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The environments of FR II radio sources

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Abstract. Using *ROSAT* observations, we estimate gas pressures in the X-ray-emitting media surrounding 63 FR II radio galaxies and quasars. We compare these pressures with the internal pressures of the radio-emitting plasma estimated by assuming minimum energy or equipartition. The majority of the radio sources (including 12/13 sources with modelled, spatially resolved X-ray emission) appear to be *underpressured* with respect to the external medium, suggesting that simple minimum-energy arguments underestimate the sources' internal energy densities. Some consequences of this result are discussed.

1. Introduction

In order for FR II radio sources to exist at all, the pressure in their lobes must at least match the pressure from the external medium. In many popular models of such objects (e.g. Scheuer 1974, model A; Kaiser & Alexander 1997) the pressure in the lobes must be very much greater than that in the external medium, in order to drive a supersonic transverse expansion.

The pressures in the lobes of radio sources are of course unknown, but we can derive lower limits from standard minimum energy arguments. The dominant external pressure comes from the X-ray emitting intra-group or intra-cluster medium, which can be observed. Comparing the internal and external pressure estimates may then give us some insight into source dynamics and into the question of the particle content in lobes. In FRI radio galaxies, where these comparisons (both in individual objects and for small samples) have been made for some time (e.g. Hardcastle, Worrall & Birkinshaw 1998, and references therein; Worrall & Birkinshaw 2000), the minimum pressures tend to be lower, typically by an order of magnitude, than the external pressure estimated from X-ray observations. Although we expect some contribution to the internal energies of FRI sources from non-radiating particles entrained as the jets decelerate, the discrepancy between minimum and external pressure is remarkably large. It therefore seems worthwhile to carry out a similar study for a large sample of FR IIs. This work is described in more detail by Hardcastle & Worrall (2000).

2. The data

We have collated X-ray data from all *ROSAT* pointed observations of FR II radio sources in the 3CRR sample (from Hardcastle & Worrall 1999). There are 63 observed sources in total, including 3C 405 and 3C 346 (the former is not in 3CRR; the latter is formally not an FR II). We have modelled the spatial distribution of the X-ray emission from 13 of these sources in detail. 34 more sources are detected, but either have too few counts to model or are dominated by a central quasar, and so we can only use the X-ray data to estimate an upper limit on the central gas density. 16 sources are not detected, and we estimate upper limits from the background noise level. To compute thermal pressures we have used temperatures derived from observation where possible and otherwise from the temperature-luminosity relation (David et al. 1993). We estimate minimum pressures in the lobes from published low-frequency radio maps, assuming an electron spectrum $N(E) \propto E^{-2}$ for the very low energy electrons, a low-energy cutoff in the electron population at $\gamma = 10$, and no relativistic proton content. Since the sound speed in the lobes is high, we can meaningfully characterize the lobes with a single lobe pressure.

3. Results

12/13 of the modelled sources have best-fit external pressures which are greater than the internal minimum pressure, in most cases by a large factor (~ 10) at all points along the length of the lobe. The great majority of the upper limits on central external pressure also lie well above the thermal pressure (see Fig. 1, top). The data are therefore consistent with a model in which most FR II sources have internal minimum pressures considerably less than the external pressure. Most of the exceptions to the trend are small sources, with lobe lengths < 10 kpc (see Fig. 1, bottom). The results are insensitive to choice of cosmology, to projection uncertainties, and to our assumptions about X-ray temperatures and electron energy spectra. In some cases, the X-ray emission is clearly resolved and cluster-like: it cannot be radio-related X-ray emission due to inverse-Compton scattering of hidden quasar emission (Brunetti et al. 1997). Some doubt remains for other sources (e.g. 3C 219) with less well-characterized X-ray emission.

4. Implications

Radio sources cannot really be underpressured. The most important implication of our result is therefore that the minimum pressure arguments must be leading us to the wrong conclusions in some, and maybe all, sources.

Observations of inverse-Compton emission in lobes and hotspots *are* currently roughly consistent with minimum pressure/equipartition of energy between magnetic fields and synchrotron-emitting electrons in all 5 lobes (e.g. Leahy & Gizani 1999), and 3/6 of the hotspots (see Hardcastle, Birkinshaw & Worrall, these proceedings) so far detected in X-rays. So models in which either the electron or the magnetic field energy density is dominant, or in which there are low filling factors, are not favoured. Thermal protons would depolarize radio emission, and in any case are inconsistent with the X-ray 'voids' coincident with lobes in a few objects, particularly 3C 405 (Carilli et al. 1994; Wilson, these proceedings). The most likely remaining candidates to make up the missing pressure are non-thermal protons or sub-relativistic electrons (not included in the equipartition calculation). This has significant consequences for the energy

