The K-band Hubble diagram for the brightest cluster galaxies: a test of hierarchical galaxy formation models.

Alfonso Aragón-Salamanca, Carlton M. Baugh and Guinevere Kauffmann

1 Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England
2 Department of Physics, Science Laboratories, South Road, Durham DH1 3LE, England
3 Max-Plank-Institut für Astrophysik, D-85740 Garching bei München, Germany

Accepted —. Received —; in original form —

ABSTRACT

We analyse the K-band Hubble diagram for a sample of brightest cluster galaxies (BCGs) in the redshift range $0 < z < 1$. In good agreement with earlier studies, we confirm that the scatter in the absolute magnitudes of the galaxies is small (0.3 magnitudes). The BCGs exhibit very little luminosity evolution in this redshift range: if $q_0 = 0.0$ we detect no luminosity evolution; for $q_0 = 0.5$ we measure a small negative evolution (i.e., BCGs were about 0.5 magnitudes fainter at $z = 1$ than today). If the mass in stars of these galaxies had remained constant over this period of time, substantial positive luminosity evolution would be expected: BCGs should have been brighter in the past since their stars were younger. A likely explanation for the observed zero or negative evolution is that the stellar mass of the BCGs has been assembled over time through merging and accretion, as expected in hierarchical models of galaxy formation. The colour evolution of the BCGs is consistent with that of an old stellar population ($z_{\text{form}} > 2$) that is evolving passively. We can thus use evolutionary population synthesis models to estimate the rate of growth in stellar mass for these systems. We find that the stellar mass in a typical BCG has grown by a factor $\simeq 2$ since $z \simeq 1$ if $q_0 = 0.0$ or by factor $\simeq 4$ if $q_0 = 0.5$. These results are in good agreement with the predictions of semi-analytic models of galaxy formation and evolution set in the context of a hierarchical scenario for structure formation. The models predict a scatter in the luminosities of the BCGs that is somewhat larger than the observed one, but that depends on the criterion used to select the model clusters.

Key words: galaxies: clusters — galaxies: formation — galaxies: evolution — galaxies: elliptical and lenticular, cD — infrared: galaxies

1 INTRODUCTION

Brightest cluster galaxies (BCGs) have been extensively studied at optical wavelengths ([Peach 1970, 1972; Gunn & Oke 1975], Sandage, Kristian & Westphal 1976; Kristian, Sandage & Westphal 1978; Lubin 1996; Stanford, Eisenhardt & Dickinson 1997)) implying that the Hubble diagram could be seriously affected by evolutionary changes even at relatively modest redshifts. Conclusions concerning $q_0$ cannot be derived from such diagrams until these changes are well-understood. Indeed, the Hubble diagram for the BCGs may well have more to teach us about galaxy evolution than about cosmology.

The study of the BCGs in the near-infrared K-band (2.2µ) has two main advantages over optical studies: first, the k-corrections are appreciably smaller (indeed, they are negative) and virtually independent of the spectral type of the galaxies (see, e.g., [Aragon-Salamanca et al. 1993]; Rakos & Schombert 1993; [Oke, Gunn & Hoessel 1990]; Lubin 1996; [Stanford, Eisenhardt & Dickinson 1997]) implying that the Hubble diagram could be seriously affected by evolutionary changes even at relatively modest redshifts. Conclusions concerning $q_0$ cannot be derived from such diagrams until these changes are well-understood. Indeed, the Hubble diagram for the BCGs may well have more to teach us about galaxy evolution than about cosmology.

