Evolution of the near-infrared luminosity function in rich galaxy clusters

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ABSTRACT

We present the $K$-band (2.2 $\mu$m) luminosity functions of the X-ray luminous clusters MS1054–0321 ($z = 0.823$), MS0451–0305 ($z = 0.55$), Abell 963 ($z = 0.206$), Abell 665 ($z = 0.182$) and Abell 1795 ($z = 0.063$) down to absolute magnitudes $M_K = -20$. Our measurements probe fainter absolute magnitudes than do any previous studies of the near-infrared luminosity function of clusters. All the clusters are found to have similar luminosity functions within the errors, when the galaxy populations are evolved to redshift $z = 0$. It is known that the most massive bound systems in the Universe at all redshifts are X-ray luminous clusters. Therefore, assuming that the clusters in our sample correspond to a single population seen at different redshifts, the results here imply that not only had the stars in present-day ellipticals in rich clusters formed by $z = 0.8$, but that they existed in as luminous galaxies then as they do today.

Additionally, the clusters have $K$-band luminosity functions which appear to be consistent with the $K$-band field luminosity function in the range $-24 < M_K < -22$, although the uncertainties in both the field and cluster samples are large.

**Key words:** galaxies : clusters: luminosity function – infrared: galaxies – galaxies: clusters: individual: MS1054-0321, MS0451-0305, Abell 963, Abell 665, Abell 1795
1 INTRODUCTION

Recent observations of rich clusters of galaxies and their galaxy populations have revealed a number of interesting results:

(i) Three X-ray luminous clusters at redshifts $z \sim 0.8$ have been discovered in the ROSAT North Ecliptic Pole (NEP) survey (Gioia & Luppino 1994, Henry et al. 1997), all of which have had their high inferred masses confirmed by weak gravitational lensing measurements of background galaxies (Luppino & Kaiser 1997, Clowe et al. 1998). In addition, one cluster at $z = 1$ has been found by ROSAT pointed observations towards the high redshift lensed quasar MG2016+112 (Hattori et al. 1997). The very existence of these high-$z$ massive clusters puts severe constraints on the cosmological geometry (e.g. Eke, Cole & Frenk 1996; Bahcall, Fan & Cen 1997; Henry 1997).

(ii) Detailed measurements of the optical – near infrared colours of early-type galaxies in clusters (Stanford, Eisenhardt & Dickinson 1998) suggest that these galaxies evolve passively from $z = 0.9$ to $z = 0$. Furthermore, Stanford et al. provide evidence based on the small scatter in the optical-IR colours that early-type galaxies in a cluster show a large degree of homogeneity in their star formation histories, with very little evidence for uncorrelated recent bursts of star formation.

(iii) Blue star-forming galaxies have been found in a number of rich clusters at $z > 0.2$. The existence of such blue galaxies in rich clusters at intermediate redshifts has been recognized for some time (Butcher & Oemler 1978, 1984), but the Hubble Space Telescope ($HST$) now allows these galaxies to be imaged at very high resolution (Dressler et al. 1994a,b). Many of these blue galaxies are similar in morphology to nearby late-type spirals. Some have disturbed morphologies and/or show evidence for mergers.

(iv) Imaging of a sample of $z \sim 0.5$ clusters with WFPC2 on $HST$ suggests that the fraction of elliptical galaxies in the $z \sim 0.5$ clusters is similar to or larger than that in local clusters (Dressler et al. 1997). However, Dressler et al. also report that the fraction of spiral galaxies
is much higher in the $z \sim 0.5$ clusters. A corresponding decrease in the fraction of S0 galaxies in the $z \sim 0.5$ clusters relative to the fraction in local clusters is also noted.

