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Environmental dependence of radio galaxy populations

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Abstract. Sensitive continuum surveys with next-generation interferometers will characterise large samples of radio sources at epochs during which cosmological models predict feedback from radio jets to play an important role in galaxy evolution. Dynamical models of radio sources provide a framework for deriving from observations the radio jet duty cycles and energetics, and hence the energy budget available for feedback. Environment plays a crucial role in determining observable radio source properties, and I briefly summarise recent efforts to combine galaxy formation and jet models in a self-consistent framework. Galaxy clustering estimates from deep optical and NIR observations will provide environment measures needed to interpret the observed radio populations.

Keywords. galaxies: jets, galaxies: active, hydrodynamics, radio: continuum

1. Introduction

Properties of radio Active Galactic Nuclei (AGN), their host galaxies and larger-scale environment are closely linked. On the one hand, radio sources are now widely accepted to be responsible for the bulk of the feedback required to restrict gas cooling and star formation in the most massive galaxies and clusters since $z \sim 1$ (e.g. Silk & Rees 1998, Croton *et al.* 2006). These objects are prevalent in environments where cooling needs to be suppressed, namely massive elliptical galaxies (Sadler *et al.* 1989) and clusters with short cooling times (Mittal *et al.* 2009); and there appears to be approximate heating/cooling equilibrium in the hot haloes (Best *et al.* 2007, Shabala *et al.* 2008). There is also strong evidence for an environmental dependence of the AGN triggering mechanisms (Sabater *et al.* 2013, Pimbblet *et al.* 2013, Poggianti *et al.* 2017, Marshall *et al.* 2018), related to two quite different accretion modes: direct cold gas fuelling of the central engine in strong line radio galaxies, and chaotic accretion of gas cooled out of the hot phase in weak line radio galaxies (Hardcastle 2018).

On the other hand, the morphologies of radio galaxies are also strongly influenced by environment. On sub-kpc scales, the jets may be mass-loaded, ultimately determining whether a core (Fanaroff-Riley type I; FR) or edge-brightnened (FR-II) structure emerges. On group and cluster scales of tens and hundreds of kpc, the observed properties of radio lobes and efficiency with which they impart feedback onto the surrounding gas are shaped by their environment (Hardcastle & Krause 2013, Yates *et al.* 2018).

Dynamical models of radio galaxies provide the framework within which observed radio galaxy properties can be interpreted. In this contribution, I describe recent development of environment-sensitive jet models, and future prospects for studying the energetics and duty cycles of radio galaxies in large continuum surveys.

2. Dynamical modeling of radio sources

Dynamical models of powerful FR-II radio sources date back to work by Scheuer (1974). In the basic picture, the momentum flux of relativistic jets drives expansion along the jet axis, while transverse growth is due to the expansion of an overpressured cocoon of radio plasma inflated by backflow from the jet termination shock. The radio cocoon expands supersonically through the surrounding gas, driving strong bow shocks. The dynamics of lobed FR-Is is similar to FR-IIs, despite differences in jet morphology and lobe particle content (Croston *et al.* 2018). Jetted FR-Is, on the other hand, are dominated by velocity structure in the sheared jet forward flow, and the surface brightness of the uncollimated jets decreases with distance from the core. Radio emissivity is calculated by making some assumptions about jet particle content and lobe magnetic field strength, the latter typically parametrised in terms of lobe pressure.

A key feature of all these models is their sensitivity to the pressure profile of the atmosphere into which the jets expand. While X-ray observations are the "gold standard" for quantifying jet environments, these are only available for a relatively small fraction of systems, and are biased towards gas-rich haloes. The alternative approach, adopted by Turner & Shabala (2015) in developing the **R**adio **A**GN **i**n **S**emi-analytic **E**nvironments (RAiSE), is to use statistical properties of galaxy haloes inferred from cosmological galaxy formation models. The RAiSE model successfully reproduces a number of key observables, including departure from self-similarity, the relationship between radio luminosity, morphology, and host galaxy mass (Turner & Shabala 2015); and by including broadband radio spectra, lobe magnetic field strengths estimated from Inverse Compton observations (Turner *et al.* 2018b). Recently, Turner *et al.* (2018a) combined the RAiSE model with numerical simulations of backflow in FR-IIs, and showed that the discrepancy between spectral and dynamical ages in the powerful radio galaxy 3C436 can be explained by the mixing of electron populations of different ages; this effect is most pronounced in regions far from the hotspots, where a relatively small number of young electrons can skew the broadband radio spectra to younger spectral ages. Combining jet and galaxy formation models within a self-consistent framework also places strong constraints on AGN feedback models: requiring observations of both galaxy *and* radio AGN populations to be matched simultaneously can rule out some feedback models (Raouf *et al.* 2017).

3. Radio source populations

Application of dynamical models to well-defined radio AGN samples can in principle yield a census of jet energetics and duty cycles. Figure 1 shows the results of applying the RAiSE model (Turner & Shabala 2015) to a volume-limited sample of local ($z < 0.1$) radio AGN. Best-fitting jet power and age are estimated for each observed point in size – luminosity space, after marginalising over all other parameters. The derived mass scaling of jet powers suggests the hot haloes are in heating – cooling equilibrium, and jet generation efficiencies are consistent with predictions of jet production models. The derived jet kinetic luminosity function shows that most of the kinetic energy budget is provided by the low number of bright radio sources.