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evolutionary diagnostic for radio galaxies (Grasdalen 1980); (Lebofsky 1980); (Lebofsky & Eisenhardt 1986); (Lilly & Longair 1982, 1984; (Lilly 1989a,b), which also have a relatively small intrinsic dispersion in their luminosities (≈ 0.4 magnitudes for 1 < z < 2; (lilly 1989a)). Substantial positive luminosity evolution was found: radio galaxies were about one magnitude brighter at z ≃ 1 than they are today. Aragón-Salamanca et al. (1993) measured K-band luminosities for a sample of 19 BCGs in the redshift range 0 < z < 1 and found that the K magnitude-redshift relation is tighter (scatter = 0.3 magnitudes) than for radio galaxies. Moreover, these authors did not detect significant K luminosity evolution for the BCGs, and concluded that their evolutionary properties were different from those of radio galaxies: powerful radio galaxies are apparently less homogeneous in their evolutionary behaviour and show stronger luminosity evolution. Aragón-Salamanca et al. also found that the colours of the early-type galaxies (including the BCGs) in these clusters have evolved since z ≃ 1 at a rate consistent with a scenario in which the bulk of their stars formed at relatively high redshifts (z > 2) and evolved passively thereafter. This conclusion has been confirmed by several more recent studies (Takos & Schombert 1993); (Oke, Gunn & Hoessel 1996); (Lubin 1998); (Ellis et al. 1997); (Stanford, Eisenhardt & Dickinson 1997).

The recent development of semi-analytic techniques has provided theorists with the tools to make predictions for the formation and evolution of galaxies, using physically motivated models set in the context of hierarchical structure formation in the universe (e.g., (White & Frenk 1991); (Cole 1994); (Lacey & Silk 1991); (Kauffmann, White & Guiderdoni 1993); (Kauffmann, Guiderdoni & White 1994); (Cole et al. 1994); (Heil et. al. 1999)). The properties of galaxies in these models are in broad agreement with the present day characteristics of galaxies, such as the distribution of luminosities, colours and morphologies and with the properties of galaxies at high redshift, including the faint galaxy counts, colours and redshift distributions (e.g., (Kauffmann 1995); (Kauffmann 1996a); (Kauffmann & Charlot 1997); (Baugh, Cole & Frenk 1996a); (Baugh et. al. 1997)). In this paper, we will test whether the models also predict the right behaviour for a special class of galaxies, namely the BCGs. In the models, these galaxies grow in mass both from the cooling of gas from the surrounding hot halo medium and from the accretion of “satellite” galaxies that fall to the cluster centre as result of dynamical friction and then merge.

In section 2 we present the observational results and derive the luminosity evolution of the BCGs in the sample. In section 3 we briefly describe two independent semi-analytic models of galaxy formation, outline their basic assumptions, limitations and uncertainties, and discuss the predictions they make for the evolution of the BCGs. Section 4 compares the model predictions with the observational results.

2 OBSERVATIONAL RESULTS

2.1 Photometric data

The clusters in our sample are all optically-selected, although most of them have also been detected in X-rays. At z ≤ 0.37 they come from the Abell (1957) and Abell, Corwin & Olowin (1989) catalogues. At higher redshifts they have been found from the projected density contrast in deep optical imaging surveys (Gunn, Hoessel & Oke 1986; (Couch et al. 1991)) and should represent the richest clusters present at each redshift.

The K-band data analysed here come from the photometric study carried out by Aragón-Salamanca et al. (1993) of galaxy clusters in the 0 < z < 1 redshift range (19 BCGs) complemented with new K-band images of 3 clusters at z ≃ 3 (Barger et al. 1996) and 6 clusters with 0.39 ≤ z ≤ 0.56 (Barger et al. 1997)). The images were obtained at the 3.8-m UK Infrared Telescope, the 3.9-m Anglo-Australian Telescope and the Palomar Observatory 1.52-m Telescope. There is some overlap in the clusters observed by Aragón-Salamanca et al. and Burger et al., bringing the number of BCGs studied here to a total of 25 (see Table 1). For the clusters in common, both sets of photometry agree very well (within the estimated errors) and we have chosen the better quality image in each case.

