Jet environments and energetics, and prospects for finding galaxy groups with new radio surveys

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Fig 1: Radio galaxy jet feedback in action. The radio lobes of Cygnus A (red) are pushing aside the ICM plasma (blue), generating shock waves and plasma flows and heating the plasma.

Summary

We have carried out the first representative survey of the hot-gas environments and energetics of the radio-loud AGN population using the largest existing radio-selected sample with well-determined cluster environments (Ineson et al. 2013, 2015, 2017), making it possible to assess the population-wide impact of powerful radio galaxies. Our main conclusions are:

- Most radio galaxies are found in groups rather than clusters, although because there is a correlation between radio luminosity and ICM richness for Low Excitation Radio Galaxies (LERGs) , powerful LERGs can inhabit clusters. This correlation is not evident for High Excitation galaxies (HERGs), which typically reside in groups and weak clusters below 3 keV.
- For FRII morphology galaxies, we can estimate the magnetic fields and internal energies of the lobes reliably from low-frequency radio observations. This is not the case for FRI galaxies.
- We have developed a new method to find and characterise evolved galaxy groups using low-frequency radio surveys (Croston et al. 2017). This is expected to yield large samples at high redshift from high-resolution, wide-field surveys such as the LOFAR Tier-1 survey.

We describe our results in more detail below.

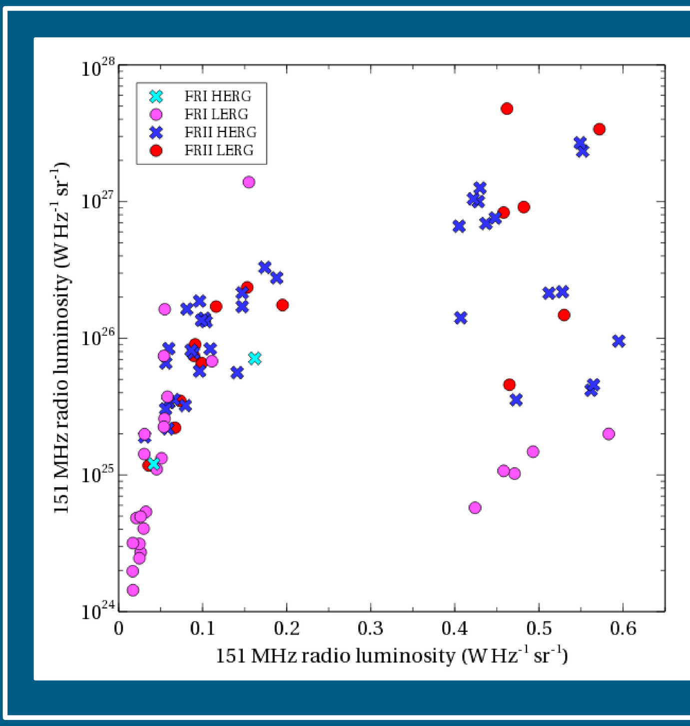

Fig. 2: Our z0.1 and z0.5 samples of radio galaxies, broken down into spectral and morphological classifications.

A representative view of radio-galaxy cluster gas distributions

We characterised the environments of a representative sample of radio galaxies, to determine the types of environment inhabited by different types of radio galaxy and how the ICM affects their properties (Ineson et al. 2013, 2015).

We used two samples for this project, one at redshift 0.1 and the other at redshift 0.5, each containing both FRI and FRII morphology galaxies and HERGs and LERGs (Fig. 2). We obtained the ICM properties from new and archival X-ray observations, and Fig. 3 shows the ICM luminosity L_X plotted against radio luminosity L_R for the different classes of galaxy. The line at 10^{44} erg s^{-1} gives a rough indication of the group/cluster boundary. Our results therefore reflect those of previous researchers (e.g. Hill & Lilly 1991, Best 2004, Hardcastle 2004), namely that *the majority of radio galaxies inhabit groups and weak clusters*, with those occupying richer environments all being LERGs at the high end of their luminosity range.

We found a good correlation between radio and cluster luminosity for the LERGs (Fig. 3, left), albeit with substantial scatter. The scatter is in part related to the morphology, so it would be possible to predict the ICM properties of the LERGs from the radio luminosity. However, radio galaxies at higher redshifts are predominantly HERGs and, as can be seen in Fig. 3 (right), there is no similar, clear correlation between radio and ICM luminosity for the HERGs once the common correlation with redshift has been taken into account.

