JET/ENVIRONMENT INTERACTIONS OF FRI AND FRII RADIO GALAXIES

J. H. Croston, M. J. Hardcastle, M. Birkinshaw, D. M. Worrall
Astrophysics Group, University of Bristol
H.H. Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1EJ, UK
JUDITH.CROSTON@BRIS.AC.UK, M.HARDCASTLE@BRIS.AC.UK, MARK.BIRKINSHAW@BRIS.AC.UK, D.WORRALL@BRIS.AC.UK

Abstract

We present the results of new *XMM-Newton* observations of FRI and FRII radio galaxies that show the importance of jet/environment interactions for both radio-source structure and the properties of the surrounding gas. The FRI observations reveal that the distribution of hot gas determines the radio-lobe morphology, and provide evidence that the subsonic expansion of the lobes heats the surrounding gas. The FRII observations show that the sources are at equipartition and in pressure balance with their surroundings. Finally, we present an analysis of a sample of elliptical-dominated groups, showing that radio-source heating is common.

1 Introduction

Interactions between radio galaxies and their surrounding X-ray-emitting hot gas regulate the expansion of the radio plasma and transfer large amounts of energy to the gas environment. X-ray observations of radio-galaxy environments are therefore important both for developing our understanding of radio-galaxy properties and dynamics, and for studying the impact of radio galaxies on groups and clusters.

In the early Universe, radio galaxies and quasars are a possible source of the energy input needed to reconcile cold dark matter models of structure formation and the observed properties of clusters (e.g., Sanderson et al. 2003, Roychowdhury et al. 2004). It has been argued for some time that the energy injected by active galactic nuclei (AGN) into cluster gas is likely to be important in balancing radiative cooling in cluster cores (e.g., Binney & Tabor, 1995), and it is now increasingly accepted that the energy input of radio galaxies can reconcile X-ray observations with cooling-flow models (Churazov et al. 2002, Fabian et al. 2003). X-ray observations can provide information about the heating mechanism used to transfer energy from the radio source to the gas; for example, *XMM-Newton* and *Chandra* observations of the nearest radio galaxy Centaurus A (Kraft et al. 2003, and these proceedings; Worrall et al. these proceedings) have shown the importance of shock-heating by young sources. Insight into other heating mechanisms has also come from X-ray observations, such as those of "ripples" in the Perseus cluster (Fabian et al. 2003).

Both low-power (FRI) and powerful (FRII) radio galaxies are expected to heat their environments. FRI radio galaxies are thought to expand subsonically for most of their lives, so that they should be in approximate pressure balance with their surroundings; they will do PdV work on the gas as they expand, but we would not expect shock-heating, except in young sources. In contrast, the standard model of FRII expansion is that the jets inflate a supersonically expanding cocoon of material that shocks and compresses the surrounding gas. In this model, we might expect to be able to observe a rim of hotter gas around the radio source. X-ray observations can test the validity of these models, as they constrain properties of the radio source, such as particle content, magnetic field strength and internal pressure, and of the environment, e.g., density and pressure.

In the following sections we describe our *XMM-Newton* observations of FRI and FRII radio galaxies. Details of these observations and further discussion are presented in Croston et al. (2003, 2004). We also discuss a survey of *ROSAT*-observed groups that provides evidence that radio-source heating is common.

