X-ray bright groups and their galaxies

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Abstract

Combining X-ray data from the ROSAT PSPC and optical data drawn from the literature, we examine in detail the relationship between the X-ray and optical properties of X-ray bright galaxy groups. We find a relationship between optical luminosity and X-ray temperature consistent with that expected from self-similar scaling of galaxy systems, $L_B \propto T^{1.6\pm0.2}$. The self-similar form and continuity of the $L_B : T$ relation from clusters to groups and the limited scatter seen in this relation, implies that the star formation efficiency is rather similar in all these systems. We find that the bright extended X-ray components associated with many central galaxies in groups appear to be more closely related to the group than the galaxy itself, and we suggest that these are group cooling flows rather than galaxy halos. In addition we find that the optical light in these groups appears to be more centrally concentrated than the light in clusters.

We also use the optical and X-ray data to investigate whether early or late type galaxies are primarily responsible for preheating in groups. Using three different methods, we conclude that spiral galaxies appear to play a comparable role to early types in the preheating of the intragroup medium. This tends to favour models in which the preheating arises primarily from galaxy winds rather than AGN, and implies that spirals have played a significant role in the metal enrichment of the intragroup medium.

Key words: X-rays: galaxies: clusters – X-rays: galaxies – intergalactic medium – galaxies: clusters: general – galaxies: evolution

1 INTRODUCTION

The environment of a galaxy may have a significant effect on the properties and evolution of the galaxy itself. For example, galaxy clusters are well known to show a relationship between galaxy morphology and density (e.g. Dressler 1980; Dressler et al. 1997), which suggests some sort of environmental influence on the galaxies. By examining the properties of galaxies as a function of environment it should be possible to gain important insights into the evolution of both galaxies and galaxy systems. Particularly interesting is the group environment, which is typically made up of between three and a few tens of gravitationally bound galaxies. It is important to understand the impact of the group environment on galaxies as the majority of galaxies are found in a group environment (Tully 1987), and galaxies in clusters and the clusters themselves will have once been part of groups. In particular, the group environment is likely to have a significant impact on its galaxies as the density and velocities of the member galaxies suggest that mergers and interactions are more common than in clusters or in the field (e.g. Mamon 1992, 2000). However, these systems are also small enough that it is possible for the member galaxies to visibly affect the properties of the group as a whole.

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or AGN, and this effect can be reproduced by theoretical analyses which include the effects of preheating (e.g. Balogh et al. [1999], Cavaliere et al. [1995, 1999]). However, the effects of cooling may also reproduce this steepening if a large fraction of the gas cools out within groups (Bryan et al. [2001], Pearce et al. [2002], Voit & Bryan [2001], Muanwong et al. [2003]). Pre-heating of the gas by the member galaxies is an example of a situation where the galaxies themselves are affecting the evolution and properties of the group. It is also likely that the group environment will play a role in shaping the properties and evolution of the member galaxies.

Little work has been published on the relationship between X-ray properties of groups and optical properties such as total optical light and spiral fraction. Previous work (e.g. Malhadi et al. [1993], Mulchaey et al. [1999]) has mostly been based on samples which are small or contain optical and X-ray data from a wide variety of sources which may not be directly comparable with one another. In this and a companion paper (Helsdon & Ponman 2002) we aim to look in some detail at the relationship between the X-ray and optical properties of X-ray bright galaxy groups using a consistent approach. In Helsdon & Ponman (2002) we focus primarily on the morphology-density relation in X-ray bright groups, whilst here we focus more on the overall relationship between X-ray and optical group properties. For the X-ray data we use the 24 galaxy groups analysed in detail by Helsdon & Ponman (2000a). These groups all contain a hot intragroup medium, and thus represent a sample of bound and collapsed groups. We will combine this X-ray data with optical data drawn from the literature, taking care to ensure that the optical data for each group is derived in a way that enables the groups to be directly compared with one another. Examining the optical properties for the groups and their relationship with the X-ray properties will enable us to gain important insights into the evolution and structure of these systems.

This paper is organised as follows. In §2 we describe the sample and how we obtain the optical information. We also explain how we attempt to ensure that the optical data for each group is derived in a fair and consistent manner. In §3 we present the basic analysis of the data, including relations between optical properties, such as total optical luminosity, and X-ray properties such as the group temperature. We also examine the relationship between the central galaxy and the group, and look at the morphological makeup of these systems. In §4 we discuss the implications of our results and look in more detail at some aspects such as the origin of preheating in these systems. Our conclusions are summarised in §5. Throughout this paper we use $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$.

2 THE SAMPLE

The X-ray properties of the groups used in this paper are taken from Helsdon & Ponman (2000a), and detailed descriptions of the data reduction and analysis may be found in that paper. The authors analyse pointed ROSAT PSPC observations of 24 X-ray bright groups, and it is these 24 systems which form the sample of groups used in this paper. These systems were originally identified from three different sources, the optical group catalogues of Nolthenius (1993) and Ledlow et al. (1999) were examined to identify 15 X-ray bright groups, and then included were the 9 X-ray bright groups from Mulchaey & Zabludoff (1998). Helsdon & Ponman (2000a) excluded contaminating sources, including background point sources and emission from non-central galaxies, and extracted a count rate and spectrum within a radius determined for each group by examining a smoothed image and group profile. A hot plasma model was then used to obtain a temperature and derive a bolometric X-ray luminosity after correction for galactic absorption. This gave 24 groups all with derived luminosities and temperatures. In addition we carried out 2D fits to the surface brightness profiles, in order to derive parameters such as $\beta_{ht}$, which is effectively a measure of the steepness of the profile. The $\beta_{ht}$ values used here are those from the extended component for the groups with 2 component models in Helsdon & Ponman (2000a), and that of a single component for the remainder.

When deriving the optical properties of each group (total $L_B$, spiral fraction, etc) it is not satisfactory to simply use the galaxy memberships as given in the original group catalogue, since the galaxies were originally selected from different sources which in general have different selection criteria. Ideally all galaxies in each group down to the same absolute magnitude would be included. Thus we initially define two different magnitude cuts, these are the magnitudes at which 50% and 90% of the total light in an assumed luminosity function would be included. The luminosity function used in this case is that derived from deep imaging and spectroscopy by Zabludoff & Mulchaey (2000) for X-ray bright groups, which is a Schechter function with $\alpha = -1.3$ and $M_* = -23.1$. This luminosity function applies in the $B$-band, whereas throughout this paper $B$-band magnitudes are used. To convert to $B$-band magnitudes, colours given in Fukugita et al. (1995) are used, giving $B - R = 1.57$ for early-type galaxies. We use the $B - R$ for early types, as the majority of the galaxies in these X-ray bright groups are early-types. This procedure gives an absolute magnitude cut in the $B$-band of $M_B = -20.55 \ (\sim 0.4L_\odot)$ for the 50% cut, and $M_B = -16.32 \ (\sim 0.008L_\odot)$ for the 90% cut. For the ‘typical’ group in our sample ($\sim 50000$ km/s) this corresponds to an apparent magnitude of $\sim 14.4$ for the 50% cut and $\sim 17.2$ for the 90% cut.