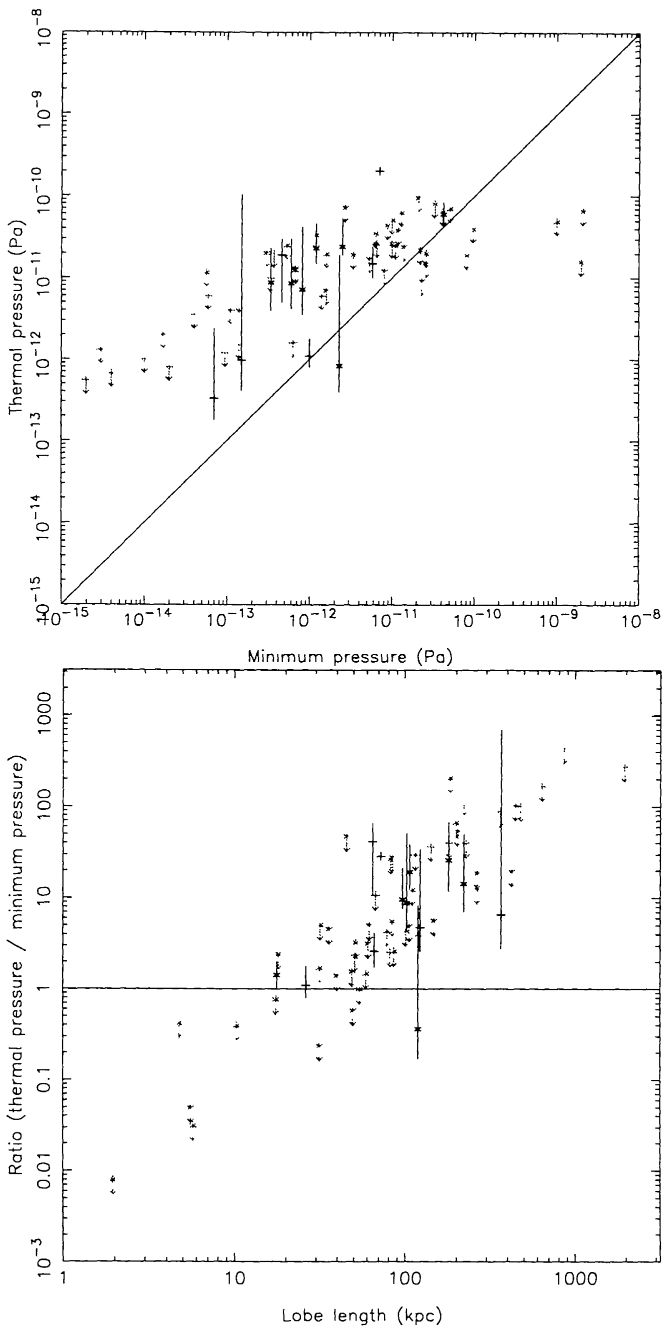

Figure 1. Top: external thermal pressure from the X-ray data plotted against internal minimum pressure from radio observations. Black data points are from the sources whose X-ray environments have been modelled; error bars represent the uncertainty in our model fits. Limits are plotted in grey. The solid line shows pressure equality. The great majority of sources lie above it. Bottom: The ratio of external to internal minimum pressure plotted as a function of lobe length (i.e. the projected length of one of the lobes; $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$). Most of the sources that lie below the line of pressure equality are small.

supplied by the beam (as argued by Leahy & Gizani 1999 and Leahy, Gizani & Tsakiris, these proceedings). For example, the commonly used Rawlings & Saunders (1991) beam powers, which rely on minimum energy arguments, must be significant underestimates.

To make sources *overpressured* as required by self-similar models requires even more 'hidden' internal energy density and even higher beam power. Perhaps all radio galaxies reach pressure equilibrium with their environments at some stage in their evolution. This would have several consequences for source dynamics; the transverse expansion of the lobe would be halted, and the inner regions of the lobe would then be compressed by the external pressure (highest in the cluster centre) in the cocoon-crushing process described by e.g. Williams (1991), eventually removing radio-emitting plasma from the centre of the source. The tapered inner lobes seen in some FR II sources may be evidence for this process.

5. Future work

Chandra and *XMM-Newton* will tell us more about the environments of radio sources, test more widely the hypothesis that thermal plasma is generally absent inside the lobes, and find more inverse-Compton evidence for or against equipartition in lobes and hotspots. These new measurements will provide tests of the model in which all sources may come into pressure equilibrium with their environments at some stage in their evolution.

In the meantime, self-similar models can be used to predict the X-ray emission expected from the environments of radio sources (Kaiser 2000). These predictions need testing against observation. The particle content of lobes can also, in principle, be explored in other ways (Wardle et al. 1998, Mannheim et al. 1991).

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