We refer the reader to the original papers for a detailed description of the data. We will concentrate here on the aspects relevant to this paper. The photometric zero-point uncertainties in the K-band images were always small (0.02–0.04 magnitudes) and are completely negligible for our analysis. As in Aragón-Salamanca et al. (1993), K photometry for the BCGs was obtained inside a fixed metric aperture of 50 kpc diameter so that the minimum aperture at high redshift is ∼ 5 arcsec thus minimising the effect of seeing. Because of the ambiguity of what constitutes a "galaxy" (∼ 30% of local first-ranked cluster galaxies are multiple-nucleus systems: i.e., more than one “galaxy” occurs within our metric aperture —see (Hoessel 1980)) we follow the approach of Schneider, Gunn & Hoessel (1983a) and adopt a working definition of the brightest cluster galaxy as the region of maximum cluster light enclosed in our metric aperture. The photometry data from the AAT and PO was transformed into the K-band system of the UKIRT (where most of the data comes from) using colour terms determined from the known filter responses. The colour terms were always ≤ 0.08 magnitudes, and we estimate that the uncertainty in the transformation is well below 2% and thus negligible. Galactic reddening corrections were estimated from Burstein & Heiles’ (1982) maps, but since the galactic latitudes were always reasonably high, they were very small in the K-band. Finally, small seeing corrections and k-corrections were also applied as in Aragón-Salamanca et al. Table 1 contains the corrected K-magnitudes for the BCG sample. Values for q0 = 0.0 and 0.5 are given to account for the difference in projected aperture at a given metric aperture as a function of the deceleration parameter. We estimate that the total uncertainty of the corrected magnitudes is below 10%, and will contribute very little to the observed scatter (see original data papers for a detailed discussion of the uncertainties).

Figure 1 shows the K magnitude-redshift relation (Hubble diagram) for the BCGs in our sample. The solid lines show no-evolution predictions which only take into account the distance modulus as a function of z, normalised with a scenario in which the bulk of their stars formed at relatively high redshifts (z > 2) and evolved passively thereafter. This conclusion has been confirmed by several more recent studies (Takos & Schombert 1993); (Oke, Gunn & Hoessel 1996); (Lubin 1998); (Ellis et al. 1997); (Stanford, Eisenhardt & Dickinson 1997)].
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Table 1. Corrected rest-frame K-band magnitudes for the BCGs

| Cluster      | z    | K$_{0=0.0}$ | K$_{0=0.5}$ | Reference |
|--------------|------|-------------|-------------|-----------|
| Abell 1656$^a$(NGC4889) | 0.023 | 8.89        | 8.88        | (1)       |
| Abell 2199 (NGC6166)      | 0.030 | 9.50        | 9.49        | (1)       |
| Abell 2197 (NGC6173)      | 0.031 | 9.54        | 9.53        | (1)       |
| Abell 2151 (NGC6034)      | 0.037 | 10.49       | 10.38       | (1)       |
| Abell 963                | 0.206 | 13.61       | 13.55       | (1)       |
| Abell 1942               | 0.224 | 13.92       | 13.88       | (1)       |
| AC103                    | 0.310 | 14.62       | 14.56       | (2)       |
| AC114                    | 0.310 | 14.54       | 14.46       | (2)       |
| AC118                    | 0.310 | 14.77       | 14.67       | (2)       |
| Cl2244$^-02$             | 0.329 | 15.35       | 15.31       | (1)       |
| Abell 370                | 0.374 | 15.05       | 14.95       | (1)       |
| Cl0024+16                | 0.391 | 15.29       | 15.14       | (1),(3)   |
| Cl0412$^-65^b$           | 0.510 | 15.60       | 15.56       | (1),(3)   |
| Cl1601+42                | 0.540 | 16.23       | 16.13       | (3)       |
| Cl0016+16                | 0.546 | 16.21       | 16.02       | (1),(3)   |
| Cl0054$^-27^c$           | 0.563 | 16.50       | 16.37       | (1),(3)   |
| Cl0317+1521              | 0.583 | 17.08       | 17.01       | (1)       |
| Cl0844+18$^d$            | 0.664 | 16.93       | 16.80       | (1)       |
| Cl1322+3029              | 0.697 | 16.90       | 16.72       | (1)       |
| Cl0020+0407              | 0.698 | 17.06       | 17.01       | (1)       |
| Cl1603+4313              | 0.895 | 17.78       | 17.64       | (1)       |
| Cl1603+4329              | 0.920 | 18.24       | 18.02       | (1)       |