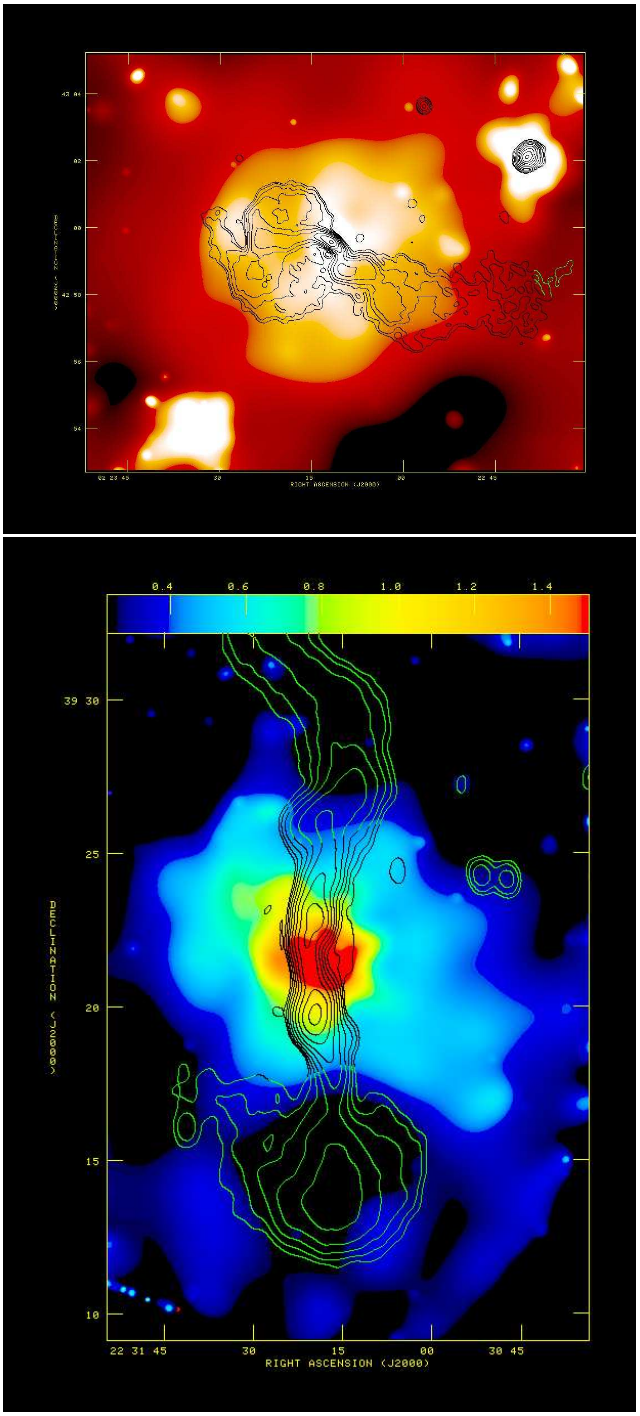

Figure 1: The X-ray environments of the FRI radio galaxies 3C66B (top) and 3C449 (bottom). Color is the smoothed, background point-source subtracted, vignetting corrected, combined MOS1, MOS2 and pn *XMM-Newton* data. Contours for 3C66B are from the 1.4-GHz radio map of Hardcastle et al. (1996), and for 3C449 are from a 608-MHz radio map from the 3CRR atlas (Leahy, Bridle & Strom 1998).

2 Observations of FRI radio galaxies

We observed the two radio galaxies 3C66B (z = 0.0215) and 3C449 (z = 0.0171) with *XMM-Newton* for 20 ks each. Figure 1 shows the X-ray emission measured by the three *XMM-Newton* cameras with radio contours overlaid, for both radio galaxies. Below we discuss what the observations reveal about the role of environment in shaping the radio lobes, the radio-source particle content and dynamics, and the impact of the radio galaxies on their environment.

2.1 Environmental influence on lobe morphology

The two sources were chosen due to their asymmetrical radio morphologies, so that we could investigate whether the asymmetries could be explained by environmental conditions rather than intrinsic differences in the jets. Figure 1 shows clear evidence that jet/environment interactions are taking place. There are deficits in X-ray surface brightness at the positions of the radio lobes, which show that the lobes are displacing material. More importantly, there is a clear relationship between the distribution of X-ray-emitting gas and the shapes of the radio lobes. For both sources, the round, sharply bounded lobe (3C66B east and 3C449 south) is embedded in bright X-ray emitting material, whereas the narrower plumes (3C66B west and 3C449 north) are relatively free of surrounding material. This suggests that the rounded lobes have formed where the jets flowed into dense material, and expansion along the jet axis was slowed; conversely, such lobe structures failed to form on the opposite side of the sources, because the jets encountered less dense material and continued to flow more freely.