(v) The $B$-band luminosity function of galaxies in rich, evolved clusters with high elliptical galaxy fractions is remarkably invariant (Trentham 1998a). Compared with the field luminosity function, it falls off more steeply at bright magnitudes ($M_B < -20$), despite the existence of superluminous cD galaxies in clusters not present in the field. This is probably due to the existence of very massive, star-forming galaxies in the field (like those seen by Cowie, Hu & Songalia 1995, Cowie et al. 1996). These galaxies do not exist in nearby clusters because cluster-related processes like ram-pressure stripping have turned off star formation in galaxies there.

A consistent picture emerging from these observations is as follows. The richest clusters were formed quite a long time ago, and were X-ray luminous by at least $z = 1$. What we see today as the stars in early-type galaxies located in rich clusters had formed by this redshift, and probably much earlier. However, it is not clear exactly how many of these stars were in a galaxy that was part of an X-ray luminous cluster at $z = 1$. As the clusters grew, they picked up additional galaxies, many of which experienced a burst of star formation as they entered the cluster (see Moore et al. 1996 for a possible mechanism). These extra galaxies are the spirals which were subsequently converted to S0 galaxies by cluster-related processes, as discussed by Dressler et al. (1997). Meanwhile, the stars in the elliptical galaxies evolved passively. By $z = 0$, most of the star formation accompanying infall of galaxies into the cluster has finished except in a very few clusters that are merging today.

We now attempt to measure the $K$-band (2.2 $\mu$) luminosity function for a sample of clusters with $0 < z < 0.8$. The aim here is to explore the evolution of the shape of the luminosity function of the old stellar populations in clusters, and its normalization (relative to X-ray luminosity). This will allow us to fill in some details in the above scenario. For example, do the stars in the giant ellipticals in nearby clusters exist in such big stellar systems at high redshift clusters, or were they in stellar systems that merged to form the big
galaxies we see today? The observations of the scatter in the optical – near-infrared colours (Stanford, Eisenhardt & Dickinson 1998) and of the scatter in the UV – optical colours of $z \sim 0.5$ ellipticals (Ellis et al. 1997) indicate that the stars themselves are very old, but do not constrain the masses or luminosities of the stellar systems in which the stars were formed. Also, the present observations will be used to determine how the integrated $K$-band luminosity of clusters (i.e. the normalization of the luminosity function) varies with redshift for clusters of a given X-ray luminosity (the results of Dressler et al. 1997 suggest that, at least for the elliptical galaxy population, it does not vary strongly between $z = 0$ and $z = 0.5$). Finally, we will confirm that the conclusions of Stanford, Eisenhardt & Dickinson (1998) regarding passive evolution are valid for our sample (we need to do this before making evolutionary corrections and comparing luminosity functions between clusters).

At near-infrared wavelengths the light is primarily sensitive to the old stellar populations (i.e. the stars that make up the elliptical galaxies) with only small contamination from young star-forming galaxies (like those observed by Dressler et al. 1984a,b). Such a study is made feasible by the advent of wide-field IR arrays on large telescopes so that we can image to faint magnitudes over wide areas, and reach the faintest galaxies while still having enough galaxies that the counting statistics are manageable. Also, negative K corrections in the $K$-band also help us to reach very faint absolute magnitudes ($M_K \sim -20$ at $z = 0.8$).

The paper is organized as follows. In Section 2 we describe our sample selection and the observations. We present the near-infrared number counts in Section 3 and luminosity functions in Section 4. In Section 5 we investigate the evolution of luminosity function with redshift. Finally we discuss our results in Section 6.
2 SAMPLE SELECTION AND OBSERVATIONS

2.1 The sample

The sample used in this study consists of six clusters (hereafter MS1054, MS0451, A41, A665, A963, and A1795) in the redshift range $0.06 < z < 0.82$. Table 1 lists the cluster richness, redshift $z$, X-ray luminosity $L_x$, the Galactic extinction in the $K$-band along our line of sight to the cluster and the critical surface density $\Sigma_c$ for lensing of distant background galaxies by the cluster dark matter. The clusters have X-ray luminosities that vary by less than an order of magnitude. The high redshift clusters (MS1054 and MS0451) were selected to have somewhat higher $L_x$ in order to give better counting statistics following background subtraction. We were also limited by the lack of known clusters at $z = 0.8$ (only three are known). In terms of absolute magnitudes, these measurements probe somewhat fainter (to $M_K \sim -20$) than most previous studies (e.g. Barger et al. (1996) reached $M_K = -23$ for their nearest clusters, and Stanford, Eisenhardt & Dickinson (1995) reached $M_K = -22$ in their study of A370 and A851).

