The Observed Properties of High-Redshift Cluster Galaxies

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Abstract

We use the semi-analytic models of galaxy formation developed by Kauffmann, White & Guiderdoni (1993) to generate predictions for the observed properties of galaxies in clusters and groups at redshifts between 0 and 0.6. We examine four different sets of cosmological initial conditions: a low-density cold dark matter model with and without cosmological constant, a flat cold dark matter model and a mixed dark matter model. These models were selected because they span a wide range in cluster formation epoch. The semi-analytic models that we employ are able to follow both the evolution of the dark matter component of clusters and the formation and evolution of the stellar populations of the cluster galaxies. We are thus able to generate model predictions that can be compared directly with the observational data. In the low-density CDM models, clusters form at high redshift and accrete very little mass at recent times. Our models predict that essentially no evolution in the observed properties of clusters will have occurred by a redshift of 0.6, in direct contradiction with the data. In contrast, in the MDM model, both galaxies and clusters form extremely late. This model predicts evolution which appears to be too extreme to be in agreement with the observations. The flat CDM model, which is intermediate in structure formation epoch, is most successful. This model is able to account for the evolution of the blue fraction of rich clusters with redshift, the relationship between blue fraction and cluster richness at different epochs, and the changes in the distribution of the morphologies of cluster galaxies by a redshift of 0.4. In this model, galaxies have assembled most of their mass by a redshift of 1, but rich clusters seen today are still undergoing considerable merging activity at redshifts as low as 0.2.

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1 Introduction

Clusters of galaxies have long been regarded as useful laboratories for studying galaxy formation. Each cluster provides a sizeable sample of galaxies that are all at the same redshift. In addition, the observed properties of clusters at different redshifts tells us how galaxy properties such as morphology, luminosity, colour and metallicity evolve with time. However, it must also be noted that clusters are rare objects in the universe and it is likely that physical processes such as mergers, gas stripping or starbursts have played a rather different role in the formation of cluster galaxies than in their field counterparts. A realistic theoretical model of galaxy formation in clusters must be able to follow the assembly of the cluster over time, and it must also be able to couple the the star formation rate in each cluster galaxy with its interactions with its neighbours and its environment.

Perhaps the most striking property of high-redshift clusters is the so-called Butcher-Oemler effect – the observation that these clusters contain a much higher fraction of blue, star-forming galaxies than do clusters seen today. Recent high-resolution imaging of blue cluster galaxies, both from the ground (Lavery & Henry 1988, 1992) and using the Hubble Space Telescope (Couch et al 1994, Dressler et al 1994), has begun to provide clues as to what may be causing this enhanced level of star formation. So far the conclusion seems to be that although the number of interacting systems does show a substantial increase over that observed in present-day clusters, the majority of the blue galaxies appear to be ordinary star-forming spirals. Future extension of the HST program to a larger sample of clusters and spectroscopic follow-up work to determine which galaxies are true cluster members will improve the statistical confidence of these results. The hope is that eventually the combination of multi-colour photometry, spectroscopy and morphological classification of a large sample of cluster galaxies at a variety of redshifts, will yield a detailed picture of the physical processes responsible for the observed star formation.

In addition to understanding the processes that govern star formation, the observed evolution of clusters with redshift can put important constraints on theories of galaxy and structure formation. Paper I in this series (Kauffmann 1994) presented a simple explanation for why it is quite natural in hierarchical clustering theories to expect that high redshift clusters should appear more “active” than clusters of similar size today. It was shown that the dark matter component of a high redshift cluster evolves much more rapidly and undergoes more merging just prior to the epoch at which it is observed. Simple star formation models were introduced to illustrate how this increased merging activity in the dark matter component might fuel more star formation in the galaxies themselves. The conclusion of Paper I was that it was easy to find plausible explanations for many of the qualitative trends seen in the high redshift cluster data.

In this follow-up paper, we present more detailed modelling designed to yield quantitative predictions for cluster galaxy evolution in a variety of different cosmological models. To do this, we now follow not only the merging history of the dark matter component of the cluster, as in Paper I, but also the detailed evolution of the gaseous and stellar components of each dark matter halo in the merging “tree”. Many of the details of this modelling have already been described in detail in a paper by Kauffmann, White & Guiderdoni (1993, hereafter KWG) where the properties of groups and clusters at $z = 0$ were studied. In this paper, we
present results for systems at high redshift in a form that can be compared directly with the
data.

