The Gaseous Environments of Radio Galaxies

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Abstract

X-ray emission traces the gaseous environments of radio sources. The medium must be present for jet confinement, but what are its influence on jet fuelling, dynamics, propagation, and disruption? The observational situation is both complicated and enriched by radio sources being multi-component X-ray emitters, with several possible regions of non-thermal emission. Recent work, primarily based on sensitive ROSAT pointings, is used to contrast the X-ray emission and environments of radio sources with (a) low power, (b) high power at high redshift, (c) high power at lower redshift, and (d) GHz peaked spectrum emission. The trends in external gas density and pressure near extended radio structures are reviewed. Imminently-available X-ray measurements with vastly improved resolution and sensitivity have great potential for resolving many open issues.

1 Introduction

A gaseous medium is essential for the propagation of a radio jet. Although hot gas is traced through its X-ray thermal bremsstrahlung and line radiation, the X-ray detection of gaseous environments around most radio sources has required the sensitivity and angular resolution available only in the last decade with ROSAT. While it is clear that an X-ray emitting medium must be present at some level for the well being of the radio source, major concerns from a radio-astronomy and jet-theory perspective are the extent to which the medium influences radio-jet fuelling, dynamics, propagation, and disruption. From an X-ray astronomy perspective, it is of interest to determine whether

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or not the X-ray environments of radio sources are special, and to use radio sources to indicate the presence of X-rays associated with large-scale structure.

The X-ray-emitting medium of radio sources is complicated to study because radio sources are multi-component X-ray emitters and include several possible regions of non-thermal emission. These non-thermal components are themselves an important probe of the physical conditions of the central engine and radio beams.

Since careful separation of the various X-ray components is essential before progress can be made, this paper first reviews non-gaseous emission components in radio galaxies, and presents examples of observational biases. The discussion of the X-ray emitting environments is broken down by radio-source power and morphology, and trends in external gas density and pressure near the extended radio structures are reviewed. There are many open issues, and I will identify the potential for resolving them using the new X-ray missions with their vastly improved resolution and sensitivity.

Because the central X-ray regions of radio galaxies experience anisotropic emission and absorption, assumptions concerning Unification color an approach to the subject and can be tested by the data. This paper makes the standard Unification assumptions that BL Lac objects, radio-loud quasars, and broad-line radio galaxies (BLRGs) are the unobscured, favorably-beamed counterparts of low-power FRI (Fanaroff & Riley 1974) radio galaxies, high-redshift FRII galaxies, and low-redshift FRIIs, respectively. $H_o = 50$ km s^{-1} Mpc^{-1} and $q_o = 0$ are adopted throughout.

2 Multi-component X-ray Emission

2.1 Cygnus A

Cygnus A is sufficiently powerful and close to show a full array of X-ray emission components. Its surrounding cluster emission is strong, but when modelled and subtracted from the $\sim 0.2 - 2$ keV ROSAT High Resolution Imager (HRI) image, Carilli et al. (1994) found pronounced soft-excess emission associated with the radio hotspots, core, and two (possibly three) regions around the limb of the lobe plasma, together with an X-ray deficit in the inner lobes. With reference to a standard model for a powerful radio source with supersonic jet (Fig. 1), it is interesting to speculate that the excesses around the lobes are parts of ring structures pinching the contact discontinuity. There was no evidence for increased X-ray emission due to higher gas density ahead of the beam, in the cocoon between the contact discontinuity (containing the

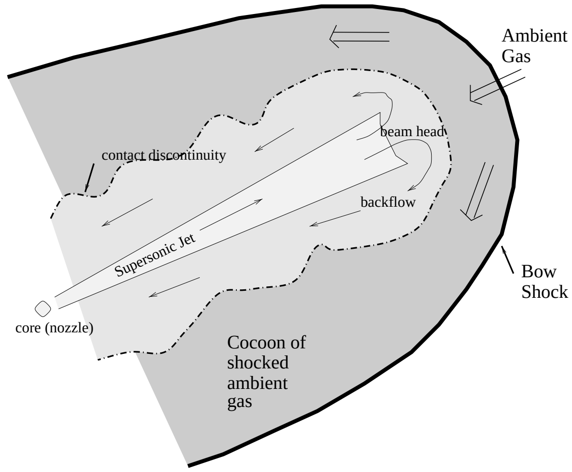

Fig. 1. Sketch of the termination region of a powerful radio jet viewed in the rest frame of the bow shock. Radio lobe emission fills the region inside the contact discontinuity. Between the contact discontinuity and the bow shock we expect the ambient X-ray-emitting medium to be both compressed and heated with respect to the medium in front of the bow shock.

radio lobes) and bow shock, as might confirm the standard model, but Carilli et al. (1994) argue that the increased luminosity due to higher density may be offset by the effect of heating, which would tend to remove X-ray emission to an energy band above that to which ROSAT is sensitive.

X-ray spectroscopy in the 2-10 keV energy band finds a poor fit to cluster gas alone, and argues for the presence of non-thermal emission seen through a large absorbing column, $N_{\rm H} \sim 4 \times 10^{23}$ cm^{-2}, and interpreted as emission from a heavily obscured central AGN (Arnaud et al. 1987, Ueno et al. 1994). Interestingly, this absorbed core emission cannot be the soft-X-ray core excess in the ROSAT HRI image (Harris et al. 1994b), because such a high column density has a disastrous effect on soft X-rays (Fig. 2). Instead, the soft X-rays may arise from a central region in the radio source where the only line-of-sight absorption is the Galactic column, $N_{\rm H} \sim 3 \times 10^{21}$ cm^{-2}. Indirect support for this suggestion comes from the fact that the ratio of the unabsorbed X-ray to core-radio luminosity is then very similar to that of core-dominated quasars and those high-redshift counterparts of Cygnus A for which the core soft X-ray emission is separated from cluster emission (Fig. 3), although the cluster-scale cooling flow in Cygnus A (Reynolds & Fabian 1996) should contribute at some level to the HRI soft X-ray core excess.

