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The intermediate-power population of radio galaxies: morphologies and interactions

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Abstract. Radio galaxies of intermediate power dominate the radio-power injection in the Universe as a whole, due to the break in the radio luminosity function, and so are of special interest. The population spans FR I, FR II, and hybrid morphologies, resides in a full range of environmental richness, and sources of all ages are amenable to study. We describe structures and interactions, with emphasis on sources with deep high-resolution *Chandra* X-ray data. As compared with low-power sources there is evidence that the physics changes, and the work done in driving shocks can exceed that in evacuating cavities. A range of morphologies and phenomena is identified.

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1. The intermediate-power population

Our motivation for studying intermediate-power radio galaxies is that the radio luminosity function breaks at intermediate powers (e.g., Best *et al.* 2005), where sources from the lower-power FR I and higher-power FR II populations (Fanaroff & Riley 1974) overlap (hereafter called the FR I/II boundary zone). This means that in weighting power by density it is the intermediate-power radio galaxies that dominate the overall radio power in the Universe. If radio power is a proxy for jet power, then these sources should dominate radio-galaxy heating in the Universe.

For radio galaxies in significant atmospheres in the local Universe, jet powers have been measured by combining the enthalpy of cavities evacuated of X-ray-emitting gas by the radio lobes with their ages (e.g., Bîrzan *et al.* 2004). Such work has led to correlations between jet and radio power (e.g., Bîrzan *et al.* 2008, Cavagnolo *et al.* 2010, O'Sullivan *et al.* 2011). Godfrey & Shabala (2016) have argued that common distance spreading, forcing correlations to slopes approaching unity, may be a strong factor driving the results, but more recently Ineson *et al.* 2017 have estimated jet powers for samples at higher radio power from measurements of lobe overpressuring with respect to the intergalactic medium (IGM). The conclusions are that correlations broadly hold, but that different radio-source morphology and composition contribute a large scatter (Croston, Ineson & Hardcastle 2018). We find the sources in the FR I/II boundary zone to be intermediate both in radio power and estimated jet power, so supporting the hypothesis that their environmental heating is of particular importance.

FR I/II boundary sources span a wide range of atmosphere type. For example, the boundary-zone sources in the sample of radio galaxies with low excitation emission lines of Ineson *et al.* (2015) span three orders of magnitude in the X-ray luminosity of their environments.

In our work we concentrate on radio galaxies at redshift less than 0.1 for the best spatial resolution. This has given us two redshift-selected subsamples from two primary samples. One is 3CRR (Laing, Riley & Longair 1983) where there are 15 low-redshift boundary-zone sources, all of which are *Chandra* observed. Our matched southern-hemisphere sample is selected from MS4 (Burgess 1998, Burgess & Hunstead 2006a, Burgess & Hunstead 2006b), and is only partially observed with *Chandra*. Additionally we've observed other FR I/II boundary-zone sources falling outside those complete samples. As a rough approximation, about 30 per cent of the radio galaxies lie in significant group or cluster atmospheres.

2. A new rich-cluster atmosphere

One of our southern-sample sources, PKS B1416-493, led to a recent discovery with *Chandra* of a $z < 0.1$ 4.6-keV cluster (Worrall & Birkinshaw 2017). Finding new nearby rich clusters has become rare. The radio source lies central to the cluster emission which, unusually for such situations, is void of a strong cool core. Detection of lobe inverse Compton emission and an X-ray lobe cavity have enabled good estimates of source energetics, and this FR I/II boundary source is consistent with jet-radio-power correlations and so should be a fair representative of a source providing heating in a rich cluster environment.

3. Two sources in a poorer cluster

The poor cluster Abell 3744 at $z = 0.038$ contains two FR I/II boundary sources, NGC 7016 and 7018 (Worrall & Birkinshaw 2014, see also Birkinshaw *et al.*, these proceedings). A pronounced cavity overlaps lobe emission from each source. The cluster temperature, at 3.5 keV, is much hotter than expected based on cluster temperature-luminosity correlations, but since it would take the energy from 85 cavities to provide such heating, a recent merger is the likely case of the excess heat. It is extraordinary that the large-scale plumes from the two radio galaxies seem to be hugging X-ray-emitting gas of different temperature. The radio plasma appears to be acting as a thermal barrier, perhaps due to magnetic-field compression and a smaller gyroradius inside the radio plasma than in the external gas.