2 Review of the Galaxy Formation Model

In this section we present only a brief summary of the physical processes governing galaxy
and star formation in our model. The reader is referred to KWG for more detailed discussion.

1. Gas Cooling
   Dark matter halos are modelled as truncated, isothermal spheres. We assume that
   the gas relaxes to a distribution that exactly parallels that of the dark matter. The
   gas temperature can then be derived from the circular velocity of the halo using the
   equation of hydrostatic equilibrium. At each timestep in our calculation, we define the
   cooling radius of a halo as the radius at which the cooling time of the gas is equal to the
   age of the universe. If the cooling radius lies outside the virial radius of the halo, the
   instantaneous cooling rate is governed by the rate at which the mass of the halo grows
   as a result of the infall of surrounding matter. Otherwise, the cooling rate is calculated
   from the time evolution of the cooling radius.

2. Star Formation and Feedback
   Once gas cools, it will fall towards the centre of the halo, forming a dense core where
   stars will be able to form. The star formation law that we choose is given by the simple
   equation
   \[ M_\star = \alpha M_{\text{cold}}/t_{\text{dyn}}, \]
   where \( M_{\text{gas}} \) is the total mass of cold gas in the galaxy, \( t_{\text{dyn}} \)
   is the dynamical timescale of the galaxy and \( \alpha \) is an adjustable parameter.
   Stars form with the standard stellar initial mass function given by Scalo (1986). The
   number of supernovae that are expected per solar mass of stars formed is \( 4 \times 10^{-3}M_\odot \).
   The kinetic energy of the ejecta from each supernova is about \( 10^{51} \) erg. We assume that
   a fraction \( \epsilon \) of this energy goes to reheat cold gas to the virial temperature of the halo,
   where \( \epsilon \) is taken to be a free parameter.

3. Merging of Galaxies
   The timescale over which the cores of halos merge once their surrounding halos have col-
   lided is modelled using the dynamical friction timescale as given by Binney & Tremaine
   (1987):
   \[ t_{\text{df}} = \frac{1.17 V_c r_c^2}{\ln \Lambda M_{\text{sat}}}, \]  
   where \( V_c \) is the circular velocity of the “primary” halo, \( r_c \) is the virial radius of the halo,
   \( M_{\text{sat}} \) is the mass of the orbiting satellite and \( \ln \Lambda \) is the usual Coulomb logarithm.
   In order to use equation (1) in our models, we need to specify a satellite mass. The
   appropriate choice of satellite mass is ambiguous. Initially, most of the mass of the
   satellite resides in its own dark halo, but as the satellite’s orbit is eroded, a large fraction
   of the dark mass may be stripped away. In addition, angular momentum losses may
   shorten the dynamical friction timescale. Recent SPH/N-body experiments studying
the assembly of galaxies in a hierarchically clustering universe (Navarro, Frenk & White 1994) have shown that equation (1) provides a good estimate of the merger timescale of gaseous cores, provided that $M_{\text{sat}}$ is set equal to the total mass of the satellite, i.e. the mass of the baryonic + dark matter component. In our models, we will simply take $M_{\text{sat}} = M_{\text{baryonic}}/\Omega_b$, where $\Omega_b$ is the fraction of the universe in baryons.

4. Formation of Elliptical Galaxies and Spiral Bulges
As in KWG, we assume that an elliptical galaxy is formed as the result of a merger between two galaxies, when the ratio of the masses of the galaxies $M_{\text{sat}}/M_{\text{central}}$ exceeds some value $f_{\text{ellip}}$, which we keep as a free parameter. A spiral galaxy consisting of both a disk and bulge component forms when gas cools onto an elliptical merger remnant. KWG discussed the possibility that a merging between galaxies would result in a burst of star formation, but they did not include this in their models. In this paper, we assume that when an elliptical galaxy forms, all cold gas present in it is instantaneously transformed into stars.

5. Evolution of the Stellar Populations in Galaxies
We have used the spectrophotometric models of Bruzual & Charlot (1993) to translate the predictions of our models into observed quantities such as magnitude and colour, which may be compared directly with the observational data.

