Session 3: Evolution of galaxies and AGN in high-density environments from high to low redshifts

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INVITED LECTURES

High density galaxy environments — the radio view

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Abstract. Radio-loud active galaxies are widely believed to have a strong impact on their environments, and often lie in groups and clusters of galaxies. In this article I summarize what we can understand about the sources' effects on their surroundings from the perspective of radio galaxy physics, with special reference to the energetics of the impact on the external medium and its inference from large statistical studies of radio galaxies.

Keywords. galaxies: active, galaxies: jets, galaxies: clusters: general, radio continuum: galaxies

1. Introduction

In this article I aim to summarize the evidence for 'feedback' from the kpc-scale lobes of powerful radio galaxies on the gas-rich environments that typically surround them. I will discuss our current understanding of the properties of radio lobes, derived from observations and modelling of individual sources, and the statistical constraints that it is currently possible to place on the energetic impact of the population of radio galaxies as a whole. Due to space limitations, I do not consider the topic of how the active galactic nucleus (AGN) is connected to the large-scale ambient conditions, which would be necessary for a complete understanding of the feedback loop. For reviews on cluster feedback in general, the reader is referred to McNamara & Nulsen (2012). Hardcastle & Croston (2020) review radio lobe and AGN physics and some of the discussion in this article summarizes points of view that are presented in more detail there.

2. Physics of radio galaxies

Radio galaxies (also radio-loud AGN or RLAGN) are AGN-driven systems in which powerful relativistic jets are generated close to the central black hole and propagate to very large (up to Mpc) physical scales. Radio emission is the result of synchrotron radiation generated by relativistic electrons/positrons and magnetic fields in the jets and the lobes that surround them. A toy (and probably excessively simplistic) model of a radio galaxy is one in which jets switch on with some kinetic power Q at time $t = 0$ and maintain constant power until they switch off at some time T which may be of the order of 10^8 years later (Hardcastle 2018). From the point of view of feedback studies, we want to know what Q and T are and what fraction of the total released power QT is injected into the various components of the environment of the RLAGN. Of course, in reality, the jet power Q may vary substantially over the lifetime of the large-scale radio structures, perhaps giving rise to multiple outbursts of RLAGN activity, but the simple model above provides a starting point for discussion.

The fact that the kpc-scale components of powerful RLAGN must have *some* effect on their environments on these scales was realised very early on (e.g. Scheuer 1974). Since radio lobes are polarized at low frequencies, they cannot be filled with material at the same density and pressure as the hot external medium; instead they must push the external medium out of the way as they expand. In doing so, at the very least, they must do the work involved in compressing and lifting that material. To do this, the lobes must be at least in pressure balance with ambient material, but their internal pressure could be significantly higher (e.g. Begelman & Cioffi 1989) and so they could in principle drive strong shocks through the ambient medium, transferring significantly more energy to the medium than a naive $p\delta V$ estimate would suggest (Kaiser & Alexander 1997). All of this was known before the first detailed X-ray observations were made.

X-ray observations with the required sensitivity to study radio galaxy dynamics began to be available in large numbers with the advent of *Chandra*, and gave us three key pieces of information:

(*a*) X-ray cavities are observed associated with many radio lobes, confirming that the lobes do indeed remove ambient medium at X-ray temperatures from the space they occupy. This was already starting to become clear with *ROSAT* data, see e.g. Böhringer *et al.* 1993; Hardcastle *et al.* 1998, and is now very well known as a result of *Chandra* studies (e.g. Fabian *et al.* 2006; Bîrzan *et al.* 2012)

(*b*) Strong shocks are rare (though not unknown: Croston *et al.* 2007). However, weak shock-like enhancements of X-ray emission are seen around many radio lobes (Kraft *et al.* 2003; Forman *et al.* 2007; Croston *et al.* 2009; Randall *et al.* 2015).

(*c*) Crucially, measurements of inverse-Compton emission from lobes allow us to measure the internal energy density in the radiating particles and field and to show that in general, for powerful sources, the internal pressure of the lobes does not *greatly* exceed that of the external material (Hardcastle *et al.* 2002b).

