measured the color-magnitude diagrams of Coma and Virgo early-type galaxies (Fig. 1.1) and derived that the rms scatter in age was less than 15%. They used this result to argue that these galaxies have likely formed at $z > 2$.

Similarly, the mass-to-light ratios of early-type galaxies are very well behaved (Faber et al. 1987). This is best expressed by the fundamental plane (Dressler et al. 1987, Djorgovski & Davis 1987), which is a relation between velocity dispersion (σ), effective radius (r_e), and surface brightness μ_e: $r_e = \sigma^{1.24}/\mu_e^{0.82}$ (taken from Jørgensen, Franx, & Kjærgaard 1996). Under the assumption of homology, the relation implies that

$$M/L \propto M^{0.24}, \tag{1.1}$$

with a small scatter (20%). The small scatter implies a small age scatter at a given mass, as the mass-to-light ratio evolves with time as $M/L \propto t^{0.8}$.

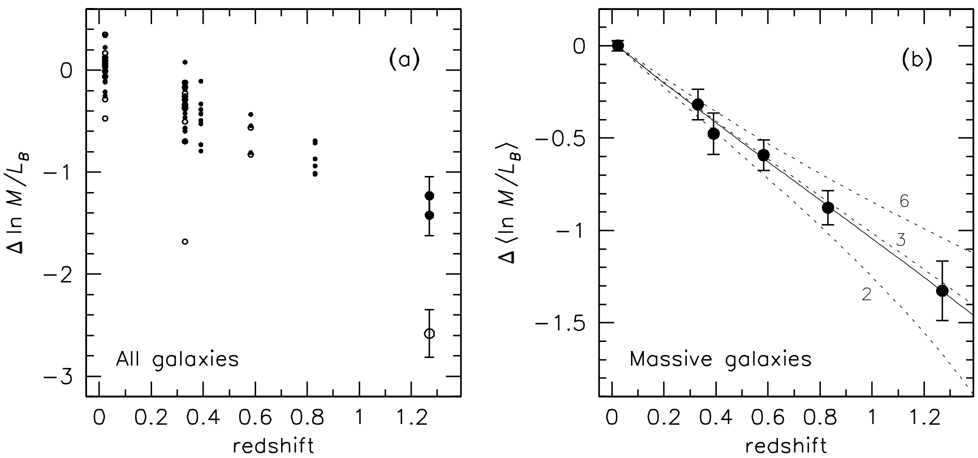

Fig. 1.2. The evolution of the mass-to-light ratios of cluster galaxies out to $z = 1.27$ (van Dokkum & Stanford 2003). The *left* figure shows the mass-to-light ratios of all galaxies; the *right* figure shows the average mass-to-light ratio for each cluster for galaxies more massive than $10^{11} M_{\odot}$. Dashed lines are model predictions assuming a single burst. The solid line is a model including morphological evolution. The fits imply a mean star formation redshift of 2 or higher. (From van Dokkum & Stanford 2003.)

The picture that emerges from these results is that the early-type galaxies, which dominate the high-density regions of clusters (Dressler 1980), formed at high redshift.

1.3 Evolution to $z = 1$

The most straightforward method to test this is by determining the properties of early-type galaxies at higher redshifts. One expects that the colors evolve slowly, that the scatter in the color-magnitude diagram remains low, but increases slightly, and that the mass-to-light ratios evolve slowly.

With the advent of the *Hubble Space Telescope* and large optical telescopes, it possible to perform such studies beyond a redshift of 1. Many of the results are consistent with the following simple picture.

(1) The evolution of the colors of early-type galaxies is generally slow (Stanford, Eisenhardt, & Dickinson 1998).
(2) Ellis et al. (1997), Stanford et al. (1998), and van Dokkum et al. (2001) found that the scatter in the color-magnitude relation remains very low out to high redshifts, indicating that the relative age spread remains very low, even at substantial look-back times.
(3) van Dokkum & Stanford (2003) have measured the fundamental plane relation for early-type galaxies out to $z = 1.23$, and found a low evolution in the mass-to-light ratio. As can be seen in Figure 1.2, this rules out models with young stellar populations. Best-fit models gave a formation redshift $z_{\rm form} = 2-3$.