To summarize:
As in paper I, we use the algorithm of Kauffmann & White (1993) to generate Monte Carlo realizations of the merging paths of dark matter halos from high redshift until the present. At a given redshift, inside a given halo, gas cools and condenses onto a central galaxy at the core of the halo. Star formation and feedback processes take place as described above. At a subsequent redshift, the halo will have merged with a number of others, forming a new halo of larger mass. All gas which has not already cooled is assumed to be shock heated to the virial temperature of the new halo. This hot gas then cools onto the central galaxy of the new halo, which is identified with the central galaxy of its largest progenitor. The central galaxies of the other progenitors become satellite galaxies, which are able to merge with the central galaxy on a dynamical friction timescale. If a merger takes place between two galaxies of roughly comparable mass, the merger remnant is labelled as an “elliptical” and all cold gas is transformed into stars in a “starburst”. Note that the infall of new gas onto satellite galaxies is not allowed, and star formation will continue in such objects only until their existing cold gas reservoirs are exhausted. Thus the epoch at which a galaxy is accreted by a larger halo delineates the transition between active star formation in the galaxy and passive evolution of its stellar population.

In Paper I, we investigated two very schematic models for star formation in cluster galaxies: 1) a model in which star formation only occurred in dark matter halos with circular velocity comparable to those of galaxies. Once these halos grew to the size of groups or clusters, all star formation was assumed to stop. 2) a model in which star formation was induced by mergers taking place between galaxy-sized halos of roughly equal mass. The model described above contains elements of both these toy models, but now also treats star formation and galaxy merging in a physically realistic and self-consistent way.
It should be noted that our models contain a number of free parameters that control the efficiency of star formation and supernova feedback and also the transformation of disk galaxies into ellipticals by merging. We fix these parameters by requiring that, on average, the central galaxy of a dark matter halo with circular velocity $V_c = 220 \text{ km s}^{-1}$ have a luminosity, cold gas mass and morphology similar to that of our own Milky Way galaxy. We set $\alpha$ and $\epsilon$ to obtain a B-band luminosity of around $2 \times 10^{10} L_\odot$ and a total (HI + molecular) gas mass of $8 \times 10^9 M_\odot$. $f_{\text{ellip}}$ is set so that the ratio of the disk to the bulge luminosity in the B band is $\simeq 5$, as is appropriate for a Hubble type Sb-Sc (see Simien & de Vaucouleurs 1986). Note that the values of these parameters will depend on our choice of cosmology and must be reset every time we investigate a new model. In practice, $\alpha$ takes on values in the range 0.05-0.2 and $\epsilon$ in the range 0.1-0.5. $f_{\text{ellip}}$ is typically around 0.2-0.3.

3 Results

3.1 Evolution of the Blue Fraction in Clusters and Groups

One traditional way of searching for evolution in the stellar populations of cluster galaxies is to measure changes in the rest-frame colours of the galaxies relative to those of early-type galaxies at the same epoch. Butcher & Oemler (1984) analyzed photometry of 33 rich clusters of galaxies with redshifts between 0.003 and 0.54. In each cluster they selected galaxies brighter than an absolute V magnitude of -20 and within a circular area containing the inner 30 percent of the total cluster population. The blue fraction $f_B$ was defined as the fraction of galaxies whose rest-frame B-V colours were at least 0.2 mag bluer than a typical early-type galaxy of the same magnitude. The blue fraction was found to increase strongly with redshift, from an average value of around 0.04 at $z < 0.1$, to a value of 0.2-0.3 at $z=0.5$. This analysis was extended to poorer systems by Allington-Smith et al (1993), who used luminous radio-galaxies as galaxy group tracers. For the poor groups, there was no observed evolution of $f_B$ with redshift. Indeed, it was found that by a redshift of 0.4, groups of all richnesses have similar fractions of blue galaxies, in contrast to the situation at $z=0$ where richer groups contain fewer blue galaxies.

In this section, we present model predictions for the evolution of $f_B$ in groups and clusters as a function of redshift. We have chosen to investigate four sets of cosmological initial conditions:

1. A low-density ($\Omega = 0.2$) open-universe cold dark matter (CDM) model.

2. A low-density ($\Omega = 0.2$) spatially flat cold dark matter model with cosmological constant $\Lambda = 0.8$.

3. A flat CDM model with $b=1.5$. This normalization is inconsistent with the amplitude of microwave background fluctuations determined by COBE, but produces roughly the correct abundance of rich clusters in the universe (White, Efstathiou & Frenk 1993).