We assume $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$ throughout this work.

2.2 The $K$-band observations and data reduction

Our observing log is presented in Table 2 which lists the field sizes, coordinates, total exposure times and seeing.

The clusters MS1054, MS0451, and A41 were imaged through a $K$ filter using the IRCAM3 256 $\times$ 256 InSb array (scale 0.286$''$ pixel$^{-1}$, field of view 1.2$'\times$1.2$'$) at the 3.8 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea. Conditions were photometric with a median seeing of 0.8$.''$. The frames were taken in sequences of nine, one-minute exposures. The exposures were dithered by up to 10$''$ so that we could use them to reject bad pixels and generate sky frames (the largest objects in the field for these distant clusters were smaller than this).
The clusters A963, A665, and A1795 were imaged through a $K'$ filter using the QUIRC 1024 $\times$ 1024 InSb array (Hodapp et al. 1996, scale 0.19$''$ pixel$^{-1}$, field of view 3.2$'$ $\times$ 3.2$'$) at the 2.2 m University of Hawaii Telescope, also on Mauna Kea. Conditions were photometric for these observations with a median seeing of about 0.9$''$, except for A1795 where the seeing was approximately 1.3$''$ due to severe windshake of the telescope. Exposures were taken in sequences of six, three-minute frames. These images were dithered by up to 30$''$ in order to reject bad pixels. Offset fields were observed with equal exposure time to the cluster fields in order to perform a sky subtraction. The cD galaxies in these fields were too large to allow the use of the object frames to create a sky image for subtraction.

Flat-field images were constructed using either median-filtered object frames from the whole night (IRCAM3) or dome flats (QUIRC), and sky images were constructed for each exposure sequence using either the object frames (IRCAM3) or offset blank sky frames (QUIRC). Individual frames were flat-fielded, sky-subtracted, and then registered and combined. The reduced images were flat to better than 1%. When combining images a clipping algorithm was used, which rejected pixels more than 3 standard deviations from the median value (this removed bad pixels). Instrumental magnitudes were computed from observations of 5 – 10 UKIRT faint standards (Casali & Hawarden 1992) per night, giving a photometric accuracy of $< 2 \%$. The final $K$-band images are presented in Figure 1.

For the QUIRC images, a correction from $K'$ to $K$ magnitudes was made using the colour calibrations of Wainscot & Cowie (1992), assuming $H - K \approx 0.75$ (this is appropriate for early-type galaxies with $0.06 < z < 0.2$ – see Stanford, Eisenhardt & Dickinson 1995). This method gives the correct $K$ magnitudes for the cluster ellipticals (which are the dominant galaxies in these clusters), although it gives magnitudes that are systematically too bright for bluer background/foreground galaxies and stars, by up to 0.1 mag.
2.3 Optical data and measurement of colours

Part of the aim of this project is to compare galaxies in different clusters at different redshift. We expect to be able to do this because of the results of Stanford, Eisenhardt & Dickinson (1998) who find that the colours and magnitudes of elliptical galaxies in clusters vary in a manner consistent with passive evolution. However, before we can compare clusters we need to confirm that the galaxies in our clusters do indeed follow the evolutionary tracks described by Stanford et al. (1998). In order to do this we need to measure optical-$K$ colours for the galaxies, and so need optical images of the clusters.

