The Formation History of Early-Type Galaxies: An Observational Perspective

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Abstract. This talk investigates the formation of early-type galaxies from a deliberately observational viewpoint. I begin by reviewing the conclusions that can be reached by comparing the detailed properties of galaxies in present-day clusters, focusing on the colour-magnitude relation in particular. The overriding picture is one of homogeneity, implying a remarkable uniformity in the formation of these galaxies. This picture contrasts with the increasing activity seen in clusters as a function of redshift, creating an apparent paradox between the obvious diversity of star formation histories in distant cluster galaxies and their uniformity in local systems. A resolution is feasible so long as star formation occurs over an extended epoch.

In addition to placing limits on variations in star formation history, the existence of a tight ‘fundamental relations’, such as the colour-magnitude relation, can be used to investigate galaxy mergers and to set limits on the degree to which present-day clusters galaxies are built by combining systems of stars formed in smaller units. The final part of this talk turns to early-type galaxies in the field, and tries to apply the same techniques that have been successful in clusters. This is an emerging field in which appropriate data-sets are only just becoming available; however, comparison of the formation histories of galaxies in a wide variety of environments is key to distinguishing between the Classical and Hierarchical models for galaxy formation.

1. Introduction

In this talk, I will review our knowledge of the formation history of early-type galaxies. Rather than approaching the problem from the theoretical side, we will take the view point of an ‘observer’. We will look at the data and asking...
what it directly tells us. Which constraints follow from which aspects of the observations. The situation is far from hopeless since we know much about the stellar populations of galaxies in local clusters. Cluster galaxies are, after all, relatively simple systems compared to field spirals in which much of the past formation history is masked by the present-day star formation rate. In addition, clusters of galaxies can be observed at high redshift, providing us with the means of reconstructing the evolution of their galaxy populations in a statistical sense.

The evolution of cluster galaxies is dominated by simple scaling relations, and we can use the existence and narrow scatter of these relations to set powerful constraints on their formation. I will argue that we have an emerging, if still incomplete, picture for the evolution of galaxies in clusters. This makes it tempting to apply the same arguments to galaxies in the field, and I will briefly compare the properties of early-type galaxies in the clusters with their counter-parts in the field.

Of course, the picture that we can hope to build from the data alone is limited: Carlton Baugh will look at the situation from the opposite, but complimentary perspective, creating a model derived from applying simple rules for galaxy formation to the growth of haloes in a hierarchical universe. Full understanding of galaxy evolution will come from a synthesis of these approaches.

2. Some Paradigms for the Formation of Early-Type Galaxies

In order to set the context of this discussion, it will first be helpful to remind ourselves of some theories that have been put forward to explain the range of galaxy morphological types. I will deliberately concentrate on two alternative scenarios in order to deliberately polarise the situation. The truth probably lies in between.

What I will call the Classical model for galaxy formation has its roots in the monolithic low collapse models of Larson, 1975. However, in my view the monolithic collapse is not the important component of this scenario: following the view of Arimoto & Yoshii (1987), the collapse of a gas cloud may be initially fragmented. Star formation is initially rapid, and is unchecked until the first massive stars evolve to the supernova phase. At this point, star formation can continue only if the dark matter halo is sufficiently massive to retain the gas against the increasing pressure of the supernova ejecta. In massive systems, star formation will continue longer, but eventually the remaining gas will be expelled from the system in a supernova-driven wind, leaving a spheroidal star system. The subsequent evolution depends on the galaxies environment: galaxies in clusters lose their wind material to the intra-cluster medium, while galaxies in low density environments may be able to reacquire their gas in the form of a gas disc, in which a quiescent mode of star formation takes place.

By contrast, in the Hierarchical (HGF) model, there is no intrinsic difference between star formation occurring at different epochs. All galaxies are view as similar star forming systems in which there is an equilibrium between the inflow of gas and the rate at which it is either consumed or driven out of the galaxies by a supernova wind. The morphological appearance of galaxies is somewhat secondary, resulting from the rearrangement of stars as the individual sub-components are brought together to make larger and larger mass units.
After each merger, the disk may or may not grow depending on the whether a gas inflow can re-establish itself. This is possible if the galaxy lies at the centre of its new halo, but not if it now orbits a larger object.