4. A mixed dark matter model with $\Omega = 1$ and a neutrino fraction $\Omega_\nu = 0.3$. This model is normalized to COBE.
In all three models we take \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) and a baryon fraction of 0.1. The parameters that control star formation, feedback and merging are fixed as described in section 2. It should be noted that the epoch of group and cluster formation moves closer and closer to the present day as we go from model 1 to model 4 in the list above. In the open model, the growth of perturbations has slowed considerably by the present epoch and clusters accrete very little mass at low redshift. In the MDM model, perturbations on small scales are erased below the neutrino Jeans length and as a result, galaxies only form in abundance at redshifts less than 1.

In our analysis, we define the richness \( N(-19) \) to be the total number of cluster or group members with absolute V magnitude less than -19. Our models do not provide any information about the spatial distribution of galaxies within clusters, so we cannot distinguish a population of galaxies residing in the cluster core from a population that has just recently been accreted. If the redder galaxies are preferentially situated in the cluster core, as is indicated by the observations (Thompson 1986, Couch & Sharples 1987), the values of \( f_b \) we quote may need to be scaled down somewhat to be directly comparable to the observations, which tend to concentrate on the central regions of rich clusters. Following Butcher & Oemler (1984), we have defined the blue fraction \( f_B \) to be the fraction of galaxies with B-V colours at least 0.2 mag bluer than the colour of the average elliptical galaxy at the given redshift. We note that in our model, elliptical galaxies do not exhibit a colour-magnitude relation; elliptical galaxies of all luminosities have very similar stellar populations. It is likely that the observed colour-magnitude relation is due to a higher degree of metal enrichment in luminous ellipticals (Faber 1977), something which we have neglected in our models.

In figure 1, we show the redshift evolution of \( f_B \) in a rich cluster for the four models described above. Each point in the scatterplot represents one Monte-Carlo realization of the formation history of a cluster of \( 10^{15} M_\odot \). Results were calculated for clusters viewed at redshifts 0, 0.2, 0.4 and 0.6. We have introduced some artificial scatter in the redshift in the plots in order to display our results more clearly. We compare these results to the observational data as given in figure 3 of the paper by Butcher & Oemler (1984). As can be seen, there is essentially no evolution in \( f_B \) for the two low-density models. The increase in blue fraction for the flat CDM model matches the observations rather well, but for the MDM model, the slope obtained is too steep.

One may well ask whether our results are sensitive to the way we have normalized our model. Indeed, we find that the zero-point of the \( f_B \)-redshift relation is very sensitive to our choice of the parameters \( \alpha \) and \( \epsilon \), which control how fast a galaxy uses up its cold gas once it has been accreted by a larger system, and hence also the timescale over which its stellar population reddens. We would thus obtain different zero points by choosing lower or higher values of \( \Omega_b \) in our models and re-adjusting \( \alpha \) and \( \epsilon \) to obtain the correct “Milky Way” normalization. Decreasing \( \Omega_b \) means that less gas is able to cool in the halos. As a result, our normalization requires smaller values of \( \alpha \) and \( \epsilon \) and the blue fraction will then increase because star formation is less efficient. It should be noted, however, that the slope of the \( f_B \)-redshift relation is a robust measure of cluster evolution in our models. This is illustrated in figure 2, where we show how the \( f_B \)-redshift relation changes in three of the models for different values of \( \Omega_b \). In the two CDM models, we lower \( \Omega_b \) to 0.05 and obtain much higher blue fractions. In the MDM model, we increase \( \Omega_b \) to 0.15 and obtain a smaller blue fraction.
However, the slope does not change in each case.

We thus come to the conclusion that the slope of the \( f_B \)-redshift relation is determined by how fast the dark matter component of a rich clusters evolves at a given redshift and not by the detailed modelling of the gas physics and star formation. Stated in another way, the same gasdynamical processes must operate in the same type of environment, regardless of the redshift. The differences between clusters of the same mass that we see at different redshifts must reflect differences in the evolutionary history of the cluster environment. We cannot explain the rapid changes in cluster properties at redshifts as low as 0.4 in the two low-density CDM models, simply because clusters at \( z=0 \) and \( z=0.4 \) have had much the same history in this model. The MDM model predicts evolution that would appear to be too rapid to match the observations. Of the three models we have studied, the flat CDM model clearly provides the best fit to the data.

