Evidence for radio-source heating of groups

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ABSTRACT

We report evidence that the gas properties of X-ray groups containing radio galaxies differ from those of radio-quiet groups. For a well-studied sample of ROSAT-observed groups, we found that more than half of the elliptical-dominated groups can be considered ‘radio-loud’, and that radio-loud groups are likely to be hotter at a given X-ray luminosity than radio-quiet groups. We tested three different models for the origin of the effect and conclude that radio-source heating is the most likely explanation. We found several examples of groups where there is strong evidence from Chandra or XMM–Newton images for interactions between the radio source and the group gas. A variety of radio-source heating processes are important, including shock-heating by young sources and gentler heating by larger sources. The heating effects can be longer-lasting than the radio emission. We show that the sample of X-ray groups used in our study is not significantly biased in the fraction of radio-loud groups that it contains. This allows us to conclude that the energy per particle that low-power radio galaxies can inject over the group lifetime is comparable to the requirements of structure formation models.

Key words: galaxies: active – X-rays: galaxies: clusters.

1 INTRODUCTION

Radio galaxies must be transferring large quantities of energy to the surrounding group- or cluster-scale gas. The $PdV$ work performed on the gas by source expansion is of the order of $10^{52}–10^{53}$ J for source ages $\sim 10^9$ yr (e.g. Croston et al. 2003). The first strong evidence for radio-source heating was recently found in the nearest radio galaxy, Centaurus A (Kraft et al. 2003): Chandra observations reveal a prominent shell of emission capping the inner southwestern radio lobe, which has a temperature 10 times that of the surrounding galactic atmosphere, providing strong evidence that Cen A is shock-heating its atmosphere. There is also evidence for heating in the powerful FRII (Fanaroff & Riley 1974) radio galaxy, Cygnus A (Smith et al. 2002), where a slight temperature increase in the X-ray gas is seen at the front edges of the lobe cavities. Another recent result helps to emphasize that more than one energy transfer mechanism is likely to operate. Deep Chandra observations (Fabian et al. 2003) of the Perseus cluster [the first cluster where ‘cavities’ were observed (Böhringer et al. 1993)] have revealed the presence of ripples in the cluster gas that are suggestive of sound waves emanating from the central radio source, 3C 84. Fabian et al. calculate that the time-scale between successive wavefronts is comparable to estimates of the radio-source lifetime, so that it seems plausible that an intermittent radio source is producing the observed ripples.

There is evidence that energy injection of some sort is required to explain the observational properties of X-ray groups and clusters, which do not agree with the predictions of cold dark matter models of structure formation (e.g. Arnaud & Evrard 1999; Ponman, Cannon & Navarro 1999). Several authors have considered the effects of heating due to feedback from star formation (e.g. Balogh, Babul & Patton 1999; Brighenti & Mathews 2001). However, in most cases it is found that heating from star formation and supernovae does not provide sufficient energy to explain the properties of both groups and clusters (e.g. Kravtsov & Yepes 2000). Wu, Fabian & Nulsen (2000) find that supernova heating can generate only $\sim 1/10$ of the energy required. These results have led many authors to consider active galactic nuclei (AGN) heating. Churazov et al. (2001) and Böhringer et al. (2002) consider the effects of radio-galaxy heating on cluster structure and conclude that sufficient heating could be provided. Evidence from recent observations of clusters, and simulations, suggest that AGN could provide a sufficiently distributed heating mechanism for this method to work (e.g. Brüggen & Kaiser 2002; Fabian et al. 2003), which removes a long-standing objection to radio-source heating models. As radiative cooling in the absence of feedback overpredicts the mass in galaxies (e.g. Cole 1991), it seems likely that some sort of feedback is required to explain observed cluster properties and the galaxy luminosity function (e.g. Voit & Bryan 2001; Benson et al. 2003; Kay 2004).

In addition, nearly all cooling-flow clusters contain a central radio galaxy (e.g. Eilek 2004), and there is considerable evidence...
that the radio galaxy displaces gas in the cooling-flow regions (e.g. Böhringer et al. 1993; Blanton et al. 2001; Fabian et al. 2003). It is therefore important to consider the different means by which radio galaxies could influence the observed properties of the cooling flow, and in particular whether they can help explain why large quantities of gas do not appear to cool past ~1/3 the outer cluster temperature (e.g. Sakelliou et al. 2002; Peterson et al. 2003). Although non-heating solutions to this problem exist, it is most plausible that the bulk of the gas in these systems is reheated by one of several possible mechanisms, such as cluster mergers, thermal conduction (e.g. Voigt et al. 2002; Voigt & Fabian 2004), or AGN heating (Binney & Tabor 1995; Brüggen & Kaiser 2001, 2002; Reynolds, Heinz & Begelman 2002); the last of these is particularly attractive because of the possibility of self-regulation via feedback. Investigating how radio galaxies can affect their hot-gas environments is therefore important to our understanding of several problems of cluster physics.

In Croston et al. (2003), we showed that radio galaxies have an important impact on groups, and found evidence that the properties of ‘radio-loud’ and ‘radio-quiet’ groups differ, in the sense that ‘radio-loud’ groups are hotter than ‘radio-quiet’ groups of comparable X-ray luminosity. That work used a fairly small and inhomogeneous sample, and the analysis methods were comparatively basic. Here we present a detailed analysis of a larger, homogeneous sample of groups (Osmond & Ponman 2004) in order to confirm and investigate further the conclusions of the earlier work.

2 SAMPLE SELECTION AND ANALYSIS

2.1 The elliptical-dominated sample

This analysis uses the GEMS (Group Evolution Multiwavelength Study) group sample where the X-ray properties were presented by Osmond & Ponman (2004) (hereafter OP04). The sample consists of 60 groups, including loose and compact groups that may be spiral- or elliptical-dominated. For the larger GEMS sample, the \( L_X/T_X \) relation shows more scatter than for the earlier work of Helson & Ponman (2000), so that it may be more difficult to distinguish heating effects.

We considered only the subset of groups in the OP04 sample that contain a large elliptical galaxy, as spiral-dominated groups are unlikely to possess a strong radio galaxy. We found that the scatter in the \( L_X/T_X \) relation is significantly reduced in our subsample, suggesting that spiral-dominated groups have different gas properties from those with a large elliptical galaxy. OP04 did not report a significant difference in the \( L_X/T_X \) properties of elliptical- and spiral-dominated groups; however, they do find that most X-ray bright groups contain a bright central early-type galaxy. They used the spiral fraction of the group to compare group properties. Our classification on the basis of the morphology of the dominant galaxy may be a more useful measure of the history and current properties of the group. This is supported by the conclusions of OP04 concerning the importance of elliptical brightest group galaxies.

In order to determine whether each group contains a large elliptical galaxy, we downloaded DSS2 (Digitized Sky Survey\(^1\)) images of each group. Typically groups were either dominated by one large galaxy, or else there were several bright galaxies of similar magnitude. In the first case, we rejected any groups where the dominant galaxy is a spiral or S0. In the second case, where there was no obviously dominant galaxy, the group was only rejected if none of the bright galaxies is an elliptical. In some cases it was not possible to tell by eye whether a galaxy has an elliptical or S0 morphology, and so we followed up all of the elliptical groups using Simbad and NASA/IPAC extragalactic data base (NED) to confirm the galaxy morphology. Unfortunately, there are many cases where these data bases disagree, and multiple classifications exist in the literature. We therefore only rejected groups where the ambiguous galaxy was classified as S0 by both Simbad and NED. In all we excluded 15 spiral-dominated groups: HCG 10, 15, 16, 40, 68, 92, NGC 1332, 2563, 3227, 3396, 4565, 4725, 5689, 5907 and 6574. In the course of following up galaxy morphologies, we also found one group, HCG 22, for which the supposed group members covered an implausibly large range in redshift. As it is unclear which galaxies are real members of this group, we excluded it as well.