For each group we searched the NASA/IPAC Extragalactic Database (NED) for galaxies lying within the group virial radius in projection on the sky, and having recession velocities within three times the group velocity dispersion ($3\sigma_g$) from the catalogued group mean. The virial radius of each group (typically $\sim 1$ Mpc) is calculated using $R_V = 1.14(T/1$ keV)$^{\frac{1}{2}}$ Mpc which can be derived from relations obtained in simulations by Navarro et al. (1999). Whilst it is known that the velocity dispersion of a group may be significantly underestimated when based on only a few members (e.g. Zabludoff & Mulchaey [1998]) this should not be a big problem for this sample. Over half the sample have velocity dispersions calculated from 15 members or more, and all but 5 have velocity dispersions calculated from at least 7 members. The centre position used for each group is the centre of the X-ray emission. In most cases this position is very close to the position of the central galaxy, with the three exceptions being bimodal systems in which the X-ray centre falls roughly between the two main galaxies. We also only selected galaxies brighter than the groups...
of galaxies to the 90% luminosity cut within the virial radius and spiral light fraction respectively. ∆_B is the extended component surface brightness index from Helsdon & Ponman (2000a); total ≈ galaxies added to the 90% cut (typically only increasing the online Lyon-Meudon Extragalactic Database (LEDA) alone gives no indication of how complete the sample of 90.

**Table 1.** The X-ray and optical data. L_X, T and β_{sp} are the X-ray luminosity (bolometric and absorption corrected), temperature and extended component surface brightness index from Helsdon & Ponman (2000a); total L_90, early L_90 and late L_90 are the total optical luminosity, early-type luminosity and late-type luminosity all in the B-band. The columns titled f_{sp} are the spiral number fraction and spiral light fraction respectively. ∆_M12 is the difference in magnitude between the first and second ranked galaxy. N_{gal} is the number of galaxies to the 90% luminosity cut within the virial radius and σ_v is the group velocity dispersion as given in Helsdon & Ponman (2000a). The flagged group names have the following commonly used alternative names — 1-HCG 42, 2-HCG 62, 3-HCG 68, 4-HCG 90.

90% apparent magnitude cut. Unfortunately this selection alone gives no indication of how complete the sample of galaxies is in each group. To try to better determine this, the online Lyon-Meudon Extragalactic Database (LEDA) catalogue was searched over the same position and velocity range. This search found no extra galaxies to each group’s 50% magnitude cut, and only 7 out of the 24 groups had galaxies added to the 90% cut (typically only increasing the total optical luminosity by ~ 4%). For galaxies with a known redshift the LEDA catalogue is ≈ 90% complete to a B-band magnitude of 14.5 (Amendola et al. 1993, Paturel et al. 2002). The typical group in this sample has the 50% magnitude cut at ~ 14.4 so most groups should be at least 90% complete to their 50% cut, just from the LEDA samples. Given this, and the fact that NED almost always lists more galaxies than LEDA (many of these systems have been the subject of specific membership studies which have been added to NED) we believe that our derived optical properties (to our 90% cut) such as the total B-band luminosity, while an underestimate, will be at the worst a factor of two too low, with most cases better than this. An estimate of the typical incompleteness can be made by comparing over all the groups the total optical luminosity within the 90% cut with 1.8 (=0.9/0.5) times the total luminosity within the 50% cut. This comparison suggests that typically we are missing ~35% of the total group light at the 90% cut. However, given that there could be some trends in incompleteness in the optical data, we will consider below the possible effects of incompleteness on our results.

Morphological types are taken firstly from NED if available, and then LEDA. The galaxies are split into early (elliptical and S0) and late (spiral and irregular) type samples. Galaxies on the borders of the morphological classes are put into the earlier type — e.g. an E-S0 will be classed as elliptical and an S0a will be classed as an S0. For each group we calculate the total light, light in early types, light in late types, fraction of light in late types and the difference in magnitude between the first and second ranked galaxies. The galaxy magnitudes used from NED are those listed on the initial search page. This means that the magnitudes of the individual galaxies may not all be exactly comparable to one another, but the effect of this on the derived total group optical luminosities should be small compared to the effects of incompleteness.

The derived optical properties for each group are listed in Table 1 along with the appropriate X-ray derived parameters. All optical parameters are derived for the virial radius, 3σ_v sample based on the 90% magnitude cut, using the distances given for the groups in Helsdon & Ponman (2000a).

It can be seen that in a few cases the early type light and late type light does not add up to the total light. This is because these groups have some galaxies which did not have types listed in either NED or LEDA, although the contribution to the total light from these untyped galaxies is almost...
Figure 1. Group optical luminosity versus X-ray temperature. Solid line is best fit to data, and dashed line is the joint fit to groups and clusters by Lloyd-Davies & Ponman (2001).

always much less (all <10% apart from NGC 5171) than the contribution from galaxies with known morphological type.

It should be noted that the group sample used here should not be regarded as being statistically complete in any way. However, we do not believe that this will introduce any particular bias, other than the fact that since we only use groups with detected diffuse X-ray emission, we do not include systems with undetectably faint intergalactic gas. The group sample should rather be regarded as a reasonably representative sample of X-ray bright groups.

3 RESULTS

3.1 Optical light in groups

The X-ray temperature of a galaxy group is a measure of the depth of the gravitational potential well, and hence a measure of the system size and mass. It is clearly of interest then, to examine how the temperature relates to the total optical light in a group. Thus we plot in Figure 1 the total B-band light for each of the groups as a function of X-ray temperature. It is clear that there is a significant correlation between these two parameters, and the significance of Kendall’s rank correlation coefficient (a distribution-free test for correlation) is $K = 3.77$ ($P = 0.00017$ of chance occurrence). Any trend in optical incompleteness, if present, would have the effect of producing a correlation in the opposite direction to that observed here (the hotter systems tend to be further away). As far as the authors are aware, this is the first time that a correlation between these two parameters has been reported for galaxy groups. Given the origin of the galaxy magnitudes it is difficult to calculate an exact error on the integrated B-band luminosity for every group and errors on the log $L_B$ values are all taken to be ±0.05. Comparison of this value with typical errors of galaxy magnitudes in NED suggest that this is a reasonable estimate of the error. The distribution of the points (with known temperature errors) suggest that there is more scatter than would be expected due to statistical errors alone. As a result of this, we do not weight by statistical errors when fitting regression lines to the data. All lines are derived using the program SLOPES (Feigelson & Babu 1992) which derives six different linear regressions on the data, along with error analysis. All fits given here use the bisector of the ordinary least squares regression of $y$ on $x$ and $x$ on $y$, as this method performs best for a symmetrical treatment of the variables (Isobe et al. 1990). Regression uncertainties are derived using jackknife resampling as the standard formulae for calculating uncertainties underestimate the errors for $N ≤ 50$ (Feigelson & Babu 1992).