1.3.1 Evidence for young ages

Whereas all this evidence points to high formation redshifts for cluster early-type galaxies, morphological studies indicate that many early-type galaxies are young. The most

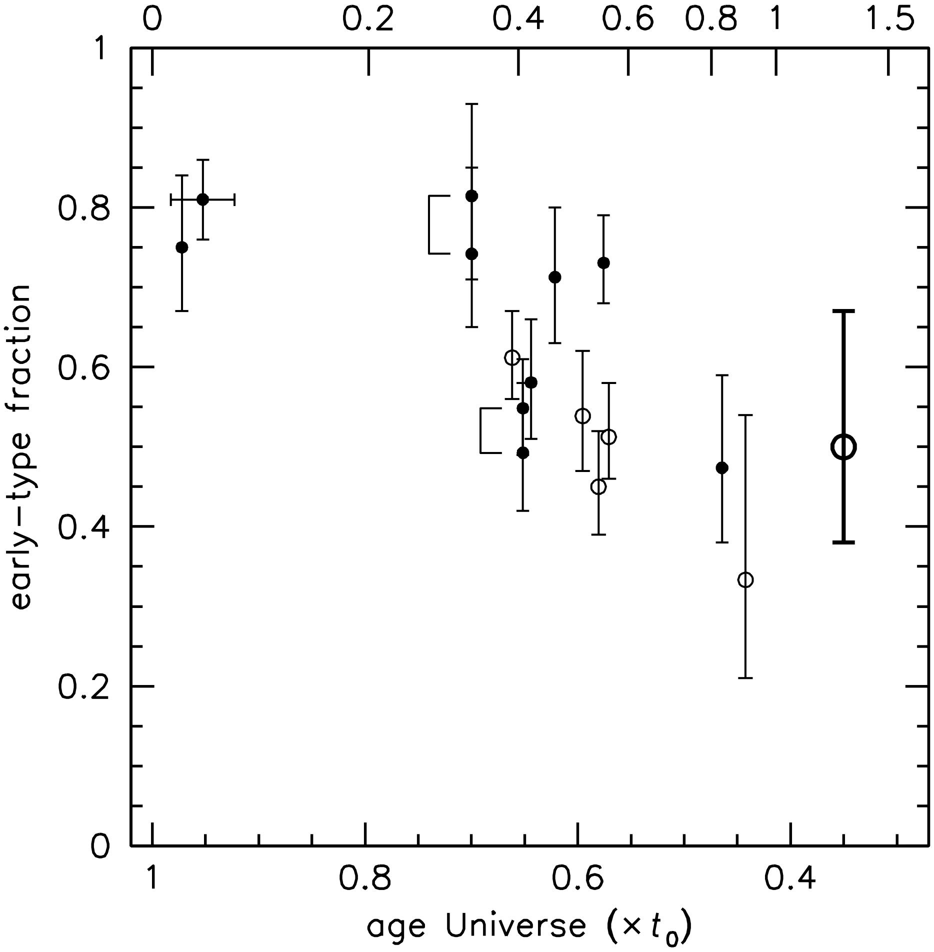

Fig. 1.3. The evolution of the fraction of early-type galaxies in rich clusters, from $z = 1.27$ to $z = 0$. The fraction decreases from 0.8 at $z = 0$ to 0.5 at $z = 1$. X-ray bright clusters, which are indicated by filled symbols, follow this trend. (From van Dokkum et al. 2001.)

comprehensive study is that of Dressler et al. (1997), who found that the fraction of S0 galaxies in concentrated and regular clusters decreases rapidly with increasing redshift. At a redshift of 0.55, the fraction of S0s is as low as 15%–20%, a decrease of a factor of 2–3 compared to the fraction of S0s in similar clusters at low redshift. The fraction of spirals increases correspondingly at high redshift. These results were interpreted by the authors as evidence that the spiral galaxies in the intermediate-redshift clusters were transformed into S0 galaxies.