In addition to excluding spiral-dominated groups, we also had to exclude 10 groups for which OP04 could not make X-ray spectral measurements: HCG 4, 48, 58, NGC 1808, 3640, 3783, 4151, 4193, 6338 and 7714. As the aim of the study was to compare the properties of radio-loud and radio-quiet groups, we also had to exclude two groups with low declinations that are not covered by the surveys used to identify the radio sources, NGC 1566 and 7144. Finally, NGC 315 was excluded, because Worrall, Birkinshaw & Hardcastle (2003) find a dominant contribution to the X-ray luminosity from the AGN and X-ray jet, and HCG 67 was excluded because of ambiguity in whether or not an identified nearby radio source is actually associated with the group. The final sample of elliptical-dominated groups contained 30 members.

2.2 Identifying radio sources

We then divided the elliptical-dominated groups into radio-loud and radio-quiet subsamples based on the properties of any radio source associated with each group. For each group in the sample, we used NED, NVSS (NRAO VLA Sky Survey; Condon et al. 1998) and FIRST (Faint Images of the Radio Sky at Twenty cm; Becker, White & Helfand 1995) to locate radio sources that could potentially be associated with a group member. We first checked NED for any known radio galaxies associated with the galaxies of the group. If an associated radio source was found, we adopted the 1.4-GHz radio flux from the NED data base. For any groups where a radio source was not found in this way, we searched for sources within a radius of 10 arcmin using NVSS and FIRST. We then checked the location of each candidate for an associated radio source on the DSS2 optical images to ensure that the radio source was roughly at the centre of a group galaxy (using SIMBAD to confirm that the galaxy is at the redshift of the group). If this was not the case, then we rejected the radio source on the basis that it was probably a background object. This method should be a more robust way of defining radio-loud and radio-quiet groups than the method we used in Croston et al. (2003), as the latter may contain spurious ‘radio-loud’ designations if any of the radio sources were not in fact associated with the group. Table 2 gives the 1.4-GHz radio flux and luminosity densities, \( L_{1.4} \), and the location for all of the associated sources. We also list the distance between the radio source and the group centre, defined in OP04 as the position of the group-member galaxy nearest to the centroid of the X-ray emission. In two cases (NGC 5171 and HCG 90) the radio source is a significant distance from the group centre, which may reduce the likelihood that it could strongly affect the group gas properties; however, as in both cases the radio-source is clearly associated with a group galaxy and lies in the extended X-ray halo detected with ROSAT, we include these two radio sources in the sample.
Table 1. The elliptical-dominated groups sample. The properties listed here are taken from OP04. $\beta$-model parameters marked with a star are estimated using the method described in the text.

| Group   | Redshift | Temperature (keV) | Abundance (Z_{\odot}) | log($L_X$ erg$^{-1}$) | $r_{\text{cut}}$ (kpc) | $\beta$ | $r_e$ (kpc) |
|---------|----------|-------------------|------------------------|------------------------|-------------------------|--------|-----------|
| HCG 42  | 0.0128   | 0.75 ± 0.04       | 0.29 ± 0.10            | 4.19 ± 0.02            | 112 ± 0.56              | 4.69   |
| HCG 62  | 0.0146   | 1.43 ± 0.08       | 2.00 ± 0.56            | 4.34 ± 0.04            | 282 ± 0.48              | 2.44   |
| HCG 90  | 0.0085   | 0.46 ± 0.06       | 0.08 ± 0.03            | 4.19 ± 0.05            | 101 ± 0.41              | 0.91   |
| HCG 97  | 0.0218   | 0.82 ± 0.06       | 0.23 ± 0.10            | 4.27 ± 0.05            | 339 ± 0.44              | 2.73   |
| NGC 383 | 0.0173   | 1.51 ± 0.06       | 0.42 ± 0.08            | 4.35 ± 0.01            | 633 ± 0.36              | 2.11   |
| NGC 524 | 0.0079   | 0.65 ± 0.17       | 0.22 ± 0.15            | 4.05 ± 0.05            | 56 ± 0.45               | 0.37*  |
| NGC 533 | 0.0181   | 1.08 ± 0.05       | 0.68 ± 0.23            | 4.27 ± 0.03            | 372 ± 0.42              | 2.21   |
| NGC 720 | 0.0057   | 0.52 ± 0.03       | 0.18 ± 0.02            | 4.21 ± 0.02            | 65 ± 0.47               | 1.15   |
| NGC 741 | 0.0179   | 1.21 ± 0.09       | 2.00 ± 0.67            | 4.42 ± 0.04            | 386 ± 0.44              | 2.30   |
| NGC 1052| 0.0042   | 0.41 ± 0.15       | 0.00 ± 0.02            | 4.08 ± 0.15            | 25 ± 0.45               | 0.04*  |
| NGC 1074| 0.0056   | 1.02 ± 0.04       | 0.23 ± 0.05            | 4.19 ± 0.02            | 105 ± 0.46              | 0.08   |
| NGC 1587| 0.0122   | 0.96 ± 0.17       | 0.47 ± 1.24            | 4.18 ± 0.09            | 77 ± 0.46               | 4.34   |
| NGC 3557| 0.0088   | 0.24 ± 0.02       | 0.00 ± 0.01            | 4.24 ± 0.04            | 95 ± 0.52               | 1.13   |
| NGC 3665| 0.0069   | 0.47 ± 0.10       | 0.17 ± 0.14            | 4.14 ± 0.08            | 71 ± 0.47               | 1.08   |
| NGC 3667| 0.0041   | 0.35 ± 0.04       | 0.23 ± 0.10            | 4.15 ± 0.05            | 62 ± 0.39               | 1.98   |
| NGC 3923| 0.0045   | 0.52 ± 0.03       | 0.18 ± 0.05            | 4.09 ± 0.02            | 34 ± 0.55               | 0.63   |
| NGC 4065| 0.0025   | 1.22 ± 0.08       | 0.97 ± 0.48            | 4.20 ± 0.05            | 425 ± 0.30              | 3.08   |
| NGC 4073| 0.0204   | 1.52 ± 0.09       | 0.70 ± 0.15            | 4.31 ± 0.02            | 470 ± 0.43              | 9.42   |
| NGC 4261| 0.0075   | 1.30 ± 0.07       | 1.23 ± 0.42            | 4.42 ± 0.03            | 112 ± 0.44              | 0.48   |
| NGC 4636| 0.0065   | 0.84 ± 0.02       | 0.41 ± 0.05            | 4.19 ± 0.02            | 68 ± 0.47               | 0.30   |
| NGC 4325| 0.0252   | 0.82 ± 0.02       | 0.50 ± 0.08            | 4.15 ± 0.01            | 307 ± 0.58              | 27.56  |
| NGC 4589| 0.0067   | 0.60 ± 0.07       | 0.08 ± 0.03            | 4.16 ± 0.05            | 122 ± 0.52              | 9.33   |
| NGC 4697| 0.0045   | 0.32 ± 0.03       | 0.07 ± 0.02            | 4.01 ± 0.02            | 53 ± 0.46               | 1.25   |
| NGC 5044| 0.0082   | 1.21 ± 0.02       | 0.69 ± 0.06            | 4.31 ± 0.01            | 180 ± 0.51              | 5.96   |
| NGC 5129| 0.0232   | 0.84 ± 0.06       | 0.66 ± 0.28            | 4.23 ± 0.04            | 151 ± 0.43              | 3.14   |
| NGC 5171| 0.0232   | 1.07 ± 0.09       | 1.47 ± 1.25            | 4.38 ± 0.06            | 298 ± 0.45              | 81.26  |
| NGC 5357| 0.0072   | 0.23 ± 0.07       | 0.00 ± 0.02            | 4.01 ± 0.10            | 43 ± 0.45               | 0.18   |
| NGC 5846| 0.0063   | 0.73 ± 0.02       | 1.25 ± 0.69            | 4.19 ± 0.02            | 94 ± 0.51               | 2.19   |
| NGC 5930| 0.0096   | 0.97 ± 0.27       | 0.17 ± 0.12            | 4.73 ± 0.07            | 29 ± 0.45               | 0.19*  |
| IC 1459 | 0.0056   | 0.39 ± 0.04       | 0.04 ± 0.01            | 4.18 ± 0.04            | 121 ± 0.45              | 0.74   |