The best fit line to the data presented in Figure 1 is

$$\log L_B = (11.70 ± 0.04) + (1.64 ± 0.23) \log T.$$

Also plotted for comparison is the line derived by Lloyd-Davies & Ponman (2001) for a sample of systems ranging from groups to clusters. These authors attempted to correct for the effect of any incompleteness in their optical sample, and derived a line with a slope of 1.5 ± 0.2. As can be seen, the slopes of the two relations are consistent with one another, and the lower normalization of the present sample is consistent with the Lloyd-Davies & Ponman line if 25% to 35% of the optical light is missed in the low luminosity end of the luminosity function for our groups. This is consistent with what we would expect given our sample selection as described in §2.

Given this correlation between $L_B$ and temperature, and the known correlation between X-ray luminosity and...
temperature (Helsdon & Ponman 2000a,b), it is expected that there would also be a correlation between $L_X$ and $L_B$. In Figure 3 we plot $L_X$ versus $L_B$ for the 24 groups in this sample. As can be seen there is a significant correlation ($K = 3.82, P = 0.00014$). Once again, any systematic trend in incompleteness would act to produce a correlation in the opposite sense to that observed - the more X-ray luminous groups tend to be further away and are thus more likely to be incomplete. We fit a line using the method outlined above (ignoring the four marked outliers which are discussed below) to obtain,

$$\log L_X = (40.88 \pm 0.18) + (2.69 \pm 0.29) \log \left( \frac{L_B}{10^{11} L_\odot} \right),$$

which is also plotted in Figure 3. Alternatively, we could have plotted $L_X/L_B$ vs $L_B$ which gives a best fit line of $\log L_X/L_B = (29.83 \pm 0.18) + (1.77 \pm 0.28) \log(L_B/10^{11} L_\odot)$. Note that we express these two fits in x-axis units of $L_B/10^{11} L_\odot$ to avoid a large correlation between the errors in slope and intercept. While the line appears to generally describe the trend well, there are four points which deviate significantly (note that the inclusion of these four points does not significantly alter the best fit — including these points gives an intercept and gradient of 40.91 ± 0.21 and 2.63 ± 0.36 respectively). The first of these outliers, NGC 4325, lies well above the trend, and is probably unusually X-ray luminous as it also lies well above the X-ray $L_X : T$ relation. The origin of this high X-ray luminosity is unclear - as far as we are aware, no indications have been reported of AGN activity, and the galaxy is undetected in the FIRST (White et al. 1997) and NVSS radio surveys (Condon et al. 1998). The other group lying above the trend, NGC 6338 (the least severe of these outliers), may have some contamination by an AGN (Hwang et al. 1999), although it is also the most distant system in this sample, and thus its optical luminosity may be underestimated more than the other groups. The remaining two groups, HCG 68 and NGC 4261 fall well below the trend, and although they both do fall just below the group $L_X : T$ relation, they do not have a particularly low $L_X$ for their temperature. The alternative is that these two systems may have an excess of optical light, possibly due to luminous galaxies at the borders of the systems. To investigate this we plot in Figure 3 the fraction of the total cumulative light as a function of group virial radius, for all groups in this sample. In Figure 4 we show the corresponding plot for HCG 68 and NGC 4261 separately.

As can be seen in Figure 3 these groups typically contain ~60% of their total light within a projected distance of a third of their virial radius. We have fit a powerlaw to these data and find a best fit of $L_B(<r) \propto r^{0.34 \pm 0.06}$ (last data point was ignored as a few groups showed ‘kicks’ in their profiles in the final bin — see below). For comparison, galaxy clusters tend to have projected galaxy number densities $\propto r^\alpha$ with $-1.4 < \alpha < -1.0$ (e.g. Beers & Tonry 1986; Oegerle et al. 1986; Squires et al. 1996; Carlberg et al. 1997; Trévese et al. 2000). This implies projected cumulative light profiles in clusters of between $L_B(<r) \propto r^{0.6}$ and $L_B(<r) \propto r^{1.0}$, consistent with that actually observed in some clusters (e.g. Squires et al. 1996). To demonstrate this more clearly, we show the cluster profile inferred from the Carlberg et al. (1997) Hernquist model fit to the surface density profile derived from their sample of 14 clusters (the normalisation is adjusted to match our fit). This means that clusters appear to have much steeper cumulative light profiles, suggesting that the optical light (and galaxies — the implied group 3D galaxy density profile is $\propto r^{-2.66}$) in X-ray bright groups is more centrally concentrated than in typical clusters.
This distribution of optical light is more concentrated than would be inferred from previous measures of the galaxy distribution in loose groups (Hickson & Rood 1988; Walker & Mann 1989; Carlberg et al. 2001), also displayed in Figure 3, and less concentrated than similar estimates for Hickson compact groups (Mendes de Oliveira & Giraud 1994; Montoya et al. 1996). However these differences are not particularly surprising. Previous studies of loose groups are based on optically selected samples, and it is possible that they included some spurious groups or systems at an early stage of virialisation (only a fraction are likely to be X-ray bright), both of which could easily act to produce a less concentrated profile. Additionally, in almost all systems in this X-ray bright group sample, a bright early-type galaxy is located at the centre, whereas the centres of optically defined groups may not be located on any galaxy, which again would act to produce a less concentrated profile. In comparison, the compact groups, while likely real systems, have generally only been studied to a small fraction of the radii used here, and large extrapolations are needed, on the profiles which are not strongly constrained.

As for offsets from the group $L_X : L_B$ relation, Figure 4 clearly shows that NGC 4261 has an unusual light profile. In fact, almost half the group optical light is found beyond a radius of 0.75 $R_V$. Clearly, for this group its high optical luminosity is caused by galaxies at large radius which might only now be joining the group, or might even be nearby foreground or background objects — this group is near Virgo. Whilst a few other groups show similar ‘kicks’ at large radius, NGC 4261 is the most extreme example by far. In contrast, the remaining $L_X : L_B$ outlier, HCG 68, does not show much evidence of contamination at large radius and just appears to have a very high optical luminosity relative to its X-ray luminosity. It should be noted that although these plots show evidence of a small amount of contamination at large radii in these groups, this contamination only represents a small fraction of the total light (5-10%), an even smaller fraction of the total number of galaxies and as such we do not expect it to significantly affect our main results.