In figure 3, we plot \( f_B \) as a function of group or cluster richness, defined by the number of member galaxies brighter than \( M_V = -19 \). This scatterplot was produced by running 200 Monte Carlo realizations of the formation of dark matter halos with masses ranging from \( 10^{13} \) to \( 10^{15} M_\odot \). Figure 3 shows results for groups and clusters at \( z=0 \). The results are compared to the best-fit curve taken from figure 19 of Allington-Smith et al (1993). This curve was fit to the blue fractions measured in radio groups, CfA groups and rich clusters. The open and flat CDM models show a strong decrease in \( f_B \) with richness, but the MDM model displays no such trend. This may be understood as follows. In poor groups, galaxies brighter than \( M_V = -19 \) are almost always central galaxies, or galaxies that have been accreted very recently by the group and are thus still actively forming stars. In clusters, however, there are many bright galaxies that were accreted long enough ago so that they have run out of gas and reddened in colour. MDM clusters are still very blue because they were assembled at such low redshift. As is the case with the \( f_B \)-redshift relation, the zero point of the \( f_B \)-richness relation may be adjusted by playing with the model parameters, but the overall trend in the blue fraction with richness remains fixed. One way that we could alter the \( f_B \)-richness relation is to invoke ram-pressure stripping of the galactic interstellar medium by the hot gas in the intracluster medium. This process is likely to be considerably more effective in rich clusters than in poorer environments and would certainly push the \( f_B \)-richness relation for the MDM model in the right direction.

It is known that the observational \( f_B \)-richness relation is a reflection of the relationship between the colour and the morphology of a galaxy, and between morphology and environment, with richer environments containing a lower proportion of blue star-forming spiral galaxies. In figure 4 we plot the spiral fraction versus richness for a flat CDM model. As can be seen, the same relationships between colour, morphology and environment occur in the models as in the data.

The most striking result in the Allington-Smith et al (1993) paper is the evolution that has occurred in the \( f_B \)-richness relation by a redshift of 0.4. The high redshift \( f_B \)-richness relation is essentially flat. This means that groups and clusters have evolved in a differential fashion, with clusters evolving much more strongly than poor groups. In Paper I, we predicted that the Butcher-Oemler effect would be more pronounced for rich clusters than for galaxy groups, simply because rich clusters are further out on the high-mass tail of the distribution of collapsed objects in the universe today. In figure 5, we show the detailed model predictions at
z=0.4. There has been essentially no evolution in the $f_B$-richness relation in the low-density models, as could be expected. The results for the flat CDM case agree well with figure 19 of Allington-Smith at al. Both groups and clusters have blue fractions of around 0.3 at z=0.4. The $f_B$-richness relation is also flat for the MDM model, but the blue fractions in this model are much too high to be in agreement with observations.

In summary, we have demonstrated that we can account for the difference in the evolutionary behaviour of galaxy systems of different richnesses. The flat CDM model again produces the best fit to the observations.

### 3.2 Colour-Magnitude-Morphology Diagrams

There has been a long-standing debate among distant cluster observers as to what is causing the enhanced star formation rates in high redshift cluster galaxies. Dressler & Gunn (1982,1983) proposed that infalling gas-rich spiral galaxies were producing most of the observed star formation. Star formation in these galaxies would then be truncated as the interstellar medium was swept away. On the other hand, Lavery and coworkers (Lavery & Henry 1988; Lavery, Pierce & McClure 1992) have presented evidence for galaxy interactions and mergers being the primary cause, based on high resolution CCD imaging of the the distant blue populations conducted from the ground. It is clear that morphological information will be the key to understanding the physical mechanisms driving star formation in cluster galaxies. Morphological classification using images made by the Hubble Space Telescope (HST) has now been published for galaxies in 3 clusters at $z \approx 0.4$ (Couch et al 1994; Dressler et al 1994). Dressler et al present their data in the form of a colour-magnitude diagram of the cluster sample, with the morphological type of the galaxy indicated by a representative symbol. Spectroscopic confirmation of cluster membership has not yet been obtained for most of the galaxies, but the indication is that although the number of interacting systems has increased substantially from what is typical of present-day clusters, most of the blue cluster galaxies are star-forming spiral systems.