For A665 and A963, we used the $R$-band data of Trentham (1998b) – note that the A665 image in that paper does not completely overlap with the field studied in the present work, but a shorter (5 min) exposure taken under the same conditions as the deeper exposures, but encompassing all the field studied here, was used. For A1795, we used the $R$-band data of Trentham (1997b). The observations and reduction of the optical data is described in those papers. For MS1054 and MS0451, we used HST archive data taken using the F814W and F702W filters respectively and WFPC2. The exposure times were 260 minutes for MS1054 and 173.3 minutes for MS0451. We reduced and calibrated these data using standard procedures – cosmic rays were identified by their presence in only one of the dithered set of images and subsequently removed.

Colours were measured using 3′′ diameter apertures placed at the same position in registered optical and $K$-band images. Using aperture magnitudes to measure colours ensures that we are studying the same stellar populations in both filters. The large aperture ensures that differential seeing effects between the two images are negligible.

3 THE $K$-BAND GALAXY COUNTS

Objects were detected at the $3\sigma$ level above the sky background in each of the six cluster images, using the FOCAS detection algorithm (Jarvis & Tyson 1981; Valdes 1982,
1989). Both $3\sigma$ isophotal magnitudes and magnitudes within a $3\arcsec$ diameter aperture were calculated.

The detection algorithm produced catalogs of 100 – 200 objects per cluster brighter than the limiting magnitude ($K \approx 19$ for A1795 and A41, $K \approx 20$ for A665 and A963, $K \approx 21$ for MS1054 and MS0451). Each object was then examined and compared with objects at the same ($\alpha, \delta$) in deeper optical images (see Section 2.3). At this stage a number of alterations were made to the catalog.

(i) The brightest objects ($K < 16$ in the QUIRC images, $K < 17$ in the A41 image, and $K < 19$ in the deep IRCAM3 MS1054 and MS0451 images) were identified as stars or galaxies, based on their morphologies, using the PSF-fitting algorithm DAOPHOT (Stetson 1987).

(ii) Multiple objects were identified either by their morphologies in the optical images or by using the FOCAS detection algorithms to search for multiple peaks within a detection isophote in the $K$-band images. A multiple object identified by either of these methods was then split into its component objects and photometry performed on each of these separately.

(iii) Objects fainter than the point-source limiting magnitudes given above were removed. For these distant clusters, the early-type galaxies are compact and the fainter ones have scale-lengths smaller than the seeing, so that the completeness limit for these galaxies will be similar to that for point sources. The few objects fainter than this limit in our catalog arise from faint galaxies being superimposed on noise peaks (these galaxies would not have been detected if they had fallen in a region of the image other than on a noise peak).

It was also apparent from comparing the $K$-band and optical images that the effects of crowding (the process by which a faint object goes undetected because it happens to fall within the detection isophote of a much brighter object) were small in the $K$-band images, and can safely be neglected when computing the number counts. This is not true for optical
CCD images where a bright star or galaxy is present because the diffraction spikes or diffuse halo can cover considerable area.

In order to measure the galaxy counts we need to determine how many of the detected objects are stars. Stars brighter than the magnitudes given in (i) above were identified by their morphology in either the $K$-band or optical images. Because the faintest detected galaxies have scale-lengths smaller than the seeing, they look like stars. Hence, we could not identify stars unambiguously based on their morphology at faint magnitudes. Therefore, we corrected for stellar contamination at faint magnitudes by computing the expected number of faint stars, given the number of stars brighter than the limits in (i) above, assuming the Galactic stellar number-count vs. magnitude relation slope of Jones et al. (1991). These corrections were small ($< 5\%$ for all clusters except for A665, where the stars comprise approximately 20\% of the total counts at the faintest magnitudes), implying that the uncertainties generated by them in the context of computing luminosity functions are negligible compared to those from counting statistics and the field-to-field variance in the background. Corrections for Galactic extinction in the $K$-band along the lines of sight to these clusters are also small ($\leq 0.01$ mag). The corrections listed in Table 1 were applied to the magnitudes of individual objects in our catalog.