In our earlier analysis (Croston et al. 2003), we chose a single cut-off to discriminate between radio-quiet and radio-loud groups. However, at lower luminosities it is difficult to distinguish between AGN-related radio emission and emission from other processes, such as starbursts. The radio source population is dominated by starbursts at 1.4-GHz luminosities below $\sim 10^{23}$ W Hz$^{-1}$ (Sadler et al. 2002). All of the radio source identifications are with elliptical galaxies, so that a starburst origin is unlikely, and the majority of...
the sources have also been previously identified as AGN. However, we may detect weak AGN emission in elliptical galaxies that have never had a radio source sufficiently powerful to have affected the group properties. We therefore tested the importance of the radio-luminosity cut-off, by carrying out all of the analysis that follows for three choices. We first used a cut-off (c0) of $L_{1.4}^\text{cut} = 0$, so that the possession of any radio source above the NVSS flux density limit meant that a group was considered to be radio-loud. We then chose two higher cut-offs, based on the luminosity density of NGC 3665, a comparatively weak double-lobed radio galaxy, as in the analysis of Croston et al. (2003). These cut-offs (c1 and c2) are $L_{1.4}^\text{cut} = 1.2 \times 10^{21}$ W Hz$^{-1}$ (NGC3665/19) and $L_{1.4}^\text{cut} = 6 \times 10^{21}$ W Hz$^{-1}$ (NGC3665/2). Table 3 gives the total number of groups in each sub-sample for the three choices of radio-luminosity cut-off. We note that the NVSS flux limit of 2.3 mJy may introduce some bias into the selections, as this corresponds to a limiting luminosity of $3 \times 10^{21}$ W Hz$^{-1}$ for the highest redshift group, NGC 4325, at $z = 0.0252$. This limit is close to the cut-off luminosities, so that for cut-offs c0 and c1 a few high-redshift groups could have been incorrectly classed as being radio-quiet despite possessing a radio-source more luminous than the cut-off luminosity. There are five groups with sufficiently high redshift that a radio source more luminous than c1 could have been missed. However, a radio source of luminosity >c2 would be detectable in all of the groups, so that the results for this cut-off should provide a check for whether this bias is important.

| Cut-off number | $L_{1.4}^\text{cut}$ (W Hz$^{-1}$) | Number in RQ sample | Number in RL sample |
|----------------|----------------------------------|---------------------|---------------------|
| c0             | 0                                | 11                  | 19                  |
| c1             | $1.2 \times 10^{21}$             | 13                  | 17                  |
| c2             | $6 \times 10^{21}$               | 16                  | 14                  |

2.3 Radio sources in the OP04 parent population groups

We found a surprisingly high fraction of radio sources in the sample of elliptical-dominated groups from the OP04 catalogue (19/30 = 63 per cent, assuming cut-off c0). It is often stated that radio galaxies are not common; a small fraction of elliptical galaxies (e.g. ~5 per cent, Schmidt 1978) host a large radio galaxy. However, the fraction is certainly higher for the brightest ellipticals (e.g. Birkinshaw & Davies 1985). Ho (1999) discusses the recent detections of small radio cores in many nearby elliptical galaxies, concluding that these are likely to be low-luminosity AGN. As the preferred environment of radio galaxies may be the centres of elliptical-dominated groups or poor clusters (e.g. Best 2004), the high fraction of ‘radio-loud’ groups in the sample may not be unexpected. If radio galaxies are found in such a high fraction of this type of group, then our results will have important implications for the properties and evolution of groups. For this reason, it is crucial to test whether or not the OP04 X-ray observed sample of groups may be biased in its radio properties. The OP04 sample was chosen by merging nine catalogues of optical groups and then cross-correlating the resulting list with the ROSAT observing log. The parent catalogue is unbiased with respect to the radio properties of the groups; however, it is possible that the ROSAT archive contains a high fraction of groups with active galaxies, as ROSAT observed many radio galaxies. This could bias the OP04 sample towards groups containing radio galaxies, although groups with previously known radio galaxies make up a fairly small fraction of the OP04 sample.

To test whether the fraction of radio-loud groups in our sample is biased, we looked at the parent catalogues used by OP04. As we were only interested in the properties of elliptical-dominated groups, we wanted to use an electronically available catalogue that contained information concerning the morphology of the dominant galaxy in each group. The whole-sky group catalogue of Garcia (1993), taken from the Lyon-Meudon Extragalactic Data base fits these criteria. It contains 485 groups having $z \leq 0.02$. This sample is large enough that we can test whether its radio properties are consistent with those of the OP04 sample.

Using Vizier,2 we extracted from the Garcia catalogue all groups where the dominant galaxy has type E (elliptical) or L (S0) (these classifications are taken from de Vaucouleurs et al. 1991). Although we excluded groups with a dominant galaxy with a convincing S0 designation in our sample definition, we decided to include them here, for two reasons. First, as mentioned earlier, we found several dominant galaxies in our sample with S0 designations where later work revealed them to be misclassified ellipticals. Secondly, a surprisingly low fraction of the groups in the sample had ‘E’ designations, so that the test sample would have been quite small. Including all the S0 groups means that the resulting radio-loud fraction will be a conservative lower limit, as many of the S0 identifications will be correct. The final sample of E and S0 groups from the Garcia sample contains 135 groups (~30 per cent of the original sample).

We then cross-correlated the Garcia E and S0 groups with NVSS, searching for radio sources within 15 arcsec of the centre of the dominant galaxy. This method is not as accurate as the method we used for the OP04 radio identifications; however, the more detailed method is too cumbersome for this larger sample. To ensure a fair comparison, we carried out the same cross-correlation for our elliptical-dominated groups sample, using the coordinates given in OP04.

For the E/S0 Garcia subsample, we found radio sources associated with 41 groups. 32 groups had coordinates outside the region covered by NVSS, so that the final ‘radio-loud’ fraction of the Garcia subsample is 41/103, or 39.8 per cent. For our elliptical-dominated sample (Table 1), using the same method, we found a ‘radio-loud’ fraction of 16/30, or 53.3 per cent. Therefore, the ‘radio-loud’ fraction of the elliptical-dominated groups in OP04 is consistent with that in this parent catalogue. The fraction we obtained here for our OP04 subsample is slightly lower than that obtained using the more accurate identification method described in Section 2.2, which was 19/30, or 63 per cent. This is unsurprising, as the detailed method would find sources associated with any large elliptical in the group, whereas this cross-correlation method will only find sources associated with the dominant galaxy.

We conclude that the OP04 group sample is not excessively biased with respect to the radio properties of the groups. The true fraction of elliptical-dominated groups with radio sources may be ~40–50 per cent (as our result for the Garcia sample is a conservative lower limit), rather than being as high as is suggested by our original analysis of the OP04 sample. It is interesting that such a high fraction of elliptical-dominated groups is likely to possess an AGN-related radio source. If all elliptical-dominated groups are capable of hosting radio sources, this result could indicate that radio galaxies have a high duty cycle. Radio sources with obvious double-lobed structure

2 http://vizier.u-strasbg.fr/
make up roughly half of the radio sources in the sample, so that perhaps only half of the 40–50 per cent of elliptical-dominated groups with radio sources could be considered to be in a very active state. None the less, this suggests that a duty cycle where every elliptical-dominated group contains a radio source that is active for \(\geq 1/4\) of the time. Weaker sources with no detected double-lobed structure may be in a less active stage, and the groups with no radio source above the NVSS limit may be in the least active phase. If this model is correct, then the effects of radio sources are likely to be important at some level in all elliptical-dominated groups. The analysis of the Garcia sample found that E/S0-dominated groups made up \(\sim 30\) per cent of the sample. Although this is a minority of groups, E/S0-dominated groups are more likely to host a group-scale X-ray atmosphere (Osmond & Ponman 2004). They are therefore likely to be in a more relaxed state, so that their X-ray properties will be of more relevance to structure-formation models.

