Mon. Not. R. Astron. Soc. 000, 1–5 (2001) Printed 22 May 2002 (MN LATEX style file v1.4)

Evolution of Brightest Cluster Galaxies in X-Ray Clusters

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Accepted... Received...; in original form 2001 September

ABSTRACT

A recent paper (Burke, Collins & Mann 2000) presents the analysis of the K-band Hubble diagram of 76 brightest cluster galaxies (BCGs) in X-ray clusters and shows that the properties of BCGs depend on the X-ray luminosity (L_X) of their host clusters. Unfortunately, the low numbers of nearby clusters in this sample makes it difficult to constrain evolutionary trends. In this letter we extend the Hubble diagram of Burke et al. (2000) to a total of 155 clusters using new data on 79 BCGs at $z \leq 0.1$ from the 2MASS extended source catalogue. We show that the major division between BCGs in high and low-L_X clusters disappears at $z \leq 0.1$, with BCGs having similar absolute magnitudes independent of the X-ray luminosity of their host clusters. At larger redshifts the K-band light of BCGs in high-L_X systems is consistent with little or no merging back to $z \sim 0.8$, whereas BCGs in the low-L_X systems have a different evolutionary history, with many increasing their mass by a factor ≥ 4 since $z \simeq 1$. This provides direct evidence of hierarchical merging in a galaxy population.

Key words: Galaxies: clusters: general – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation

1 INTRODUCTION

Brightest cluster galaxies (BCGs) provide a unique sample with which to study the evolution of galaxies in a cluster environment. They are the most luminous galaxies emitting purely photospheric light in the universe and are uniquely positioned at the centre of the cluster gravitational potential. A classic observation of BCGs is that they vary little in luminosity within a fixed metric aperture (e.g. Sandage 1972a,b) and in recent years the near-infrared K-band Hubble diagram has been analysed to redshifts $z \simeq 1$ (e.g. Aragón-Salamanca, Baugh & Kauffmann 1998; Collins & Mann 1998). The K-band is ideal to study BCG evolution as extinction at 2.2 μm is considerably smaller than at optical wavelengths and the K-correction is relatively insensitive to the star formation history of the galaxies (e.g. Madau, Pozzetti & Dickinson 1998).

Knowledge of the X-ray luminosity of a cluster is vitally important in the study of BCG evolution (Edge 1991). X-ray parameters provide objective information about the cluster environment since the strength of X-ray emission is directly related to the depth of the cluster gravitational potential well and therefore the cluster mass. In both Collins & Mann (1998) and Burke, Collins & Mann (2000 – hereafter BCM) it was established that, in general, BCGs in clusters with an X-ray luminosity $L_X \geq 2.3\times10^{44}$ erg s^{-1} (in the EMSS passband $0.3 - 3.5$ keV) have mean absolute magnitudes $\simeq 0.5$ mag brighter with a dispersion half as large ($\simeq 0.24$) as those in less luminous clusters. Despite these efforts, it is unclear whether this effect is evolutionary as there are few BCGs with redshifts below $z \simeq 0.1$ in these studies. For example, in Aragón-Salamanca et al. (1998) there are only 3 BCGs below $z = 0.1$ (2 in high-L_X clusters) and 13 in BCM (3 in high-L_X clusters). To ascertain whether the variation of BCG properties with cluster X-ray luminosity seen at high redshift is a genuine evolutionary effect we significantly extend the K-band Hubble diagram of BCM below $z \simeq 0.1$ in this letter, using the 2 Micron All Sky Survey second incremental release extended source catalogue (hereafter 2MASS catalogue; Jarrett et al. 2000).

In Section 2 we give a brief outline of the 2MASS catalogue, describe our sample and then present the new Hubble diagram in Section 3. In Section 4 we discuss the implications of our results for the evolution of BCGs and draw our conclusions. Throughout this letter we assume a cosmology consistent with the supernovae data (see Bahcall et al. 1999):

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$\Omega_m = 0.3, \Omega_\Lambda = 0.7$ and $H_0 = 100\ h$ km s^{-1} Mpc^{-1}, with $h = 0.7$. This affords the chance to present earlier results for the Hubble diagram, which assumed an Einstein–de Sitter universe and $h = 0.5$, in the framework of the most recent estimates of the cosmological parameters.