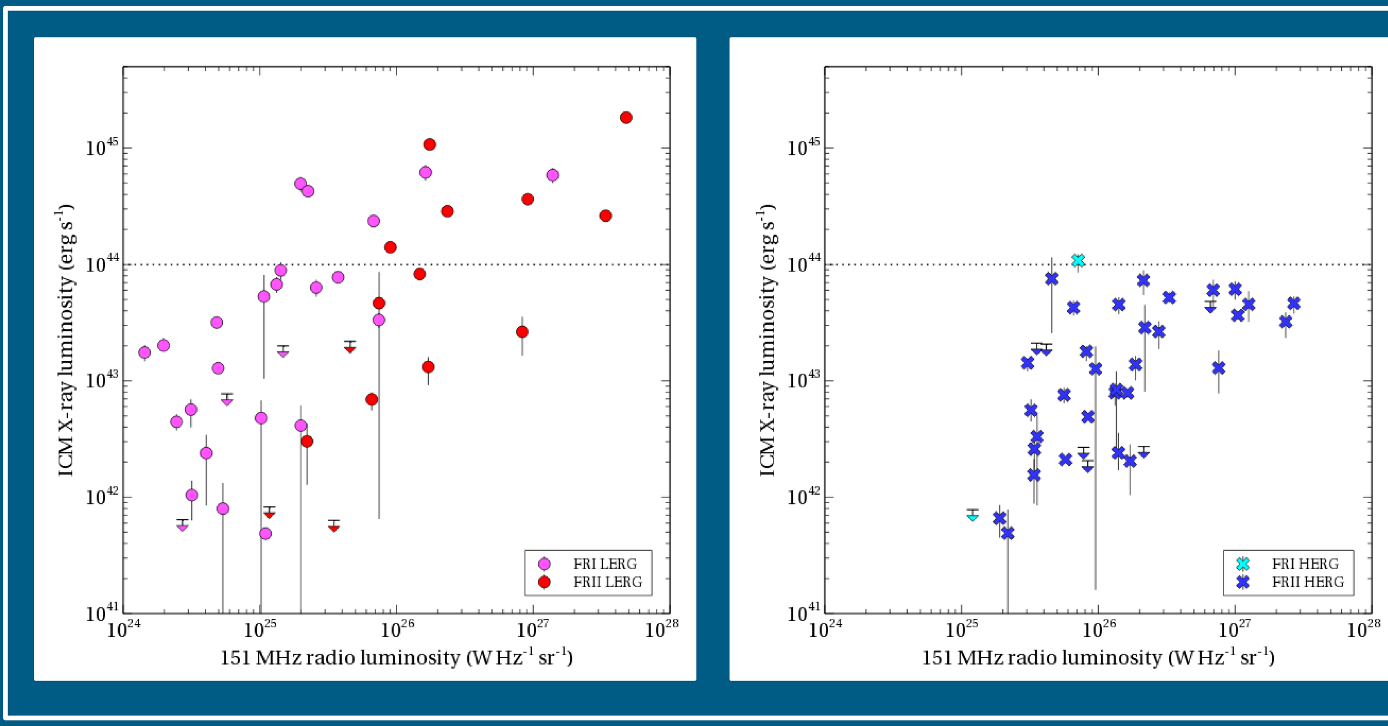

Fig. 3: ICM luminosity plotted against radio luminosity for the LERGs (left) and HERGs (right). There is a correlation between the two factors for the LERGs, with evidence of a difference between the FRI and FRII morphology galaxies, but not for the HERGs.

Population-wide radio-lobe energetics and dynamics

Having looked at the effect of the environment on the radio galaxy, we then looked at the converse process – how the radio galaxy affects its large scale environment (Ineson et al. 2017).

To quantify the effect of the jets on the ICM, we need to know their internal energy. Because of the degeneracy between magnetic field and particle energy, this cannot be determined by radio flux alone. So without further information, the lobe energy can only be estimated by assuming equipartition between the energy in the magnetic field and particles. However, inverse Compton scattering of the CMB by the relativistic particles in the lobes can be detected in X-ray observations of many FRII galaxies (e.g. Croston et al. 2005, Ineson et al. 2017). We used this to estimate the electron content and so to calculate the magnetic field and electron energy for the FRII lobes in our samples (Hardcastle et al. 1998). We found that the magnetic fields were at about 40% of their equipartition value – $B=0.4B_{eq}$ (Fig. 4, left) and that the lobe internal pressure P_{int} matched the external ICM pressure P_{ext} near the middle of the lobe (Fig. 4, right).