A concern is the difficulty in distinguishing between elliptical and S0 galaxies, as discussed above. This can be avoided by considering ellipticals and S0s together in the single class of early-type galaxies. Figure 1.3 shows the evolution of the fraction of early-type galaxies in rich clusters, taken from van Dokkum et al. (2001). The fraction decreases from 0.8 at $z = 0$ to ~ 0.5 at $z = 1$, with considerable scatter. The fraction for a given cluster is fairly stable when different groups have classified the galaxies. Hence, the separation between early-type galaxies and spiral galaxies is repeatable.

In summary, the evidence is compelling that a significant fraction of early-type galaxies have transformed at late times from spirals into S0s and/or ellipticals. This may have been caused by gas stripping, merging, or other processes. This appears to be at odds with the evidence that the early-type galaxies are old. Below we discuss models that address this issue.

1.4 Complex Models of Galaxy Evolution

The morphological evolution implies that the formation history of the early-type galaxies is more complex than assumed in the simple "burst" models. Obviously, some of the early-type galaxies at $z = 0$ were spirals at redshifts $z = 0.5 - 1$. Although we lack accurate determinations of the star formation rates in these spirals, some star formation was obviously ongoing, and the models need to incorporate this.

The effect of late star formation on the mass-to-light ratio and late conversion to early-types is shown in Figure 1.4. The figure shows the mass-to-light ratios of a population of early-type galaxies that is enhanced by a steady conversion of star-forming galaxies into "dead" galaxies. As a result, the set of early-type galaxies at $z = 1$ is a very special subset of the galaxies at $z = 0$, and the evolutionary diagnostics such as the evolution of the mass-to-light ratio and color evolution do not give the correct constraints on the ages if they are modeled by single-burst populations. This effect is called "progenitor bias."

A full description of the models can be found in van Dokkum & Franx (2001). The models are very simple, and lack the physical basis of earlier models by Baugh, Cole, & Frenk (1996) and Kauffmann & Charlot (1998). Nevertheless, they demonstrate that the effects are fairly small, because the scatter in the mass-to-light ratios and in the colors are so small. To first order, the correction for progenitor bias is proportional to the scatter in the observed quantity at $z = 0$. van Dokkum & Franx (2001) find that the mean formation redshift of the early-type galaxies decreases from 2.6 to 2 if the maximum correction is applied.

One of the main uncertainties in this modeling is the fact that one needs a comprehensive study of all high-redshift progenitors of low-redshift early-types galaxies in clusters. Many of these galaxies may be outside of the clusters at $z = 1$, and the rich clusters studied at $z = 1$ may be an exceptional, rare environment, atypical for early-type galaxies that end up in nearby rich clusters. Hence, a proper understanding of the evolution of the early-type galaxies at $z = 0$ requires a determination of the environment of their progenitors at $z = 1$, and higher, and this is a very challenging project. It requires an accurate determination of the cluster mass function at $z = 1$, and a study of the morphological types as a function cluster properties.

1.5 Comparison of Field and Cluster Early-type Galaxies

Early-type galaxies in rich clusters have traditionally been studied because of the ease with which one can study many simultaneously using wide-field imagers and spectrographs. We should realize, however, that most early-type galaxies are found outside rich