We have also examined the $L_B : T$ and $L_X : L_B$ relations as a function of morphological type. The data for these are plotted in Figures 5 and 6 and the correlation strengths and fit results are summarised in Table 2. As can be seen the total light in early type galaxies correlates well with both X-ray temperature and luminosity whilst the same relations...
Table 2. Correlations and fits to full and morphological subsets of data versus X-ray temperature and luminosity. All fits are in log space.

| Relation                              | correlation | P         | intercept | slope   |
|---------------------------------------|-------------|-----------|-----------|---------|
| Total optical light versus temperature| 3.77        | 0.00017   | 11.70 ± 0.04 | 1.64 ± 0.23 |
| Early type light versus temperature   | 3.52        | 0.00043   | 11.52 ± 0.04 | 1.53 ± 0.19 |
| Late type light versus temperature    | 1.82        | 0.009     | 11.11 ± 0.11 | 2.3 ± 0.7   |
| (Total optical light/10^{11}) versus $L_X$ | 3.82    | 0.00014   | 40.88 ± 0.18 | 2.69 ± 0.29 |
| (Early type light/10^{11}) versus $L_X$ | 3.77    | 0.00017   | 41.26 ± 0.15 | 2.87 ± 0.31 |
| (Late type light/10^{11}) versus $L_X$ | 1.29    | 0.2      | 42.54 ± 0.17 | 1.36 ± 0.24 |

As can be seen in Figure 5, there is a significant correlation between $\beta_{\text{spec}}$ and the light in early-types ($K = 2.98$, $P = 0.003$), but not with the late-type light ($K = 1.08$, $P = 0.28$). There is unlikely to be any trend due to incompleteness, as $\beta_{\text{spec}}$ does not correlate with distance. Low values of $\beta_{\text{spec}}$ would tend to suggest that there is more energy in the gas than in the galaxies and that some sort of energy has been added to the gas. A naive interpretation of this result would be that late type galaxies do not contribute in a systematic way to the injection of energy, and that systems with few early types have had the most energy injected. However there are a number of complicating factors. Smaller systems will show the effects of any energy injection more readily than larger systems, and will also tend to contain a lower fraction of early-types (e.g. see Figure 10). Most of the light in these systems is contained in early-type galaxies, so there is likely to be more scatter in relations involving late-type light. Finally $\beta_{\text{spec}}$ is calculated from the group velocity dispersion which may be quite poorly determined for some of the poorer systems in this sample. We will return to the issue of the origin of injection of energy into the intragroup medium in §4.3.

3.2 Central galaxies in Groups

Most X-ray bright groups contain a bright early-type galaxy located at the centroid of the group X-ray emission. These galaxies are also centrally located according to both the projected and velocity distributions of the member galaxies (Zabludoff & Mulchaey 1998), and may be formed by galaxy merging which occurs soon after the initial collapse of the group (Governato et al. 1996). Given their special position within the group these galaxies are likely to have properties closely related to the group. For example, the position angle of the optical light of the central galaxy tends to align with the position angle of the group X-ray emission (Mulchaey & Zabludoff 1998). In a previous paper (Helson et al. 2001) we derived X-ray luminosities for 11 central galaxies in groups for which we had two-component models. These two-component models allowed the separation of a component coincident with the central galaxy and an extended component associated with the bulk of the group. Here we examine the relationship between the X-ray and optical properties of these central galaxies and those of the group as a whole.

In Figure 6 we plot 4 graphs showing the relationship between central galaxy X-ray luminosity (luminosity of central X-ray component), central galaxy optical luminosity,
Figure 7. Group $\beta_{\text{spec}}$ versus total early type light (a) and total late type light (b). The dashed line corresponds to $\beta_{\text{spec}} = 1$.

Figure 8. a) Central galaxy $L_X : L_B$ relation. The dashed line is from Beuing et al. (1999). b) Group $L_X$ versus galaxy $L_B$. c) Galaxy $L_X$ versus group $L_X$. Dotted line marks galaxy $L_X = 33\%$ of group $L_X$. d) Group $L_X$ versus galaxy $L_X/L_B$. Solid line is best fit to data. The group luminosities do not include the central galaxies.
and group X-ray luminosity (for the 11 groups with two component models to the X-ray emission). We use a slightly different group X-ray luminosity in Figure 9 as the luminosities quoted in Helsdon & Ponman (2000a) (and used throughout the rest of this paper) include the contribution assigned to the central galaxy. We subtract this central component from the group luminosity to avoid any bias when comparing the group luminosity to the galaxy X-ray luminosity (which is calculated from this central component). Firstly we show the galaxy \( L_X : L_B \) for these galaxies, and plot for comparison the best fit line obtained by Beuing et al. (1999) for a large sample of early-types (in a variety of different environments). It can be seen that the points are not strongly correlated \( (K = 0.47) \) and that they scatter about the Beuing et al. (1999) line. This is not particularly surprising as the range in \( L_B \) is small and the early-type \( L_X : L_B \) relation is known to have a scatter of between one and two orders of magnitude (e.g. Canizares et al. 1987; Edge & Ekebridge et al. 1991). We also show the relationship between central galaxy optical luminosity and group X-ray luminosity, which shows no correlation \( (K = -0.31) \). However there is a pronounced correlation between the central galaxy X-ray luminosity and the group X-ray luminosity \( (K = 2.10, P = 0.036) \). This correlation is approximately linear with the X-ray luminosity of the central galaxy being about 33\% that of the group (shown by the dotted line — equivalent to 25\% of the total group luminosity including this component). The correlation is strongest in the final plot which shows the group \( L_X \) against the galaxy \( L_X / L_B \) \( (K = 2.41, P = 0.016) \), along with the best fit line \( (\text{slope}=0.9 \pm 0.2) \).

The much stronger correlation between the X-ray properties of the central galaxies with the group, rather than the optical light of the galaxy suggests that the majority of the X-ray emission of these central X-ray components is associated with the group, rather than the galaxy itself. Given that almost all of the groups shown in Figure 9 show evidence of a temperature drop in their central regions (Helsdon & Ponman 2000a), it seems likely that the central components seen in these X-ray bright groups is actually due to a group cooling flow, rather than any property of the galaxy itself.