The key difference between the models is that while morphology is set at an early time in the Classical model, morphology is a fluid quantity in the Hierarchical model that can change in both directions. This division between the Classical and Hierarchical model parallels the division between the roles of nature and nurture in forming the morphology of the galaxies.

3. Galaxies in Local Clusters

The overriding feature of galaxies in local clusters is their homogeneity: the uniformity in properties and the way in which they can be scaled between galaxies of different luminosities according to a set of ‘fundamental relations’. One key example is the fundamental plane: the correlation between the luminosity, effective radius and central velocity dispersions ($\sigma$) of early-type galaxies. This seems to have its origin in the virial theorem, but also requires considerable uniformity in stellar populations (eg., Pahre et al., 1998). Similar strong scalings also exist between the Mgb line-strength index and $\sigma$ and between colours and magnitudes (the colour-magnitude relation: CMR). In this talk I'll concentrate on the CMR, because this is what I am most experienced in working with, but the same discussion could equally apply to these other relations.

Figure 2 shows the U-V colour-magnitude relation for galaxies in the Coma cluster, taken from Terlevich et al., 1998. The diagram has been limited to
The colour-magnitude relation in the Coma Cluster of galaxies, from Terlevich et al., 1998. Colours and magnitudes are measured within an 8.7 kpc aperture. Absolute magnitudes include an average correction for light outside this aperture. The figure shows the CMR of spectroscopically confirmed cluster members. Symbol colours differentiate E, S0 and S0/a and later galaxies.

galaxies for with spectroscopically confirmed cluster membership (mainly from Colless & Dunn, 1996) and at brighter magnitudes, morphologies have been assigned from Andreon et al., 1996. The over-riding feature of this diagram is the strength of the colour-magnitude sequence, extending linearly down to the limit of the spectroscopic catalogues and beyond. Although there are a few galaxies lying blueward of the relation, most galaxies lie very close the ridgeline. The scatter about the ridgeline, measured with a biweight regression estimator (Beers et al., 1990), amounts to 0.05 mag for the central $r < 20'$ region even if all galaxy morphological types are included. This can be used to set important constraints on the formation history of these galaxies. We will assume that the overall driving force for the CMR is variations in the metal abundances of these galaxies, and that the scatter is primarily due to variations in age. On the basis of the colours alone, this can only be justified by a plausibility argument; however, the picture is supported by measurements of line indices in cluster galaxies (Kuntschner & Davies, 1998, Terlevich et al., 1998) and by the evolution of the CMR sequence with redshift (Ellis et al., 1997, Kodama et al., 1998, Stanford et al., 1998).

Bower et al., 1992, considered the limits that could be set if the galaxies were formed in a single burst of star formation. Immediately after their creation, galaxies are extremely blue. They become redder, at first quickly, then more slowly after a few Gyr, until they asymptotically redden to the colours of the reddest galaxies in the sequence. The narrow scatter implies either that all the galaxies are formed in a well coordinated single event, or that the galaxies are
old enough that the U-V colour is evolving only slowly. Using stellar population synthesis models to quantify this argument, Bower et al., found that star formation would need to been completed before a look-back time of around 10 Gyr, corresponding to a median formation redshift of $z \sim 2$.

This is a powerful argument, but how is it affected if we assume that star formation takes place over a more extended period? First it is necessary to understand why a single burst model is appealing. The key is to generate a well defined correspondence between the mass of a galaxy and its metal abundance. In Arimoto & Yoshii’s model of early-type galaxy formation, this occurs because of the competition between the tendency of star formation to expel the gas from the galaxy in a supernova-driven wind, and the galaxy’s gravitational potential that keeps the gas trapped. The larger the galaxy, the longer star formation is able to continue before the gas escapes. If star formation continues for longer, a large fraction of gas is consumed and the mean metal abundance of the stars reaches higher values. This process can only be effective if the star formation period is short lived.