$^a$Coma cluster.
$^b$Also known as F1557.19TC (Couch et al. 1991).
$^c$Also known as J1888.16CL (Couch et al. 1991).
$^d$Also known as F1767.10TC (Couch et al. 1991).

References. — (1) Aragón-Salamanca et al. 1993; (2) Barger et al. 1996; (3) Barger et al. 1997

to the three lowest redshift points. Since we do not have K magnitudes for many low redshift galaxies, the normalisation of the no-evolution line could be somewhat uncertain. However, extensive optical photometry exists and, given the homogeneity in the colours of these galaxies ([Postman & Lauer 1995]), we feel justified to use the \(R\)-band photometry of Lauer & Postman (1992) to estimate K-band magnitudes.

The shaded area at low-redshift in Figure 1 represents the K-band magnitudes for \(z < 0.06\) BCGs estimated from the R-band data of Postman & Lauer, corrected to our metric aperture (using \(d \log L/d \log r = 0.5\); from the same authors), and assuming a typical \(R - K = 2.6\) (cf. [Bower, Lucey, Ellis 1992a,b]). The width of the shaded area reflects the observed scatter. The agreement with our local normalisation is remarkably good.

In agreement with the results of Aragón-Salamanca et al., the scatter of the observed magnitudes around the no-evolution prediction is 0.30 mag. Assuming that the K-band light provides an estimate of the total stellar mass of the galaxies, this very low scatter implies that BCGs at a given redshift have very similar masses in stars (within 30% r.m.s.), which has yet to be explained by any model of galaxy formation (see section 3).

Morphological information is available for the low redshift clusters from the ground-based images. Many of intermediate and high redshift clusters have been imaged with HST, thus morphological information exists for 16 of the \(z > 0.3\) clusters ([Smail et al. 1996, 1997; [Couch et al. 1997]). In general, the BCGs are either cD galaxies or giant ellipticals, although for the highest-\(z\) clusters there could be some ambiguity since the extended cD halos might not be clearly visible given the relatively high surface brightness limits achievable with HST. Thus some of the BCGs classified as ellipticals could be cD galaxies. The exception to this rule is the BCG in the 3C295 cluster, which is a radio galaxy and shows an un-resolved AGN-like morphology in a disturbed disk or envelope.

The optical and optical-infrared colours (from ground-based and HST data) of the BCGs are compatible with those of the colour-magnitude sequence of cluster ellipticals and S0s. The exception is, again, 3C295, which is substantially bluer (by \(\simeq 0.8\) mag in \(R - K\)). The peculiar colours and morphology of this galaxy are probably related to its being a powerful radio source. However, its K-band luminosity agrees very well with that of the rest of the BCGs in our sample, and we have kept it in our analysis. Taking it out would not alter our conclusions.
2.2 Interpretation using evolutionary synthesis models

Figure 1 shows that the luminosity of the BCGs (inside a fixed metric aperture of 50 kpc diameter) does not evolve strongly with redshift. This is shown more clearly on the top panel of Figure 2, where the no-evolution prediction has been subtracted from the data. The shaded area represents the K-band magnitudes of $z < 0.06$ BCGs estimated from the R-band data of Postman & Lauer. The width of the shaded area reflects the observed scatter (see text for details). $H_0 = 50 \text{km s}^{-1} \text{Mpc}^{-1}$ and $q_0 = 0.0$ were assumed. (b) As (a) but for $q_0 = 0.5$.