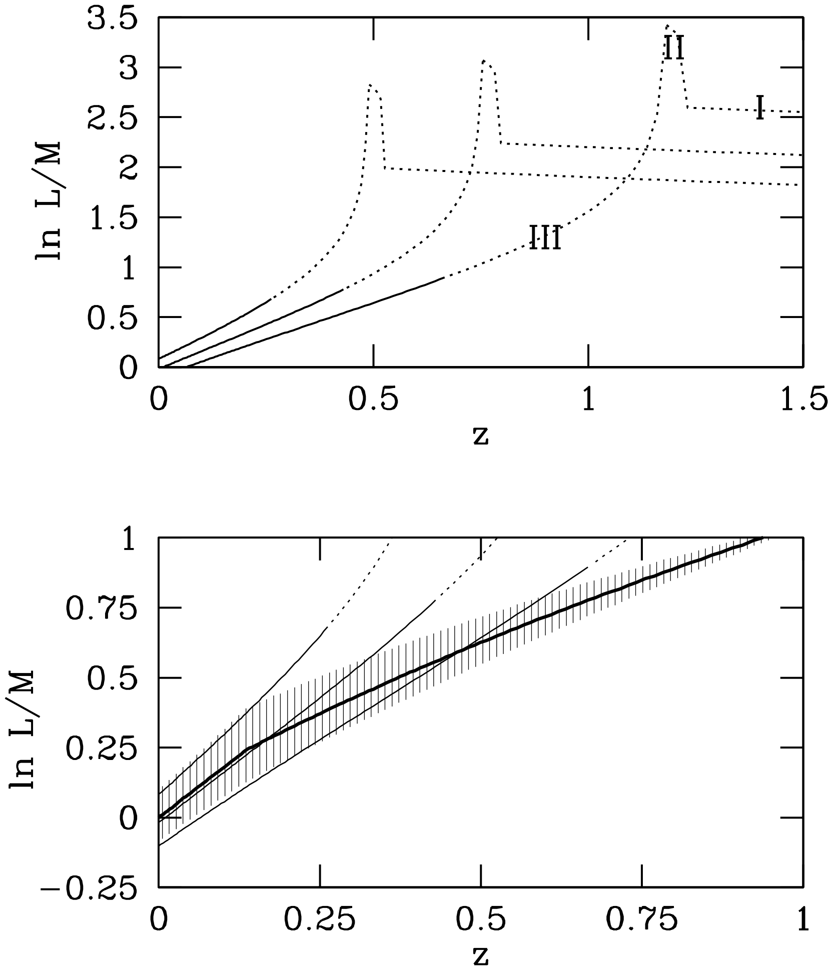

Fig. 1.4. The effects of morphological evolution on the measured mass-to-light ratios. The *top* panel shows the mass-to-light ratios of individual galaxies, which first form stars (indicated by "I"), undergo a burst (phase "II"), become post-starburst galaxies (phase "III"), and finally evolve into early-type systems (solid curve). If galaxies undergo these transformations at different times, the fraction of early-types evolves with redshift, and the sample of early-type galaxies at low redshift is different from that at high redshift (van Dokkum & Franx 2001). The *bottom* panel shows the effect on the measured evolution of the mass-to-light ratios: the measured evolution is slow, as only the oldest early-type galaxies are included in the sample at high redshift. The best-fit curve to the observed evolution out to $z = 1$ underestimates the evolution of all progenitors of early-type galaxies at $z = 0$.

clusters, typically in groups. Hence, whereas the cluster galaxies can provide us reference samples, a proper understanding of early-type galaxies requires field galaxy studies.

Early studies of the color-magnitude relation have established that field early-type galaxies are less homogeneous than cluster early-type galaxies (e.g., Larson, Tinsley, & Caldwell 1980). Similarly, within clusters evidence for environmental effects has been found (e.g., van Dokkum et al. 1998; Terlevich, Caldwell, & Bower 2002): early-type galaxies in the outskirts can have slightly younger populations as derived from their colors.

Similarly, the mass-to-light ratios of early-type galaxies in poor groups is slightly lower than the mass-to-light ratios in rich clusters. This can be derived from the data of Faber et al. (1989), and was also found in a recent study by Bernardi et al. (2003).

The evolution of the mass-to-light ratios of field early-type galaxies has been studied by several groups, with slightly contradictory results. Van Dokkum et al. (2001) and Treu et al. (2001) determined the evolution to $z = 0.4 - 0.6$ and found evolution very similar to that of cluster early-type galaxies. At higher redshifts, however, Treu et al. (2002) found significantly faster evolution, whereas Kochanek et al. (2000), Rusin et al. (2003), and van de Ven, van Dokkum, & Franx (2003) found slow evolution based on lensed galaxies, and van Dokkum & Ellis (2003) found slow evolution to $z = 0.9$ based on an optically selected sample. The last authors found a small offset between field galaxies and cluster galaxies, on the order of 0.14 ± 0.13 mag at $z = 0.88$.

