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Jet/Environment Interactions in Low-Power Radio Galaxies

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Abstract. The interactions between low-power radio galaxies and their environments are thought to play a crucial role in supplying energy to offset cooling in the centres of groups and clusters. Such interactions are also important in determining large-scale radio structures and radio-source dynamics. I will discuss new *XMM-Newton* observations of the hot-gas environments of a representative sample of nine FRI radio galaxies, which show strong evidence for the importance of such interactions (including direct evidence for heating) and provide important new constraints on source dynamics and particle content. In particular I will show that the widely discussed apparent imbalance between the internal lobe pressure available from relativistic electrons and magnetic field and the external pressure of hot gas correlates with radio structure, so that naked jets require a large contribution from non-radiating particles, whereas lobed sources do not. This may provide the first direct observational evidence that entrainment of the ICM supplies the missing pressure.

1. Introduction

Low-power (FRI) radio galaxies are common in groups and clusters of galaxies, where they are thought to play an important role as part of feedback processes regulating gas cooling and galaxy evolution. The dynamics and evolution of the jets in FRI radio galaxies are essentially controlled by interactions with their hot-gas environments on galaxy, group and cluster scales, resulting in a wide variety of large-scale radio structures ranging from narrow tails to rounded lobes. The environmental impact of an FRI radio galaxy is highly dependent on its large-scale morphology, so that it is important to understand in which environmental conditions different types of structures are produced. *ROSAT* observations first established that the brightest and most well-studied FRI radio galaxies typically reside in group-scale hot-gas environments (e.g. Komossa & Böhringer 1999; Worrall & Birkinshaw 2000), while the majority of cool-core clusters also possess low-power sources (often of a more amorphous morphology). With *Chandra* and *XMM-Newton* it is possible to study radio-galaxy environments, and jet/environment interactions in more detail (e.g. Croston et al. 2003; Blanton et al. 2001; Sanders & Fabian 2007); however, to date the environmental properties of only a few of the nearby, well-studied FRI radio galaxies have been studied in depth.

One of the key uncertainties in modelling radio-galaxy dynamics and in establishing their energetic impact is the lack of constraints on their particle content. In the case of powerful (FRII) radio galaxies, two lines of evidence suggest that synchrotron minimum energy estimates are fairly reliable: (1) measurements of inverse-Compton emission from the lobes of FRII radio galaxies suggest that their electron energy densities are close to the value for equipartition in the absence of an energetically important proton population (e.g. Croston et al. 2005a; Kataoka & Stawarz 2005), which would have to be coincidental if such a proton population was present; (2) for cases where both external pressure measurements and inverse-Compton internal electron pressures are available, they are in reasonable agreement (e.g. Hardcastle et al. 2002; Croston et al. 2004; Belsole et al. 2004) so that there is no requirement for an additional particle population on energetic grounds. However, in low-power (FRI) radio galaxies, it has been known for several decades that the radio-emitting relativistic electrons, together with an equipartition magnetic field, cannot provide sufficient pressure to balance the measured external pressure if it is at equipartion (e.g. Morganti et al. 1988; Hardcastle et al. 1998; Worrall & Birkinshaw 2000). In Croston et al. (2003), we showed for two FRIs that the additional pressure cannot be due solely to electron dominance as this would result in detectable X-ray inverse-Compton emission, which is not seen, and the presence of sufficient thermal gas at the temperature of the environment was also ruled out by the presence of deficits in X-ray surface brightness at the positions of radio lobes. These conclusions also apply for the cluster cavity systems studied by Dunn & Fabian (2004) and Bîrzan et al. (2004). The most plausible origin of the required additional pressure is therefore either material that has been entrained and heated, or magnetic pressure; however, these scenarios are both difficult to test.