Another interesting issue to examine is whether systems which have a very dominant central galaxy (i.e. much brighter than any other group members) show any difference from systems with several galaxies of similar optical luminosity. The dominance of the central galaxy is estimated by obtaining the difference in blue magnitude between the brightest and second brightest galaxies in the group \( (\Delta m_{12}) \). Strictly speaking, \( \Delta m_{12} \) only measures the dominance of the central galaxy if the central galaxy is indeed the brightest galaxy. For two of the groups (NGC 5353 and NGC 4261) the central galaxy is not the brightest galaxy and both have a more luminous spiral in the outer regions. For consistency we simply use the definition of \( \Delta m_{12} \) above but note that excluding the bright spiral in these groups does not significantly change our results. The brightest galaxy in all other groups is a centrally located early-type. It is of particular interest to compare \( \Delta m_{12} \) with offset from the mean group \( L_X : T \) relation. It might be expected that systems with high values of \( \Delta m_{12} \) will lie above the relation, since there is some evidence that fossil groups (Ponman et al. 1994; Mulchaey & Zabludoff 1999; Vikhlinin et al. 1999; Jones et al. 2000), which generally have \( \Delta m_{12} \geq 2.5 \), lie above the \( L_X : T \) relation (Jones et al. 2000).

In Figure 9 we plot \( \Delta m_{12} \) versus residual from the \( L_X : T \) relation given by Helsdon & Ponman (2000b). As can be seen, there is no trend in the data, and no suggestion that systems with high values of \( \Delta m_{12} \) lie above the \( L_X : T \) relation. We also find no correlation of \( \Delta m_{12} \) with any other group property.

3.3 Spiral fractions
X-ray bright groups tend to have low spiral fractions (Mulchaey et al. 1996) and generally contain bright early-type galaxies at their centres (Zabludoff & Mulchaey 1998). Given that there is some sort of connection between the morphological makeup of a group and its X-ray properties, it is natural to look for trends in X-ray properties as a function of spiral fraction.

We initially examine the relation between spiral fraction and group temperature. In Figure 10 we plot the group temperature as a function of spiral fraction and fraction of light in spirals. Note that only 22 systems are plotted, as we have excluded 2 systems with fewer than 4 galaxies of known morphological type. There is a weak trend \( (K = -1.3) \) for cooler systems to contain more spirals, although the fraction of light contained in spirals shows a lot more scatter \( (K = -0.54) \). These trends are consistent with those seen in the Hickson compact groups (Ponman et al. 1996), but offset relative to those seen in clusters (Edge & Stewart 1991). This offset is in the sense that for a particular spiral fraction the groups have a much lower temperature relative to the cluster trend. This is consistent with a scenario in which the morphological transformation of spirals to ellipticals is more efficient in the group environment as is suggested from the morphology-density relation of these systems (Helsdon & Ponman 2002). We have also examined residuals from the group \( L_X : T \) relation to check if any of the scatter in this relation was related to the morphology of the galaxies present. However we found no trend with spiral fraction (e.g. see Figure 14 later) or with the fraction of total group light in spirals.

Finally we have examined trends in \( \beta_{\text{fit}} \) as a function of both spiral number fraction and spiral light fraction. \( \beta_{\text{fit}} \)
**Figure 10.** X-ray temperature of galaxy groups as a function of both a) spiral number fraction and b) the fraction of light in spirals. Note that the two groups with less than four typed members have been excluded.

**Figure 11.** $\beta_{\text{fit}}$ as a function of a) spiral number fraction and b) spiral light fraction, for the eight groups with the most reliable values of $\beta_{\text{fit}}$ identified in Helsdon & Ponman (2000a).
is derived by modelling the surface brightness distribution of the systems with a modified King profile (β-model) of the form $S(r) = S_0 (1 + (r/a)^2)^{-\beta_{\text{fit}} + 0.5}$, where the surface brightness as a function of radius, $S(r)$, is determined by the central surface brightness, $S_0$, the core radius, $a$ and the index, $\beta_{\text{fit}}$. Thus, $\beta_{\text{fit}}$ is effectively a measure of the slope of the gas profiles in these groups, with low values indicating a flatter profile. Although the $\beta_{\text{fit}}$ values for these systems are derived from systems with emission observed to different fractions for the group virial radius, this is unlikely to introduce significant biases in the $\beta_{\text{fit}}$ values. This is because the core radii of these systems are generally much smaller than the maximum extent of the observed emission (Helsdon & Ponman 2000a). Furthermore, Sanderson et al. (2002) show that, at least for clusters, truncating the profiles does not introduce any significant bias in the derived values of $\beta_{\text{fit}}$.

Unfortunately, $\beta_{\text{fit}}$ is still a difficult parameter to measure, especially in data with poor statistics. In addition it is likely that most groups’ surface brightness profiles are described by a two-component model (Helsdon & Ponman 2000a), whereas the data are often only of sufficient quality to fit a single component model. Given this, it is no surprise that the plots of $\beta_{\text{fit}}$ versus spiral fraction for the full sample show a lot of scatter and no significant correlation. However (Helsdon & Ponman 2000a), identified a subset of eight groups which have good quality data, and which are well fit by two-component models. $\beta_{\text{fit}}$ for the extended component in each of these eight systems is plotted as a function of each of the spiral fractions in Figure 1 (We use the alternative form $S_{\gamma}(r/a)^{\beta_{\text{fit}}}$). While it is clear that there is still real scatter in these plots, both the spiral number fraction and the spiral light fraction show a weak negative trend ($K = -1.13$ and $K = -1.48$ respectively, probability of chance occurrence, $P = 0.258$ and $P = 0.139$). This trend is in the sense that groups with more spirals have flatter profiles. It is possible that these trends in $\beta_{\text{fit}}$ as a function of spiral fraction could just be the result of trends in $\beta_R$ and spiral fraction as a function of mass (more massive systems tend to have higher values of $\beta_{\text{fit}}$ and lower spiral fractions). This will be discussed in more detail in §4.3.


the fraction of the baryonic mass found in stars) in these systems. Some previous work has suggested that there is a trend of decreasing star formation efficiency from clusters to groups (David et al. 1990; Arnaud et al. 1992; Pildis et al. 1993; Bryan 2000). However if this were the case then one would also expect the $L_B : T$ relation for groups to be flatter and/or have a higher normalisation than the self-similar cluster relation. Note also, that while using $L_B$ as a trace of system mass could introduce a small bias (lower temperature systems tend to have a higher fraction of spirals which could give an enhancement in $L_B$ relative to the true stellar mass), removing this bias would tend to steepen the observed relation in the direction of lower star formation efficiency in groups. Therefore, the apparent accordance of the $L_B : T$ relation with the self-similar trend seen in clusters suggests that the star formation efficiency does not change significantly between X-ray bright groups and clusters, although it could still change if other parameters conspired to hide this effect. For example, the star formation efficiency would be best quantified from the available mass in gas and the unique $L_B : T$ relation could hide a gas mass fraction that increases with temperature and an optical luminosity to gas mass ratio drops with increasing temperature.