Thus for the majority of FRII sources *we can predict the internal conditions of the lobe and the external pressure at mid-lobe from the radio flux alone*.

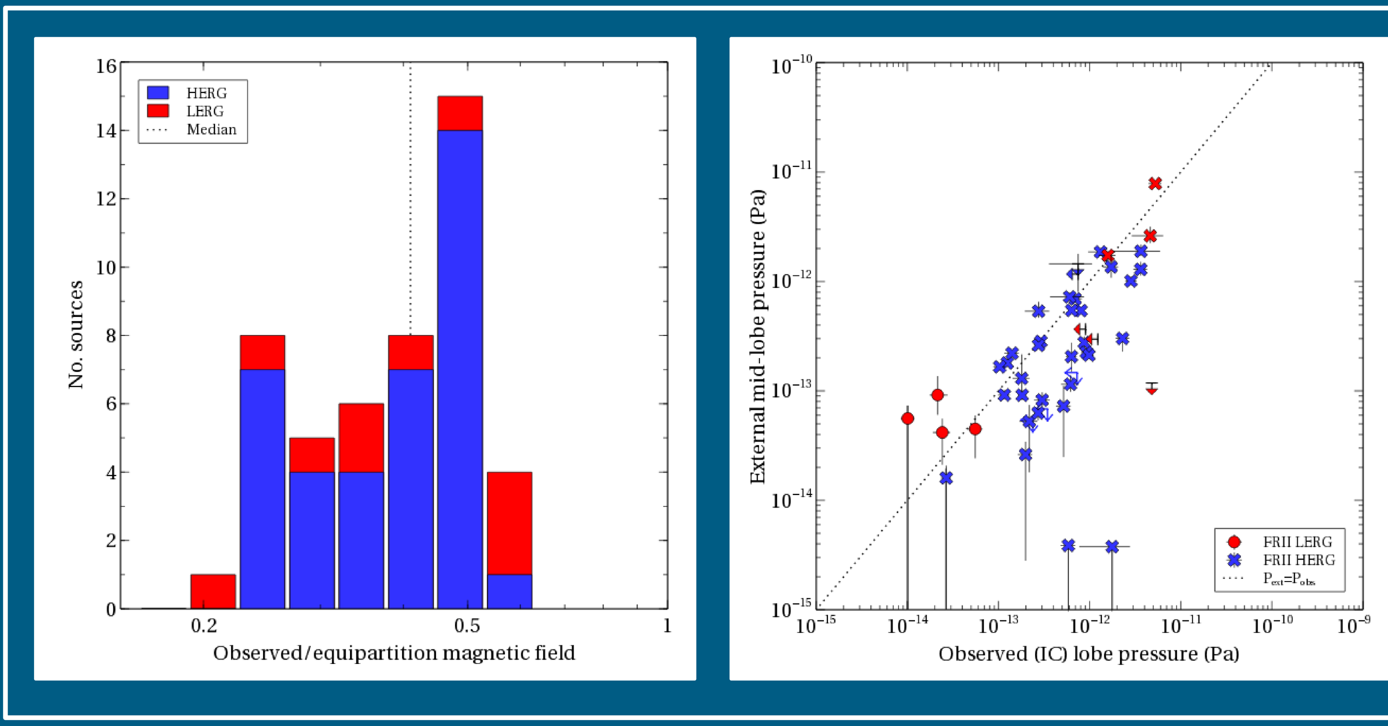

Fig. 4: FRII lobe internal conditions. On the left, the ratio between the measured magnetic field and the equipartition value has a small range with a median of 0.4. On the right, the internal lobe pressure compared with the mid-lobe ICM pressure, showing that for most sources the lobe is in pressure balance near mid-lobe.

A new method for finding and characterizing evolved galaxy groups

In Croston et al. (2017), we demonstrate that, as a result of our improved understanding of FRII internal conditions and environments, it is possible to predict group/cluster X-ray luminosities from radio properties alone, potentially providing a new tool for finding and characterizing high-redshift galaxy groups.

We applied a morphological selection to include only regular FRII radio galaxies of "classical double" morphology (82% of the parent sample of Ineson et al. 2017). Fig. 5 shows that the estimated radio-lobe pressures, based only on lobe radio flux and geometry and assuming a magnetic field strength of $B=0.4B_{eqp}$,reliably predict the external ICM pressure at the mid-lobe distance.