2.4 Issues with X-ray luminosity comparisons

The analysis we carried out in Croston et al. (2003) is based on the \(L_X/T_X\) relations for radio-loud and radio-quiet groups. In that analysis we did not take into account the choice of radius to which the X-ray luminosity was measured. OP04 used an X-ray extraction radius defined by the extent of X-ray emission at a significant level above the background. They then used the luminosities obtained for these regions and their fitted \(\beta\)-model parameters to extrapolate the luminosity to a fixed overdensity radius, \(r_{500}\) (= the radius corresponding to \(500\times\) the critical density of the Universe). We were concerned that the choice of radius used for the luminosity determination might affect the results. There are problems in this context with both radii used by OP04. A cut-off radius defined by the extent of X-ray emission biases the X-ray luminosity—temperature \((L_X/T_X)\) relation in the sense that a smaller fraction of the atmosphere will be measured for fainter groups, because the surface brightness drops below the background at a smaller radius. However, choosing a cut-off at \(r_{500}\) may not be suitable for our analysis either, as the method used by OP04 to define \(r_{500}\) is temperature-dependent, so that the luminosity is measured to a larger physical radius for hotter groups. If groups have been heated by the presence of a radio source, the choice of \(r_{500}\) will have the effect of reducing the significance of any heating effect we measure.

Clearly, it would be preferable to use the luminosity integrated out to infinity. Unfortunately, this is not possible using a \(\beta\)-model representation of the groups, as the solid angle integral of the galaxy-scale extended X-ray emission detected with Chandra X-ray observations. Zhang & Xu (2004) examine the X-ray binary population in Centaurus A. There is a clear tendency for radio-loud groups to be on the hotter side of the radio-quiet relation for all combinations of radio cut-off in Fig. 2 (showing only the points for \(r_{200}\) and the fitted \(\beta\)-model parameters to calculate the luminosity to \(r_{200}\). We neglected the axial ratio parameter, \(e\), included in the OP04 fits, which means that the extrapolated luminosities will be slightly overestimated for groups that have a large axial ratio. The maximum value of \(e\) for a source in our sample is 2.65 (NGC 4589), but most \(e\) values are in the range of 1.0–1.5. The radio-loud and radio-quiet groups have similar distributions of \(e\), and so our conclusions should not be affected. OP04 could not fit a \(\beta\) model for five sources, and for these we used \(\beta = 0.45\) (the median value measured for the sample) and \(r_e\) determined by using the rough correlation between X-ray luminosity and \(r_e\) shown in Fig. 1, \(L_X = 2.9 \times 10^{41}(r_e/\text{kpc})^{1.11}\) erg s\(^{-1}\).

Another consideration is whether the measured X-ray luminosities contain any contribution from sources other than the group gas, i.e. from AGN and X-ray binaries. Chandra observations can resolve the X-ray binary population and allow the integrated luminosity from X-ray binaries to be determined. Kraft et al. (2001) find an integrated X-ray luminosity of \(\sim 5 \times 10^{39}\) erg s\(^{-1}\) for the population of X-ray binaries in Centaurus A. Z. Zhang & X. (2004) examine the X-ray binary population in NGC 1407, one of the groups in the sample, which has a comparatively prominent X-ray binary population, and find that resolved X-ray binaries account for \(\sim 20\) per cent of the galaxy-scale extended X-ray emission detected with Chandra (or \(\sim 1.5 \times 10^{39}\) erg s\(^{-1}\), only \(\sim 3\) per cent of the ROSAT—measured \(L_X\) for the group-scale emission from NGC 1407). We conclude that contamination from X-ray binaries is not important to our results. Any contamination from X-ray binary emission that cannot be resolved by Chandra should affect the radio-quiet and radio-loud groups in the same way. We discuss the issue of AGN contamination in Section 3.1.

2.5 \(L_X/T_X\) relations

For each of the 12 combinations of radio and radius cut-offs, we fitted an \(L_X/T_X\) relation to the radio-quiet and radio-loud subsamples. Using the temperature measurements of OP04 and the luminosities determined as described above, we fitted the OLS (ordinary least squares) bisector (Isobe et al. 1990) to each data set for consistency with OP04. Table 4 gives the parameters for the resulting fits. We plot \(L_X\) versus \(T_X\) for each radio cut-off in Fig. 2 (showing only the results for \(r_{200}\) with the best-fitting radio-quiet relation overlaid. There is a clear tendency for radio-loud groups to be on the hotter side of the radio-quiet relation for all combinations of radio cut-off and luminosity extraction radius. (One major exception to this trend is NGC 3557, a radio-loud group that is much cooler than the prediction for its luminosity, but this may be due to including the cooler galaxy atmospheres of group members, which are prominent in a Chandra observation.)
We tested the significance of the trends illustrated in Fig. 2 for each choice of luminosity cut-off. We transformed the luminosity values into a predicted temperature using the appropriate best-fitting radio-quiet $L_X/T_X$ relation, as given in Table 4. We then rotated the coordinate system by $-45^\circ$ so that the $x$-coordinate in temperature corresponds to perpendicular distance from the best-fitting line. We then performed a one-dimensional (1D) Kolmogorov–Smirnov (KS) test comparing the distributions of $x$ (perpendicular distance from the line) for the radio-quiet and radio-loud samples of each case. The results are given in Table 4. In all but two cases, the probability that the two subsamples have the same parent population is $< 10$ per cent, and in more than half of the remaining cases, the probability is less than $< 5$ per cent.

We therefore conclude that there is good evidence that radio-loud and radio-quiet groups display different gas properties. The choice of radio-luminosity cut-off does not appear to have an important effect, whereas the choice of X-ray luminosity radius is crucial. To obtain a more consistent set of X-ray luminosity and temperature measurements, higher sensitivity data would be required so that the temperature and luminosity could be measured to much larger radii, and the need for extrapolation would be reduced.

### 3 Interpretation of the Results

The gas properties of radio-loud and radio-quiet groups differ in the sense that radio-loud groups of a given luminosity are likely to be hotter than the radio-quiet groups. There are several possible explanations for this result, which we examine in this section.

The first question is whether contamination from AGN emission could have affected the results for radio-loud groups. We test this in Section 3.1. We then consider three possible physical origins for the difference in the properties of radio-loud and radio-quiet groups: radio-source heating (model I), a luminosity deficit caused by the radio source (model II), or an external mechanism that is triggering the radio source and heating the gas (model III). Models I and II are related, as any temperature increase would lead to an increase in pressure, expansion and a subsequent decrease in density on timescales determined by the speed of sound; however, as a first step in understanding the radio-source impact, it is important to test whether the primary effect seen in our results comes from an increase in the group temperature or a decrease in X-ray luminosity. In Section 3.2 we test model I (radio-source heating), by examining whether there is any evidence that the strength of the inferred heating of radio-loud groups correlates with the properties of the radio sources. In Sections 3.3 and 3.4, we carry out two investigations to test model II (a radio-source-induced luminosity decrement). First, we examine the distribution of gas, parametrized by the $\beta$-model, to determine whether this differs for radio-quiet and radio-loud groups. We then examine the correlation between $L_X$ and optical luminosity to see whether the X-ray luminosities of radio-loud groups are lower relative to their optical luminosities than is the case for radio-quiet groups, as would be expected in the second model. In Section 3.5, we test model III (an external mechanism), by examining the optical properties of the two subsamples to find out whether the radio-loud groups could be in a specific evolutionary state, different from that of the radio-quiet groups, where the triggering of radio sources and the heating of gas might be favoured. Finally, in Section 3.6 we present a study of archive Chandra observations of the radio-loud groups to look for further evidence of radio-source heating and interactions between the radio source and group gas.
Evidence for radio-source heating of groups

3.1 AGN contamination and the reliability of the OP04 results

OP04 state that they have taken into consideration any contribution from a central AGN to the X-ray emission via their point-source exclusion method. Central AGN were excluded in 22 cases (Osmond, private communication); however, this does not include all of the radio-loud groups in our sample. Contamination from strong non-thermal emission might result in higher fitted gas temperatures, which could shift groups with AGN on the $L_X/T_X$ plane. However, if there were a large contribution from AGN-related X-ray emission, then the measured X-ray luminosity from the group gas would be overestimated; this would act in the opposite sense. It is therefore essential to check that AGN contamination is not leading to spuriously high temperatures or overestimation of the group luminosities. The measured temperatures and luminosities in our sample are therefore likely to be reliable for groups with $L_X > 10^{42}$ erg s$^{-1}$. For this reason, we selected three groups with lower X-ray luminosities: NGC 4261, 1407, where OP04 did not exclude the central AGN, and HCG 90.