Hierarchical galaxy formation models require an alternative explanation for the mass-metallicity relationship. The chemical evolution of a closed box of gas tends to a final abundance that depends on the duration of star formation (Tinsley, 1980). Adding inflow to the systems means that an asymptotic metallicity is reached, but this depends only on the stellar ‘yield’ (i.e., the mass of metals returned to the interstellar medium for each solar mass of stars that are formed). The advance made by the HGF models is to consider both the inflow and outflow of gas and metals. An essential part of these models is that the outflow is stronger (and star formation less efficient) in low mass systems. A side product is that the ‘effective yield’ is also dependent on mass — in low mass systems, the metals produced in supernovae tend to be expelled from the galaxy rather than being incorporated into the ISM (White & Frenk, 1991, Kauffmann & Charlot, 1998). In this situation a mass-metallicity relation is expected even if the star formation occurs over an extended period.

A single burst model for the formation of early-type galaxies is thus far too restrictive. In Bower, Kodama & Terlevich (1998) we have explored a wider range of star formation histories. We adopted a decaying star formation rate ($\tau = 5$ or $10$ Gyr), and assumed that all galaxies commence star formation at an early epoch (for our adopted cosmology this corresponds to a look-back time of 13 Gyr). We modelled the effect of galaxy infall into the cluster by cutting of star formation at a look-back time $t_{\text{stop}}$ that we assume to be randomly distributed between 13 Gyr and minimum $t_{\text{stop,min}}$ (Figure 3), that we adjusted to match the observed scatter in the Coma cluster CMR relation (using the same bi-weight estimator for the model and the real data).

In this model, star star formation is allowed to continue in some galaxies until recent epochs: for $\tau = 5$ Gyr, $t_{\text{stop,min}} = 3$ Gyr, for $\tau = 10$ Gyr, $t_{\text{stop,min}} = 5$ Gyr. This is considerably less restrictive than we found for the single burst case, but it is essential to emphasise that the bulk of the stellar population is still old. The statement that clusters are dominated by old stellar populations remains true, but this does not preclude finding relatively young populations in a small fraction of galaxies. This is particularly important if we consider the evolution of the observed galaxy populations of clusters as a function of redshift.
Figure 3. This figure shows the limits that can be set on the last epoch of star formation from the homogeneity of the local galaxy population. (a) An illustration of the type of star formation history considered in the BKT model. (b) The CMR scatter as a function of the last star formation epoch \( t_{\text{stop}, \text{min}} \). Acceptable models must lie below the horizontal dashed line.

4. The Galaxy Populations of Distant Clusters

Detailed studies of local clusters is one way to reconstruct the evolutionary histories of cluster galaxies, but observing clusters at high redshift, and hence cosmologically significant look-back times, is a more direct approach. With the Hubble Space Telescope, observations can be made with comparable resolution and accuracy to the ground-based observations of the Coma cluster. Even in the most distant systems studied (e.g., \( z = 1.27 \), Stanford et al., 1997) the CMR still exists. Its evolution is well described by the anticipated passive evolution of an old stellar population (e.g., Kodama et al., 1998), and even the scatter of morphologically selected early-type galaxies shows little increase over local clusters. These observations fit in well with the classical picture of uniform old stellar populations; however, this passive evolution does not provide a complete picture of the evolution of galaxies in clusters.

The key counter-point is the Butcher-Oemler effect (Butcher & Oemler, 1984). Their surprising result was that the fraction of galaxies lying blueward of the colour-magnitude relation increased dramatically with redshift, from an average fraction of a few percent in local clusters to \( \sim 25\% \) at \( z = 0.5 \). Although initially, criticised for the accuracy of the field corrections that needed to be supplied, the increase in the "activity" of cluster galaxies has subsequently been confirmed in spectroscopic studies (e.g., Dressler & Gunn, 1983, Couch & Sharples, 1987, van Dokkum et al., 1998, Poggianti et al., 1998, but see Balogh et al., 1998), and also in the morphological distribution of cluster members (Dressler et al., 1997, Couch et al., 1998).
Figure 4. A comparison of the CMR in clusters at $z = 0.45$ and $z = 0.24$. This data should also be compared with the CMR of the Coma cluster (Figure 3). Note both the increase in the number of galaxies lying blueward of the CMR in the most distant clusters, and the increase in their characteristic magnitude. This is the Butcher-Oemler effect seen in the colour-magnitude plane. The data for $z = 0.24$ clusters is taken from Smail et al., 1998. Data for $z = 0.45$ clusters is from the Morphs collaboration (Dressler et al., 1998). The large scatter about the CMR is due to the accuracy of the ground-based photometry (cf., Ellis et al., 1997).
The strength of the Butcher-Oemler effect is well illustrated by Figure 4. This compares the CMR in intermediate redshift clusters (from the Morphs collaboration, Smail et al., 1997, Dressler et al., 1998) with the CMR for galaxies in rich X-ray selected clusters at redshift $z = 0.24$ (Smail et al., 1998). In both cases, colours and magnitudes have been transformed to the same rest frame system. The high redshift data shows only galaxies whose cluster membership has been confirmed by spectroscopy, while the lower redshift data has been field corrected on a statistical basis. The figures should also be compared to the Coma cluster as a local calibrator. In each case, the CMR ridgeline is well defined (the larger scatter in the highest redshift data results from the ground based photometry that has been used to compile the diagram).