A convenient parametrisation of the luminosity evolution is $L_K(z) = L_K(0) \times (1 + z)^\gamma$. Least-squares fits to the data yield $\gamma = -0.06 \pm 0.3$ and $-0.6 \pm 0.3$, for $q_0 = 0.0$ and 0.5 respectively. Thus the BCGs show no or marginally negative luminosity evolution. However, as mentioned above, the colours of these galaxies show the same evolution as the early-type cluster galaxies: they get progressively bluer with redshift at a rate which indicates that their stellar populations were formed at $z > 2$ and evolved passively thereafter. If the total stellar mass of the galaxies has remained constant, we would expect them to get progressively brighter with redshift, as the average ages of their stellar populations get younger. Since that brightening is not observed, the most likely explanation is that the total mass in stars in the BCGs has not remained constant but has grown with time. We will now estimate the rate of this growth.

We used evolutionary population synthesis models
3 Galaxy Formation and Evolution Models

In this section, we discuss the predictions of the semi-analytic models of the Durham and Munich groups. Full details of the Durham models can be found in (Cole et al. 1994) and (Baugh, Cole, & Frenk 1996b). The version of the Munich models used here is the same as that described in (Kauffmann & Charlot 1997). Further details about the Munich models can be found in (Kauffmann, White & Guiderdoni 1993). Although the two models are very similar in outline and in their basic framework, many features, for example the simple parameterisations used to describe star formation and feedback, are different in detail.

Briefly, the hierarchical collapse and merging of an ensemble of dark matter halos is followed using Monte Carlo techniques. Gas virialises in the dark matter halos, cools radiatively and condenses onto a central galaxy at the core of each halo. Star formation occurs at a rate proportional to the mass of cold gas present. The supply of cold gas is regulated by feedback processes associated with star formation, such as stellar winds and supernovae. As time proceeds, a halo will merge 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 this 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 instantaneously into stars in a “starburst”. The same stellar population models ((Bruzual & Charlot 1997) used in Section 2.2 are employed to turn the star formation histories of the model galaxies into broad band luminosities.

In these models, there are three different ways in which the stellar masses of the brightest galaxies in clusters can grow:

(i) merging of satellite galaxies that sink to the center of the halo through dynamical friction
(ii) quiescent star formation as a result of gas cooling from the surrounding hot halo medium
(iii) “bursts” of star formation associated with the accretion of a massive satellite.

As noted by (Kauffmann, White & Guiderdoni 1993), the colours and absolute magnitudes of central cluster galaxies are predicted to be bluer and brighter than observed if all the gas present in the cooling flows of massive clusters turns into visible stars. To fix this problem, these authors simply switched off star formation in cooling flows when the circular velocity of the halo exceeded 500 km s⁻¹. This value was chosen so as to obtain a good fit to the bright end of the Virgo cluster luminosity function. Another solution is to assume that gas in the central regions of halos follows a different density profile to that of the dark matter. In particular, if the gas has a constant density core, cooling is very much less efficient in the centres of massive clusters. The precise form of the gas density profile is much less impor-
Figure 3. The build up in stellar mass of the largest progenitor in four examples of BCGs taken from the Munich models, which reside in dark matter halos with circular velocity 1000 km s\(^{-1}\) at the present day. Star formation is switched off in any progenitor halo whose circular velocity is in excess of 500 km s\(^{-1}\). The solid lines show the accumulation of stellar mass from merging events, the dashed lines show the mass contributed by stars forming from gas cooling from the surrounding hot halo medium, and the dotted lines show the mass contributed by star formation bursts associated with major mergers.