2 DATA

The 2MASS catalogue (Jarrett et al. 2000) covers ∼40 per cent of the sky and contains J, H and K_s-band images and photometry for ∼585,000 galaxies. The extended source detection limit (10σ) at K_s is 13.1 mag and together with the spatial resolution of 2 arcsec means that 2MASS is well suited for detecting luminous galaxies, such as BCGs, out to $z \sim 0.1$. The typical astrometric accuracy of sources in 2MASS is 0.5 arcsec rms.

Our input cluster catalogue is that of Lynam (1999). This consists of a sample of 150 rich Abell clusters with measured redshifts $z \leq 0.1$ and $|b| \geq 15°$, which have extended X-ray emission above a flux limit of 3×10^{-12} erg s^{-1} cm^{-2} in the *ROSAT* hard-band ($0.5 - 2.0$ keV). The X-ray data comes from the second reduction of the *ROSAT* All Sky Survey, paired with co-ordinates from Abell, Corwin & Olowin (1989). X-ray flux measurements are essentially the same as that of the NORAS and REFLEX cluster surveys (Böhringer et al. 2000). The Lynam sample was constructed specifically to study streaming flows of galaxy clusters (Lynam et al. 2002, in preparation) and contains clusters with a wide range in X-ray luminosity selected over a large fraction of the entire sky, thus fulfilling our requirements. The BCGs were identified by the positional coincidence between the centroid of the X-ray cluster emission and the first ranked galaxy, which in general show very good agreement being coincident to ≤ 30 arcsec (Lazzati & Chincarini 1998).

The matching with the 2MASS catalogue was done by searching around the BCG positions given by Lynam (1999) out to a maximum radius of 60 arcsec. A total of 79 BCGs were common to both catalogues, this constitutes only 50 per cent of the Lynam (1999) catalogue due to the partial sky coverage of the 2MASS second incremental release. Only 19 of these had separations > 3 arcsec, and all had separations less than 20 arcsec. These 19 BCGs were checked carefully to ensure that the correct object had been identified. In 3 other cases the 2MASS algorithm had missed the BCG but found another source nearby, possibly due to source confusion. As these BCGs had no reliable K magnitude it was not possible to include them in the analysis.

The major strategy behind the photometric reductions of the 2MASS data was to be as consistent as possible with the procedures of BCM for the 76 BCGs discussed in that paper. Out of the wide range of photometry values available in the 2MASS catalogue we chose to use those measured in circular apertures as they are more robust than those in elliptical apertures (e.g. Pahre 1999, Jarrett et al. 2000). The catalogue contains magnitudes within 11 circular apertures with radii between 5 and 70 arcsec. A Hermite polynomial fit to the aperture photometry of the 2MASS data was performed to estimate the apparent magnitude at the metric radius of $r_m = 12.5h^{-1}$ kpc used by BCM. The internal photometric error in the 2MASS magnitudes is $\sim \pm 0.1$ mag. The data was then corrected for Galactic absorption using the maps of Schlegel, Finkbeiner, & Davis (1998) – the correction is small, typically ~ 0.02 mag. The colour correction between the 2MASS K_s-band and the UKIRT K-band, used by BCM, is typically 0.006 ± 0.01 mag (Carpenter 2001), and so was neglected.

One difference between the datasets is that in the BCM sample no attempt was made to remove flux due to other cluster galaxies falling within the aperture, although flux due to contaminating stars and obvious non-cluster galaxies was excluded. In contrast, the 2MASS magnitudes are automatically corrected for the presence of stars and other galaxies within each aperture. We examined the difference that this makes by measuring the magnitudes of 10 2MASS galaxies in circular apertures directly from the 2MASS 'postage stamp' images. The mean difference in the photometry between the uncorrected postage-stamp images and the 2MASS magnitudes is only 0.03 ± 0.01 mag. Finally, as an external check on the consistency of the 2MASS photometry, we obtained K-band magnitudes for 12 BCGs using QUIRC on the University of Hawaii 2.2m telescope. The 12 BCGs cover the range of redshift and cluster X-ray luminosity values in the Lynam (1999) sample. The mean difference (2MASS-UH) is only 0.028 ± 0.042 mag. We also compared the magnitudes of the 6 BCGs below $z = 0.1$ in BCM which are in common with 2MASS. The mean difference (2MASS-BCM) is 0.04 ± 0.09. Therefore we conclude that there are no significant offsets between the respective datasets.