2.2 Observational Biases

Because radio galaxies are multi-component X-ray emitters, the energy-band, sensitivity, and spatial and spectral resolution of the observing instrument in-

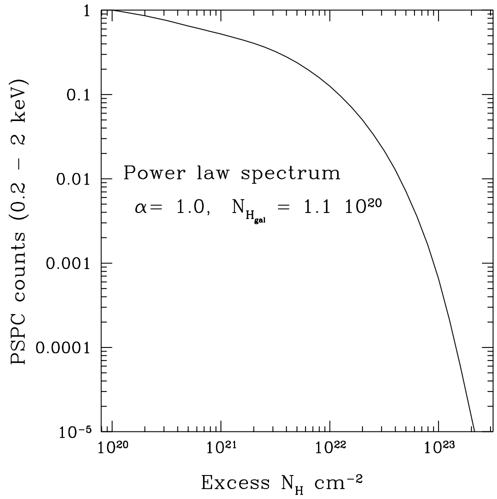

Fig. 2. As the excess (intrinsic) column density rises to more than a few 10^{22} cm^{-2}, the counts measured with ROSAT quickly fall. The example is for the PSPC detector, assuming a source with a power-law spectrum of $\alpha = 1.0$ ($f_\nu \propto \nu^{-\alpha}$) and galactic column density of 1.1×10^{20} cm^{-2}, but a similar situation applies to the HRI and its measurement of the X-ray core of Cygnus A.

fluence what is measured. Focussing X-ray optics have the major advantage of decreasing the background, and so *Einstein* was the first mission to detect some tens of radio galaxies in soft X-rays (e.g. Fabbiano et al. 1984) and to separate components in nearby objects such as Cen A and M 87 (Feigelson et al. 1981, Schreier et al. 1982). The mission contributing most to the subject over the last decade has been ROSAT. The combination of improved sensitivity (roughly twice *Einstein's* collecting area at ~ 1 keV) and a longer mission have permitted relatively large samples of radio galaxies to be studied, and the point response function (PRF) of $\sim 15''$ Half Energy Width (HEW) for the Position Sensitive Proportional Counter (PSPC) and $\sim 4''$ HEW for the HRI (although with poorer sensitivity and no spectral resolution) has led to component separation in many sources for which pointed observations were made. An object can look rather different when viewed with the PSPC and HRI, with the former emphasizing extended emission and the latter the compact components (Fig 4). ASCA has increased the number of radio galaxies with *spectroscopic* component separation (e.g. Sambruna et al. 1999) although, with its relatively poor spatial resolution (HEW $\approx 3'$), weak sources often give ambiguous results, with different combinations of spectral models giving similarly good fits to the data. The payload of BeppoSax covers the broad energy range from soft X-rays to 300 keV, although mostly with non-focussing optics (Boella et al. 1997); its strengths are therefore in broad-band studies of bright beamed counterparts of radio galaxies, although there are tentative claims for the detection of heavily-obscured AGN nuclei (as for Cygnus A) in some FRIs (Trussoni et al. 1998).

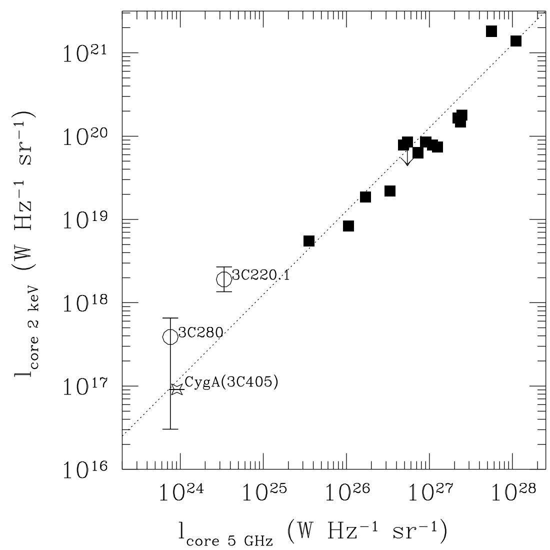

Fig. 3. The two high-redshift ($z > 0.6$) radio galaxies for which core soft X-ray emission is separated from cluster emission, 3C 280 (Worrall et al. 1994) and 3C 220.1 (Hardcastle et al. 1998b), are roughly consistent with an extrapolation of the core radio/X-ray correlation for core-dominated quasars of comparable redshift (Worrall et al. 1994). Since these quasars are believed through Unification models to be powerful radio galaxies oriented with their jets in the line of sight (e.g. Barthel 1989), the correlation supports the interpretation of the core soft X-ray emission from these radio galaxies as being beamed and associated with the radio jet. Cygnus A, although local, has comparable radio-core luminosity to 3C 280, and fits remarkably well on the correlation when the HRI core X-ray emission is interpreted as radio-related.

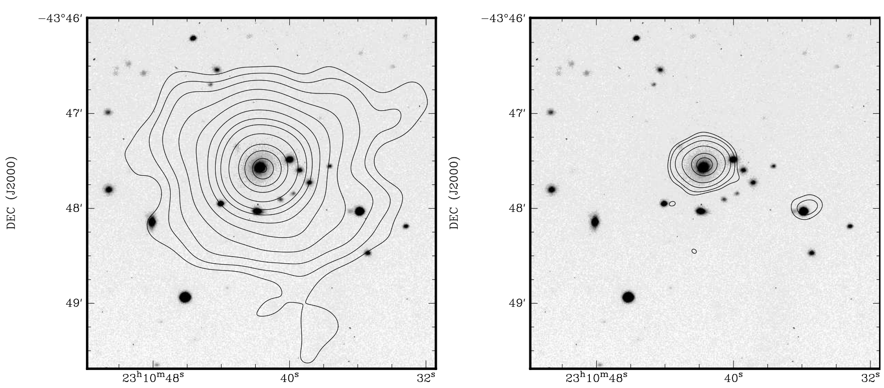

Fig. 4. The ROSAT PSPC and HRI are sensitive to different structures in a complex source, such as J2310-437 (Worrall et al. 1999), a BL Lac object in an X-ray cluster. The PSPC is more sensitive to low surface brightness extended structures (left panel shows X-ray contours from a 4 ks PSPC exposure), whilst the superior spatial resolution of the HRI pin-points features which are unresolved or of small spatial scale (right panel shows 31 ks HRI exposure). Lowest contours are at 3.8σ, and grey-scale is R-band CCD image.