Here I present preliminary results of an *XMM-Newton* study of a representative sample of nine low-power (FRI) radio-galaxy environments, with the aims of constraining particle content and measuring the environmental impact of FRI radio galaxies with a wide range of large-scale morphologies. The sample consists of 3C 76.1, NGC 1044, 3C,296, 3C 31, NGC 315 (new *XMM-Newton* observations), 3C 66B, 3C 449, NGC 6251 (observations published in Croston et al. 2003 and Evans et al. 2005), NGC 4261 (archival data set). All nine radio galaxies are found to lie in group-scale hot-gas environments, with bolometric X-ray luminosities ranging from $\sim 10^{41} - 10^{43}$ erg s^{-1}. Full details of the X-ray analysis will be published in Croston et al. (in prep).

2. Relationship Between Radio and X-Ray Structure

The importance of jet/environment interactions for group and cluster gas has been highlighted by the large number of X-ray cavity systems now known, ranging from elliptical galaxies to the richest clusters (e.g. Dunn & Fabian 2004; Bîrzan et al. 2004). Of the nine systems studied here with *XMM-Newton*, 6 have clear, statistically significant detections of cavities associated with the radio lobes (two new examples are shown in Fig 1). In several cases where a cavity is not identifiable in the X-ray data, the emission is nevertheless elongated perpendicular to the direction of the radio axis, thus demonstrating a clear link between the structure of the X-ray emitting gas and the radio source. While the distribution of group gas clearly indicates an important relationship between the radio and X-ray properties, I found no correlations between global X-ray and radio properties, including luminosities, sizes, and structural parameters. It is unclear which properties control the radio luminosity and power of the group-scale AGN outbursts, but this work suggests that small-scale properties related to AGN fuelling may play a stronger role than large-scale environment in determining the luminosity and size of the radio structure.

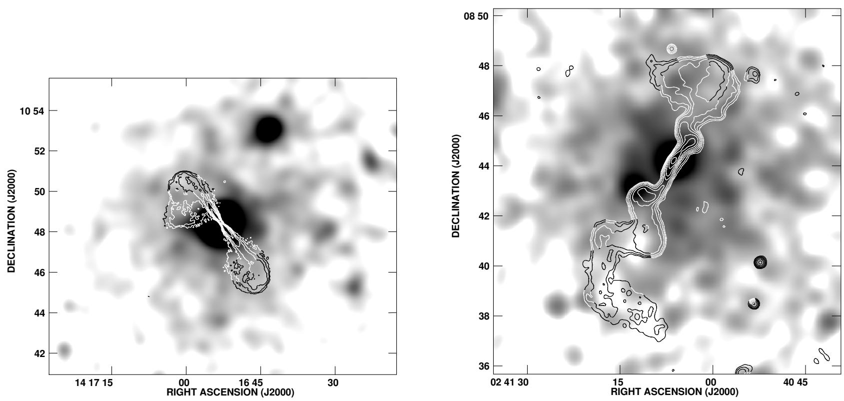

Figure 1. Combined *XMM-Newton* MOS1, MOS2 + pn image of the X-ray environments of 3C 296 (left) and NGC 1044 (right) with radio contours overlaid, indicating X-ray cavities at the positions of the radio lobes.

3. Particle Content

In agreement with previous studies using earlier X-ray observatories (e.g. Morganti et al. 1988; Worrall & Birkinshaw 2000) and using *XMM-Newton* (e.g. Croston et al. 2003), we found that the measured external pressures from the hot gas environments were in nearly all cases significantly higher than the minimum internal pressures for the radio lobes. Fig. 2 (left) shows a histogram of the pressure ratios (P_{ext}/P_{int}) for the 16 lobes in the sample (only one lobe is within the *XMM-Newton* field-of-view for NGC 315 and NGC 6251) showing that the lobes are underpressured by factors ranging from ~ 0.02 to 1.