The striking difference between the diagrams is the increase in both the fraction and absolute magnitudes of blue galaxies in the $z \sim 0.4$ dataset. This is the Butcher-Oemler effect, but it seems that the effect is both in the fraction of objects, and in their luminosity. This maybe related to the phenomenon of ‘down-sizing’ (ie., the active population of objects moving to lower intrinsic luminosities at lower redshifts) that has been observed in field galaxy samples over this redshift range (eg., Cowie et al., 1997, Guzman et al., 1997). It is important to emphasise that this is not simply a result of the density–morphology relation (Dressler, 1980), and that the blue galaxies are found in the cluster cores. It is worth a note of caution, however, that the blue galaxies may be seen in the cluster core only due to projection effects (eg., Morris et al., 1998): this has still to be factored into the analysis.

5. Local and Intermediate Redshift Studies in Conflict

While local clusters present a picture of uniformity and regularity in star formation history, the distant clusters show evidence of considerable activity. How can these two sides be compatible? The galaxies seen in the distant clusters cannot escape them, and (in a statistical sense) their descendents are found among the galaxies of present-day clusters that appear so uniform.

The solution to this apparent paradox lies in the freedom to vary the last epoch of star formation so long as the bulk of the stellar population remains old. In Bower, Kodama & Terlevich, 1998 (BKT), we explored the feasibility of this approach, using the truncated star formation models discussed in §2 as our starting point. Taking a random distribution of truncation epochs (spread over look back times ranging from 0-13 Gyr), produces an $\sim 50\%$ fraction of actively star forming galaxies at $z = 0.5$. This is more extreme than the canonical Butcher-Oemler effect, so we considered a variant model in which the cluster was composed of a 50/50 mix of galaxies with an extended star formation history and galaxies that are intrinsically old, forming all of their stars above a look back time of 10 Gyr. This produces a good match to the observed Butcher-Oemler effect. We included a 10% burst of star formation at the moment of truncation in order to reproduce the spectral features of E+A galaxies.

It is of course questionable whether the random truncation model is reasonable. In order to produce a more physical motivated model, we used the extended Press Schechter theory to generated that infall history of a typical cluster. The mathematical background to this model is discussed in Bower, 1991. The re-
resulting curve depends on the mass scale at which it is assumed that cluster processes truncate star formation in the accreted galaxies. We chose the mass scale of a large group for this calculation, although the results are not sensitive to this assumption. Again, if this infall model is used on its own, it tends to over produce the Butcher-Oemler blue fraction at $z = 0.5$, so a variant mixing truncated and intrinsically old star formation histories was also considered.

These models are normalised to match the observed Butcher-Oemler blue fractions at $z = 0.5$. We continued the star formation history forward in time in order to compare with the CMR cross-section at low redshift. The scatters we determined from this high idealised model are shown in Table 1, and should be compared with the scatter of $\sim 0.05$ mag that we measured in the Coma cluster. Neither of the pure truncation models is able to reproduce a sufficiently narrow observational relation, although the match to the PS model is better. However, the models that mix the infalling population with the intrinsically old component are successful. In these cases, the reddening of the Butcher-Oemler galaxies is sufficiently rapid that a well confined present day CMR is recovered. There is not much room for additional sources of scatter, however.