In order to test the influence of AGN contamination, we extracted a spectrum for the extraction region used by OP04 (a circle of radius $r_{cut}$), but excluding the central two arcmin, so as to ensure that the majority of the AGN emission was excluded. We used a surrounding annulus for background and excluded any contaminating point sources by eye. Our analysis is therefore significantly cruder than that of OP04, who carried out a more complicated background estimation and performed good-time interval analysis. In all cases our measured temperature is the same within the (1σ) errors. However, the measured luminosities in two cases are significantly lower than the OP04 results. We conclude that there is no risk that the observed difference in the temperature distribution of radio-quiet and radio-loud groups.

From the XMM analysis of Croston et al. (2003), we found that the AGN in 3C 66B and 3C 449 (which are more powerful than most of the radio sources in the sample we use here) would not significantly contaminate the spectral measurements for the group atmospheres. The measured temperatures and luminosities in our sample are therefore likely to be reliable for groups with $L_X > 10^{42}$ erg s$^{-1}$. For this reason, we selected three groups with lower X-ray luminosities: NGC 4261, 1407, where OP04 did not exclude the central AGN, and HCG 90.

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Figure 2. $L_X/T_X$ plots for $r_{cut}$, top left-hand side for $c0$, top right-hand side $c1$ and bottom $c2$. Overplotted are the best-fitting radio-quiet relations for each set. Plus symbols are radio-quiet groups and filled circles are radio-loud groups.
radio-loud groups is due to spuriously high temperatures as a result of AGN contamination. The lower luminosity for NGC 4261 is likely to be due to our larger AGN exclusion region (which must include significant group emission). In the case of NGC 1407, the slightly lower luminosity is likely to be because OP04 did not exclude the AGN. If the AGN contributes some of the measured luminosity in a few sources, then the OP04 luminosity measurements for some of the radio-loud groups may be slightly overestimated, which would mean that the significance of the effect we observe is underestimated. If the true errors on temperature for these groups are slightly larger than those given by OP04, this would not have any effect on the KS test results and our conclusions. Finally, as OP04 excluded the AGN in the poorest radio-loud groups, including NGC 1052 and IC 1459, we conclude that AGN contamination is unlikely to be a problem for our results.

Even if the AGN emission does not significantly affect the measured temperature, it can have a more important effect on the surface brightness profile. The neglect of OP04 of an AGN may affect the fitted β-model parameters for a few groups. Several of the most powerful radio galaxies in the sample (e.g. NGC 383, from which the AGN was not removed, and NGC 4261) are among the groups fitted with a second central β-model. It is possible that these inner β-models are, in fact, principally modelling the point-source emission from the central AGN, although there is also evidence for a galaxy atmosphere in NGC 383 (Hardcastle et al. 2002). As an AGN component would be modelled out in this way, the β-model parameters for the extended emission should be reliable. That a second β-model was not required for many of the radio-loud groups, in combination with the lack of any effect on the measured temperatures, supports the conclusion that for most of the less powerful radio sources the AGN contribution to the X-ray emission is not significant.

The radio-quiet groups chosen to check the reliability of the OP04 results were selected to cover a wide range in X-ray luminosity and temperature. They are NGC 97, 720 and 4325. For each group, we extracted a spectrum using the extraction region of OP04 (a circle of radius r_{cut}) using the same background and point-source identification methods as above, and fitted a mekal model with free abundance to determine the temperature and X-ray flux of the group atmosphere. In all cases the results are in good agreement with those of OP04, so we conclude that the OP04 luminosity and temperature determinations are reliable both for radio-quiet and radio-loud groups.

### 3.2 Testing model I: correlations with radio luminosity

The results presented in Section 2 strongly suggest that radio galaxies are having an important effect on the properties of the surrounding group gas. We therefore decided to investigate whether there is any relationship between the observed ‘temperature excesses’ and the radio properties of the associated sources, as would be expected in a radio-source heating model. In the following analysis, we use only the results for radio-luminosity cut-off $c0$ so as to include the widest range of radio powers.

We used the 1.4-GHz radio luminosity density (Table 2) as a measure of the amount of energy a given source might be able to provide. Radio luminosity is not an ideal indicator of radio source energy input, as the amount of energy transferred from the expanding radio plasma to the surrounding gas depends on several factors, such as source size and age, which are in many cases unknown. The size of the source depends on its angle to the line of sight, which is usually poorly constrained. The age of the source, which is also required to estimate the total energy input, is even more difficult to determine. Indeed, a few of the radio sources in the sample are unresolved with NVSS and FIRST, and do not have identifiable double-lobed structure. However, low-frequency radio luminosity should trace the jet kinetic luminosity reasonably well, so that in the absence of useful information on the sizes and ages of all of the sources, the 1.4-GHz luminosity is the best measure of energy input available.

We first compared the radio luminosity with $\Delta T$, the difference between the measured temperature and that predicted by the appropriate RQ $L_X/T_X$ relation. Table 5 gives the results of Spearman rank correlation tests for each choice of X-ray luminosity radius. For the Spearman test, groups with no temperature increase were assigned $\Delta T = 0$: this applies to 5/19 groups for $r_{cut}$ and $r_{500}, 6/19$ for $r_{phys}$, and 3/19 for $r_{400}$. In all cases there is little evidence for a correlation. This is perhaps unsurprising, because the observed temperature increase produced by a radio galaxy of given luminosity should depend not only on the unknown properties of the radio source, as mentioned above, but also on the heat capacity of the group gas being heated. A similar analysis using the fractional temperature change, $\Delta T/T$, did not give an improved correlation.

We therefore estimated the heat capacity of the environment of each group using the spectral and spatial properties of the X-ray emission given by OP04. The heat capacity is $C = (3/2) Nk$, where $N$ is the total number of particles, obtained by integrating over the density profile using the best-fitting β-model parameters, with a central proton density obtained from the X-ray luminosity and best-fitting mekal model parameters.