Simulations of distant compact galaxies indicate that the $3\sigma$ isophotal magnitudes ($\sim 21.5K$ mag arcsec$^{-2}$ for the QUIRC images and for A41, and $\sim 22.5K$ mag arcsec$^{-2}$ for the IRCAM3 images of MS1054 and MS0451) are close to the total magnitudes (Trentham 1997a), and we assume this to be the case for all the galaxies here. Making this assumption, we bin the data in one-magnitude intervals, correct for stellar contamination as above, and generate the galaxy number count – magnitude relation for each of the cluster fields. These are presented in Fig. 2, where we also show the average background counts, computed from the compilation in Mobasher & Trentham (1998).
It is clearly visible from Figure 2 that for all clusters except A41, the galaxy number counts significantly exceed the background. We can now subtract the background from these counts and compute the luminosity functions (Section 4). We do not consider A41 further because the cluster is not visible above the background at any magnitudes fainter than that of its cD galaxy. It is the least X-ray luminous cluster in our sample, and is the third most distant so it is not surprising that the background contamination is the worst here.

4 THE LUMINOSITY FUNCTIONS

The luminosity functions are computed by subtracting the background (the dashed lines in Figure 2) from the number counts in each cluster field (the points in Figure 2). Additional uncertainty is generated by the fact that background fields of a given angular size have a substantial field-to-field variance (see Figure 3 in Mobasher & Trentham 1998). Poisson statistics are used to correct for the different area in the fields.

The background contribution and its variance is further multiplied by a correction factor that takes into account the gravitational lensing of the background galaxies by the cluster dark matter (see Fig. 3). We need to make this correction because we are looking at the background galaxies through a large concentration of dark matter which will distort their fluxes and angular separations due to gravitational lensing. The correction is the largest for MS0451. For MS1054, the cluster is sufficiently distant that many faint non-cluster members are foreground galaxies so that the average amplification per galaxy is low. For the lower redshift clusters, the increase in angular spacing between galaxies due to gravitational lensing progressively becomes more important compared to the increase in flux of the galaxies, so that the average amplification per galaxy is also low. For a more detailed description of the shapes of the curves in Fig. 3, the reader is referred to Trentham (1998b).

The luminosity functions are presented as a function of the absolute magnitude plus K correction (Fig. 4); this is the most general way of presenting the luminosity functions because the K corrections are slightly different for different galaxy types. The error bars here
represent the quadrature sum of the uncertainties from counting statistics and uncertainties from the field-to-field variance of the background galaxies. The luminosity functions have approximately the same shape for all the clusters (the normalizations depend primarily on the area of the cluster surveyed – see Table 3); however, the error bars are large. Before performing a detailed comparison between the luminosity functions, we need to correct the galaxy magnitudes for evolutionary effects, as well as make appropriate K corrections. This is the subject of the next section.

5 EVOLUTION OF THE NEAR-INFRARED LUMINOUSITY FUNCTION

Figure 5 presents the optical-$K$ colour-magnitude diagrams for individual clusters. The elliptical galaxy sequence is clearly visible in each of the panels; the slight tendency towards bluer colours at fainter magnitudes is due to a decrease in metallicity (see e.g. Bower, Lucey & Ellis 1992). The median colour of galaxies within 3 magnitudes of the brightest galaxy detected in each cluster (this is the cD for all but A1795) is presented in Table 4 where it is compared with the predicted colour for passively evolving luminous ellipticals at the redshift of the cluster. The table shows that the two numbers agree very well for all our clusters which is not surprising in light of the results of Stanford, Eisenhardt & Dickinson (1998), as described in Section 1. This implies that we can now make joint evolutionary (which arise because the spectral energy distributions of the galaxies vary with cosmological time) + K (which arise because the $K$-band is probing different regions of rest-frame wavelength space for galaxies in clusters seen at different redshifts) corrections to the cluster luminosity functions directly from stellar population synthesis models. We can then compare galaxies in clusters at different redshifts.