Table 1. Bi-weight scatter in simulated present-day colour distributions for a range of star formation histories compatible with observations of the Butcher-Oemler effect. Model 1 assumes that all cluster galaxies undergo truncation of their star formation at a random time between $t = 0$ and 13 Gyr. Model 2 mixes a 50% population of these galaxies with a 50% population of galaxies that cease star formation between 10 and 13 Gyr. Models 3 and 4 are similar except similar to Model 1, except that the distribution of truncation times is taken from the infall rate given by Bower (1991).

| Model | $\tau = 5$ Gyr | $\tau = 10$ Gyr |
|-------|----------------|-----------------|
| (1)   | 0.122 ± 0.018  | 0.136 ± 0.021   |
| (2)   | 0.052 ± 0.009  | 0.054 ± 0.010   |
| (3)   | 0.075 ± 0.010  | 0.085 ± 0.012   |
| (4)   | 0.052 ± 0.009  | 0.059 ± 0.010   |

Nevertheless, whilst the simple model that we have presented is encouraging it is not satisfactory. Two competing processes have not been modelled in adequate detail. Firstly, the galaxies that are counted in the Butcher-Oemler blue fraction are only those galaxies located in the core of the cluster (within the radius containing 30% of the total galaxy population). Our model assumes that the cluster is static, and does not allow for galaxies that are in the outer parts of the cluster at intermediate redshift becoming incorporated into the cluster center at the present day. One way to deal with this might be to consider galaxies out to a larger radius in the distant clusters, compared to the local systems. Allowing for this effect would tend to make it considerably harder to reconcile the local and intermediate redshift colour-magnitude diagrams. Carefully modeling through
N-body simulations is required to adequately calibrate this effect, however. For example, Morris et al. (1998), argue that the Butcher-Oemler galaxies in the cluster MS1621.5+2640 are located on the periphery of the cluster in velocity space.

Secondly, the model is inaccurate because it takes no account of the fading of galaxies after the truncation of their star formation. This will tend to remove the fading galaxies from a magnitude limited sample, helping to make the intermediate and low redshift data more compatible. For galaxies with simple truncated star formation the effect is expected to be $\sim 1$ mag if they are selected in blue light. The mismatch could be minimised by selecting at near-infrared wavelengths, however.

6. The CMR as a Constraint on Growth through Mergers

In addition to setting a limit on the star formation histories of galaxies, the CMR can also be used to set a limit on the number of mergers that a galaxy might have undergone after the formation of its stars. The limit results from the fact that mergers between randomly selected galaxies tend to average the galaxy colours, reducing the slope of any CMR that is initially present. The scatter also increases since galaxies undergo different numbers of mergers. Thus, using the observed ratio of the CMR scatter to slope, we can estimate the number of sub-units that may have been combined to form a present-day massive elliptical galaxy. It is important to realise, however, that this argument cannot set a limit on the number of gas-rich components that may have been combined, and subsequently formed new stars.

The basic procedure we use is to assign galaxies to an initially scatter-free CMR. The actual slope of the relation is not important. Galaxies are then selected to be merged together. In BKT, we investigated two models: one in which galaxies were selected at random, and another in which the galaxies were selected according to a hierarchical merging tree - as used in HGF simulations (e.g., Baugh et al., 1998). In the random case, just a few mergers are enough to erase the memory of the initial CMR and to result in a relation that is incompatible with the observed one. The effects in the hierarchical merging case are more subtle, however, with galaxies of equal mass being more likely to merge together at large look-back times, and unequal mass mergers dominating at later times.

In terms of a time sequence the growth of the scatter:slope ratio ($R$) is very different for the two cases. However, the results are similar if $R$ is plotted as a function of the factor by which the mass of a typical galaxy has grown. This is illustrated in Figure 5, and compared to the observed ratio (taking into account the aperture in which the CMR colours have been measured). In both cases, we obtain similar limits: the observational ratio requires that the mass of these galaxies cannot have grown by more than a factor of 2–3 after the formation of the bulk of the stellar population. This is quite a stringent limit, even though it assumes that the whole of the scatter is contributed by the merger process, and makes no allowance for the scatter resulting from differences in stellar populations.
Figure 5. The growth of scatter in the CMR as a function of the factor by which the mass of an average galaxy has grown. The parameter $R$ is the ratio of the scatter to slope in the resulting colour-magnitude relation.