The photometric study of Bell et al. (2004) indicates that the fraction of red galaxies in the field increases significantly from $z = 1$ to $z = 0$. Although a color-selected sample is not the same as a morphologically selected sample, it shows that the effect of morphological evolution and progenitor bias needs to be studies too for the field samples. It may actually be much easier to do this for the field sample than for the cluster sample, as no special selection criteria need to be applied to define the environments.

To conclude, in order to study this topic comprehensively, wide-area studies are needed to measure the evolution of the fraction of early-type galaxies as a function of redshift and to study all progenitors.

The similarity of cluster early-type galaxies and field early-type galaxies cannot be reproduced by models of galaxy formation. The comparisons done by Kochanek et al. (2000) and van Dokkum et al. (2001) show that the semi-analytical models by Diaferio et al. (2001) predict differences that are very large, on the order of 0.6 mag for the mass-to-light difference. The observed differences are much smaller.

1.6 Redshifts $\gg 1$

The high formation redshifts derived for early-type galaxies with $0 < z < 1$ implies that it should be possible to find their star-forming counterparts at $z > 2$. The study of star-forming galaxies at high redshift has progressed rather dramatically in the past years with the discovery of the large population of Lyman-break galaxies (Steidel et al. 1996a,b, 1999). The integrated star formation rate of these galaxies much higher than the star formation rate in the nearby Universe (e.g., Madau et al. 1996; Steidel et al. 1999), and presumably they are the progenitors of early-type galaxies in groups and clusters in the nearby Universe.

Given the rarity of rich clusters at low redshifts, studies of large volumes at high redshifts are needed to determine what the progenitors are of the early-type galaxies in rich clusters.

The masses of the Lyman-break galaxies are thought to be fairly low, on the order of $10^{10}\,M_\odot$ (Papovich, Dickinson, & Ferguson 2001; Shapley et al. 2001), and hence recurrent merging is necessary to build up massive early-type galaxies in clusters.

On the other hand, the Lyman-break galaxies form a fairly special population of relatively dust-free galaxies, and many other galaxies may have been missed by selection in the rest-