4. Shocks

While earlier Chandra work argued for weak or absent shocks around radio galaxies (see McNamara & Nulsen 2007), the situation changes for FR I/II boundary-zone sources, perhaps due to their more representative range of atmospheres. Moderate Mach 2 shocks are seen in 3C 305 and 3C 310 from the 3CRR sample (Hardcastle *et al.* 2012, Kraft *et al.* 2012). In PKS B2152-699 from our southern sample, we measure shocks of roughly Mach 2.7 (Worrall *et al.* 2012). Here the detection of lobe inverse Compton emission coupled with *Chandra* measurements of the gas properties enables a secure estimate of the source energetics, leading to the important conclusion that the work in driving shocks dominates that in producing cavities, so jet power can be sorely underestimated from cavity estimates alone.

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5. Protons not contributing to minimum energy

Our studies have led to an important conclusion concerning minimum energy. The argument is as follows. Measurements of X-ray inverse Compton emission from the lobes of FR II radio galaxies have found magnetic fields that are typically about a third of the minimum-energy value calculated using the radiating leptons as the only significant contributer to the particle energy density (e.g., Croston *et al.* 2005). More recently we find the same situation for the lobes/plumes of FR I radio galaxies (Duffy, Worrall & Birkinshaw 2018). It's known from pressure-balance considerations that FR II lobes cannot contain significant proton pressure (Croston *et al.* 2005, Ineson *et al.* 2017, Croston, Ineson & Hardcastle 2018) while FR Is do (e.g., Morganti *et al.* 1988, Worrall & Birkinshaw 2000), for which the best candidate is re-energized entrained particles (Croston *et al.* 2008). So, similar departures from minimum energy are seen in FR Is and IIs, but only FR Is contain a significant proton pressure. The logical physics conclusion is that only electrons are relevant to the state of minimum energy, even in the presence of protons. This is perhaps because electrons are light, and so should react quicker to magnetic field irregularities. A further conclusion is that if relativistic protons enter lobes from FR II jets (including quasars) in similar numbers to electrons, they need a lower minimum Lorentz factor than the electrons so as not to increase lobe pressure significantly.

6. Local versus large-scale heating

A relatively small fraction of FR I/II boundary sources appears to be interacting with their environments on a scale that may provide large-scale heating. In some cases, significant environments appear already to have been lost, with heating complete. However, local heating is rather common.

In this regard, study of our 3CRR subsample of FR I/II boundary-zone sources finds almost half to show evidence of enhanced central belt-like gas structures, seen between and roughly orthogonal to the lobes (Duffy, Worrall & Birkinshaw 2018). Such gas can have originated from mergers, fossil groups or cool cores. Less clear is whether or not the radio plasma is driving the gas towards the AGN nucleus, as might assist fuelling, since measurements of temperature structure in the belt gas are generally insufficient for firm conclusions. The low-redshift radio galaxy best supporting inflow is 3C 386 (Duffy *et al.* 2016), but this source is underpowered for the FR I/II boundary zone by a factor of two to three.

On an even more localized scale, FR I/II boundary-zone sources show cases where the jets have bent appreciably in interactions with large gas clouds. A well-studied case is PKS 2152-699 at $z = 0.0282$, where the jet shows at least two distinct bends on its path to the northern hotspot (Worrall *et al.* 2012). The outer bend lies adjacent to a bright high ionization cloud (Tadhunter *et al.* 1987), and a recent kinematic study of the gas argues for a proton contribution to the jet to avoid ram-pressure deflection exceeding that observed (Smith *et al.* 2018). The gas cloud, of mass of order 10^8 $M_\odot$, has been heated to X-ray temperatures by the jet's passage (Worrall *et al.* 2012). The inner jet bend is embedded within galaxy emission and less amenable to study, but lies adjacent to a bright feature seen in HST data and which in a similar way is likely to be responsible for the jet deflection here. A further example is the FR I/II boundary-zone radio galaxy 3C 277.3 (Coma A) at $z = 0.0853$. Despite the source lying closer to the plane of the sky than PKS 2152-699, the projected deflection is greater, at 40°, and again the gas cloud adjacent to the bend is heated to X-ray temperatures (Worrall, Birkinshaw & Young 2016).

Both PKS 2152-699 and 3C 277.3 also show interfaces for heating on hundred-kpc scales. PKS 2152-699, which fills much of its 1-keV group atmosphere, is strongly shocking gas around its lobes, as mentioned above. At the outer extremities of the lobes of 3C 277.3 lie Hα-emitting filaments believed to be merger remnants (Tadhunter *et al.* 2000). An anti-correlation between the locations of arms of enhanced X-ray emission and the filaments suggests that shocks advancing around the lobe are inhibited by the dense colder material (Worrall, Birkinshaw & Young 2016).

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