All X-ray luminosities were corrected to the new cosmology, denoted by Λ, using the form:

$$L_\Lambda = L_{\rm EdS} \left(\frac{d_{\rm L(\Lambda)}}{d_{\rm L(EdS)}} \times \frac{apcorr_{(\Lambda)}}{apcorr_{(\rm EdS)}} \right)^2, \qquad (1)$$

where EdS denotes an Einstein–de Sitter cosmology with $h = 0.5$, d_L is the luminosity distance to the cluster and *appcor* is the value of the aperture correction. The BCM data incorporates X-ray catalogues, principally EMSS (Gioia & Luppino 1994) and the SHARC surveys (Burke et al. 1997; Romer et al. 2000), which extrapolate their measured X-ray flux to total flux assuming a King surface brightness profile and a fixed core radius. The appropriate value of *apcorr* was used for each survey (giving rise to luminosity corrections $\simeq 20$ per cent), neglecting the RASS-based measurements as these fluxes are $\geq 90\%$ of the total flux from the cluster (Böhringer et al. 2000, 2001) resulting in a negligible aperture correction. Finally, to maintain consistency with BCM, the X-ray luminosities given by Lynam (1999) were transformed from the RASS ($0.1 - 2.4$ keV) passband to the EMSS passband ($0.3 - 3.5$ keV). Assuming a 6 keV thermal bremsstrahlung spectrum (the choice of temperature has negligible effect on the correction factor): the passband corrections are of the form: $L_X(0.3 - 3.5$ keV$) = 1.08 L_X(0.1 - 2.4$ keV$)$. At the mean redshift of the sample ($z = 0.27$), the X-ray luminosity 2.3×10^{44} erg s^{-1} ($0.3 - 3.5$ keV), reported in BCM as marking a transition in the properties of the constituent BCGs, transforms to $\simeq 1.9 \times 10^{44}$ erg s^{-1} in the supernovae cosmology adopted here. Hence we report the results below using this new X-ray luminosity threshold.

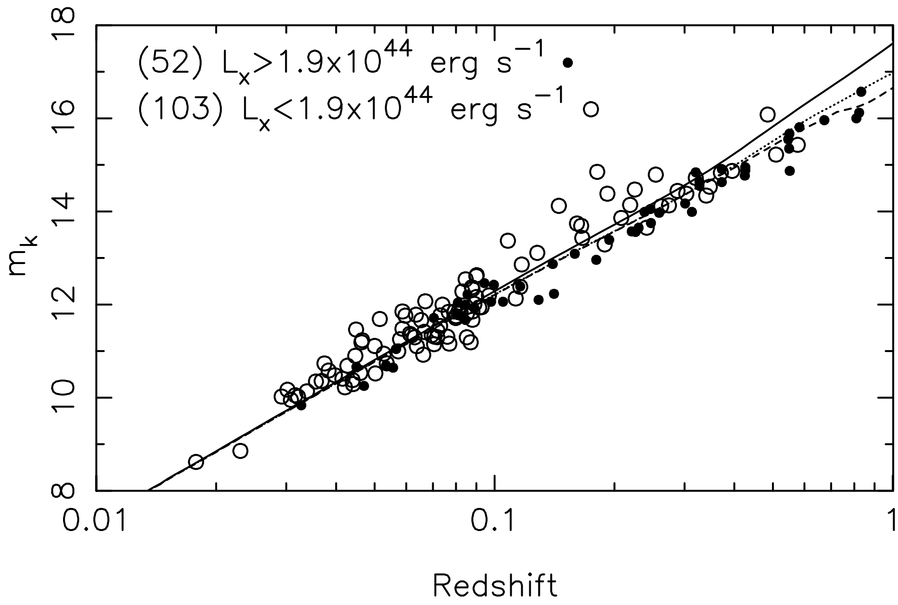

Figure 1. The Hubble diagram. The filled points denote BCGs in clusters with $L_X(0.3-3.5\,\mathrm{keV}) > 1.9\times10^{44}\mathrm{erg\,s^{-1}}$. The no-evolution prediction, assuming a 10 Gyr old stellar population, is shown by the solid line, the $z_f = 2$ model by the dashed line and the $z_f = 5$ model by the dotted line. All the models were normalised in the same way using the 18 BCGs below $z = 0.1$ with $L_X \geq 1.9\times10^{44}$ erg s^{-1} which gives $M_k = -25.78 \pm 0.05$.