More evidence that the environment has played an important role in determining the source structure comes from the bright blob of emission at the end of the eastern jet of 3C66B. This denser gas appears to be blocking the jet expansion, leading to the sharp boundary at the end of the lobe. It also appears that material in the south is beginning to flow around the obstacle. In Sect. 2.3, we discuss evidence that this blob of gas is being heated by its interaction with the jet.

2.2 Radio-source dynamics and particle content

It has been known for some time that the minimum internal pressures of FRI radio lobes are typically lower by at least an order of magnitude than external pressures inferred from X-ray observations (e.g., Morganti et al. 1998; Worrall & Birkinshaw 2000). We measured the external pressures in the environments of 3C66B and 3C449 and compared them with the minimum internal lobe pressures obtained from radio data. Both sources appear to be underpressured by factors of $\sim$ 20, consistent with the earlier work on this type of source. This discrepancy can be solved either by relaxing the minimum energy assumption or by assuming some additional non-radiating particle component in the lobes that is providing the required pressure [see Hardcastle, Worrall & Birkinshaw (1998) for more discussion of this problem].

Our X-ray observations allow us to rule out the possibility of increasing the relativistic electron population (and decreasing the magnetic field strength) to increase the internal pressure, because an electron population sufficiently large to provide pressure balance would produce X-ray inverse-Compton (IC) emission at an easily detectable level, which we do not see. Therefore, if a departure from equipartition solves the pressure balance problem, then it must be in the direction of magnetic dominance.

We can also rule out a dominant pressure contribution from entrained gas at the temperature of the surroundings, as the observed level of thermal emission from the lobe regions is too low. We cannot rule out a contribution from relativistic protons, but the required proton-to-electron number ratios are high ($\sim$ 200). An additional population of low-energy electrons is also possible; however, the required electron spectrum is physically implausible. We conclude that a contribution from significantly heated, entrained gas is perhaps the most likely explanation.

2.3 Radio-source heating

The bright blob of gas that is interacting with 3C66B's eastern jet is hotter than the surrounding material ($kT_{\rm blob}$ = 2.4±0.4 keV; $kT_{\rm env}$ = 1.73±0.03 keV). We interpret this temperature difference as evidence for local heating due to the work being done by the jet on the gas. In addition to this local heating, there is also evidence for more general heating by 3C66B. The average group temperature of 1.73 keV is significantly hotter than predicted by L_X/T_X relations for groups. This result is discussed further in Sect. 4.