This is the first time that a study has been carried out for a reasonable sized sample that includes the full range of observed FRI radio morphologies, and so a primary aim was to investigate whether the amount of "missing" pressure is related to the properties of the radio-source and/or its environmental interaction. Fig. 3 shows the external pressure profiles for the two sources with the most extreme behaviour: 3C 296 (top left) appears to be in approximate pressure balance, assuming equipartition, so that no additional pressure contribution is required; NGC 1044 (bottom left) has a high ratio of P_{ext}/P_{int} (~ 40). Fig. 3 also shows the corresponding radio maps for the two sources. It is clear that their radio morphologies are quite different: NGC 1044 has naked jets that remain fairly well collimated over large distances before gradually spreading into plumes or tails, whereas the jets of 3C 296 appear to enter radio lobes at a small distance from the nucleus. This morphological difference suggests a model in

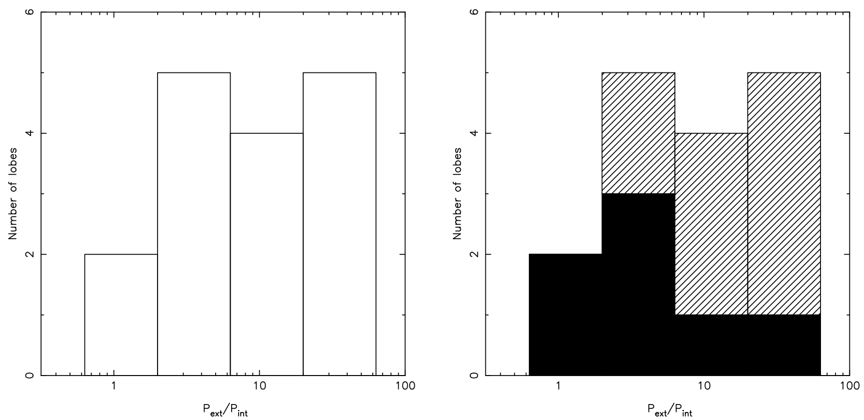

Figure 2. Histogram of the ratios of external to internal (minimum) radio-lobe pressure for the full sample of 9 radio galaxies (16 lobes), right; separated into 'naked jet' sources (filled) and 'lobed' sources (hatched), right.

which jet/environment interactions affect the particle and/or energy content of the radio lobes; for example, the dominant factor in determining the ratio of radiating to non-radiating particles may be the efficiency of the entrainment process.

To test this hypothesis, I separated the 16 radio lobes into the two categories of 'naked jet' sources and 'lobed' sources. The sources classified as having 'naked jets' are: 3C 31, NGC 1044, NGC 315, 3C 449, NGC 6251; those categorised as 'lobed' are: 3C 296, 3C 76.1, NGC 4261, 3C 66B. The right-hand panel of Fig. 2 shows a histogram of the pressure ratios for the two categories, which demonstrates that there is indeed a significant difference in the two populations in the expected sense: the 'lobed' sources are typically closer to pressure balance at equipartition than the 'naked jet' sources. This comparison therefore supports the hypothesis that entrainment of the jet's surroundings on scales of tens to hundreds of kpc is responsible for the apparent pressure imbalance of FRI radio galaxies. Unfortunately there is no obvious observational proxy for jet deceleration or entrainment that can be used to test this hypothesis further with the current data. Comparisons with the models of Laing & Bridle (2002, and in prep.) show that naked jet sources such as 3C 31 have an entrainment rate that increases with distance from the nucleus, whereas lobed sources such as 3C 296 may not.

If this explanation is correct for the FRIs studied here, then an obvious question is whether it is consistent with the pressure offsets observed in cluster centre radio sources (e.g. Dunn & Fabian 2004; Bîrzan et al. 2004, and McNamara et al., this meeting), which typically do not possess well-collimated jets on large scales. Given the amorphous structures of many cluster centre sources, suggestive of strong environmental influence, it seems plausible that there is considerable mixing of cluster gas with radio-lobe plasma (and heating, as required in order for the cavities to be detected). In addition, Dunn et al. (2006) argue, based on a comparison of the leptonic content of the small-scale jet and the en-