In figure 3, we consider the evolution of a subset of the \(z = 0\) BCGs in a model with star formation switched off in halos with circular velocity greater than 500 km s\(^{-1}\). The solid line shows the cumulative growth in stellar mass of the BCG due to merging events. The dashed line shows the cumulative contribution from stars formed from quiescently cooling gas, and the dotted line is the contribution from stars formed in bursts during major mergers. As can be seen, star formation from bursts and cooling gas account for only a few percent of the final mass of the BCG. The rest comes from accreted galaxies. The four panels in the figure represent independent Monte Carlo realizations of the formation of a BCG in a halo of circular velocity 1000 km s\(^{-1}\). It is striking that although each BCG has a significantly different merging history, their final stellar masses differ very little from one realization to another.

We will now make a comparison with the data presented in section 2. The observational selection picks out the richest clusters at each redshift, but the sample is not complete in any well-defined sense. We mimic the observational selection as best we can by calculating the masses of BCGs in halos with circular velocities greater than some fixed value as a function of redshift. This means we are selecting rarer objects with increasing redshift. We also explore the effect of selecting clusters by mass instead of circular velocity.

We present the model predictions for two Cold Dark Matter cosmologies; one with the critical density and an open model with density parameter \(\Omega_0 = 0.2\). The density fluctuations in each case are normalised to reproduce the abundance of rich clusters (e.g. (White, Efstathiou & Frenk 1993); (Eke, Cole & Frenk, 1996); (Viana & Liddle 1996)). At several redshifts in the range \(0 \leq z \leq 1\), we have selected \(\sim 200\) halos with circular velocities greater than 700 km s\(^{-1}\). Note that the clusters are weighted so that they are representative of the mass distribution of halos at the given redshift.

The evolution of the average stellar mass of the brightest galaxies in the halos with redshift is shown in Figure 4. We have divided the average mass of the BCGs at each redshift by the average mass of BCGs found in the redshift zero clusters. The open triangles show the results of the Durham models, which adopt the halo density profile of (Navarro, Frenk & White 1995) for the dark matter. The gas is assumed to follow a different density profile, with a constant density at the core of the halo (full details of these extensions...
The K-band Hubble diagram for the brightest cluster galaxies

Figure 5. The rest frame $V-I$ colour of the model BCGs as a function of redshift. Again, (a) shows the results for a critical density CDM universe, whilst (b) shows the model output for an open universe with $\Omega_0 = 0.2$. The filled symbols show the Munich models and the open symbols show the Durham models. The open stars in (a) show a Durham model in which the gas density profile is the same as that of the dark matter in the halo. Hence, gas cools more efficiently and more recent star formation takes place, making the BCG’s bluer. The line is a fit to the observed colour evolution of the BCG’s taken from Aragón-Salamanca et al. (1993).

In Figure 6, we show the evolution in the average rest-frame $V-I$ colours of the BCGs. Once again, the open triangles show the Durham models and the filled circles the Munich models. The curves are a fit to the observed colour evolution given in (Aragón-Salamanca et al. 1993). For the $\Omega = 1$ cosmology, both models fit the observed colour evolution very well.

An important question to consider is how our results would be affected by adopting a different selection criterion for the clusters in the model. To explore this, Figure 6a shows how the average mass of a $z = 0$ BCG changes as a function of circular velocity cutoff for both the Munich and Durham models. This plot shows that more massive BCGs are found in more massive halos. The stellar mass of a BCG changes by a factor of 2 for a factor 5 increase in halo mass. Figure 6b shows how the predicted scatter in K-band absolute magnitude changes as a function of circular velocity cutoff. As can be seen, the scatter decreases as richer clusters are selected. Both the Munich and Durham models predict larger scatter than that observed, even if a different density profile is assumed.

It should be noted that clusters of fixed circular velocity are less massive at high redshift by a factor $\approx (1+z)^{3/2}$ (this scaling arises from the fact that halos collapse and virialize at a density $\sim 200\bar{\rho}(z)$, where $\bar{\rho}(z)$ is the mean density of the Universe at redshift $z$). Selecting clusters according to a halo mass cutoff, rather than a circular velocity cutoff, will thus select more massive BCGs at high redshift. The effect of mass selection on the predicted evolution is shown by

exhibit opposite trends in colour. The Munich models are redder than in a flat cosmology, because the BCGs form earlier and contain older stars. On the other hand, the Durham models are bluer. This is because halos in a low-density Universe are more concentrated and gas still cools at the cluster centres, even if a different density profile is assumed.
the open circles in Figure 3, where we have selected clusters greater than $2 \times 10^{14} M_\odot$ at each redshift. The mass evolution is now slightly weaker, but the effect is small and the model results are still in good agreement with the observations.