To study the relationship between the observed ‘heating’ and radio luminosity, we examined the correlation between $E_{req}$, the energy required to heat the gas in a given group from the predicted temperature to the measured temperature ($C\Delta T$), and $L_{1.4}$. The heat capacities were calculated separately for each of the four choices of limiting radius. Fig. 3 shows the relationship between $L_{1.4}$ and $E_{req}$ for each choice of $r$. For groups with no temperature excess, we calculated an upper limit to the energy input by determining the amount of energy that would be required to shift the group significantly to the ‘hotter’ side of the appropriate $L_X/T_X$ relation. As the sample includes upper limits, we used survival analysis techniques to determine the generalized Kendall’s $\tau$ correlation coefficient using ASurv (Lavalle, Isose & Feigelson 1992). Table 5 contains the results of the correlation analysis for each case. There is a less than 5 per cent probability of obtaining the measured value of $\tau$ by chance for two out of four cases. The high value of 14 per cent for $r_{400}$ is probably because in many cases $r_{400}$ is physically small compared with the other choices for $r$, so that the heat capacity does not include much of the gas. For all four choices of radius, there is a stronger correlation here than was found for $\Delta T$ alone.

| Data set | $\Delta T$ Probability | Kendall’s $\tau$ Probability | $E_{req}$ Probability | $C$ Probability |
|---------|------------------------|-------------------------------|-----------------------|----------------|
| $r_{cut}$ | 0.184 0.450 1.992 0.046 0.312 0.193 |
| $r_{500}$ | 0.214 0.379 1.921 0.055 0.325 0.175 |
| $r_{phys}$ | 0.369 0.121 2.555 0.011 0.312 0.193 |
| $r_{400}$ | 0.168 0.491 1.472 0.141 0.314 0.190 |
Evidence for radio-source heating of groups

As the calculated heat capacity is related to the measured X-ray luminosity, we were concerned that the correlation between $L_{1.4}$ and $E_{\text{req}}$ could be caused by an $L_X/L_{1.4}$ correlation due to the flux limits in the X-ray and radio samples. We therefore also carried out Spearman rank tests to look for a correlation between heat capacity and $L_{1.4}$. Those results are also included in Table 5, and show that the correlation between $L_{1.4}$ and heat capacity is much weaker than that with $E_{\text{req}}$ in all cases.

The presence of a correlation (albeit with a large scatter) between radio luminosity and the energy input needed to cause the observed temperature increase provides support for a model where the temperature increase is due to radio-source heating. The large scatter is not surprising, given the many unknown factors, such as source size and age, that would affect the amount of observed heating.

3.3 Testing model II: $\beta$-model properties

We studied the $\beta$-model properties of the radio-quiet and radio-loud groups to determine whether the spatial distribution of gas is affected by the presence of a radio source. We compared three parameters, $\beta_{\text{fit}}$, the fitted value of $\beta$ from OP04, $\beta_{\text{spec}}$, the spectroscopic value of $\beta$ from OP04 and $R_{\beta} = \beta_{\text{spec}}/\beta_{\text{fit}}$. For each of these properties, we compared the values for the radio-quiet and radio-loud subsamples for radio cut-off $c0$. We performed a 1D KS test to determine whether the ‘radio-quiet’ and ‘radio-loud’ subsamples differed in each case. Fig. 4 shows histograms of the distributions of $\beta_{\text{fit}}$, $\beta_{\text{spec}}$ and $R_{\beta}$ for the radio-quiet and radio-loud samples.

There is no evidence that the parent population differs significantly for any of the three parameters. As the $\beta_{\text{spec}}$ have large errors, using the KS test to compare the two samples may not be very reliable. We also used a median test to compare the two samples, and find a low probability that the distributions of $\beta_{\text{fit}}$ have a different median. However, there is a probability of $\sim 93$ per cent that the distributions of both $\beta_{\text{spec}}$ and $R_{\beta}$ have different medians for radio-quiet and radio-loud groups, in the sense that $\beta_{\text{spec}}$ is higher for RQ groups. This is not a strong result, because of the large errors on $\beta_{\text{spec}}$ and therefore $R_{\beta}$. There is no evidence that RL groups have flatter profiles than RQ groups, as might be expected if the luminosity had been significantly decreased as a result of
radio-galaxy input. In Section 4 we present further discussion of how the group density distribution might be affected by radio-galaxy energy input.

3.4 Testing model II: $L_X/L_B$ relation

The X-ray and optical luminosities of groups are correlated, because gas mass and galaxy mass should scale similarly. OP04 show that such a correlation exists for their sample. If the effects we observe in Fig. 2 are caused by a decrease in X-ray luminosity in the radio-loud groups, then the $L_X/L_B$ relation should be affected: radio-loud groups should have a lower X-ray luminosity relative to their optical luminosity. In Fig. 5, we show the $L_X/L_B$ relation for radio-quiet and radio-loud groups (using $c1$ and $r_{cen}$). Unlike what is seen for the $L_X/T_X$ relation, there is no apparent difference in the two sub-samples. We note that the radio luminosity will be related to $L_B$, which may introduce a slight bias, but this should not affect the X-ray-to-optical luminosity ratio of the radio-loud groups. Therefore, this is a strong argument against X-ray luminosity decrements in radio-loud groups, as the radio source should not affect the optical luminosity of the group.

3.5 Testing model III: optical properties of the RL and RQ subsamples

To test the possibility that radio-quiet and radio-loud groups are in different stages of evolution, so that an external mechanism might be causing the heating effect, we compared two measures of their

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**Figure 4.** Histograms showing the distribution of $\beta_\text{fit}$ (top left-hand side), $\beta_\text{spec}$ (top right-hand side), and $R_B$ (bottom) for the sample. Filled rectangles are the radio-quiet sample, with the radio-loud sample overplotted as hatched rectangles.
optical properties. If radio-quiet groups are at a different stage of evolution from radio-loud groups, then \( N_{\text{gals}} \), the number of galaxies in the group, might be expected to differ, in the sense that older groups might be expected to have fewer members. Older groups might also have a larger ratio between the brightest and second-brightest group galaxies, as the largest mergers should have already taken place. We therefore compared both \( N_{\text{gals}} \) and \( L_{12} \), the luminosity ratio of the brightest to second-brightest group galaxy, as determined by OP04, for the two subsamples (using \( c_1 \) and \( r_{\text{cut}} \)). In Fig. 6, we show histograms of the distribution of these parameters for the two subsamples. In neither case is there a significant difference in the distributions for the two subsamples. Both have a peak in the value of \( N_{\text{gals}} \) between 5 and 10, and the preferred value of \( L_{12} \) for both subsamples is \(<2\), so that most groups have at least one reasonably large secondary galaxy, whether radio-loud or not. There are no radio-loud groups in the sample with \( L_{12} > 10 \), whereas there are two radio-quiet groups with \( L_{12} > 20 \). However, a KS test indicates no significant difference in the distributions of either. A median test also finds no significant difference in the medians of the two subsamples for either parameter. We conclude that the galaxy distributions in radio-quiet and radio-loud elliptical-dominated groups are similar, so that there is no evidence that the two subsamples are at different evolutionary stages. However, a thorough investigation using more sophisticated measures of group history is required to test this model fully.

### 3.6 Chandra and XMM–Newton observations of heating and interactions in the RL groups

Many of the radio-loud groups in this sample have been observed with Chandra or XMM–Newton. The high resolution of Chandra is excellent for resolving an AGN component, and for detecting inner structure in groups; however, as a result of the high resolution, its sensitivity to extended emission is reduced, so that in some cases it is unable to detect low surface-brightness emission from the weaker groups. In those cases ROSAT temperature and luminosity measurements are likely to be superior. We discuss here a few groups in the sample for which Chandra and XMM–Newton observations show evidence for heating or interactions between a radio-source and its environment.

#### 3.6.1 NGC 4261

An XMM–Newton observation of this group was made on 2001 December 16 (ObsID 0056340101). An analysis of the extended emission has not yet been published, although Sambruna et al. (2003) presented an analysis of the nuclear emission. We extracted the archive XMM–Newton data and carried out standard processing and filtering as described in Croston et al. (2003).
Figure 7. An adaptively smoothed, background point-source subtracted, vignetting-corrected 0.5–5.0 keV image of NGC 4261 made from the combined MOS1, MOS2 and pn data from the archive XMM observation described in the text. Clear evidence for interactions between the radio galaxy (3C 270) and gas environment are seen in the form of holes in the X-ray surface brightness at the positions of both radio lobes.