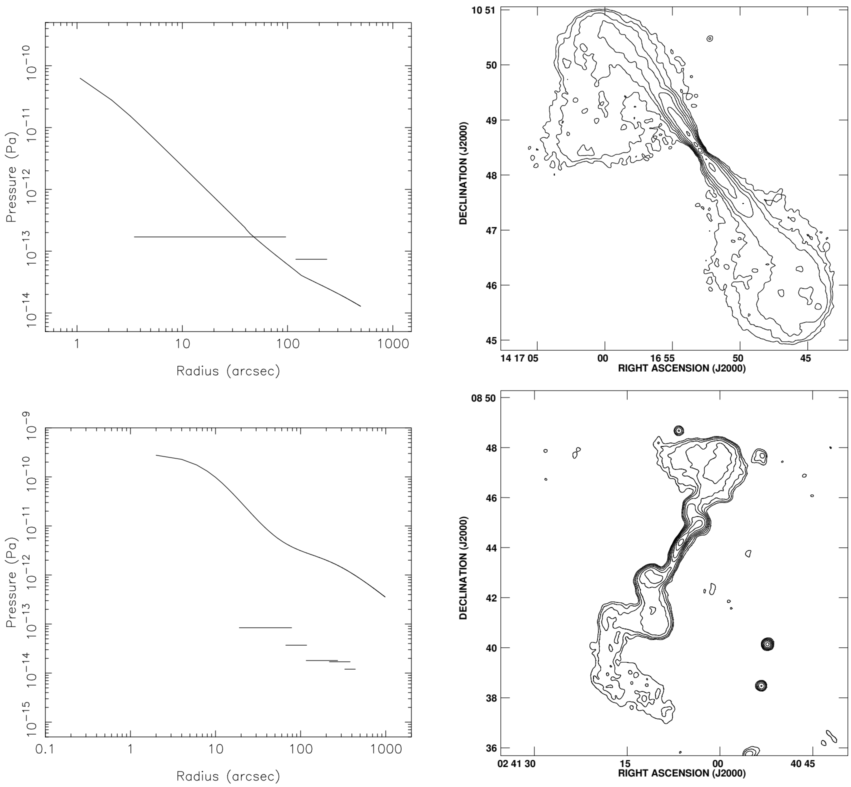

Figure 3. External pressure profiles for 3C 296 (top left) and NGC 1044 (bottom left) with horizontal lines indicating internal minimum lobe pressures for different components of the source. The corresponding radio maps are shown to the right of each profile to illustrate the apparent link between radio morphology and pressure deficit as shown in the right-hand panel of Fig. 2.

ergetics of the cluster bubbles, that even in bubbles with large apparent pressure offsets such as those of the Perseus cluster, the jet is leptonic, so that the pressure offset on large scales is more likely to be due to entrainment rather than a relativistic proton population, consistent with the picture I present here. Hence, while the categorization of group-scale sources into ‘lobed’ and ‘naked-jet’ morphologies with different energetics may not apply for cluster centre sources, these results may nevertheless provide some insight into the solution of the pressure balance problem for these systems as well.

4. Environmental Impact

As discussed in Section 2. and shown in Fig. 1, it is clear that the group gas surrounding FRI radio galaxies is strongly affected by their presence. Earlier *XMM-Newton* studies of the group environments of FRIs found direct evidence for localised heating of the group gas, and indirect evidence for more generalised heating (Croston et al. 2003). In Croston et al. (2005b) I reported an apparent systematic difference in the radio properties of galaxy groups with and without central radio sources, in the sense that radio-loud groups appear to be systematically hotter for a given luminosity. A recent study comparing REFLEX/NORAS clusters with NVSS has found similar results (Magliocchetti & Brüggen 2007), and a recent *Chandra* study of a subset of the Croston et al. (2005b) sample by Jetha et al. (2007) has shown that the gas properties in the innermost regions of the group do not appear to be significantly affected by the presence of a radio source, so that any heating processes must be most significant on larger scales.