An apparently constant star formation efficiency agrees with recent work by Lloyd-Davies & Ponman (2001) who calculate the star formation efficiency for a number of groups and clusters and see no apparent trend, and with theoretical work by Baugh et al. (1999) who predict approximately the same fraction of cold baryons in group and cluster sized halos. The contrary results from earlier observational work most likely arises because values were derived at a small fraction of the virial radius and extrapolated using a β-model with a value of $\beta_{\text{fit}} = 0.67$. Galaxy groups tend to have flatter X-ray profiles than this (Helsdon & Ponman 2000a), and will therefore contain a large fraction of their gas mass at large radii. Using a value of $\beta_{\text{fit}} = 0.67$ would tend to underestimate the gas mass in groups which, in turn, would lead to an overestimate of the star formation efficiency.

A constant star formation efficiency in groups and clusters has implications for models which invoke cooling as a possible cause of entropy injection (Pearce et al. 2000; Voit & Bryan 2001; Yuanwong et al. 2001). In these models radiative cooling results in the removal of low entropy gas, which in turn leads to an increase in temperature and reduction in luminosity, which is most noticeable in groups. However, if the star formation efficiency is indeed the same in clusters and groups then any cooling gas could not form large quantities of stellar material as this would act to increase the star formation efficiency. Instead the material would have to cool to some dark form.

We have also examined the scatter about the $L_B : T$ relation, as there is clearly more scatter than the statistical errors alone would suggest. A Monte Carlo approach was used to quantify the amount of scatter observed beyond that expected from the statistical errors alone. Initially the orthogonal deviation of the points about the best fit line was calculated. This gave a measure of the total scatter, given that scatter in both the $x$ and $y$ directions may be important. To calculate the scatter expected from the statistical errors we took a dataset in which all the points lay on the best fit line and we then scattered the points in the $x$ and $y$ direction according to the statistical errors. This was re-
peated 1000 times to obtain an average orthogonal deviation expected from the statistical errors. By subtracting this expected statistical scatter from the total scatter, a measure of the intrinsic real orthogonal scatter is obtained. By assuming that all of this orthogonal scatter has its origin in either the \( x \) or \( y \) direction we can estimate the maximum possible scatter in each direction.

For the \( L_B : T \) relation we find that there is about twice as much scatter about the best fit line than the statistical errors would suggest. This corresponds to a scatter of 45% in \( L_B \) for accurate \( T \) or a scatter of 26% in \( T \) for accurate \( L_B \). The 45% scatter allowable in \( L_B \) is actually fairly small, given that some of this scatter is likely to be in the temperature, and that there may be varying levels of optical completeness amongst the groups which would act to increase the scatter. For comparison, the non-statistical scatter in \( L_X \) for a fixed \( T \) is more than 130%. This small scatter in \( L_B \) suggests that variations in the star formation efficiency of X-ray bright galaxy groups must also be small (<45%). Thus overall it would appear that all X-ray bright groups have a fairly similar star formation efficiency, which is similar to that for galaxy clusters.

The relation obtained between X-ray and total optical luminosity (figure 2), \( L_X \propto L_B^{2.6 \pm 0.4} \), is consistent with the relation expected given the previously derived \( L_B : T \) relation and the known \( L_X : T \) relation (Helsdon & Ponman 2000b). This relation has been examined previously by Mahdavi et al. (1997) for groups in the CfA redshift survey, who derive a much flatter relation of \( L_X \propto L_B^{1.06 \pm 0.11} \). However Mahdavi et al. (1997) only have a total of nine data points after removing upper limits, and their X-ray luminosities are based on RASS data, rather than the better quality pointed data used here. Furthermore Mahdavi et al. (1997) extract their X-ray data from a region defined by the optical positions of the galaxies, thus they also include any emission from the galaxy members themselves. This means that their scatter relation may be caused by the galaxy contribution (not necessarily related to the group) becoming significant at lower luminosities.

We have also examined the scatter about the \( L_X : L_B \) relation, as for the \( L_B : T \) relation, (after removing the 3 discrepant points – see §3.1) and find that there is \( \sim 2 \) times as much scatter as the statistical errors would suggest. Taking the scatter in each of the two directions separately we find that the scatter in \( L_B \) is comparable to that derived for the \( L_B : T \) relation, whilst the scatter in \( L_X \) is \( \sim 100\% \), which is comparable to the scatter seen in \( L_X \) about the \( L_X : T \) relation. Thus, as a function of temperature the scatter in \( L_X \) is much greater (3 to 4 times larger) than the scatter in \( L_B \). This suggests that physical processes which vary from group to group have a more marked effect on the gas properties than on the galaxies. For example, processes which have moved gas around will have a significant effect on \( L_X \), as \( L_X \) is dependent on the square of the gas density (e.g. the groups may have experienced variable amounts of preheating). It is also worth noting that the self-similar slope of the \( L_B : T \) relation suggests that \( T \) has been little affected by any preheating (since any boost in \( T \) for low temperature groups would be expected to steepen the \( L_B : T \) relation), whilst in contrast, both the relations involving \( L_X \) (\( L_X : T \) and \( L_X : L_B \)) show a significant steepening, indicating that \( L_X \) has been reduced in cool systems.

Differences in the \( L_B : T \) and \( L_X : L_B \) relations as a function of morphological type are interesting but care is needed in their interpretation. At a first glance they suggest that early-type galaxies are far more closely related to the group properties than the late types. However most of these systems are dominated by early-types, and only 3 systems have more than half their total light originating in late-type galaxies. Given this lower number of spirals in these groups it is unsurprising that the relations involving them show more scatter. It should also be noted that the correlations for \( L_B : T \) and \( L_X : L_B \) are stronger when all morphological types are combined. The lack of any correlation in the \( \beta \)spec versus late-type light could also be due to poorer statistics for the late-type data. The correlations seen between \( \beta \)spec and total or early-type light most likely represent a trend of lower \( \beta \)spec in smaller systems (smaller systems also tend to contain a lower fraction of early-types) as discussed in §5.1.

4.2 The relationship between the central galaxy and the group

Another interesting relationship is that between the X-ray properties of a group central galaxy and the X-ray properties of the group (see Figure 8). While the relation between central galaxy \( L_X \) and \( L_B \) appears to be consistent with previous relations derived over a much larger range of \( L_B \), there is clearly a substantial amount of scatter. This scatter is unsurprising as previous work has noted that the scatter in \( L_X \) can be as much as one or two orders of magnitude (e.g. Canizares et al. 1987; Eskridge et al. 1995). However there does appear to be a strong correlation between the X-ray luminosities of the galaxy and group. Given this, and the fact that the optical luminosity of the central galaxy does not correlate with the group X-ray luminosity, it appears that the X-ray properties of the central galaxies are more closely related to the group than to the galaxy itself, in the sense that the most X-ray overluminous (higher values of \( L_X / L_B \)) galaxies are found in the brightest groups. This is consistent with our previous work (Helsdon et al. 2001) which has shown that the X-ray properties of the central galaxies are different to those of other non-central galaxies in groups.