Fig. 7 shows the adaptively smoothed, background point-source subtracted, vignetting-corrected 0.5–5.0 keV image made from combined MOS1, MOS2 and pn data, with radio contours from a 1.4-GHz map made from VLA archive data overlaid. This figure illustrates a striking relationship between radio and X-ray morphology similar to that seen in 3C 66B (Croston et al. 2003). It is interesting that such evidence for interactions between the radio source and hot gas on large scales is found in every FRI radio galaxy for which deep XMM images of the large-scale structure exist (see also Evans et al. 2004).

3.6.2 NGC 4636

The Chandra observation of the atmosphere surrounding NGC 4636 revealed striking substructure in the form of symmetrical bright arms (Jones et al. 2002). Jones et al. find that the leading edges of the arms are $\sim$30 per cent hotter than the surrounding gas, and postulate a model in which the arms are produced by shocks driven by symmetric off-centre AGN outbursts. The central radio source appears to be extended to the northeast and southwest (e.g. Birkinshaw & Davies 1985); however, it is small and too weak to have produced the shock-heating. Jones et al. argue that this indicates that a more direct nuclear outburst may have produced the shocks, but it is difficult to think of such a mechanism. The radio source could be more extended at low frequencies; however, it remains unlikely that a currently active radio source is producing the shocks. It is possible that a previous radio outburst is responsible, although it is unclear for how long the sharp density and temperature structure would persist. The shock-heated arms of gas in this group may be the main contributor to the overall temperature of 0.84 keV measured by ROSAT. As NGC 4636 has one of the largest temperature excesses, this example strongly suggests that we are indeed identifying groups with interesting AGN/group interactions.

3.6.3 NGC 1052

The Chandra observation is too short to detect much low surface-brightness emission from this poor group. However, as shown in Fig. 8, there is evidence for radio-related X-ray emission, as discussed by Kadler et al. (2004). They attribute most of the X-ray emission to the jet; however, the distribution of X-ray counts around the eastern radio lobe seems to be reminiscent of the bright shell of hot gas around the southwestern inner lobe of Centaurus A. These Chandra observations therefore suggest that the young radio source in NGC 1052 may be shock-heating its surroundings. The measured X-ray temperature from ROSAT may contain a large contribution from these radio-related regions, although it is also possible that the entire environment has been heated, as we have argued to be the case for 3C 66B (Croston et al. 2003).

3.6.4 HCG 62

The X-ray emission from HCG 62 provides one of the clearest examples of ‘holes’ in a group atmosphere (Vrtilek et al. 2000). However, the current AGN is a weak radio emitter, and does not show any extension. As with NGC 4636, it is plausible that a previous radio outburst (which may still be detectable in low-frequency radio observations) has produced the observed X-ray structure.

3.6.5 NGC 5044

This group shows prominent substructure in the Chandra image of Buote et al. (2003), who associate holes in the gas with the radio source. Although the NVSS image of this source does not show evidence for any extended radio emission, they suggest that observations at lower frequency might reveal the presence of radio emission filling the cavities. We have been unable to resolve the AGN or detect larger-scale radio emission in our analysis of VLA archive data.
3.6.6 Summary of the Chandra and XMM–Newton observations

The Chandra and XMM–Newton observations discussed above show that radio-source/group interactions are complex. In two cases, NGC 1052 and 4261, there is clear evidence that the X-ray structure has been affected by the current radio galaxies. In two groups where there are no detected large-scale radio lobes, HCG 62 and NGC 4636, the Chandra observations reveal striking X-ray morphologies suggestive of outbursts from the AGN. Smaller-scale substructure is also present in NGC 5044. Finally, localized heating appears to be present in NGC 1052 and 4636, suggesting that the heating effects we observe from the ROSAT sample could be caused by several different processes.

4 EVIDENCE FOR RADIO-SOURCE HEATING?

The results presented in Section 2 support the argument that radio galaxies have an important effect on the X-ray properties, and therefore the physical conditions, of group gas, as suggested by previous work (e.g. Croston et al. 2003). This is shown by the difference in $L_X/T_X$ properties of the two subsamples, and by the high incidence of radio-related substructure in radio-loud groups.

In the next two sections we discuss the three models of Section 3 in detail. In Section 4.1, we compare models I and II, and argue in favour of a radio-source heating model (model I) and against a luminosity deficit (model II). In Section 4.2, we consider one possible external mechanism that could lead to model III explanation, that of mergers and interactions, and argue against such a model. In Section 4.3, we attempt to explain the results for all of the radio-loud groups in the context of a model of radio-source heating and discuss what can be inferred concerning the heating processes.

4.1 Temperature increase versus luminosity decrement

Radio galaxies must displace large amounts of gas and this could have a significant effect on their luminosity. For 3C 66B, which is larger than most of the sources in the samples studied here, we calculated that the gas with which the radio source can have directly interacted provides only 7 per cent of the luminosity of the group (Croston et al. 2003). It is therefore unlikely that removal of gas by the radio galaxy could produce the luminosity deficits needed by this model, in some cases an order of magnitude in luminosity. However, the group luminosity will also be decreased if a significant fraction of the jet kinetic energy is transferred into potential energy.

In the context of pre-heating models of energy injection into group gas, it has been argued (e.g. Metzler & Evrard 1994; Helsdon & Ponman 2000) that the main effect of the energy injection will be an increase in the potential energy of the group, so that the central density decreases (and hence luminosity will decrease). While (by the virial theorem) this will eventually be the case, heating effects are still likely to be detectable on shorter time-scales. More recently, Kay (2004) has carried out cosmological simulations of cluster formation including cooling and feedback (which could be due to AGN or a different energy source such as supernova winds) and find gas properties in agreement with observations, with a $\sim 10$ per cent increase in temperature at the virial radius. Their simulations consider only massive clusters, but suggest that at least some fraction of AGN-injected energy is likely to end up in the thermal energy of the group.

In some of the groups in our sample an order of magnitude decrease in luminosity is required: the density would have to be dramatically reduced to produce such an effect. A strong argument against such large luminosity deficits in radio-loud groups comes from the $L_X/L_B$ relation discussed in Section 3.4. We find that the radio-loud groups follow the same trend as the radio-quiet groups and show no evidence for having lower X-ray luminosities relative to their optical luminosities, as would be expected if an X-ray luminosity decrease had been caused by the radio galaxy.

Another strong argument in favour of heating as the dominant effect, as opposed to a change in luminosity, is the result of Section 3.2, where we found evidence for a correlation between radio luminosity and the energy required to heat the gas from the predicted to the observed temperature. This result would be harder to explain in a model where the impact of the radio-source was principally on the luminosity of the group.

As shown in Section 3.6, several groups with a temperature excess possess additional evidence for radio-source heating. In Fig. 9, we show the $L_X/T_X$ relation for $c1$ and $r_{cut}$, with NGC 4636 and 1052, as well as 3C 66B, 3C 449 and NGC 6251 (Croston et al. 2003; Evans et al. 2004) marked to illustrate how they compare to the sample studied here. We conclude, based on the additional evidence for heating in several sources, and the arguments above, that heating is a more plausible explanation than a radio-source induced luminosity deficit.

On the longest time-scales, the energy injected by radio galaxies into group or cluster gas must predominantly end up as potential energy, and any long-term temperature increase will be small. However, information concerning the energy injection cannot travel faster than the speed of sound, so that temperature effects may be detectable for a few sound-crossing times. The fact that an $L_X/T_X$ relation for elliptical-dominated groups exists at all is evidence that, on average, the temperature increase must disappear on time-scales less than the radio-source recurrence time; for a 50 per cent radio-galaxy duty cycle, this is comparable to a few sound crossing times in a typical group. It is plausible that occasionally a second AGN outburst would occur before the group has recovered from the previous outburst, so that the temperature increase is more persistent;
3C 66B could be one example of such a system. Our results therefore suggest that we are detecting the short-term effects of radio-source heating in many elliptical-dominated groups. The fact that we have found no systematic differences in the properties of radio-loud and radio-quiet groups, other than their $L_X/T_X$ relations, is consistent with a model in which all elliptical-dominated groups have had similar numbers of radio-galaxy outbursts averaged over the group lifetime, affecting the groups by causing a temporary increase in temperature, with less easily detectable long-term effects on the group luminosity and surface brightness distribution.