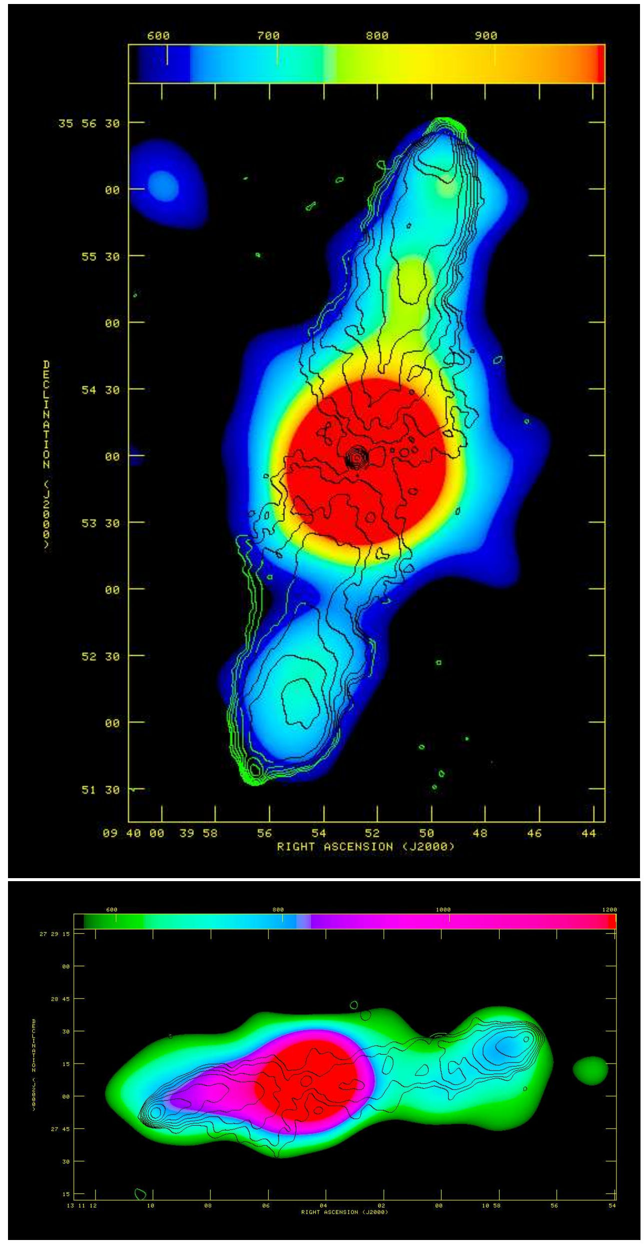

Figure 2: The X-ray emission from the radio lobes of the FRII radio galaxies 3C223 (top) and 3C284 (bottom). Color is the smoothed, background point-source subtracted, combined MOS1, MOS2 and pn *XMM-Newton* data. Contours for 3C223 are from the 1.4-GHz radio map of Leahy & Perley (1991), and for 3C284 are from a radio map made from 1.4-GHz archive Very Large Array data.

3 Observations of FRIIs

We observed the powerful radio galaxies 3C223 (z = 0.1368) and 3C284 (z = 0.2394) with *XMM-Newton* for 35 ks and 45 ks, respectively. Figure 2 shows the X-ray emission from the three *XMM-Newton* cameras, with radio contours overlaid, for both sources. Below we discuss the origins of the different components of X-ray emission, and the implications for radio-source properties and dynamics.

3.1 Emission from the cores, lobes and environments

Figure 2 shows that X-ray emission is detected from the cores, lobes and hot-gas environments of both sources. The nuclear emission is not discussed here – for its interpretation, see Croston et al. (2004).

The X-ray spectra for the lobe-related regions of both sources are consistent with IC emission, as in other FRII radio galaxies (e.g., Hardcastle et al. 2002; Isobe et al. 2002; Belsole et al. 2004 and these proceedings). We used multi-frequency radio data to model the electron population in the lobes of each source (using the code of Hardcastle, Birkinshaw & Worrall 1998), assuming that the lobes are in the minimum energy condition, and determined the predicted X-ray flux from IC emission. For the lobes of both sources (each modeled separately), the measured X-ray fluxes are in good agreement with the predictions for IC scattering of the cosmic microwave background, with magnetic field strengths within a factor of 2 of equipartition.

Both sources have group-scale environments ($L_X \sim 10^{43}$ erg s^{-1}) with temperatures of ~ 1.5 keV (3C223) and ~ 1 keV (3C284). These results are in agreement with the predictions of L_X/T_X relations. The data quality is not good enough to measure small temperature variations such as local heating around the radio source. In the following section, we discuss the implications of our results for the radio-source dynamics and heating.

3.2 Pressure balance and dynamics of FRIIs

From our model for the lobe-related X-ray emission of 3C223 and 3C284 we find the internal energy of the radio lobes to be close to the minimum energy values. We can compare these values with the external pressure from the X-ray-emitting gas to study the lobe dynamics. We find that the lobes of both sources appear to be in pressure balance with their surroundings.

This result leads to a self-consistent picture for the properties of these two large FRII radio galaxies: they are at equipartition and in approximate pressure balance. This is consistent with earlier work (Hardcastle et al. 2002). If this picture is correct, it seems likely that many moderately large FRIIs of similar radio structure have reached a stage where lateral expansion is no longer supersonic, so that the cocoon will have collapsed in the center, where the gas pressure is highest (this is consistent with the "pinched" central radio structure of 3C223, 3C284 and other sources). In this stage of evolution, heating effects will move outward at the sound speed and potentially affect gas at greater distances from the radio lobes than is possible in the supersonic stage where the heated material is confined to a rim surrounding the source.