In Fig. 4 I show the X-ray luminosity-temperature relation for the current sample of 9 radio galaxy group environments (filled circles). The $\times$ and $+$ symbols indicate the radio-quiet and radio-loud samples of Croston et al. (2005b), respectively, and the solid line indicates the best-fitting relation for the radio-quiet groups. The *XMM-Newton* radio-galaxy sample all lie to the high temperature side of the radio-quiet relation, thus confirming the earlier result: groups containing extended radio sources scatter to higher temperatures for a given X-ray luminosity. In Croston et al. (2005b), we argued, based on a lack of difference in the X-ray-to-optical luminosity ratios for the two subsamples, that this effect must be due to a temperature increase, rather than a luminosity decrease, as might be expected. The origin of this effect therefore remains unclear: for the current sample, the $P\mathrm{d}V$ work available from the currently observable radio source is in most cases insufficient to provide the energy to heat the cluster gas by the required amount, and there is no correlation between radio luminosity and temperature excess.

5. Summary

Study of a representative sample of nine low-power (FRI) radio-galaxy environments with *XMM-Newton* has led to the following conclusions:

- Low-power radio galaxies typically inhabit group-scale environments, which can range in X-ray luminosity from $10^{41} - 10^{43}$ erg s^{-1}. It is therefore important for models of radio-galaxy evolution to take into account the wide range of possible environments in which these sources can occur.

- The apparent pressure imbalance seen in low-power radio galaxies appears to be related to radio-source morphology. 'Naked jet' sources require a large contribution from non-radiating particles or magnetic pressure, whereas 'lobed' sources do not. This suggests that entrainment efficiency may be the dominant factor in determining the energetics of the large-scale radio structure in FRIs.

- The environments of all nine radio-galaxies in this sample appear to be hotter than is predicted by the L_X/T_X relation for radio-quiet groups. The origin of this apparent heating effect remains unclear.

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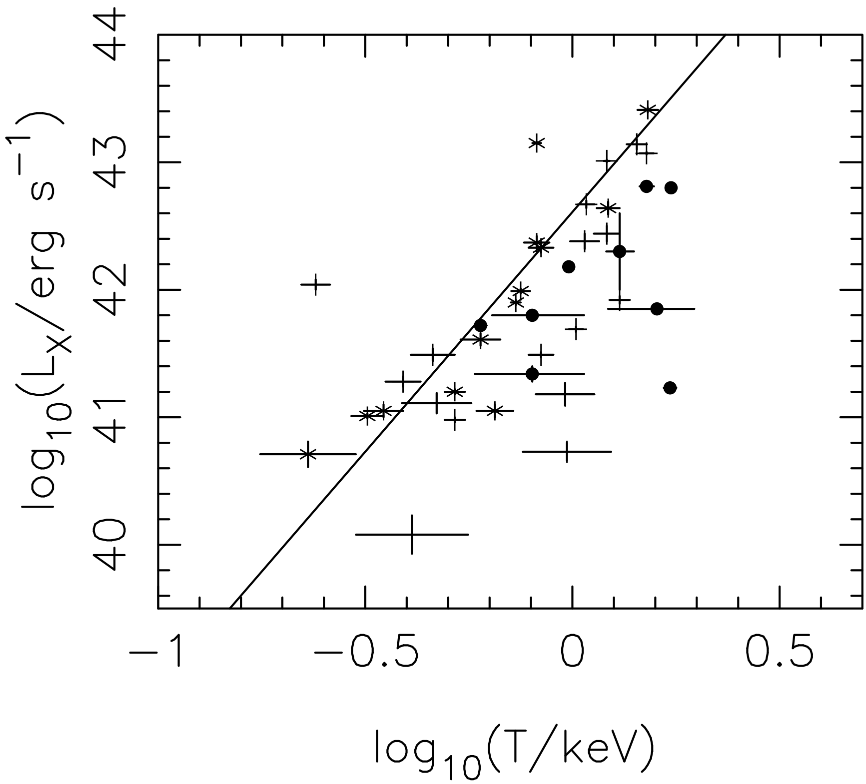

Figure 4. The L_X/T_X relation for the *XMM-Newton* radio-galaxy environments sample (filled circles) compared with the radio-quiet (stars) and radio-loud (+ symbols) samples of Croston et al. (2005). Solid line indicates the best-fitting relation for radio-quiet groups.

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