As described in section 2, star formation in our models is regulated both by galaxy infall and by mergers. We do not have a detailed model for the interaction of an infalling galaxy with the hot gas of the intracluster medium. We simply assume that the star formation rate in the galaxy will decline over some timescale as it uses up its own internal reservoir of cold gas. Obviously processes such as ram-pressure stripping may accelerate this decline in the star formation rate. A merger between two galaxies of similar mass results in the transformation of all the cold gas into stars in an instantaneous “burst” and the production of an elliptical merger remnant.

In figures 6-8 we present colour-morphology-magnitude diagrams for three of the cosmological models listed in section 3.1. The diagram for the model with cosmological constant is omitted as it is very similar to that of the open CDM model. We show two representative clusters of $10^{15} M_\odot$ at redshifts 0 and 0.4, and we plot the rest-frame B-V colours of the cluster galaxies against their rest-frame V absolute magnitudes. Elliptical galaxies are plotted as filled circles, S0s as filled squares, and spirals as 3-pronged pinwheels. Large open circles indicate galaxies which have undergone a major merging event ($M_{sat}/M_{central} > 0.25$) in the last gigayear before the cluster is observed.
At z=0, early-type galaxies form a narrow band in B-V colour in the diagram. The average B-V colour of ellipticals is 0.85 in the flat CDM model and 0.92 in the open model. This difference in colour may be attributed both to the fact that structure forms earlier in the open model, and to the greater present-day age of an open universe (16.64 Gyr, as opposed to 13 Gyr for the flat model). Real elliptical galaxies have B-V colours that range from about 0.8 to 1. As mentioned previously, we do not obtain a color-magnitude relation for the ellipticals, probably because we have not included any metal enrichment in the models. The spiral galaxies in our model have a much broader distribution in colour and are significantly bluer than ellipticals or S0s. Their B-V colours range from about 0.5 to 0.8, depending on when they were accreted by the cluster and how much of their cold gas reservoirs have been consumed by star formation. In the the flat and open CDM model, spiral galaxies constitute only about 20-30 % of the total cluster population at z=0. However, in the MDM model, spiral galaxies form 50-80 % of the cluster population. This is not surprising, because we saw in the previous section that \( f_B \) for MDM clusters was much too high to match the observations. At z=0, the number of interacting systems is typically less than 2-3% of the total cluster population in all three models.

In the flat CDM and MDM models, the number of interacting systems increases markedly at z=0.4. In addition, the spiral fraction is also enhanced. Most of the spirals are very blue, actively star-forming systems. Our diagrams show that it is these star-forming spiral galaxies that are primarily responsible for the Butcher-Oemler effect. In the flat CDM model, the spiral fraction is typically about 40-50 % at a redshift of 0.4. In the MDM model, virtually all the galaxies are spirals. In contrast, the open CDM model shows very little evolution in either the number of blue spiral galaxies or interacting systems. The colour-magnitude diagrams at z=0 and z=0.4 are virtually indistinguishable, except for a small shift in the colour of the elliptical population, which may be explained simply by the passive evolution of the stellar populations of these galaxies.

In figure 9, we present colour-morphology-magnitude diagrams for the flat CDM model, this time in the observer’s frame. Following Dressler et al, we plot \( g - r \) colours versus apparent \( r \) magnitude for four clusters of \( 10^{15} \, M_\odot \) viewed at redshift 0.4. The resemblance of these plots to figure 2 of Dressler et al is striking, particularly for the cluster in the lower left-hand panel. The cluster in the lower right-hand panel has a very low spiral-fraction and only one merging system. Its appearance is more typical of clusters at z=0. This illustrates that our models predict considerable scatter in the observed properties of high redshift galaxies. The source of this scatter is simply the variation in the evolutionary history of a cluster of fixed mass at a given redshift, as predicted by the Monte-Carlo algorithm.