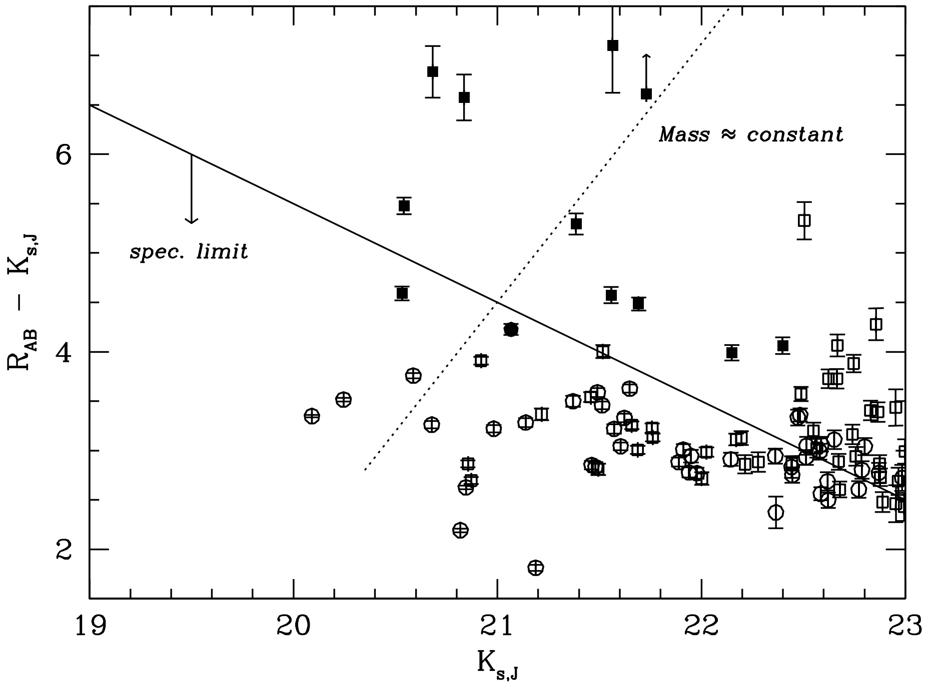

Fig. 1.5. The $R-K$ colors of high-redshift galaxies in the HDF-South (Franx et al. 2003). The galaxies have been selected to have photometric redshifts between 2 and 3.5. The range in $R-K$ colors is very large, more than 5 magnitudes. The filled symbols are galaxies selected to have $J-K > 2.3$, which is an effective criterion to select red galaxies with $z > 2$. Lyman-break galaxies are indicated with round symbols. The two classes have very little overlap. The red galaxies contribute significantly to the integrated K-band flux, and may contribute a comparable fraction to the stellar mass density as the Lyman-break galaxies, down to $K = 22.5$ mag. Larger area studies are needed to verify the density of these red sources. They are possibly the oldest galaxies at high redshift and the progenitors of early-type galaxies at low redshift. (From Franx et al. 2003.)

frame UV. For example, strong starburst galaxies have been identified based on their sub-mm emission (e.g., Smail et al. 2002). Their contribution to the integrated star formation rate is significant.

It is also possible to select high-redshift galaxies based on their near-infrared fluxes. Since a typical L_* galaxy at redshift $z = 0$ can be as faint as $K = 23$ mag at $z = 3$, very deep imaging is required to do this. Recent studies have shown that significant populations of "red" galaxies exist at $z > 2$, which would not be selected by the Lyman-break criterion because they are too faint in the observed optical window (e.g., Franx et al. 2003; van Dokkum et al. 2003)

Figure 1.5 shows the $R-K$ colors of galaxies in the Hubble Deep Field South, with photometric redshifts $2 < z < 3.5$. The Lyman-break galaxies are indicated by closed symbols; the squares are galaxies that satisfy $J-K > 2.3$ mag, which is a very simple criterion to select "red galaxies" with redshifts larger than 2. Although the number of these galaxies is much lower than the number of Lyman-break objects, their contribution to the K-band light is 24%, and their contribution to the stellar mass density may be comparable to that of Lyman-break galaxies.

These red galaxies could be the more evolved counterparts of Lyman-break galaxies, for example those that experienced a burst of star formation at higher redshift. Wide-area studies are needed to determine the true density of these infrared-selected galaxies and their relevance to the formation of early-type galaxies in clusters. Since early-type galaxies in clusters are thought to be the oldest galaxies in the nearby Universe, it might be expected that their counterparts at $z = 2-3$ are among the oldest, and hence reddest, galaxies at that redshift.

1.7 Conclusion

Early-type galaxies in clusters form a very homogeneous population, and evolve slowly to $z = 1$. Their formation redshifts are likely higher than 2. Nevertheless, significant morphological evolution occurs in rich clusters: the fraction of early-type galaxies decreases to high redshift, showing that their formation histories are more complex than a single burst. Detailed wide-field studies are necessary to determine the evolution of the progenitors of early-type galaxies at $z = 0.5-1$.

Field early-type galaxies are quite comparable to cluster early-type galaxies, but probably slightly younger. Direct evidence for morphological transformations is absent, but the evolution of the color-magnitude diagram suggests a strong evolution of the fraction of red galaxies. The similarity of early-type galaxies in the field and in clusters cannot be reproduced by the semi-analytical models of galaxy formation: in these models, the field early-type galaxies form too late.

These results imply that early-type galaxies formed at $z = 2$ and higher. It has become possible to study these galaxies directly with current telescopes. A large population of UV-bright galaxies has been found by using the Lyman-break technique (Steidel et al. 1996a,b). If these galaxies are the progenitors of early-type galaxies, they need recurrent merging, as their masses are fairly low. On the other hand, sub-mm sources have been found with very large star formation rates, and the role that these galaxies play needs to be elucidated further. Finally, a new population of galaxies has been identified based on very deep near-infrared imaging. These galaxies, selected by $J-K$ color, are generally too faint in the optical to be selected by the Lyman-break technique. They may represent the oldest galaxies at $z > 2$ and may be most typical of progenitors of cluster early-type galaxies.

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