We then used the universal pressure profile of Arnaud et al. (2010) to determine the cluster mass from our single pressure estimate, and the L_X – M_{500} relation of Pratt et al. (2009) to predict the X-ray luminosity. Fig 5 (right) demonstrates that our method succeeds in predicting group/cluster X-ray luminosities to within a factor of ~2 *using only the radio properties of the embedded radio galaxy*.

This method, applied to the new generation of wide-field radio surveys, could therefore provide an effective tool to find and characterise large samples of relaxed galaxy groups and low mass clusters at redshifts too high to be observed with current techniques, providing data for studies of large-scale structure evolution and the effects of radio-loud AGN feedback.

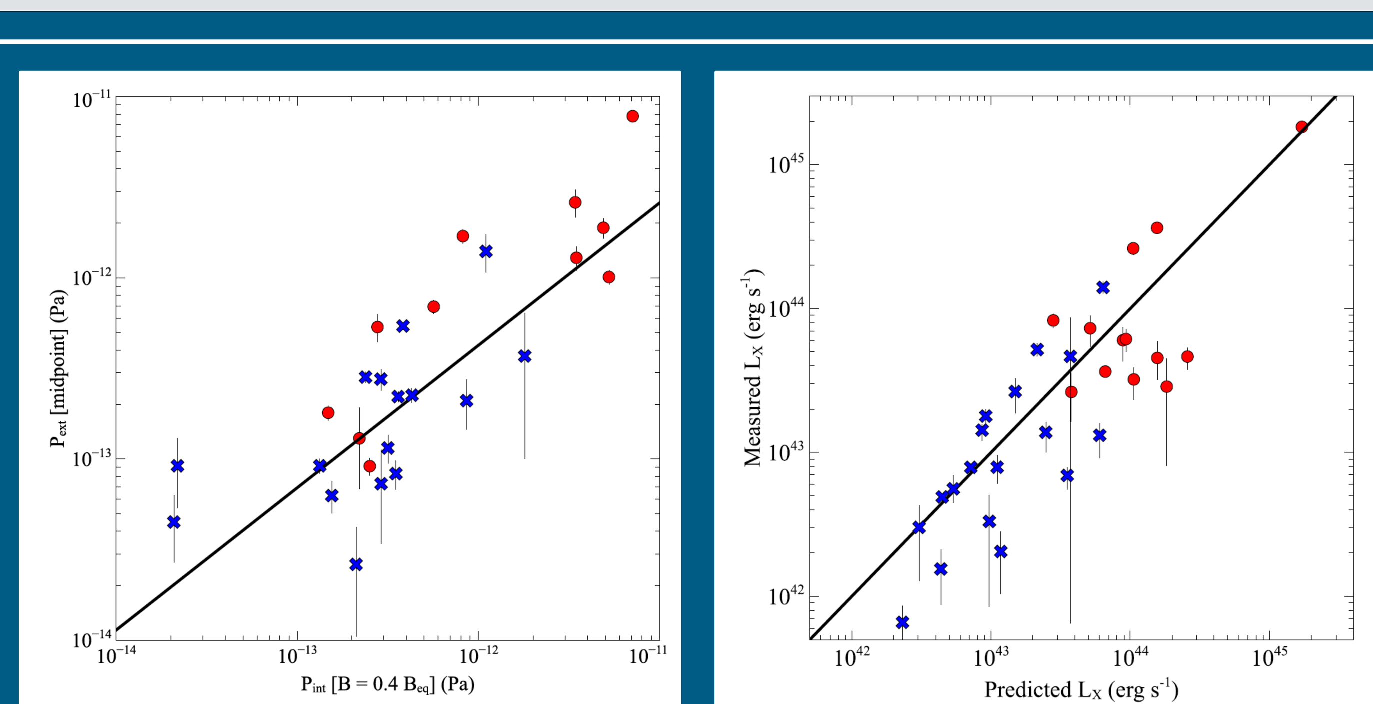

Fig. 5: Predictions of the ICM properties for our sub-sample of mature, morphologically regular FRII radio galaxies. On the left, the internal lobe pressures P_{int} calculated assuming a magnetic field of $0.4B_{eq}$ compared with the measured external ICM pressure P_{ext} at the mid-lobe distance. On the right, the predicted ICM X-ray luminosities determined from the radio-measured lobe pressures and the universal pressure profile compared with their measured X-ray luminosities, demonstrating that for this sample the environments can reliably be predicted from low-frequency radio observations.

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