7. The Evolution of Field Galaxies

As I have outlined in the previous sections, the existence of the CMR in clusters of galaxies has allowed us to learn a great deal about the evolution of galaxies in dense environments. It is of course tempting to apply the same techniques to Elliptical and S0 galaxies in lower density environments: by sampling only galaxies in clusters, we have only looked at the formation histories of a small fraction of the early-type galaxy population.

However, caution is needed. Within cluster cores, most galaxies have early-type morphology, and, at low-redshift, we obtain very similar results regardless of whether a morphological filter is applied or not. Indeed, we have argued that it is preferable to disregard morphology completely if we are to use observations of intermediate redshift clusters to reconstruct the full picture of star formation. In the field, our results will obviously be sensitive to the criterion by which the galaxies are selected. Early-type galaxies from only a small fraction ($< 20\%$) of the field galaxy population. Therefore by selecting galaxies of one particular morphological type, we have strongly influenced or results and need to be very careful about how we are biasing our answers through this selection process.

A first stopping point, could be the CMR in Hickson Compact Groups. A composite of many different groups is shown in Figure 6 from Zepf et al., 1991. In these systems, we might have expected to find considerably less uniformity than in the rich clusters because the short dynamical timescale in these systems makes them a ripe environment for morphological transformations. Yet, the CMR is remarkably similar to that seen in the Coma cluster. Possibly it is slightly shallower, (however the colours are total rather than aperture values) but the overall appearance is similar and the scatter is relatively small, especially allowing for the difficulty in achieving homogeneous photometry across a wide
The CMR of early-type galaxies in Hickson Compact groups. The figure has been made by combining the data for many separate groups from Zepf et al., 1991. The CMR is similarly well defined as in rich clusters. Although there is a suggestion that the relation maybe shallower and have large scatter, the differing observational approaches need to be carefully allowed for.

Data on the CMR of genuine field galaxies is remarkably scant. Most redshift surveys reach magnitudes at which morphological classification becomes unreliable, and it is extremely difficult to accurately tie together the calibration of data-sets covering small numbers of galaxies. One of the most comprehensive studies remains that of Larson, Tinsley & Caldwell (1980). Their data suggested that the CMR for elliptical galaxies showed considerably larger scatter in the field, indicating a wide diversity of star formation histories. Surprisingly, however, the CMR for S0 galaxies did not show the same variation. And independent confirmation of their result is clearly needed.

Perversely the best field data may come from substantially higher redshifts. The Hubble deep field provides an opportunity to study a sample of tens of early-type galaxies with deep, well-calibrated uniform photometry. Franceschini et al., 1998, have used this data-set to study the evolution of early-type galaxies. However, the red sequence is also very well defined. Only a small subset of the early-type galaxies have confirmed spectroscopic redshifts (Cohen et al. 1996), however, photometric redshifts should be reliable for these systems since they poses a well defined 4000Å break (Kodama, Bell & Bower, 1998). Figure 7 shows the CMR reconstructed in this way. Many of the blue ellipticals show morphological peculiarities suggestive of recent interactions. By contrast, the majority of the galaxies have red colours adhering quite closely to the CMR
Figure 7. The CMR of early-type galaxies in the Hubble Deep Field (Kodama, Bower & Bell, in prep). The galaxies have been corrected both to the rest frame filter, and have been corrected for the passive evolution between the true redshift and the median redshift of the sample ($\bar{z} = 0.9$). The dashed line illustrates the position of the coma cluster CMR at $z = 0.9$ corrected for passive evolution.

defined by the Coma cluster. The scatter in the relation is quite large, our best estimate indicates 0.11 mag after allowing for the uncertainties in the K-corrections; however, the galaxy sample has a median redshift of $z = 0.9$, and the formation redshift for the stars in many of these systems seems to lie above $z = 2$. Although, the effects of the morphological filter need to be carefully incorporated, it is likely that this data will be a significant hurdle for the formation of early-type galaxies through a continuous transformation of morphology. On the other hand, the evolution of K-band number counts (e.g., Bershady et al., 1998) and the space density of early-type galaxies at $z > 1.5$ (Franceschini et al., 1998) suggest a decline in the numbers of bright early-type galaxies at high redshifts. It is not clear how these results will be reconciled, but dust obscuration and galaxy merging may be crucial factors.