The correlation of central galaxy X-ray luminosity with group X-ray luminosity appears to be a problem for models in which the central component is due to a central mass excess associated with a central galaxy (e.g. see Makishima et al. 2001 and references therein). In this model it is argued that the central X-ray component is made up of a combination of the central galaxy ISM and an excess of intracluster gas due to an additional potential drop caused by the central galaxy. Thus, in this model, the central emission excess is entirely due to components associated with the central galaxy. This suggests that there should be stronger correlations between the central component properties and the galaxy properties, than between the central component and the group. This is not the case for our data.

Gas loss from the central galaxies themselves is unable to explain the high X-ray luminosities or the extent of the emission observed in these bright central galaxies, and simulations have shown that additional infalling material is required to adequately reproduce their observed properties (Brighenti & Mathews 1998, 1999). Given the strong corre-
X-ray bright groups and their galaxies

Figure 12. Residual from $\beta_{\text{fit}} : T$ relation (data-model) as a function of a) spiral number fraction and b) spiral light fraction, for the eight groups with the most reliable values of $\beta_{\text{fit}}$ identified in Helsdon & Ponman (2000a).

The correlation between galaxy and group X-ray luminosities and the fact that almost all of these central galaxies are in groups which show evidence of a central temperature drop (Helsdon & Ponman 2000a), it is likely that this additional infalling material is in the form of a group cooling flow. If indeed the X-ray properties of this central component are a property of the group rather than the galaxy itself, this would account for some of the observed scatter in the early-type galaxy $L_X / L_B$ relation. A group cooling flow could also explain the apparent lack of rotationally enhanced X-ray ellipticity in the cooling flows of elliptical galaxies (Hanlan & Bregman 2001), and the correlation of X-ray luminosity with the relative sizes of the X-ray and optical emission (Mathews & Brighenti 1998), in that the most X-ray overluminous galaxies should be found in the centre of bigger groups.

We have also seen that the degree of dominance of the central early-type galaxy does not appear to correlate with any other group property, including residual from the group $L : T$ relation (Figure 8). Previous work on fossil groups (Jones et al. 2000) has suggested that these groups (which generally have $\Delta m_{12} \geq 2.5$) may lie above the mean $L : T$ relation. Fossil groups are thought to be the result of a number of galaxy mergers within a compact group, thus leaving a single bright early-type in the centre of the group potential, with no other bright galaxies nearby. They would be expected to have high X-ray luminosities if they formed at an early epoch when the density of the universe was higher, leading to a higher gas density and thus higher X-ray luminosity. The number of fossil groups with reliable temperatures is still small, and the present results do not fit in with the tentative pattern proposed by Jones et al. (2001), despite the fact that two groups have values of $\Delta m_{12}$ close to that of fossils (both have $\Delta m_{12} > 2.2$), and may be examples of local fossils.

4.3 Galaxy morphology and preheating in groups

Finally we come to the relation between $\beta_{\text{fit}}$ and spiral fraction. Although the sample size is small and the correlation is weak, Figure 11 suggests that the systems with higher spiral fractions have flatter profiles. Systems which have experienced more preheating should show flatter profiles (e.g. Voit et al. 2002) so this result suggests that spiral galaxies may play a significant role in any preheating in these systems. This is not what would be expected given the results of Arnaud et al. (1992) who looked at the correlation between iron mass and optical luminosity in clusters of galaxies. They found little correlation between iron mass and spiral luminosity and thus concluded that only early-type galaxies have contributed to the enrichment of the intracluster medium. If early-types are primarily responsible for the enrichment of the ICM then it would also be expected that they should be the primary origin of any preheating in these systems, which would produce trends in the opposite direction to those seen here. However some care is needed here as groups also show trends in $\beta_{\text{fit}}$ with temperature (and thus mass) in that smaller systems have flatter profiles. In order to examine the effects of preheating as a function of morphological type, any trends with system mass must also be taken into account.

We use two different approaches to attempt to remove the effects of system mass on $\beta_{\text{fit}}$ – residuals from the $\beta_{\text{fit}} : T$
relation, and trends in $\beta_{\text{fit}}$ and optical light as a function of morphological type after an appropriate scaling. In addition we can investigate the morphological origin of preheating by examining the effect of spiral fraction on the slope of the $L_X : T$ relation. All three methods are described in more detail below.

The first method examines the residual from the $\beta_{\text{fit}} : T$ relation as a function of morphological type. We first fit a mean trend to the cluster and group $\beta_{\text{fit}}$ and log temperature data given in Helsdon & Ponman (2000a). We then calculate the residual (data - fit) for each of the eight good quality group points from this trend, and plot it as a function of spiral fraction. Do systems which lie above the mean trend (i.e. have steeper profiles, which would suggest less preheating) tend to be preferentially elliptical or spiral-rich?

The residuals are plotted against both spiral number fraction and spiral light fraction in Figure 12. As can be seen there are weak trends present ($K = -0.88$ for spiral number fraction, and $K = -1.73$ for spiral light fraction). Although the sample size is small and the correlations are not particularly strong, the trends in the data are in the sense that that systems with higher fractions of spirals tend to have flatter profiles.

The second method we use to examine the origin of any preheating in the systems is to look at relations involving optical light for each morphological type. If early-type galaxies are primarily responsible for the preheating then the effects of the preheating should scale with the amount of light in early types. Note that this will also be true if AGN are primarily responsible for the preheating, as black hole mass is correlated with the total light of the spheroidal components of galaxies (Magorrian et al. 1998). However the effects of any energy injection will also vary with system mass – the impact of the energy injection should scale as the ratio of the injected energy ($\propto L_B$) to the total thermal energy ($M_{\text{gas}}T$). Given also that $M_{\text{total}} \propto T^{3/2}$ and $M_{\text{total}}/M_{\text{gas}} = \text{constant}$, we obtain a scaling factor of $T^{5/2}$ for the total thermal energy of the gas in self similar systems. Thus if early-type galaxies are the origin of the preheating in these systems then there should be a correlation between early-type light divided by $T^{5/2}$ and $\beta_{\text{fit}}$.

In Figure 13 we plot $\beta_{\text{fit}}$ as a function of both scaled (divided by $T^{5/2}$) early and late-type light, for the same systems as plotted in Figures 11 and 12 earlier. As can be seen there is indeed a correlation of $\beta_{\text{fit}}$ with normalised early-type light ($K = -2.22, P = 0.0264$). However there is also marginal evidence for a correlation with late-type light ($K = -1.73, P = 0.0836$). This suggests that both early and late-type galaxies play a role in the preheating of the intragroup medium.