Observational biases occur from redshift effects, not only in the sense that in flux-limited samples the more distant sources are the more powerful. Extended X-ray emission tends to be seen around high-redshift radio sources only if it is of cluster size and strength; around low-redshift sources it is easier to detect the more compact gaseous components than larger-scale emission which fills the detector field of view. Spectral measurements attempt to measure excess absorption over that in the line of sight in our Galaxy, and small fitted excesses become large intrinsic excesses when transformed to the rest frame of a high-redshift source, where this would not happen for a more local source.

3 Non-gaseous X-ray Emission

3.1 Central Engine

The strength of central X-ray emission should depend on the accretion process and black-hole mass, coupled with the effects of geometry and absorption. X-ray imaging has insufficient angular resolution to separate such emission from beamed radiation associated with an inner radio jet. However, in sources where an absorbed power-law component is present, it is easily recognized if it is dominant, and a heavy excess absorption helps to make spectral separation possible even if much of the emission is from surrounding hot gas. The best case is the hard X-ray detection of emission from the core of Cygnus A (§2.1), and absorbed power-law components are claimed in other radio galaxies with ROSAT, BeppoSAX and ASCA (e.g. Allen & Fabian 1992, Trussoni et al. 1998, Sambruna et al. 1999).

Where the excess absorption is only modest, and this covers many of the cases where the absorbed X-ray component is dominant, an association with the central engine is questionable, and the absorbed X-ray emission is most likely beamed emission associated with the radio jet (§3.2). This is illustrated by NGC 6251, where the X-ray absorption of $\sim 10^{21}$ cm^{-2} agrees both with that inferred from reddening through the large-scale disk measured with HST (Ferrarese & Ford 1999) and with an HI radio absorption-line measurement (Worrall & Birkinshaw 1999b), and where the strength of X-ray relative to radio emission in comparison with other radio galaxies argues independently for a radio-related origin for the power-law X-ray emission (Worrall & Birkinshaw 1994). The 'puzzling' excess absorption seen in BLRGs (Sambruna et al. 1999) might also be explained, at least in part, by cool gas on larger scales than an inner torus absorbing jet-related X-rays. This is consistent with the relatively strong X-ray emission of BLRGs and the required orientation of their jets under Unification models.

3.2 Beamed X-ray Emission

ROSAT pointed observations have shown that the central soft X-radiation of low-power radio galaxies is almost certainly dominated by nonthermal emission associated with the radio jet. Canosa et al. (1999) find that the core X-ray and radio emission are well correlated in the B2 radio-galaxy sample (Fig 5), and a similar situation holds for the low-power 3CRR radio galaxies (Hardcastle & Worrall 1999a). M 87 and Cen A are sufficiently close that jet-related X-rays are resolved, and the fact that their X-ray to radio ratio is similar to that for more distant unresolved X-ray cores is further support for a jet-related origin of the core soft X-ray emission in all such sources (Worrall 1997). Although in principle such X-ray emission could be either synchrotron or inverse Compton in origin, the relative proportions of radio, optical (HST) and X-ray core emission, as compared with radio-selected BL Lac objects, argue in favor of inverse Compton emission and predict a relatively flat spectral index (Hardcastle & Worrall 1999b). Flat-spectrum components superimposed on thermal X-rays from hot gas are reported in the ASCA spectra of several low-power radio galaxies, but are variously interpreted as thermal emission associated with an advection dominated accretion flow (Allen et al. 1999) and as higher than previously suggested (e.g. Fabbiano et al. 1989) X-ray emission from stellar and post-stellar X-ray sources (Matsumoto et al. 1997). Jet-related X-ray emission is also likely to be a major contributor to the compact soft X-ray emission of powerful radio galaxies (see Fig 3 and Hardcastle & Worrall 1999a), although in general their greater distance with respect to low-power sources leads to the expectation of a larger contribution from extended gaseous emission within an unresolved X-ray core.

3.3 Non-thermal emission components away from the core

X-ray emission from compact radio hotspots has been detected in a handful of sources, as summarized by Hardcastle et al. (1998a) and Harris (1998). Such measurements are potentially of great physical interest since the radio-emitting regions are normally well localized and, if it can be shown that the X-rays are of inverse Compton origin (e.g. Harris et al. 1994a), the radio and X-ray emission together probe the magnetic field strength and the balance between particle and magnetic energy density. A similar probe on larger scales is provided through inverse Compton scattering of cosmic microwave background (CMB) photons on particles in the radio lobes, with detections reported in a few sources (Feigelson et al. 1995, Tsakiris et al. 1996, Tashiro et al. 1998). Brunetti et al. (1999), in discussing extended emission in 3C 219, have emphasized the role of AGN photons in Compton up-scattering, but at present sources with extended X-ray emission of gaseous origin vastly outnumber those for which

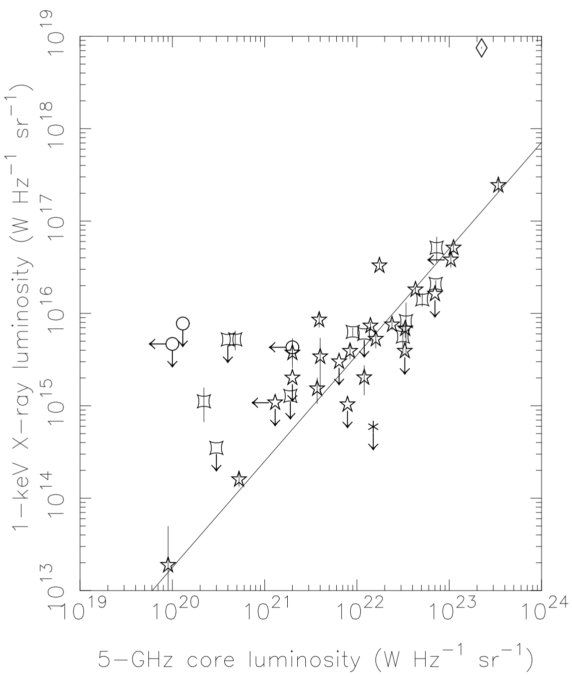

Fig. 5. Core X-ray *vs.* core radio luminosity for the sample of B2 low-power radio galaxies observed with ROSAT in pointed observations, after separation of any extended X-ray emission. The best-fit correlation taking into account non-detections (solid line) excludes (based on astrophysical arguments) a starburst galaxy (cross) and the broad-line radio galaxy 3C 382 (diamond) which fall in the sample. Radio galaxies in previously known optical clusters are shown as squashed squares, relic radio sources are open circles, and other sample members are shown as stars. Figure from Canosa et al. (1999).

extended inverse Compton X-ray emission is likely to have been detected.