8. Conclusions

What have we learned from this brief tour? This list attempts to provide a brief summary.

- The stellar populations of galaxies in local clusters are predominantly old. However, this does not preclude some of the stars in some of the systems having being formed at relatively recent epochs.

- Distant clusters show passive evolution of the red sequence. But this is not the complete picture. There is a strongly evolving population of actively star forming galaxies.
• The star forming galaxies in distant clusters must be included in the progenitors of the red homogeneous population seen in local clusters. A simple model for infall into the clusters appears to balance these opposing constraints, but is over simplified. A more complete model is needed that takes into account the radial distribution of the galaxies and their fading from magnitude limited samples.

• CMR also places a limit on merging of galaxies. Luminous early-type galaxies in clusters cannot, on average, have grown by a factor of more than 2-3 in mass after the formation of the bulk of their stars.

• We finally considered the CMR for galaxies in the field. Modern data is surprisingly sparse, and our best results have come from the Hubble Deep Field using galaxies with a median redshift of $z = 0.9$. Even at this redshift, in low density environments, the CMR is well defined and has quite small scatter.

At the beginning of this talk I deliberately polarised the discussion of early-type galaxy formation scenarios into two view points: the Classical model and the Hierarchical model. Can we now choose between the two? Initially, the small scatter of the cluster CMR seems to favour the Classical model. However, the situation is not quite this simple since clusters of galaxies — especially the rich ones that have been the primary targets to date — are special places in the universe in which galaxy formation is advanced with respect to the background cosmos. For example, Lyman break galaxies at $z \sim 3 - 4$ are strongly clustered and seem to be destined to become the core population of today’s clusters (Governato et al., 1998). In these regions the two models are not as different as the seem at first sight — indeed Kauffmann & Charlot (1998) showed that the narrow CMR could be reproduced in the HGF model. The key difference between the models lies in the prevalence of old stellar populations, and in the way in which morphology is tied to stellar age. The best tests will come from galaxies in field regions and lower density clusters, and from galaxies in clusters at high ($z \gtrsim 1$) redshifts. In these regions the differences should become more pronounced as the biasing effect of the selected structure becomes weakened. Nevertheless, detailed predictions are required for both models in order that our resources can be efficiently targeted.

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References

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Discussion

Carlton Baugh: The Classical and Hierarchical models may predict similar properties for cluster ellipticals today. However, at high redshift the hierarchical model would predict these galaxies to be in small fragments, while in the classical picture they should have similar size. Can this be used to distinguish the models?

Richard Bower: Yes - that’s an important consideration, and there does seem to be some evidence to support the hierarchical viewpoint from the redshift distribution of red galaxies and from the evolution of the K-band number counts (eg., Bershady et al., 1998, Kauffmann & Charlot, 1998, MNRAS, 297, 23). These studies suggest that there are too few brighter red galaxies at $z > 1.5$. The interpretation of this result is more complex however: is it due to the red galaxies becoming fragmented, or due to them becoming bluer because of star formation, or fainter because of dust reddening. It’s a very powerful way to explore early-type galaxy evolution.

Mike Pahre: In the work of Rakos & Schombert (1995, ApJ, 439, 47), they measured the blue galaxy fractions in clusters out to $z = 1$. Have you looked at whether the blue fractions at these high redshifts can be reproduced?

Richard Bower: Rakos & Schombert find that the blue galaxy fractions go on increasing beyond intermediate redshifts. This is qualitatively consistent with what you’d expect for infall: at $z = 1$, there is very little time to put the cluster together before the epoch at which it is observed, so the infall rate has to be very high. We ran into several problems trying to make an accurate quantitative comparison though, its hard to make sense of the non-standard filter systems especially. It’s also true even the most distant clusters can have low blue fractions (eg., Stanford et al., 1997).