The final method we use to examine the origin of preheating in these systems is to compare the slope of the $L_X : T$ relation for spiral and elliptical rich systems. We split the full sample of 24 groups into two equal sized subsamples based on their spiral fractions. The groups in the early-type rich subsample all have spiral fractions of $\leq 0.4$. If early-type galaxies are primarily responsible for the preheating of the IGM then one would expect the spiral rich sample to have a shallower $L : T$ slope than the spiral poor sample.

As can be seen in Figure 14, the two subsamples follow a similar relation – the spiral rich subsample has a slope of $5.5 \pm 0.9$ while the spiral poor subsample follows a relation of $c_2001$ RAS, MNRAS 000, 1–17
of slope $4.3 \pm 0.5$. Again, this $L_X : T$ data does not support a scenario in which early-types are the dominant source of any preheating, but suggests that late-type galaxies play at least a comparable role to early-types.

The above results favour a situation where spirals have contributed significantly to the heating, and hence also presumably to the enrichment, of the intragroup medium, probably at a level comparable to the contribution from early-types. We can use this in an attempt to discriminate between AGN heating and supernova-driven wind heating, as the AGN heating should be proportional to the luminosity of the spheroidal component whereas the rate of supernovae is roughly proportional to the total luminosity. Note that, in both cases these heating estimates are for the systems at the epoch at which they are observed, and that ideally a hierarchical model, integrated over the age of the Universe, would be needed to estimate the effects of the different heating mechanisms.

If indeed spiral galaxies do play a significant role in the preheating of the intragroup medium then it is unlikely that AGN heating is the dominant preheating mechanism, as the most massive AGN are found in early-type galaxies. However some caution is needed with these results as the actual stellar mass contribution from disks (as compared to spheroids) in these groups is fairly small ($\sim 10\%-15\%$ — spirals have spheroidal components as well), so only modest trends with spiral fraction would be expected. However, this result does suggest that galaxy winds may play the dominant role in the preheating of the intragroup medium and it also suggests that spiral galaxies may have played a significant role in the metal enrichment of intergalactic space.

5 CONCLUSIONS

Using optical data drawn from the literature we have examined the relationship between the X-ray properties of a galaxy group and its member galaxies. Our main results may be summarised as follows:

(i) The total optical light in an X-ray bright galaxy group appears to correlate well with the X-ray temperature. In addition the $L_B : T$ relation ($L_B \propto T^{1.6\pm0.2}$) appears to be consistent with a straight extrapolation of the cluster relation and is also consistent with self similar scaling of galaxy systems. This continuation of the cluster trend and the small amount of scatter observed about this line suggest that the star formation efficiency is fairly constant across all these systems.

(ii) A constant star formation efficiency does not support a scenario in which cooling of material is responsible for the observed steepening of the $L_X : T$ relation. The substantial amount of cooled material required to reproduce the $L_X : T$ relation would require the star formation efficiency in groups to be substantially higher than in clusters, unless the cooled gas fails to form stars, and is sequestered as baryonic dark matter.

(iii) The $L_X : L_B$ relation ($L_X \propto L_B^{2.6\pm0.4}$) is significantly steeper than has been seen in some previous studies, although this steeper slope is consistent with preheating models which also steepen the $L_X : T$ relation. In addition, the scatter in $L_X$ in both the $L_X : L_B$ and $L_X : T$ relations is much greater than in $L_B$ or $T$, which suggests that the result of any physical processes in these systems (e.g. pre-
heating) primarily affects the distribution of the gas in these systems.

(iv) The optical light in these groups appears to be more centrally concentrated than the light in clusters. The projected cumulative light profile of these groups is given by $L_B(< r) \propto r^{0.34 \pm 0.06}$, which in turn implies a 3D galaxy density profile with an index of 2.66. In contrast, with clusters one would expect a relation nearer $L_B(< r) \propto r^{1.6}$.

(v) For the groups with two spatial components to their X-ray emission, the most X-ray overluminous galaxies (high $L_X/L_B$) appear to reside in the brightest groups. In addition the X-ray luminosity of these central galaxies appears to make up about 25% that of the group itself. Given that these galaxies are located in the centres of groups which show evidence of a central temperature drop, it is likely that the X-ray luminosity in these systems is primarily a product of the group, such as a group cooling flow. If so, then this could explain some of the large scatter seen in the $L_X : L_B$ relation for early-type galaxies.

(vi) The dominance of the central galaxy as measured by the difference in magnitude of the two brightest galaxies does not appear to correlate with any of the X-ray properties of the group. Studies of fossil groups have suggested that systems with very dominant galaxies may lie above the $L_X : T$ relation, however we see no evidence for this. In particular, the two groups with the most dominant galaxies lie below the $L_X : T$ relation.

(vii) We have examined the relationship between galaxy morphology and group properties and see evidence of a weak anti-correlation between spiral fraction and group temperature. We have also looked at the relation between galaxy morphology and $\beta_{gt}$. $\beta_{gt}$ should be related to the amount of preheating in a system. Although our sample of good values of $\beta_{gt}$ is small we do see a weak correlation between spiral fraction and $\beta_{gt}$ in the sense of the profiles being flatter as spiral fraction increases. However as $\beta_{gt}$ also scales with system mass we need to also take this into account. We do this in two ways. Firstly we examine the residual from the mean $\beta_{gt} : T$ relation as a function of spiral fraction. Secondly we scale the optical light (which we assume to be proportional to the amount of preheating) as a function of galaxy morphology by a factor proportional to the total thermal energy of the X-ray gas and look for correlations between this and $\beta_{gt}$. Although the statistics are poor and the expected contribution from disks is modest, the results from both these studies conflict with a scenario in which early-type galaxies alone are responsible for the preheating of the intragroup medium. Instead it appears that spiral galaxies may play a comparable role. This conclusion is also supported by examining the slope of the $L_X : T$ relation for spiral rich and spiral poor groups.

(viii) If indeed spiral galaxies do play a significant role in the preheating of galaxy systems then it is unlikely that AGN heating is the dominant preheating mechanism, as the most massive AGN are found in early-type galaxies (although some caution is needed as the stellar mass contribution from disks in these systems is small). This suggests that galaxy winds are likely to play the dominant role in any preheating. In addition if spiral galaxies are significantly involved in any preheating then they are also likely to have contributed to the enrichment of the intra-group medium.

This study demonstrates the potential of looking at trends, and the scatter about those trends, in the X-ray and optical properties of galaxy groups. As more information, such as the metallicity and temperature structure of these groups, becomes available from the new generation of X-ray telescopes, it will be possible to look in far greater detail at the complex relationship between groups and their member galaxies.

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