4 The gaseous X-ray-emitting medium

4.1 Questions and Timescales

There are a number of interesting questions we would like to answer when studying the gaseous X-ray emitting environment around a radio source. Is the external gas pressure greater than or equal to the minimum pressure calculated for the jet, in which case alternative methods of jet confinement are not required? We would like to know if the radio galaxy is moving in the X-ray medium (so that the jet is affected by ram-pressure forces), or if there are large-scale gas motions (cooling-flows, mergers, winds, etc) which affect the production of jets or cause their disruption. Is the gas distribution smooth between large and small scales, or do abrupt transitions in temperature and density induce observable radio deformations? Do we see evidence of direct interaction between the jets and the surrounding medium (e.g., heating of the X-ray gas) which can be tested against model predictions?

We can compare the inferred age of a radio source with the timescale over which the environment is likely to change.

- The sound crossing time in gas of size d is $\approx 2(d/\mathrm{kpc})\ (kT/\mathrm{keV})^{-1/2}$ Myr. This means that a medium 100 kpc in size has not had time to change as a result of the presence of a 100 Myr-old radio source, and a young radio source should be in an environment which is similar to that of its older counterparts.
- The cooling time of gas of temperature kT and density n_e is $\approx 3 \times 10^4$ $(kT/\mathrm{keV})^{1/2}$ $(n_e/10^{-3}\ \mathrm{cm}^{-3})^{-1}$ Myr. Wide ranges of temperature and density relate to a wide range of cooling times, in many cases approaching the Hubble time. If a cooling-flow is key to the fuelling of a radio source, as suggested for powerful radio galaxies by Bremer et al. (1997), then it is curious that most radio sources appear to be 100 Myr old or younger, where we might expect some to last for a Gyr or more.
- The phases of development of an elliptical-galaxy atmosphere (supernova wind, density increase, cooling, etc; e.g. Ciotti et al. 1991) are long compared with the measured lifetimes of radio galaxies. Are the host galaxies of radio sources in one of these phases, or all?

4.2 The Evidence

4.2.1 FRI radio galaxies

Hot atmospheres have been detected around FRI radio galaxies with *Einstein* and ROSAT. For representative results I turn to the largest sample of such objects with sensitive pointed X-ray observations: the B2 radio-galaxy sample. This is a 408 MHz flux-limited sample of 50 radio sources identified with elliptical galaxies of $m_{\mathrm{Zw}} \leq 15.4$ mag (Colla et al. 1975, Ulrich 1989), of which 40 were observed in ROSAT pointings, 39 being on-axis (Canosa et al. 1999). Apart from one starburst galaxy and one BLRG, all are FRIs at $z \leq 0.072$. Two of the galaxies are the dominant members of catalogued Abell clusters (A1795 and A2199), and two are galaxies of the Coma cluster. The environments of other sample members are measured through their X-ray observations, with particularly useful data for sources observed with the PSPC (Worrall & Birkinshaw 1999a). Fig. 6 shows four representative X-ray images, illustrating group to cluster scales typical of X-ray emitting atmospheres. Such gas engulfs the radio structures (Fig. 7), but the lack of correlation between radio-source size, and size or central density of the X-ray-emitting medium, means that the gas has indeed not had sufficient time to adjust to the pres-