For the most powerful sources (Fanaroff-Riley class II or FRII objects: Fanaroff & Riley 1974), a consistent picture emerges from these observations. Jets are light (probably electron-positron) bulk-neutral outflows, and the energy density on large scales is entirely explained by the relativistic leptons and magnetic field that give rise to the synchrotron and inverse-Compton emission (Hardcastle *et al.* 2002b). Initially these sources drive a strong shock into their environment, but the internal pressure in the lobes and the ram pressure due to the jet both drop with lobe size (i.e. with time) and by the time sources have grown to scales of hundreds of kpc they are in rough pressure balance transversely while continuing to expand supersonically longitudinally (Ineson *et al.* 2017). They are, however, surrounded by a shell of swept up, shocked and compressed gas and it is this that can be seen in X-ray observations. Numerical modelling shows that the fraction of the total energy in this shocked shell is about equal to the total energy stored in the lobes themselves (Hardcastle & Krause 2013; English *et al.* 2016) and all of this energy will eventually be available to heat the external medium, though it remains unclear whether it does so on the most useful scales (Omma & Binney 2004; Hardcastle & Krause 2013, and see further Section 4.3, below). One can gauge the energetic impact of a radio galaxy of this type, and/or its environment simply by making radio observations and inferring the internal energy density or pressure (Croston *et al.* 2017).

Low-power radio galaxies (Fanaroff-Riley class I, FRI) present a more complex picture. Firstly, inverse-Compton observations that would allow a direct measurement of magnetic field strengths do not exist in general (Hardcastle & Croston 2010). Secondly, it has been clear for some time that the radiating particles and field cannot on their own balance the pressure of the X-ray observed external environment for these objects (e.g. Morganti *et al.* 1988; Böhringer *et al.* 1993; Hardcastle *et al.* 1998; Worrall & Birkinshaw 2000; Croston *et al.* 2003; Dunn *et al.* 2005). In other words, there must be some other, dominant

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contribution to the internal pressure that we are not seeing, as discussed in detail by Croston *et al.* (2018). Various possibilities exist. In my view the most likely is that the entrained baryonic matter that is required to decelerate the large-scale jets from relativistic speeds is heated to high temperatures and comes to dominate the energetics of the source (Wykes *et al.* 2013; Croston & Hardcastle 2014). This material is not directly observable and so other methods, such as the 'cavity power' method of Bîrzan *et al.* (2012) must be applied to infer the radio source's energetic impact: these rely on expensive X-ray observations. Even when, as in the best-studied FRI objects, jet power can be inferred, it is not always clear that the jet is having any effect at all on the rapidly cooling central regions of the host environment (Hardcastle *et al.* 2002a). In systems such as Perseus A, where the radio source undergoes continuous, small-scale outbursts (Fabian *et al.* 2006) the AGN is certainly well coupled to the cooling material, but that does not appear always to be the case.

3. The impact of next-generation radio surveys

To make a quantitative estimate of the effect of radio galaxies (or more generally radio-loud AGN, which include the radio-loud quasars) it is first necessary to be able to find and characterize the RLAGN population. For many years radio astronomy has lagged behind other wavebands (particularly optical and infrared) in terms of its capability to survey the sky. Although wide-area sky surveys such as the 3C survey and its descendants (Laing *et al.* 1983) appeared very early on in the history of radio astronomy, these were both extremely shallow (thus selected only the most radio-luminous sources at any given redshift) and very low in angular resolution, so that radio sources that they detected could not easily be identified with their optical counterparts. The radio telescopes that succeeded these early survey instruments, with the capability to make high-resolution images (such as the 5-km telescope, now the Ryle Telescope, or the Very Large Array (VLA)) also tended to be based on large dishes and had correspondingly small fields of view, and so were of limited use in carrying out surveys, although extremely valuable in following up sources that were already known. The VLA survey with the best resolution to date, FIRST (Becker *et al.* 1995), unfortunately has little or no sensitivity to the extended structures that act as calorimeters for powerful RLAGN.

Next-generation radio surveys improve, or will improve, on the VLA's survey capabilities by having some or all of the following features:

- Few-arcsec resolution for source identification
- Much larger instantaneous field of view
- Much higher sensitivity
- Much better instantaneous *uv* plane coverage, in particular a combination of long and short baselines giving sensitivity to extended structure.