If, instead, we believe that these sources must be expanding supersonically, then additional material is required in the lobes to make them overpressured. Entrainment is not thought to be important in FRIIs, so that such additional material would have to have a different origin from that in FRIs (see 2.2). The supersonic cocoon model for FRIIs therefore requires that the agreement between the detected X-ray emission and the equipartition prediction in both sources is a coincidence: the energetics of both FRIs and FRIIs would have to be dominated by particles other than the relativistic electrons, with a different origin for the dominant particle population in each type of source. We therefore conclude that the self-consistent model of FRII radio lobes at equipartition and in pressure balance with their surroundings is more plausible.

4 Evidence for radio-source heating in a sample of groups

Radio-loud AGN are preferentially found in groups or poor clusters (Best 2004). In addition to studies of individual objects, it is important to get an idea of how common radio-source heating is in groups, the degree to which groups are affected by the presence of a radio galaxy, and the length of time for which these effects persist. We therefore looked at a sample of groups observed with *ROSAT* to compare the gas properties of "radio-loud" and "radio-quiet" groups. Preliminary work on a small sample was described by Croston et al. (2003). We discuss below more detailed analysis of a larger sample.

4.1 Gas properties of groups with and without radio sources

The sample used for this study is taken from Osmond & Ponman (2004). We used their measurements of gas temperature, luminosity and other properties. We used

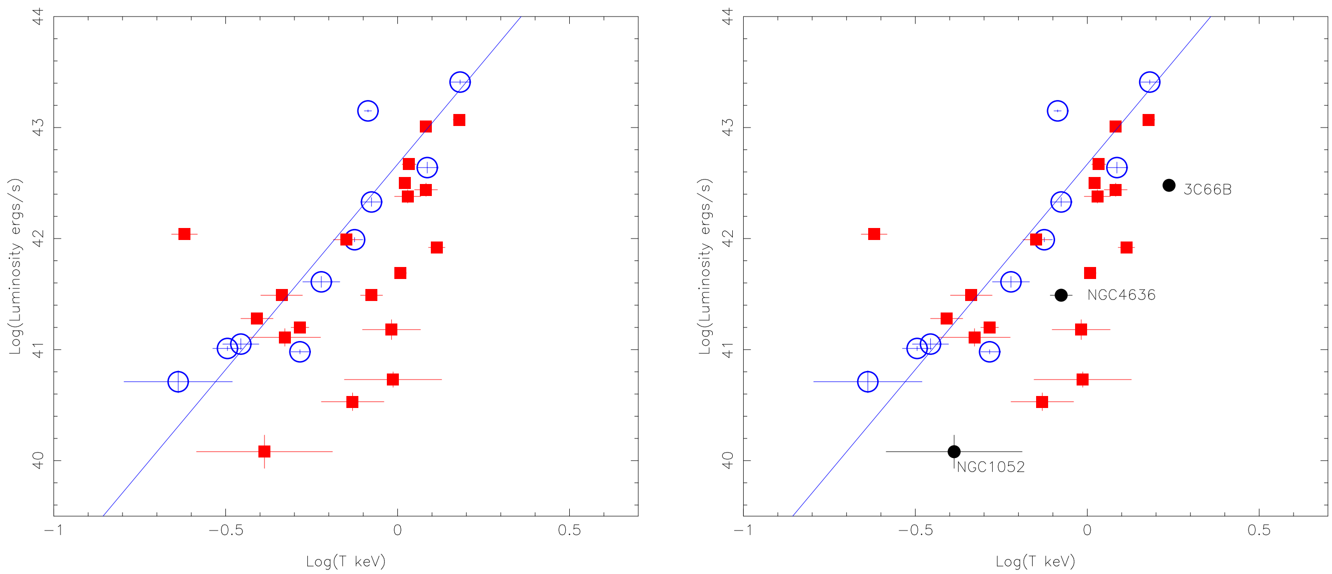

Figure 3: L_X/T_X plots for "radio-loud" and "radio-quiet" groups. On the left, the two subsamples are plotted, showing that the "radio-loud" groups (red filled squares) are hotter for their luminosity than "radio-quiet" groups (blue hollow circles). The best-fitting relation for "radio-quiet" groups is shown for comparison. The right-hand plot shows the same sample with the three groups that have additional evidence for heating marked by black filled circles.