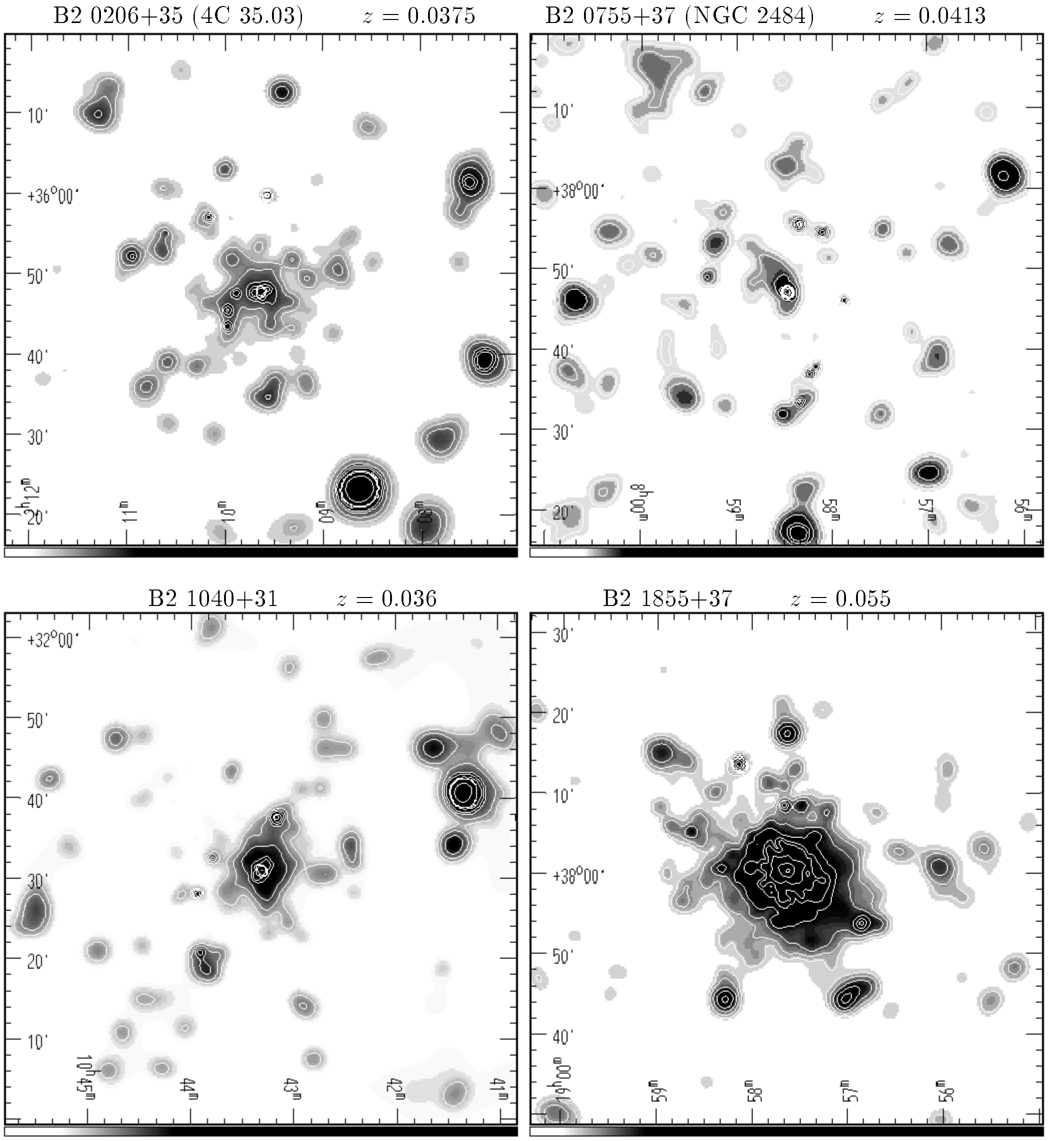

Fig. 6. Four representative > 8 ks-exposure ROSAT PSPC images centered on B2 radio galaxies not in catalogued clusters. Fields are 1.3 square degrees, and 10 arcmin corresponds to between 600 and 900 kpc. A range of sizes of X-ray-emitting atmosphere (group to cluster dimension) is seen. Figure adapted from Worrall & Birkinshaw (1999a).

ence of the radio source (§4.1), and it must be small-scale processes, on size scales less than those of the overall gaseous environments, which are the major influence on radio-source dynamics and propagation.

Although the ROSAT PSPC's spectral resolution is poor by the standards of the CCD detectors on ASCA, *Chandra*, and XMM, and of Astro-E's calorimeters, the energy band is well matched to the typical temperatures of groups and poor clusters. The PSPC-derived luminosities and temperatures of the environments of B2 radio galaxies lie close to an extrapolation of the luminosity-

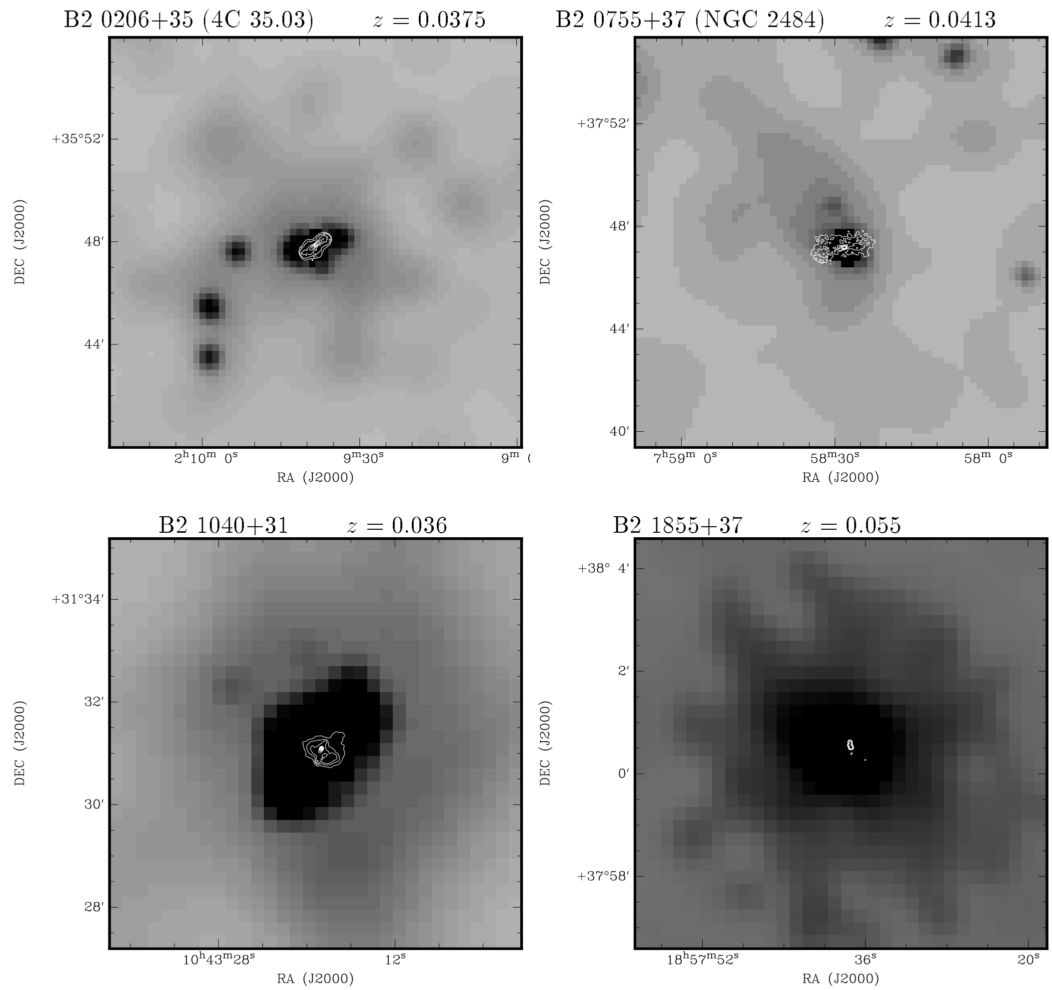

Fig. 7. The X-ray atmospheres (grey scale) of the B2-sample galaxies in Fig. 6 are substantially larger than the VLA radio structures (contours). Note the change of scale from Fig. 6. Radio data are at 5 GHz for NGC 2484 (image kindly provided by M. Birkinshaw) and 1.4 GHz for the other sources (images kindly provided by R. Morganti).

temperature ($L_{\rm bol} - kT$) correlation for more-luminous optically-selected clusters (Fig. 8). Since $L_{\rm bol}$ is principally governed by the gas mass, and kT by the total gravitating mass, this implies that the presence of the radio galaxy does not affect the gas fraction of the environment.