4 DISCUSSION

We have shown that the K-band Hubble diagram for a sample of brightest cluster galaxies in the redshift range $0 < z < 1$ has a very small scatter (0.3 magnitudes), in good agreement with earlier studies. The BCGs exhibit very little luminosity evolution in this redshift range: if $q_0 = 0.0$ we detect no luminosity evolution; for $q_0 = 0.5$ we measure a small negative evolution (i.e., BCGs were about 0.5 magnitudes fainter at $z = 1$ today). But substantial positive luminosity evolution would be expected if the mass in stars of these galaxies had remained constant over this period of time: BCGs should have been brighter in the past since their stars were younger. The most likely explanation for the observed zero or negative evolution is that the stellar mass of the BCGs has been assembled over time through merging and accretion, as expected in hierarchical models of galaxy formation. Since the colour evolution of the BCGs is consistent with that of an old stellar population ($z_{\text{form}} > 2$) that is evolving passively, we have used evolutionary population synthesis models to estimate the rate of growth in stellar mass for these systems. We find that the stellar mass in a typical BCG has grown by a factor $\approx 2$ since $z \approx 1$ if $q_0 = 0.0$ or by factor $\approx 4$ if $q_0 = 0.5$.

Two independent groups of galaxy formation modellers predicted the decrease in stellar mass of the BCGs with increasing redshift, in advance of seeing the data and without any fine tuning of their semi-analytic model parameters. We have extracted the properties of BCGs in massive halos with circular velocities greater than 700 km s$^{-1}$ or masses greater than $2 \times 10^{14} M_\odot$, at various redshifts. The average stellar mass of the BCGs increases by a factor of $\approx 4 \sim 5$ in the critical density models. In the low density models, the growth in stellar mass is more modest, between a factor 2 to 3. This is because clusters assemble at higher redshift in a low density Universe. Note, however, that both models agree well with the data when the appropriate value of $q_0$ is used in the analysis. It is not possible to make statements about a preferred cosmology from this exercise.

We also find that in order to reproduce the observed colours of the galaxies, some mechanism must act to suppress visible star formation in the cooling flows of the most massive halos. It has been postulated that much of this gas may be forming low-mass stars (Fabian, Nulsen & Canizares, 1982) or cold gas clouds (White et al. 1994). Another possibility we have explored is that the gas may be less concentrated in the centres of clusters than the dark matter, and hence not able to cool efficiently. In both cases, the evolution in the K-band luminosities of the BCGs comes about almost exclusively as a result of the merging of satellite galaxies in the cluster. An important and unanticipated result of our analysis is that the predicted scatter in the stellar masses of the BCGs built through merging and accretion is still quite small, although somewhat larger than the observed one. The scatter depends on the criteria used to select the model clusters.

ACKNOWLEDGMENTS

AAS acknowledges generous financial support from the Royal Society. We thank T. Shanks for encouraging us to have a closer look at the K-band Hubble diagram, and G. Bruzual and S. Charlot for allowing us to use their model results prior to publication. We thank the anonymous referee for useful comments. The version of the Durham semi-analytic models used to produce the predictions in this paper is the result of a collaboration between Shaun Cole, Carlos Frenk, Cedric Lacey and CMB, supported in part by a Particle Physics and Astronomy Research Council rolling grant. This work was carried out under the auspices of EARA, a European Association for Research in Astronomy, and the TMR Network on Galaxy Formation and Evolution funded by the European Commission.

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