We estimate these corrections using the prescription of Pozzetti, Bruzual & Zamorani (1996) which is based on the population synthesis models of Bruzual & Charlot (1993) – see Table 5. In effect what is done is to evolve a local old stellar population backward in time and derive the corrections for the $K$-band at each cluster redshift. We then apply the corrections
to the LFs and correct them to \( z = 0 \). We apply the correction to the LF as a whole, assuming corrections appropriate to E/SO galaxies, and not to each galaxy individually since we are unable to measure the morphologies and Hubble types of the galaxies in the distant clusters because the scale-lengths are smaller than the seeing (for the nearby clusters the \( K \)-band evolutionary + \( K \) corrections only vary weakly with Hubble type; see Fig. 2(b) of Pozzetti et al. 1996). That the E/S0 approximation is a good one is suggested by the results of Stanford, Eisenhardt & Dickinson (1998) and confirmed for the clusters in our sample by the colours that we measure, as presented in Figure 5 and described in the previous paragraph.

A weighted average of luminosity functions of these five individual clusters is computed and presented in Fig. 6. The \( K \)-band field luminosity function from a recent medium-deep survey (Szokoly et al. 1998) is presented there as well, normalized to minimize scatter with the cluster points.

The luminosity functions for individual clusters are all consistent with this composite function within a normalization constant (see Table 6 for the normalization constants and parameters that describe the quality of the fits). The agreement between the individual clusters and the composite function appears to be very good, but the statistics for each individual cluster are very poor (particularly for MS1054). However, within the uncertainties, it appears that the shape of the \( K \)-band luminosity function in rich clusters does not vary strongly with redshift.

A similarly close agreement was found between the luminosity functions of different rich clusters in the \( B \)-band (Trentham 1998a), where the statistics were much better. The average slopes of the luminosity function between \( M_{cD} + 1.5 \) and \( M_{cD} + 4.5 \) is \( \alpha = -1.33 \pm 0.07 \) in the \( B \)-band and \( \alpha = -1.38 \pm 0.24 \) in the \( K \)-band (here \( M_{cD} \) is the magnitude of the brightest cD galaxy in the sample and \( \alpha \) is the logarithmic slope of the luminosity function: \( \log N = -0.4(\alpha + 1)M + \text{constant, by convention} \)). The concordance between these two numbers is not surprising because both luminosity functions are probing the same galaxy
population (i.e. the giant ellipticals) at bright magnitudes – in Abell 963, which is a Butcher-Oemler cluster, the blue population is < 20% of the total galaxy counts at bright magnitudes.

We also note a concordance between the composite cluster and field luminosity functions in the $K$-band, although this may in part be due to poor statistics. The significant difference observed between the Trentham (1998a) cluster and Loveday et al. (1992) field samples at the very bright end was only seen at $M_B < -20$. In the $K$-band, this corresponds to $M_K < -24$. The luminosity functions presented in this work have error bars that are too large to assess whether such a difference is present in the $K$-band (if the interpretation given in Section 1 of this paper is correct, we would expect the difference to be significantly smaller in $K$ than in $B$).

Therefore, the numbers in Table 6 suggest that the shape of the luminosity function is consistent within our sample. In Fig. 7 we investigate how the normalization varies. Here we plot the projected $K$-band luminosity density of the cluster relative to the total X-ray luminosity. The figure has large error bars, but this ratio does not appear to systematically vary with redshift. The likelihood here is that the total $K$-band luminosity of a rich cluster of given X-ray luminosity at any redshift, when passively evolved to $z = 0$, does not depend strongly on the redshift of that cluster. For this to be true, we need to assume that the clusters in this sample are representative for rich X-ray clusters at their respective redshift. While this assumption is fairly secure for $z \sim 0.2$, there are hints that it may not be correct at higher redshifts. This is addressed in the next section. As more deep $K$-band images of galaxy clusters become available, better statistics will be acquired for the kind of comparison shown in Fig. 7 (the other studies that we list in Section 1 are not deep enough to be placed on this figure); these observations will provide a strong constraint on both the formation and evolution of old stellar populations in clusters.
6 DISCUSSION AND CONCLUSIONS