The gas densities for the atmospheres of B2 radio galaxies do not generally suggest the presence of cluster-scale cooling flows – the exceptions being for the two Abell clusters, A2199 and A1795. A2199 is a particularly interesting case, where Owen & Eilek (1998) have pointed out that the rotation measure of the core of B2 1626+39 (3C 338) implies appreciable central magnetic energy density, complicating the interpretation of any cooling flow. Possible galaxy-scale cooling flows, which may play a role in fuelling the radio galaxies, need

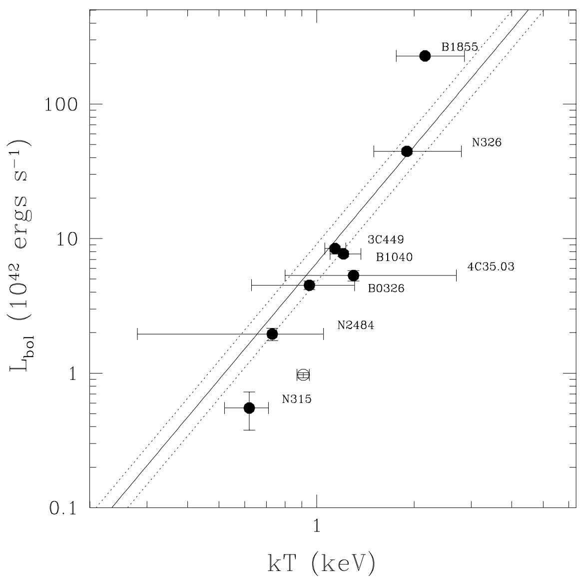

Fig. 8. The X-ray-emitting atmospheres of representative B2 radio galaxies with good ROSAT PSPC measurements fit an extrapolation of the luminosity-temperature ($L_{\rm bol} - kT$) correlation for more-luminous ($\sim 10^{44} - 10^{46}$ ergs s^{-1}) optically-selected clusters (Arnaud & Evrard 1999; dotted lines show rms spread). This implies that the radio galaxy does not greatly influence the gas fraction of the environment. Figure from Worrall & Birkinshaw (1999a).

further investigation using the sensitivity and spatial resolution now available with *Chandra*.

There is widespread evidence for pressure confinement of the kpc-scale radio structures of FRI sources by the X-ray emitting medium (e.g. Fig. 9 and Morganti et al. 1988, Killeen et al. 1988, Feretti et al. 1995, Trussoni et al. 1997), and in some cases an apparent evacuation of the external medium by the jets argues that additional internal jet pressure is required and must be supplied by something other than thermal gas (Böhringer et al. 1993, Hardcastle et al. 1998c). The exception to this picture, a moderately low-power radio galaxy which appears to require an alternative method of confining its long, straight, jet, is NGC 6251 (Fig. 10 and Birkinshaw & Worrall 1993, Werner et al. 1999).

This review will not attempt a detailed discussion of how bending and disruption of the kpc-scale jet structures of low-power radio galaxies may relate to the motion of the radio galaxy through the gas or *vice versa*. However, various factors are likely to be influential, including gas flows and density enhancements resulting from cluster mergers (e.g. Bliton et al. 1998), density and temperature discontinuities at the interface between the galaxy and cluster atmospheres (e.g. Sakelliou & Merrifield 1999), and buoyancy forces (e.g. Worrall et al. 1995).