Here I focus on the LoTSS survey (Shimwell *et al.* 2017). This is at the time of writing the furthest advanced of the next-generation continuum surveys with arcsec resolution, and is carried out with the Low-Frequency Array (LOFAR: van Haarlem *et al.* 2013). LoTSS has a wide tier and a deep tier — only the first of these will be discussed in detail here. The wide tier aims to survey the whole sky above $\delta = 0°$ at 144 MHz, initially with 6-arcsec resolution, to a sensitivity better than 100 μJy beam^{-1} at favourable declinations. At the time of writing the second LoTSS data release (DR2), which will cover 5,700 deg^2 at a typical rms noise level of 70 μJy beam^{-1} and contains around 4.4 million radio sources, is in preparation. The scientific results presented here are taken from LoTSS DR1, covering 424 deg^2 in the HETDEX Spring field (Shimwell *et al.* 2019) with comparable quality to the DR2 area. Not only is the depth of the LoTSS survey much better than that of FIRST (for synchrotron emission with $\alpha = 0.7$ it goes ten times deeper while having essentially the same spatial resolution) but the images, though surface-brightness limited, are sensitive to structure up to degree scale. LoTSS thus allows us to carry out the best characterization yet of the low-z RLAGN population.

4. Feedback results from LoTSS

4.1. *Ubiquity of radio AGN activity*

Sabater *et al.* (2019) investigated the level of RLAGN activity in the overlap between the well-known MPAJHU SDSS-based spectroscopic sample of galaxies (Brinchmann *et al.* 2004), which also provides SDSS-based galaxy mass estimates, and the DR1 dataset. A crucial complication in extragalactic surveys is to separate radio emission originating in the AGN from that which is generated by star formation. In most cases, only the radio luminosity and the multiwavelength properties of the host galaxy exist to allow us to make this distinction. Where a star formation rate can be estimated, the radio/star-formation-rate relation (Gürkan *et al.* 2018) can be used to try to select objects whose radio emission is dominated by AGN activity, since these will have radio luminosity significantly greater than the level predicted from their star-formation rate. However, star-formation rates are best estimated using far-infrared data, and so Sabater *et al.* (2019) were forced to use various proxies of AGN activity that correlate with a radio excess. With this caveat, their result is still very striking. They reproduce the well-known result that RLAGN incidence depends on galaxy mass (Auriemma *et al.* 1977; Best *et al.* 2005) but, because of the sensitivity of LOFAR, are able to show for the first time that *all* galaxies above $\sim 10^{11} M_{\odot}$ have excess radio emission at the level of 10^{21} W Hz^{-1} or higher. The nature of this AGN activity, which in some cases is at very low levels, and its effect on the host environment remains to be investigated, but the fact that it is there at all is of great interest in feedback models.

4.2. *Energetic impact of the RLAGN population*

Hardcastle *et al.* (2019b) considered the larger RLAGN dataset obtained by cross-matching with the PanSTARRS/*WISE* optical/IR data in the DR1 field (Williams *et al.* 2019) and obtained a sample of 22,000 candidate RLAGN with usable spectroscopic or photometric redshift, using selections based on those of Sabater *et al.* (2019) where possible and *WISE* colour selection to exclude star-forming galaxies otherwise.

The objective of this study was to model the actual jet power of the population, and derive the jet kinetic luminosity function, the volume density of energy being generated by RLAGN as a function of jet power. Inference of jet power from the radio emission is a complex process, and has generally been done in the past by making use of simple scaling relations between radio luminosity and jet power, which cannot be correct in detail. Numerical modelling (Hardcastle & Krause 2014; English *et al.* 2016) shows that radio luminosity for a source with a given jet power Q evolves in a complex way with time and also depends on host environment and redshift, so inferring jet power from observations is not trivial. However, observed physical size is a proxy for source age, so jet power can be inferred by first using the observed size distribution to obtain the lifetime distribution, and then using that plus the radio luminosity distribution to infer jet power.

In detail, we used the analytic models of Hardcastle (2018) to represent the evolution of radio luminosity and physical size with lifetime. We constructed grids of models over the redshift range spanned by the RLAGN sample ($0 < z < 0.7$) and marginalized over the known distribution of angle to the line of sight and an assumed distribution of environmental richness (we assume that RLAGN environments are drawn from the group/cluster mass function). For each radio source in the LOFAR sample, we could then match the