The main result of this study is that the shape and normalization (relative to the total X-ray luminosity of the cluster) of the $K$-band luminosity functions of X-ray luminous clusters do not change between $z = 0.2$ and $z = 0.8$ (the redshift of the most distant known X-ray luminous clusters), within the errors of our measurements. One cannot be certain that we are probing the same population of objects seen at different redshifts because the X-ray luminosities of specific objects in a given X-ray energy band may increase with time because of accretion of gas or decrease because of evaporation. However, at all redshifts, these X-ray luminous clusters are the largest bound objects known in the Universe. Therefore, the indications are that by looking at galaxies in such objects at different redshifts, we are probing the evolution of galaxies in a single population of clusters. The fact that the luminosity function does not change significantly suggests that neither tidal destruction (which would skew the luminosity function towards lower luminosities at lower redshifts) or merging of galaxies (which would skew the luminosity function towards higher luminosities at lower redshifts) are important processes for early-type galaxies in clusters between $z = 0.8$ and $z = 0.2$. Presumably tidal destruction is not an efficient process because the early-type galaxies are dense (this is inferred from their position in the infrared fundamental planes – Pahre, Djorgovski & De Carvalho 1997, Mobasher et al. 1998) and not easily destroyed. Also, merging is not expected to be an efficient process because the clusters have high velocity dispersions and hence galaxies are moving fast relative to each other. When combined with the results of Stanford, Eisenhardt & Dickinson (1998), our results suggest that not only had the stars seen in present-day cluster ellipticals formed by $z = 0.8$, but they existed in as luminous galaxies then as they do today.

The $K$-band luminosity functions are very insensitive to contributions from late-type galaxies that are currently forming stars and are very luminous in the $B$-band. As explained in Section 1, such galaxies do exist in clusters at high redshifts, but they are probably a different population of galaxies altogether from the present-day cluster ellipticals (they
are more likely to be associated with present-day cluster lenticular galaxies – Dressler et al. 1997).

The main limitations of this work are as follows. Firstly, the sample is small and the error bars in Figs. 6 and 7 are quite large. Obtaining better statistics at the faint end is very difficult because the background contamination is severe. Better statistics at the bright-end are difficult to obtain because we need to image over wide areas to improve counting statistics. Such measurements will be much easier with the next generation of 2K and bigger mosaic infrared arrays that are currently under construction. With larger arrays we would also be able to extend our analysis down to \( z = 0 \). Secondly, it is not clear that we really are probing typical examples of the most X-ray luminous objects in the Universe at high redshift. If optically dark high redshift clusters (the MG2016+112 lensing cluster may be an example) are common, those at \( z > 1 \) would be undetected in the ROSAT NEP survey, and those at \( z \sim 1 \) which are detected with ROSAT would be difficult to identify as a galaxy cluster based on optical follow-up work. These would have very different galaxy populations from clusters like MS1054. If MS1054 is atypical for an X-ray luminous cluster at high redshift, this would weaken or invalidate the above conclusions.

Finally, the clusters have a \( K \)-band luminosity function which is consistent with the \( K \)-band field luminosity function of Szokoly et al. (1998) for \(-24 < M_K < -22\). We cannot make a comparison brighter than this because of poor counting statistics in the cluster sample, or fainter than this because the field sample does not reach such faint limits.

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FIGURE CAPTIONS

Figure 1. The $K$-band images of the clusters fields used in this study. In each image North is up and East is to the left. The images were reduced as described in the text; instrumental configurations, exposure times, and field sizes are given in Table 2.