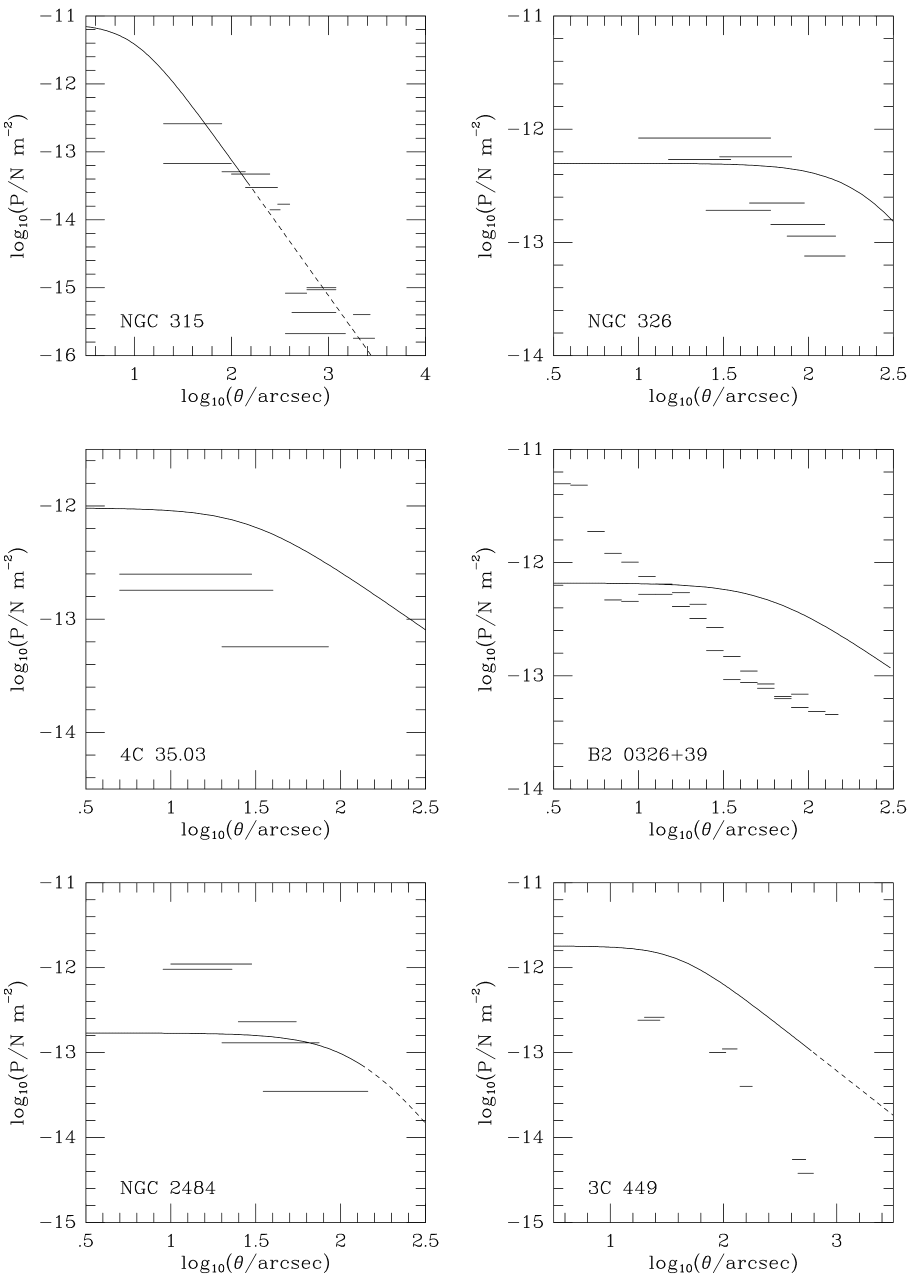

Fig. 9. Thermal pressures in the atmospheres of six B2-sample radio galaxies as deduced from fits to their ROSAT PSPC images (solid line, shown dashed where extrapolated beyond region of clear X-ray detection) compared with minimum internal pressure estimates in the radio sources (horizontal bars). The intergalactic medium is sufficient to confine the outer parts of the radio structures, and in some cases even to within 10 arcsec (5–10 kpc) of the core. In the case of NGC 315 the (extrapolated) pressure of the atmosphere matches the minimum pressure in the radio source over a factor of ~ 100 in linear scale. Figure from Worrall & Birkinshaw (1999a).

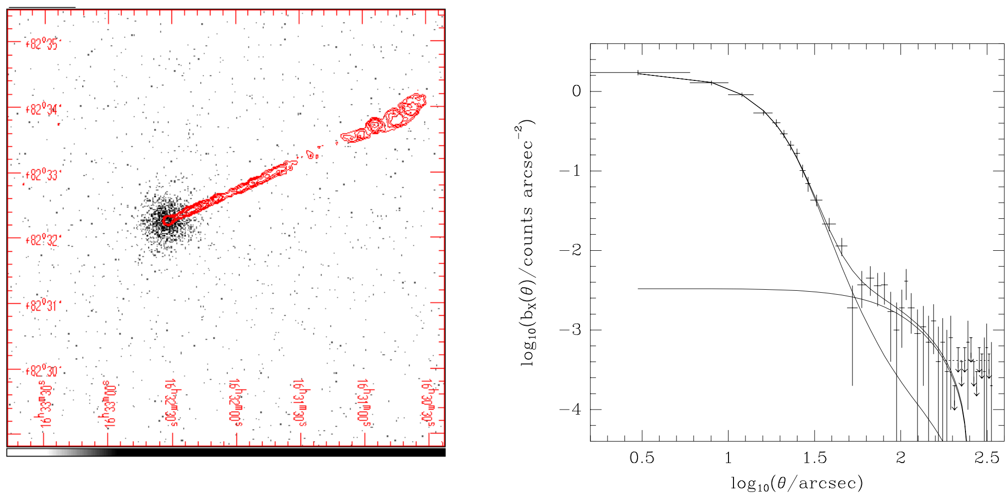

Fig. 10. NGC 6251. 330 MHz radio contours on ROSAT PSPC image (left) and X-ray radial profile with best-fit model of unresolved emission plus weak group-scale gas described by a β-model (right). Radio jet features between 10 arcsec and 4.4 arcmin from the core are all overpressured with respect to the X-ray medium in this giant radio source. Figure from Birkinshaw & Worrall (1993).

4.2.2 High-redshift FRII radio galaxies

A major success of ROSAT has been the first detection of high-power radio galaxies at high redshift. Of the 38 radio galaxies at $z > 0.6$ in the 3CRR sample (Laing et al. 1983), 12 were observed in ROSAT pointed observations and 9 were detected (see summary in Hardcastle & Worrall 1999a), with the four most significant detections exhibiting source extent (Worrall et al. 1994, Hardcastle et al. 1998b, Dickinson et al. 1999). Moreover, extended emission is detected around five 3CRR quasars at redshifts greater than ~ 0.4, one of which is at $z > 0.6$ (Hardcastle & Worrall 1999a, Crawford et al. 1999). Fig 11 plots the extended luminosities for sources for which the structure can be well modelled, together with upper limits for the other 3CRR FRII sources observed in ROSAT pointings (roughly half the sample). Powerful radio sources are finding some of the highest-redshift X-ray clusters known to date, pointing to deep gravitational potential wells early in the Universe.