3 RESULTS

The K-band Hubble diagram for 155 BCGs is shown in Figure 1. The lines show model predictions calculated using the GISSEL96 code (Bruzual & Charlot 1993), for a solar metallicity stellar population with a Salpeter initial mass function. The solid line indicates a no-evolution model for a 10 Gyr old stellar population, while the other lines are for stellar populations which form in an instantaneous burst of star formation at a single epoch, $z_f = 2$ and $z_f = 5$, and then evolve passively.

In Figure 2 we present the absolute magnitude – X-ray luminosity relation for the high and low redshift samples. The M_K values are calculated using the K-correction from the $z_f = 2$ model. The figure illustrates clearly how the M_K values for BCGs at $z \geq 0.1$ depend on the X-ray luminosity of the host cluster and contrasts this behaviour with the M_K distribution at $z \leq 0.1$. This difference is quantified in Table 1 which gives the mean absolute magnitudes as a function of X-ray luminosity and redshift. To test the significance of this difference we carried out a non-parametric two-tailed Kolmogorov–Smirnov (KS) test on the absolute magnitudes of the BCGs in clusters above and below $z = 0.1$. Above $z = 0.1$ the test gives a probability of only 0.013 per cent that BCGs in high and low L_X clusters are drawn from the same parent population, whereas the corresponding probability for BCGs below $z = 0.1$ rises to 36 per cent.

Table 1. Statistical properties of the absolute magnitude as a function of X-ray luminosity and redshift.

z	$L_X(0.3-3.5\,\mathrm{keV})\ \times10^{44}\mathrm{erg\,s^{-1}}$ (N, 1σ) < 1.9	> 1.9
< 0.1	-25.67±0.04 (74, 0.34)	-25.78±0.05 (18, 0.21)
> 0.1	-25.51±0.09 (29, 0.47)	-25.93±0.04 (34, 0.24)

4 DISCUSSION AND CONCLUSIONS

We consider the amount of merging that BCGs may have undergone to further examine the difference in BCG properties with host cluster environment. The parametric form introduced by Aragón-Salamanca et al. (1998) and used by BCM: $M(z) = M(0) \times (1+z)^{\gamma}$ was used to estimate the growth in the stellar mass content of the BCGs. Figure 3 shows the residuals about a $z_f = 2$ model with the lines corresponding to growth factors of 0, 2, 4, 16 since $z = 1$. It is clear from Figure 3a that those BCGs in more X-ray luminous clusters have not experienced any significant stellar mass growth since $z = 1$, whereas Figure 3b indicates that the BCGs in low X-ray luminosity clusters show a wide range of mass evolution since redshift $z = 1$. Very similar results are found if the formation redshift is increased to $z_f = 5$. This suggests that BCGs have different evolutionary histories depending on the X-ray properties of their cluster hosts.

Our results on the merging history of BCGs have been qualitatively confirmed recently by Nelson et al. (2001) using the I-band Hubble diagram for BCGs selected from the Las Campanas Distant Cluster Survey in the range

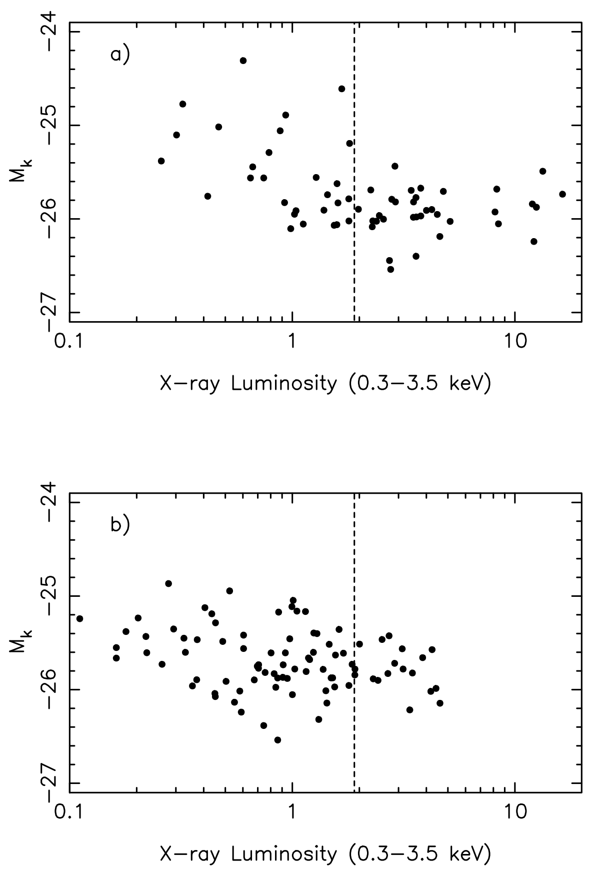

Figure 2. The absolute magnitude - X-ray luminosity relation for a) those BCGs with redshift $z \geq 0.1$ and b) those with redshift $z \leq 0.1$. The dotted line represents the $L_X = 1.9 \times 10^{44}$ erg s^{-1} cluster luminosity boundary.