4 Discussion and Conclusions

It is important to point out that the models we have explored in this paper were developed originally to explain the properties of groups and clusters at \( z = 0 \) (see KWG for more details). The free parameters in the models are fixed so that the central galaxy of a halo of circular velocity 220 km s\(^{-1}\) has a luminosity, gas mass and morphology that match those of the Milky Way at the present day. It is therefore quite remarkable that the models are also successful at
reproducing so many of the observed trends in the properties of groups and clusters at high redshift. In particular, we have demonstrated that our models can account for the evolution of the blue fraction of rich clusters with redshift, the relationship between blue fraction and richness, both at z=0 and at high redshift, and the changes in the morphologies of cluster galaxies by a redshift of 0.4.

The real key to why rich clusters are more “active” at high redshift lies in the evolutionary behaviour of the dark matter component of these clusters. Rich clusters at high redshift originate further out on the high-sigma tail of density fluctuations in the early universe than do rich clusters today. As shown in Paper I, it follows that high redshift clusters had a much more turbulent merging history just prior to the epoch when they are observed as single, virialized systems of galaxies. If the same gas-dynamical and star formation processes operate in the same type of environment, regardless of redshift, the observed evolution of rich cluster properties should provide a direct measure of how rapidly structure in the universe is evolving on cluster scales.

In this paper, we have presented the predictions of three different sets of cosmological initial conditions. These cosmological models were chosen in order to explore a range of different cluster formation epochs. In the low-density CDM model, the growth of perturbations has slowed considerably by the present epoch. Clusters form at redshifts greater than 1 and accrete very little mass at recent times. Our models predict that essentially no evolution in the observed properties of clusters will have occurred by a redshift of 0.6, in direct contradiction with the data. In contrast, in the MDM model, both galaxies and clusters form extremely late. This model predicts evolution which appears to be too extreme to be in agreement with the observations. The flat CDM model is most successful. In this model, a typical galaxy has assembled the bulk of its mass by a redshift of 1, a group by a redshift of 0.8 and rich clusters do not assemble most of their mass until a redshift of 0.2.
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Figure Captions

**Figure 1:** The evolution of blue fraction with redshift for the four cosmological models described in section 3.1. Each point represents one Monte Carlo realization of the merging history of a cluster of mass $10^{15} M_{\odot}$. The solid line is a fit to the observational data taken from figure 3 of Butcher & Oemler (1984).

**Figure 2:** An illustration of the shift in the $f_B$-redshift relation for different values of $\Omega_b$ in the models. In all three panels, filled circles are for models with $\Omega_b = 0.1$. In the two CDM models, filled triangles are for models with $\Omega_b = 0.05$. In the MDM model, the filled triangles are for a model with $\Omega_b=0.15$.

**Figure 3:** The blue fraction versus richness relation for clusters and groups at $z = 0$. The blue fraction is plotted against $\log N[-19]$, where $N[-19]$ is defined to be the number of galaxies in the group or cluster brighter than $V = -19$. The solid curve is the fit to the observational data as given in figure 19 of Allington-Smith et al (1993).

**Figure 4:** The spiral fraction versus richness relation for a flat CDM model.

**Figure 5:** The blue fraction versus richness relation for clusters and groups at $z = 0.4$. The solid curve is the fit to the observational data at $z = 0$ as given in figure 19 of Allington-Smith et al (1993).

**Figure 6:** Rest-frame B-V versus V colour-morphology-magnitude diagrams for galaxies in clusters of $10^{15} M_{\odot}$ in the open CDM model. The top two panels show two representative clusters at $z = 0.4$ and the bottom panels show two clusters at the present day. Elliptical galaxies are plotted as filled circles, S0s as filled squares and spirals as 3-cornered pinwheels. Large open circles indicate galaxies that have undergone a major merger in the past Gyr.

**Figure 7:** Rest-frame B-V versus V colour-morphology-magnitude diagrams for galaxies in clusters of $10^{15} M_{\odot}$ in the flat CDM model.

**Figure 8:** Rest-frame B-V versus V colour-morphology-magnitude diagrams for galaxies in clusters of $10^{15} M_{\odot}$ in the MDM model.
Figure 9: Observed-frame $g-r$ versus $r$ colour-morphology-magnitude diagrams for four different $10^{15}M_\odot$ clusters seen at $z=0.4$ in the flat CDM model.