DSS images to identify spiral-dominated groups and excluded these from the analysis so as to obtain a sample of groups homogeneous in their likelihood of containing a radio galaxy. We then searched for associated radio sources using NED, NVSS and FIRST, and confirmed identifications with group member galaxies using the DSS images. Radio sources were found in 18 of the 29 groups in the sample.

We then divided the sample into radio-loud and radio-quiet groups based on a radio luminosity cutoff, the choice of which does not significantly affect our results. Figure 3 shows the two subsamples plotted in L_X/T_X space. It is immediately apparent that the properties of the two samples differ. The best-fitting L_X/T_X relation for the "radio-quiet" subsample is shown on the plot. "Radio-loud" groups are more likely to be to the right of the line, or hotter for a given luminosity. On a K-S test, we find there is a less than 5 percent probability that the two subsamples have the same parent population. There are two possible interpretations of this result: radio-loud groups either have a temperature excess or a luminosity deficit. In the next section, we discuss the arguments in favor of each of these scenarios.

4.2 Are the "radio-loud" groups heated?

It is tempting to interpret this result as evidence that radio-source heating is occurring in many groups. However, radio galaxies could also affect the group luminosity. Radio galaxies must displace large amounts of gas (as shown in Sect. 1), and this could have a significant effect on the luminosity. For 3C66B, we calculate that the gas with which the radio source can have directly interacted provides only 7 percent of the group's luminosity. It is therefore unlikely that any removal of gas by the radio galaxy could produce the luminosity deficits needed by this model. It is possible, however, that the energy input from the radio galaxy could cause the group to expand, which might have a larger effect. However, in some cases the luminosity must be reduced by an order of magnitude, which seems implausible.

There is another reason to favor a heating interpretation: several individual sources showing a "temperature excess" do in fact have additional evidence for radio-source heating. *Chandra* observations of two groups in the "radio-loud" sample that are hotter than predicted for their luminosity reveal detailed structure in the group gas. The observation of the NGC4636 group shows arms of bright gas, which are hotter than the surrounding group (Jones et al. 2002), supporting a model where the departure from the L_X/T_X relation is due to heating. This group is particularly interesting, because the currently active radio source is too small and weak to provide the required heating, showing that heating effects can be longer lived than the radio galaxy. A short observation of the young radio-source NGC1052 reveals radio-related X-ray structure (Kadler et al. 2003) suggestive of shock-heating similar to that seen in Cen A. Finally, as reported in Sect. 1, the environment of 3C66B is significantly hotter than predicted, and there is other evidence for radio-source heating in the group gas. These three sources are plotted in the right-hand panel of Fig. 3. As there is direct evidence for radio-source heating in three groups with a "temperature excess", we conclude that this effect is largely due to heating rather than a decrease in luminosity caused by the radio source.

4.3 A more complicated picture?

The three groups with direct evidence for radio-source heating discussed in the previous section each represent different stages in the life of a group containing a radio source. NGC1052 is an example of a young radio source likely to be shock-heating its surroundings (like the inner regions of Cen A); 3C66B is an older radio source that is gently transferring energy to the gas; and NGC4636 is a group where the heating effects of a previous generation of radio source are still important. These examples suggest that we would not expect all groups containing a radio source to have similar gas properties.

In Fig. 3, we can see 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 (NGC3557). Although 3C66B would be capable of providing the energy needed to heat its environment by the amount observed, the majority of the currently active radio sources in the sample would not. We therefore conclude that the effects of radio-source heating are long-lived (as shown by the example of NGC4636), so that much of the heating in the sources far from the radio-quiet L_X/T_X relation has been caused by previous generations of radio-galaxy activity.