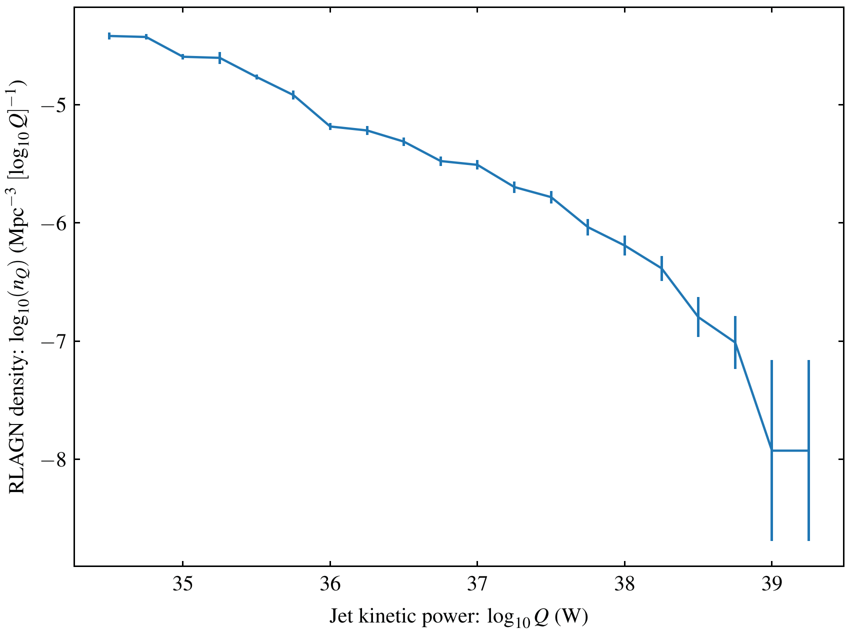

Figure 1. The kinetic luminosity function computed by Hardcastle *et al.* (2019b) for $z < 0.7$ LoTSS AGN. Note the low-power power-law behaviour and the steepening at the highest jet powers, which means that energy injection is dominated by sources with jet powers around $Q = 10^{38}$ W.

radio luminosity, observed size and redshift to points on this grid and read off an estimate of the jet power and its uncertainty. Constructing an ordinary luminosity function based on these jet powers (with the usual sample completeness corrections) leads to a jet kinetic luminosity function for jet powers in the range 10^{34} to 10^{40} W (Fig. 1).

The kinetic luminosity function can be directly integrated to obtain the power density injected by all radio-loud AGN in the local universe per unit volume: 7×10^{31} W Mpc^{-3}. Remarkably, this is comparable to the total X-ray cooling power of all groups and clusters in the local universe, estimated from the X-ray luminosity function of Böhringer *et al.* (2014) to be $\sim 2 \times 10^{31}$ W Mpc^{-3}. Thus the radio AGN population is capable of offsetting all the local radiative cooling of their environments. This is an essential test of feedback models in which RLAGN prevent the cooling of the hot phase of their environments. Our results are consistent with those of Best *et al.* (2006) and Smolčić *et al.* (2017), who used simple radio luminosity-based jet power inference rather than a sophisticated model. The latter authors also showed that the AGN heating density that we (and they) infer is consistent with the expectations from the SAGE model of Croton *et al.* (2016).

There remain questions about the detailed modelling of these sources, particularly the inference of jet power for low-luminosity FRI-type objects (see Section 2) but the overall picture is very encouraging and the next stage would be to investigate feedback effects e.g. as a function of host environment and redshift to see whether they are consistent with the predictions of galaxy formation models in more detail.

4.3. *The fate of the cosmic rays*

In active sources, as discussed in Section 2, about half the energy that is injected by the jet goes into the internal energy of the radio lobes, i.e. into the cosmic rays that dominate the energy density. These may be essentially pure electron/positron in the case of FRIIs or