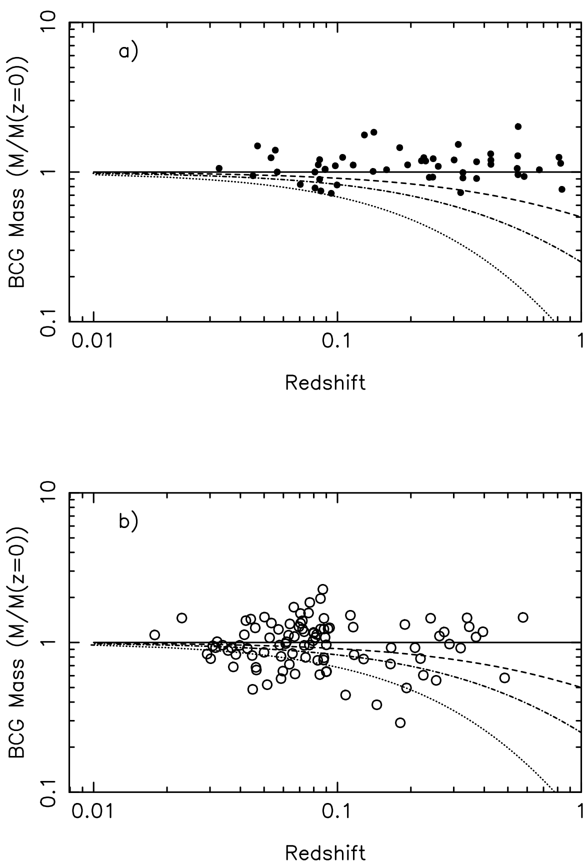

Figure 3. Inferred mass of BCGs from residuals about the $z_f = 2$ model for BCGs in a) high-L_X clusters and b) in low-L_X clusters. The model plots are for $M(z) = M(0)(1+z)^{\gamma}$, with $\gamma = 0, -1, -2, -4$, corresponding to growth factors of 0, 2, 4, 16 since $z = 1$. The models are normalised independently for each figure using the absolute magnitudes below $z = 0.1$.

$0.3 \leq z \leq 0.9$. In this sample only BCGs in low mass clusters must have accreted significantly since $z \simeq 1$. Furthermore, the V-I colour evolution seen by Nelson et al. (2001) is consistent with the accretion in low-L_X BCGs consisting of old stellar populations. From a theoretical perspective, N-body simulations naturally produce massive, central dominant cluster galaxies through merging (Dubinski 1998, Athanassoula, Garijo & García Gómez 2001), although relatively little theoretical work has focussed on predicting the merging history of BCGs as a function of environment: the semi-analytical models presented by Aragón-Salamanca et al. (1998), predict that BCGs in the most massive clusters have grown by a factor $4-5$ since $z = 1$, which is clearly inconsistent with the results in Figure 3a. More recently, Gottlöber, Klypin & Kravtsov (2001) argue that at $z \sim 1$ the merger rates in groups are significantly higher than in richer systems, resulting in a more diverse range of evolutionary properties of their constituent galaxies.

We conclude that those BCGs in high redshift, high luminosity clusters are brighter and more uniform than those in their low luminosity counterparts and that this separation is significantly weaker at low redshift. This is a direct indication of how a single homogeneous population of galaxies evolves hierarchically. Both this work and future studies of the near-infrared surface brightness profiles of BCGs along with velocity dispersion measurements should help constrain the evolutionary parameters and stimulate more theoretical predictions.

ACKNOWLEDGMENTS

SB acknowledges PPARC for a Postgraduate Studentship. DJB acknowledges the support of SAO contract SV4-64008 and NASA contract NAS8-39073(CXC). RGM acknowledges support from PPARC. This publication makes use of data products from the Two Micron All Sky Survey (2MASS) which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. We acknowledge the use of the UH 2.2m telescope at the Mauna Kea Observatory, Institute for Astronomy, University of Hawaii.

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