4.2 The evolution of groups: a common cause for heating and radio activity?

An alternative explanation is that some common cause triggers a radio source and heats the gas. It is possible that the elliptical-dominated groups containing radio sources exist at a particular stage in the evolutionary process for groups, where the gas is hotter relative to the group luminosity. One possibility is that the incidence of mergers, and/or the type of mergers that the two subsamples of groups have undergone, is different for the two subsamples.

Recent simulations by Rowley, Thomas & Kay (2004) find that in major mergers (defined as increasing the cluster mass by $\geq 20$ per cent) clusters become brighter and heat up roughly parallel to the $L_X/T_X$ relation, whereas in minor mergers, the temperature increases and the luminosity decreases. Although these simulations are for more massive clusters, this suggests a possible interpretation of our results. If the radio-loud groups had recently undergone, or are continuing to undergo, minor mergers, then their $L_X/T_X$ properties could be explained. In this model, the radio-quiet groups must either have undergone mainly major mergers, or be in more isolated environments where mergers are less common. One possibility is that radio-quiet groups could be more evolved, so that most merging has undergone mainly major mergers, or be in more isolated environments where mergers are less common. Such a model of group evolution should be testable using the optical properties of the group. However, we found no evidence for a difference in either the number of galaxies in the group or the degree of domination by the central galaxy for the radio-quiet and radio-loud groups (Section 3.5). A model of this sort cannot be ruled out, as mergers remain the most plausible model for how radio galaxies are triggered. However, there does not appear to be any evidence that the radio-quiet and radio-loud groups are in different stages of evolution, based on the comparison of the optical group properties. We therefore conclude that radio-source heating is the most plausible of the three explanations for our results.

4.3 Models for radio-source heating

If the radio-source heating model is adopted, then it is necessary to consider whether it is possible to explain the observed results for all of the radio-loud groups in the context of this model. In Fig. 2, it is apparent that there are some ‘radio-loud’ groups that do not show a temperature excess, and one particularly anomalous group that is much cooler than predicted (NGC 3557). In addition to the sources with no large temperature excess, most of the currently active radio sources in the sample are unlikely to be capable of producing heating of the type that is observed. The two groups HCG 62 and NGC 4636, which show strong evidence for radio-related structure and a large heating effect (especially in the latter), are particularly problematic. Either there is low-frequency radio structure that has not yet been observed, which indicates active or recently switched-off large-scale radio jets and lobes, or else the heating effects are long-lived. Some of the most powerful radio sources, such as 3C 66B, 3C 449 and NGC 4261, are probably capable of producing the heating that is observed (Croston et al. 2003), but the heating in many of the radio-loud groups must be longer-lived than the radio source.

It is also interesting to consider the mechanisms for heating in different stages of radio-source evolution. In Croston et al. (2003), we argued that large, powerful FRIs are subsonic and likely to be heating their surroundings gently via $PdV$ work as the lobes expand. However, in the early stages of FRI evolution, the sources are known to be overpressured (even assuming minimum energy pressures), and the recent observation of a heated shell around the inner lobe of Cen A shows that shock-heating is not only likely to be an important mechanism in FRIs, but plays a role in the early stages of FRI evolution as well. This process may also be occurring in one of the groups in this sample, NGC 1052 (see Section 3.6.3). Finally, the Chandra observations of NGC 4636 show that additional mechanisms for AGN heating may exist, as it is difficult to explain the morphology of the shocked arms of gas via radio-lobe expansion. We conclude that the heating effects found in the study of the ROSAT sample presented here are likely to be the result of different types of radio-source heating, so that one simple model for the entire sample is unlikely to be correct. In some sources there may be small regions of shocked gas, unresolved in the ROSAT data, leading to the temperature increases, whereas in others more widespread heating is necessary. A detailed analysis of XMM observations, which now exist for a significant number of the radio-loud groups, would help to investigate these possibilities, as would a low-frequency radio study to constrain the properties of the radio sources.

4.4 The importance of radio galaxies in structure formation models

We have shown that radio galaxies at some stage of development are present in up to 50 per cent of elliptical-dominated groups (Section 2.3), and have also presented evidence that radio-source heating is common. It is therefore of interest to consider whether their energy input is of significance in the context of structure formation models. We carried out some simple calculations to determine whether the energy input from low-power radio sources in elliptical-dominated groups could be important in the context of the energy-injection requirements of structure formation models.

We estimated the energy input rate from the average radio source in the sample by taking the average value of $L_{1.4}$ for the 19 radio-loud groups ($3.5 \times 10^{23}$ W Hz$^{-1}$) and scaling the kinetic luminosity of 3C 31 (from the model of Laing & Bridle 2002) by the ratio of $L_{1.4}$ for the average radio source and 3C 31, which gives $7 \times 10^{38}$ W. We then assumed that one-third of the kinetic luminosity is transferred to the group gas, a conservative lower limit. We assumed a duty cycle of 50 per cent, based on the fraction of radio sources in the Garcia catalogue (Section 2.3). This gives a typical energy input rate of $2.3 \times 10^{51}$ keV s$^{-1}$ over the lifetime of the group. The energy rate per particle was determined using the average number of particles in the group (determined as part of the heat capacity calculations in Section 3.2) to be $6.6 \times 10^{-18}$ keV particle$^{-1}$ s$^{-1}$. Assuming the injection energy is required to be of the order of 1 keV particle$^{-1}$ (e.g. Wu et al. 2000), then the average radio source in the sample can provide the necessary input over $\sim 5 \times 10^7$ yr, which is a plausible group lifetime (this is approximately 10 times the standard radio-galaxy lifetime, so that the radio source must have $\sim 5$ active
phases during the group lifetime). We conclude that low-power radio sources may be capable of providing the necessary energy input in elliptical-dominated groups. As it is the elliptical-dominated groups that principally determine the $L_X/T_X$ relation for groups, as they dominate the population of groups with luminous, group-scale X-ray environments, it is therefore possible that the energy input from low-power radio galaxies can explain the X-ray properties of groups.

Other workers have carried out calculations of the energy input of radio galaxies into clusters. It seems likely that low-power radio galaxies can provide sufficient energy on average to balance cooling flows (e.g. Fabian et al. 2003); however, to explain the cluster $L_X/T_X$ relation may require more energy than can be supplied by FRIs [although Roychowdhury et al. (2004) found that effervescent heating by rising bubbles could solve the entropy problem by heating at large radii]. The energy contribution from FRII radio galaxies and quasars is also likely to be important in the rarer situations where they occur.

5 CONCLUSIONS

We have presented a detailed study of the gas properties of radio-quiet and radio-loud elliptical-dominated groups based on the ROSAT groups sample of Osmond & Ponman (2004). We reach the following conclusions.

(i) 63 per cent of the elliptical-dominated groups (19/30) in the OP04 sample have associated radio sources at the centre of a dominant group galaxy.

(ii) Our sample of elliptical-dominated groups is not significantly biased in its radio-loud fraction: the true fraction in the parent population may be ∼40–50 per cent.

(iii) Radio-loud groups are likely to have a higher temperature than radio-quiet groups of the same luminosity.

(iv) The energy required to produce the observed temperature excess correlates weakly with the 1.4-GHz radio luminosity of the sources.

(v) The difference in gas properties for radio-quiet and radio-loud groups is most plausibly interpreted as evidence for radio-source heating.

(vi) Evidence for radio-source interactions with the surrounding gas is found in Chandra or XMM-Newton observations of many of the radio-loud groups, although there are also several groups that show disturbances not directly related to observable radio structure.

(vii) The radio-loud groups are at different stages in the heating process, so that some may be experiencing shock-heating by young radio sources, some are being gently heated by a currently active large radio galaxy, and some show longer-lived heating effects from a previous generation of radio-source activity.

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