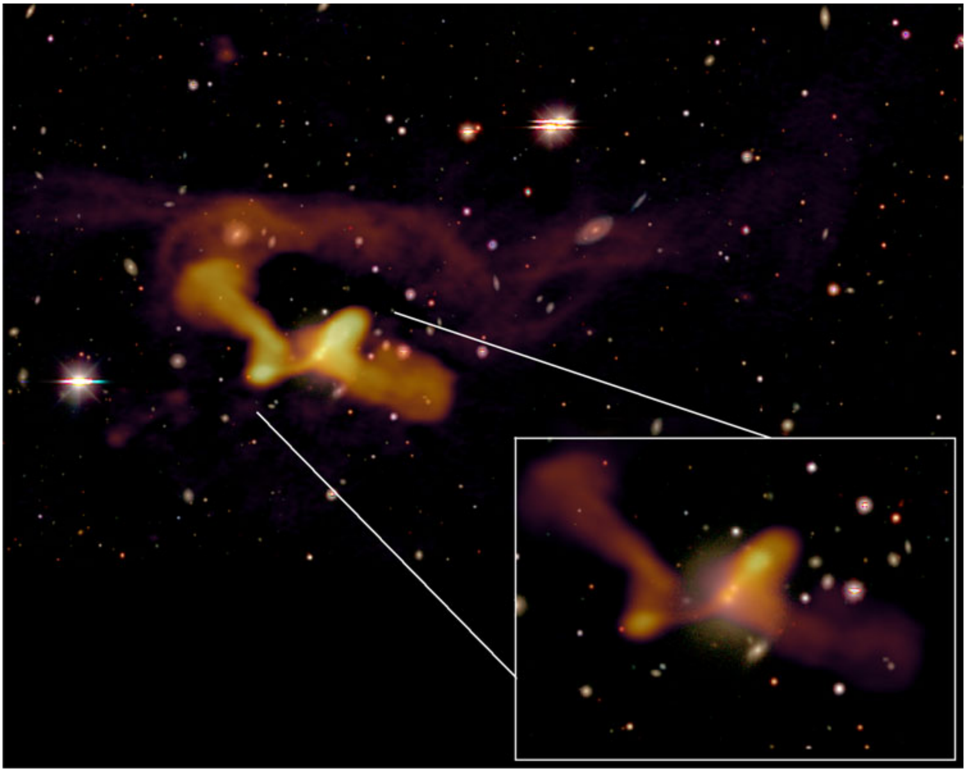

Figure 2. NGC 326 as studied with LOFAR (Hardcastle *et al.* 2019a); radio emission (orange/purple) is superposed on an RGB image from the Legacy survey. A trail of radio emission, 700 kpc long in projection and with complex internal structure, leaves the radio lobes and extends into the source's merging cluster environment. LOFAR images, taken from the unpublished LoTSS Data Release 2, allow both the large-scale structure and (inset, lower right) the details of the inner radio lobes and jets to be seen.

there may be high-energy hadrons in the mixture as argued above for FRIs. In either case, the long-term feedback effects of these particles is unclear. Numerical studies of sources in which the jet becomes disconnected in a simple environment show a significant loss of internal energy as the lobes 'coast' outwards, dragging external material behind them (English *et al.* 2019) on the way out towards neutral buoyancy at very large radii: any energy dissipated on these large (>Mpc) scales can have no effect in offsetting cooling. But there is a good deal of observational evidence in low-power sources (e.g. Fig. 2) that the process is more complex than that, and that substantial hydrodynamical mixing is taking place on hundred-kpc scales, presumably because the host galaxies of these systems are *not* at the centre of spherically symmetric hot-gas halos in pure hydrostatic equilibrium, but rather in a much more complex and unrelaxed hydrodynamical environment. New deep radio surveys are revealing the connection between radio galaxies of this type and the complex structures seen in radio emission in clusters of galaxies (van Weeren *et al.* 2019) and it seems clear that there is much more modelling work to do to understand the physics of feedback as mediated by processes like cosmic ray heating in such objects.

5. Prospects for future work

In the short term we plan a good deal of further work both on the LOFAR surveys and on modelling. In wide fields, we already have an order of magnitude more sky area in hand

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than covered by Hardcastle *et al.* (2019b): the combination of this with better optical data (from the Legacy survey), with better photometric redshifts, and with spectroscopic data for WEAVE-LOFAR will make the ideal parent survey for a detailed study of radio feedback in the local universe e.g. as a function of environment, with many thousands of LOFAR AGN even at low z. Do radio galaxies actually provide feedback energy at a higher rate in systems where radiative cooling is more effective? The new data will allow us to find out.

Crucial to improving the inference of jet powers is the currently little exploited long baseline capability of LOFAR, which in principle can provide a resolution ten times higher than we currently achieve, giving us a sensitive proxy for lobe physical size and so source age. Polarization at low frequencies also provides environmental information that has so far not been exploited. In the LoTSS deep fields, we are now working towards a study of the evolution of the kinetic luminosity function out to $z \sim 2$; here there are important synergies with deep surveys being carried out with MeerKAT (Jarvis *et al.* 2016) and with the JVLA. On the modelling front, our main concern is to obtain a better understanding of the low-power source population — if we greatly underestimate their jet powers, that will complicate any attempt to infer their feedback effects.

In the longer term, the Square Kilometer Array (both low-frequency and high-frequency components) should be able to carry out still more sensitive surveys, though its resolution will not approach that of LOFAR at low frequencies for some time — its use for deriving an understanding of radio source life cycles is discussed by Kapinska *et al.* (2015). The development of models for accurate bulk inference of feedback effects incorporating all the information provided by the SKA (and the deep optical data available from e.g. the LSST) is our long-term goal.

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