4.2.3 More local FRII radio galaxies

The nearer a source, the more likely it is that its various X-ray emission components can be separated and the better will be the model fitting to any extended emission. FRII sources are rarer than FRIs and thus typically more distant. Cygnus A and high-redshift FRIIs with good X-ray data have extended X-ray luminosities one to two orders of magnitude higher than a typical FRI, but

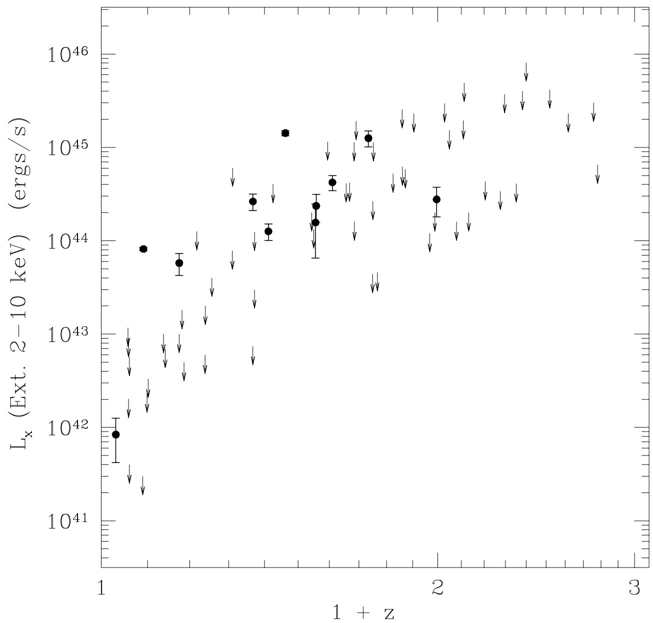

Fig. 11. The extended soft X-ray luminosity of high-power (FR II) quasars and galaxies from pointed observations of the 3CRR sample (from the work of Hardcastle & Worrall 1999a). Detections, in order of increasing redshift, are galaxies 3C 98 and 3C 388, BLRG 3C 219, CSS quasar 3C 48, quasar 3C 215, galaxy 3C 295, quasars 3C 334 and 3C 275.1, galaxy 3C 220.1, quasar 3C 254, and galaxy 3C 280. Upper limits are uncertain, particularly at low redshifts, due to the need to model spatial extent and adopt a value for the gas temperature.

what about other more local FRIIs? Their extended emission should be as easy to detect if it really is so luminous. The situation appears mixed, with the extended luminosities for 3C 98 ($z = 0.0306$, $L_x \sim 10^{42}$ ergs s^{-1}) and 3C 388 ($z = 0.0908$, $L_x \sim 10^{44}$ ergs s^{-1}) differing by two orders of magnitude, and atmospheres for many sources not yet detected (Fig 11). This luminosity range spanned by 3C 98 and 3C 388 is similar to that of representative low-redshift FRIs (see Fig 8), although the full distribution of extended X-ray luminosities for FRIIs is uncertain while many nondetections remain. Despite this, an interesting picture emerges. Contrary to earlier work with less sensitive data (Miller et al. 1985), the X-ray atmospheres, where detected, provide sufficient pressure to confine the radio lobes, with no disagreement from the many sources for which only X-ray upper limits currently exist (Hardcastle & Worrall 1999c). In a detailed study of 3C 388, Leahy & Gizani (1999) have argued that that this implies the lobe energy density is higher than given by minimum-energy arguments, and they make the interesting point that if this is the case, jet kinematic luminosities (normally calculated as energy density times volume, divided by spectral age) are underestimated.

4.2.4 Young Radio Galaxies

GHz Peaked Spectrum (GPS) radio sources are believed to be young FRII sources and, even if only ~ 100 pc in size, the sound-crossing time in the surrounding medium ($\sim 10^5$ years: §4.1) is likely to be appreciable compared with the age of the source (Conway 2000). We therefore expect the environments of such sources to be similar to those in the inner parts of their older counterparts. A search with ROSAT and ASCA for X-ray emission in or around the archetypal GPS radio galaxy $2352 + 495$, at $z = 0.237$, has set an upper limit for the soft X-ray band (0.2 - 2 keV) of about 2×10^{42} ergs s^{-1} (O'Dea et al. 1996, O'Dea et al. 1999). From Fig 11, this is already below the level at which the atmospheres of some FRII radio galaxies are detected, suggesting that slightly more sensitive observations with forthcoming missions should see the atmosphere of this source.

5 The Near Future

A new era for X-ray astronomy has begun with the launch of *Chandra* on July 23rd 1999, soon to be followed by XMM (December 1999) and Astro-E (January 2000). Arcsecond imaging and detailed spectroscopy with *Chandra* (see http://chandra.harvard.edu/) will probe the central regions of radio galaxies, telling us whether or not radio sources have dense cooling gas on sub-cluster/group scales, a possible jet trigger, and will provide information on the role of mergers and clumping in radio-galaxy formation, evolution, and intermittency. We expect new X-ray detections of knots, hotspots, and compact jets, from which physical parameters of the emission regions will be deduced. XMM's unprecedented throughput coupled with ~ 15 arcsec imaging and CCD spectroscopy (see http://astro.estec.esa.nl/XMM/) will measure large samples of more distant sources, probing the relationship between X-ray environment and radio-source structure. Spectroscopic separation of components (non-thermal and thermal) will be easier, testing, among other things, models for jet disruption. The Astro-E mission (see http://astroe.gsfc.nasa.gov/), with its calorimeter spectral resolution of ~ 12 eV FWHM, should open the door to new radio-source science – kinematic and dynamical studies via X-ray line emission – paving the way for a future generation of X-ray missions with high-throughput eV-level spectroscopy (see http://constellation.gsfc.nasa.gov/ and http://astro.estec.esa.nl/SA-general/Projects/XEUS/).

6 Summary

- Radio galaxies are multi-component X-ray emitters.

- Jet-related emission dominates the soft X-radiation from the cores of low-power radio galaxies, and may also be important in high-power sources.
- X-ray emission probes the magnetic field strength in compact hot spots (via the synchrotron self-Compton process) and extended regions (via inverse Compton scattering of CMB photons).
- An extended X-ray medium is expected to take a relatively long time to respond to the influence of a radio jet.
- FRI radio sources reside in galaxy/group/cluster hot atmospheres with densities which don't require cluster-scale cooling flows, and pressures which are generally sufficient to confine the radio jets.
- High-redshift FRIIs may all reside in clusters with likely cooling flows.
- More local FRIIs may all be in environments which are rich enough for radio-lobe pressure confinement.
- There are many open issues which the new X-ray observatories will imminently address.

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