Figure 2. Galaxy number counts versus $K$ magnitude for the sample clusters. The clusters which were observed through the $K'$ filter have their magnitudes converted to $K$ magnitudes using the conversion equation $K' - K = 0.22(H - K)$ (Wainscoat & Cowie 1992), assuming $H - K \approx 0.75$ (Stanford, Eisenhardt & Dickinson 1995) for typical cluster galaxies at $0.06 < z < 0.2$, most of which are early-type. The dashed lines show the predicted background counts (from the compilation of Mobasher & Trentham 1998). The error bars come from counting statistics.

Figure 3. Corrections for gravitational lensing applied to the background counts before subtraction, for each of the cluster fields. The ratio $f_{\text{lens}}$ represents the ratio of background/foreground number counts for a line of sight seen through the cluster dark matter relative to the background/foreground number counts in a typical random blank field. The results here were calculated according to the recipe given in Trentham 1998b, assuming isothermal sphere lenses with velocity dispersions $\sigma$ of 1210 km s$^{-1}$ for MS1054, 1510 km s$^{-1}$ for MS0451, 1290 km s$^{-1}$ for A963, 1200 km s$^{-1}$ for A665 and 887 km s$^{-1}$ for A1795. The velocity dispersion for A1795 is that measured by Girardi et al. 1996); the others were derived using the $L_x - \sigma$ correlation of Quintana & Melnick (1982).

Figure 4. Luminosity functions for the sample clusters, computed from the number counts (Fig. 2) as described in the text. The luminosity function of A41 is not presented since the background counts dominate at all magnitudes fainter than that of the cD galaxy. The error bars here represent the quadrature sum of errors from counting statistics and the field-to-field variance in the background.
Figure 5. Colour-magnitude diagrams for the cluster fields. The colours are those for a 3 arcsecond diameter aperture as described in the text. This aperture is large enough (> 2 FWHM for A1795, and > 3 FWHM for the other clusters) that systematic effects due to differences in the seeing between the optical and $K$-band images are small. The colours for MS1054 and MS0451 assume ST magnitudes (see e.g. Synphot Users Guide published by STScI).

Figure 6. The composite luminosity function. This is the weighted average of the combined evolution- and K- corrected luminosity functions of the individual clusters, where the corrections are made as described in the text. Here $M_{K,corr}$ represents the absolute $K$-band magnitude of a galaxy in a distant cluster passively evolved to $z = 0$. The normalization is arbitrarily selected to be for a cluster having the same number of galaxies as A963 in the $-23 < M_{K,corr} < -22$ bin. The field points are from the data of Szokoly et al. (1998; median sample redshift $z \sim 0.2$), evolved to $z = 0$ in a manner consistent with the cluster data. This was normalized so as to minimize the scatter with the cluster luminosity function.

Figure 7. The integrated $K$-band luminosity per square kpc in galaxies brighter than $M_{K,corr} = -20$, relative to the X-ray ($2 - 10$ keV) luminosity for our sample, plotted as a function of redshift. Presenting the $K$-band total luminosities as a density allows us to correct for the (small) areas in our cluster field rest-frame sizes, while maintaining as small error bars as possible. In all cases the field size corresponds approximately to the cluster core (see Table 3). We do not include A1795 on this plot since only a small region of the core is imaged there which was selected a priori to have a higher than average density of elliptical galaxies. The X-ray luminosities were computed from the luminosities in Table 1, assuming a thermal brehmsstrahlung spectrum (neglecting the frequency dependance of the Gaunt factors – see Sarazin 1986) and the temperature-luminosity relation of Mushotzky (1984).
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Composite

- Cluster
- Field

$\log_{10}(N_{\text{gal}} \text{ deg}^{-2} \text{ mag}^{-1})$

$M_{K,\text{corr}}$