Figure 1 clearly shows selection effects. The observed dearth of low-luminosity, large sources is simply a consequence of survey surface brightness sensitivity limit. By extrapolating inferred properties of sources just above the detection limit, it is possible to quantify the fraction of sources missed in the survey (see right panel).

The overabundance of compact, low-luminosity sources is more puzzling. Sometimes referred to as FR-0 radio sources (e.g. Baldi *et al.* 2015), these have been variously proposed to be young radio sources, or "frustrated" older jets whose expansion has been impeded by a dense atmosphere. The other possibility is that at least some of these objects

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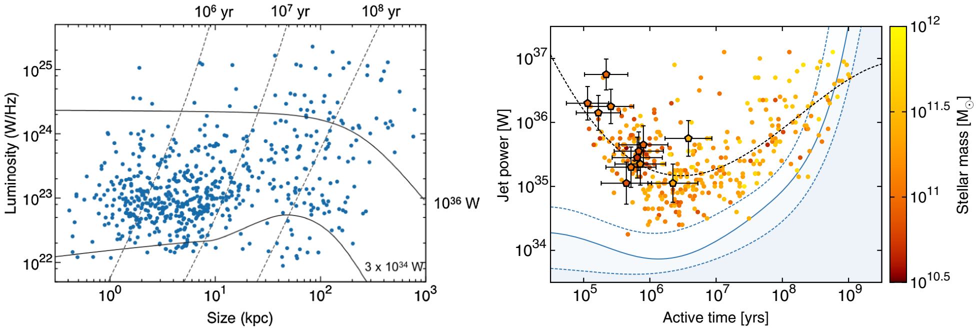

Figure 1. Application of the RAiSE model to a local ($z < 0.1$) sample of radio AGN from Shabala *et al.* (2008). *Left*: size-luminosity distributions at 1.4 GHz, with two representative tracks. *Right*: inferred jet kinetic power - age distributions (from Turner & Shabala 2015). Lines are detection limits for 50 (solid), 16 and 84 (dashed) percent of low surface brightness sources.

are cores whose diffuse lobes are below the surface brightness detection threshold. This scenario is supported by the modelling of Shabala *et al.* (2017), who showed that lobes inflated by VLBI-detected jets will rapidly become too diffuse for detection if the AGN host galaxy is located in a poor environment, consistent with observational evidence for an increased fraction of compact radio AGN in lower-mass haloes (Shabala 2018).

The potential implications of such a population of radio sources could be important. If jets can form lobes which rapidly fade below the detection limit, existing models would be underestimating both the lifetimes and kinetic powers of jets, and hence the energy available for feedback on their hot haloes. If there is sufficient pressure to collimate the jets and form well-defined lobes (Krause *et al.* 2012), more sensitive observations may constrain jet parameters through measurements of lobe volume and/or spectral ageing. Jetted FR-Is are a more challenging proposition, since the lack of backflow in these objects ensures that the oldest electrons will be located in the most diffuse regions; here, observations sensitive to low surface brightness emission are the best hope, as spectacularly shown by Heesen *et al.* (2018) for the archetypal jetted radio galaxy 3C31. Environment-sensitive simulations connecting galaxy and hot halo scales will provide the theoretical framework within which observations can be interpreted.

4. Probing environment through asymmetric radio sources

Jet production models predict that the two anti-parallel jets should be intrinsically identical. Hence asymmetric radio sources provide the ideal test bed for both models of jet – environment interaction, and metrics used to quantify environment. Rodman *et al.* (2019) used data from the Radio Galaxy Zoo citizen science project (Banfield *et al.* 2015) to test the hypothesis that any observed asymmetry in the radio continuum emission associated with the two jets is due to interaction with the environment. To minimize the effects of projection and model uncertainties, this analysis was restricted to a sample of straight FR-II lobes; environment associated with each lobe was quantified by counting SDSS galaxies with redshifts consistent with the AGN host. These authors found that the observed correlation between lobe length and galaxy clustering† is in excellent quantitative agreement with model predictions. Galaxy clustering therefore provides an environmental metric which can be used in conjunction with radio source models to extract physical parameters of radio source populations.

† Correlations with lobe luminosity are much weaker, in agreement with model predictions of highly non-linear relations with age and environment (e.g. Shabala & Godfrey 2013).

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5. Conclusions and future prospects

We are fast entering an era of large radio surveys. Dynamical models provide a mechanism for interpreting radio source energetics and lifetimes, yet both these models and inferences about radio source population properties are sensitive to assumptions about the environments into which the jets expand. We have developed a dynamical model in which the adopted measure of environment is halo mass. Studies of asymmetric radio sources suggest that halo masses measured through galaxy clustering will provide an excellent description of jet environments. A combination of sensitive radio surveys with ancillary galaxy clustering data therefore holds much promise. The in-progress GAMA Legacy ATCA Southern Survey (GLASS; Huynh *et al.* in prep.) will survey 60 deg^2 of the GAMA G23 field; on much larger scales, over the next few years SKA surveys will be complemented by optical catalogues from next-generation optical/IR instruments.

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