5 Conclusions

Our X-ray observations of FRI radio galaxies have shown that:

- differences in the distribution of hot gas around the source lead to the development of the varied types of radio-lobe morphologies seen in FRIs.
- FRIs cannot be in the minimum energy condition, and the additional pressure required for pressure balance with the surrounding gas cannot come from an increase in the density of synchrotron-emitting electrons or from entrained gas at the temperature of the surroundings. Heated, entrained material is perhaps the most plausible candidate to provide the required pressure.
- FRIs can heat their environments gently via subsonic expansion.

Our X-ray observations of FRII radio galaxies have shown that:

- 3C223 and 3C284 are in the minimum energy condition and in pressure balance with their surroundings.
- Older FRIIs are likely to come into pressure balance and no longer shock-heat their surroundings via a supersonically expanding cocoon.

We have shown that by studying the group atmospheres of individual sources, we can investigate the energy transfer mechanisms for different types of source and at different stages in source evolution. The presence of shock-heating in sources like Cen A (Kraft et al. 2003) and more gentle heating in 3C66B are consistent with a change of energy transfer mechanism in FRIs as they expand and come into pressure balance. Our FRII observations suggest that a similar picture is also true for these objects, although the overpressured, supersonic stage probably lasts for a larger fraction of the source's life.

Finally, our study of a sample of groups has shown that radio-source heating is common, and that the effects of radio-source heating on groups are significant and long-lived.

Acknowledgments

JHC acknowledges support from a PPARC studentship. MJH thanks the Royal Society for a fellowship. We thank Trevor Ponman for providing results in advance of publication.

References

Belsole, E., Worrall, D. M., Hardcastle, M. J., Birkinshaw, M., Lawrence, C. R. 2004, MNRAS, submitted

Best, P. N. 2004, MNRAS, in press, astro-ph/0402523

Binney, J., Tabor, G. 1995, MNRAS, 276, 663

Churazov, E., Sunyaev, R., Forman, W., Böhringer, H. 2002, MNRAS, 332, 729

Croston, J. H., Hardcastle, M. J., Birkinshaw, M., Worrall, D. M. 2003, MNRAS, 341, 1046

Croston, J. H., Birkinshaw, M., Hardcastle, M. J., Worrall, D. M. 2004, MNRAS, submitted

Fabian, A. C., et al. 2003, MNRAS, 344, L43

Hardcastle, M. J., Alexander, P., Pooley, G. G., Riley, J. M. 1996, MNRAS, 278, 273

Hardcastle, M. J., Birkinshaw, M., Cameron, R. A., Harris, D. E., Looney, L. W., Worrall, D. M. 2002, ApJ, 581, 948

Hardcastle, M. J., Birkinshaw, M., Worrall, D. M. 1998, MNRAS, 294, 615

Hardcastle, M. J., Worrall, D. M., Birkinshaw, M. 1998, MNRAS, 298, 1098

Isobe N., et al. 2002, ApJ, 580, 111

Jones, C., et al. 2002, ApJ, 567, 115

Kadler, M., et al. 2003, NewAR, 47, 569

Kraft, R. P., et al. 2003, ApJ, 592, 12 9

Leahy, J. P., Perley, R. A. 1991, AJ, 102, 537

Leahy, J. P., Bridle, A. H., Strom R. G. 1998, URL: http://www.jb.man.ac.uk/atlas/

Morganti, R., Fanti, R., Gioia, I. M., Harris, D. E., Parma, P., de Ruiter, H. 1998, A&A, 189, 11

Osmond, J. P. F., Ponman, T. J. 2004, MNRAS, in press, astro-ph/0402439

Roychowdhury, S., Ruszkowski, M., Nath, B. B., Begelman, M. C. 2004, astro-ph/0401161

Sanderson, A. J. R., Ponman, T. J., Finoguenov, A., Lloyd-Davies, E. J., Markevitch, M. 2003, MNRAS, 340, 989

Worrall, D. M., Birkinshaw, M. 2000, ApJ, 530, 719