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Radio source populations: Results from SDSS

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This contribution provides a review of our current understanding of radio source populations and their host galaxies, as derived from studies of the local Universe, in particular using the Sloan Digital Sky Survey. Evidence is presented that low luminosity radio sources are fundamentally distinct objects to high radio luminosity sources and optically or X-ray selected AGN, suggesting that these are fuelled by a different mechanism. The low-luminosity radio sources are argued to be fuelled by the accretion of hot gas from their surrounding X-ray haloes, and this offers a potential feedback loop via which the radio-loud AGN can control the cooling of the hot gas, and thus the growth of their host galaxy. The energetic output of the radio sources is derived in order to show that this is indeed feasible. It is emphasised that the difference between these two modes of AGN fuelling is distinct from that of the two different radio morphological classes of radio-loud AGN (Fanaroff-Riley classes 1 and 2). The origin of the FR-dichotomy is investigated using Sloan data, and argued to be associated with the environment and evolution of the radio sources. Finally, the role of CSS and GPS sources within this picture is discussed.

1 Introduction

In recent years it has become apparent that active galactic nuclei (AGN) may play an important role in the process of galaxy formation and evolution. Essentially all nearby galaxies contain a massive black hole at their centre, the mass of which is tightly correlated with that of the stellar bulge of the galaxy (e.g. Magorrian et al. 1998). Furthermore, the cosmic evolution of the star formation rate, and that of the black hole accretion rate, match each other remarkably well back to at least $z \sim 2$. These results imply that the build-up of a galaxy and that of its central black hole are fundamentally linked. Theoretical interpretations of this favour models in which 'feedback' from the growing black holes is responsible for controlling star formation in the host galaxy (e.g. Silk & Rees 1998; Fabian 1999).

A related issue is that models of galaxy formation have had a long-standing problem in explaining the properties of the most massive galaxies. Unless the cooling of gas is somehow switched off, then semi-analytic models of galaxy formation predict that massive galaxies will continue to accrete gas and form stars in the nearby Universe, leading to much larger masses and bluer colours than observations dictate. The incorporation of AGN feedback into these models has now been shown to provide a good solution to these problems (e.g. Bower et al. 2006; Croton et al. 2006) and evidence is growing which suggests that it is the radio-loud AGN which play the dominant feedback role. A number of critical questions need to be answered, however. If radio-loud AGN feedback is responsible for the control of galaxy growth, what are the physical processes involved, and by what mechanism is the activity triggered? Do the energetics work out correctly: does the energy provided by AGN match that required to balance the radiative cooling losses? In what galaxies is this feedback process important, and how do the properties change with galaxy mass? Of particular relevance to this conference is also the question of what the role of CSS and GPS sources is: are these involved in the feedback process?; how do they relate to the larger-scale Fanaroff & Riley (1974) radio morphological classifications (FR1s and FR2s)? More generally, what is the relation between these radio morphological classes and the triggering mechanism of the radio sources? Addressing these questions is the goal of the current contribution.

2 The host galaxies of radio-loud AGN

It has long been known that radio-loud AGN are preferentially hosted by massive elliptical galaxies. Combining the SDSS (e.g. York et al. 2000) with the large-area radio surveys NVSS (Condon et al. 1998) and FIRST (Becker, White & Helfand 1995) allows much more detailed statistical study of these host galaxies: not only can large samples of radio-loud AGN be constructed, but it is also possible to compare the host galaxies of the radio-loud AGN with those of the rest of the galaxy population. In this way, both the origin of the radio-loud AGN activity, and the role that radio-loud AGN can have on the evolution of their host galaxies, can be investigated.

Best et al. (2005a) cross-compared the main galaxy sample of the second data release of the SDSS, with a com-

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bination of the NVSS and FIRST radio surveys designed to optimise the advantages of each radio survey. They defined a sample of 2215 radio-loud AGN which forms the basis sample for the analysis here. The left panel of Fig. 1 shows the fraction of galaxies with redshifts $0.03 < z < 0.1$ that are classified as radio-loud AGN (with 1.4 GHz radio luminosity above 10^{23}, 10^{24} and 10^{25} $\mathrm{W\,Hz^{-1}}$), as a function of the stellar mass of the galaxy (note that these are essentially all low-luminosity radio-loud AGN, in the luminosity regime traditionally associated with FR1-class sources). The radio-loud fraction rises from 0.01% of galaxies with stellar mass 3×10^{10} $\mathrm{M_\odot}$ up to over 30% of galaxies more massive than 5×10^{11} $\mathrm{M_\odot}$. The right panel shows the equivalent relations as a function of black hole mass. Once again, a strong trend with mass is seen; the slope of the relation is $f_{\rm radio-loud} \propto M_{\rm BH}^{1.6}$.

Figure 2 shows the fraction of the SDSS galaxies which are radio-loud AGN brighter than a given radio luminosity, as a function of radio luminosity, for six bins in black hole mass. A remarkable feature is that the shape of the functions are very similar for all mass ranges: there is little evidence for any dependence of the break luminosity on mass. Thus, whilst the *probability* of a galaxy becoming a radio source is a very strong function of its mass, the *luminosity* of the radio source that results is broadly independent of mass.

3 The triggering mechanisms of radio sources

The strong mass dependence of the radio-loud AGN fraction described above is in stark contrast to the lack of mass dependence found for the fraction of galaxies identified by their optical emission lines as hosting AGN (hereafter referred to as emission-line AGN; Kauffmann et al. 2003; Best et al. 2005b). In addition, Best et al. (2005b) show that the probability of a galaxy hosting a radio-loud AGN is independent of whether or not it is classified as an emission-line AGN. They thus conclude that emission-line AGN activity and low–luminosity radio activity must be independent physical processes. They argue that low-luminosity radio activity is associated with the re-fuelling of already well-formed massive black holes, and that this gas accretion occurs in a radiatively-inefficient flow.

This concept of a radiatively-inefficient accretion flow powering low luminosity radio sources is very different to the situation at higher radio luminosities. Powerful (FR2-class) radio sources are generally either hosted by quasars or have evidence for a dust-obscured quasar nucleus (cf. unified schemes of radio galaxies and radio-loud quasars; e.g. Barthel 1989). These sources also display extended high-power, high-excitation emission line regions (e.g. Rawlings & Saunders 1991). Thus, most powerful radio sources host radiatively-efficient AGN, with properties similar to those of the optically or X-ray selected AGN. On the other hand, it has long been known that most FR1 radio sources have only very weak, low-excitation line emission (e.g. Zirbel & Baum 1995), and also that there is a population of low-luminosity FR2 sources with similarly weak emission lines (e.g. Hine & Longair 1979). As reviewed by Hardcastle, Evans & Croston (2007), these low excitation objects also show no evidence for a (visible or hidden) quasar nucleus at optical, infrared or X-ray wavelengths, indicating that indeed these low luminosity radio sources do have radiatively-inefficient nuclei.

The radiatively-efficient AGN (both the luminous radio sources and the optical or X-ray AGN) need a plentiful supply of fuelling gas to power them. According to standard theories for these objects, this is likely to be supplied by galaxy mergers or interactions, and is frequently associated with star formation activity (e.g. Kauffmann et al. 2003; Holt, this volume). To power the low luminosity radiatively-inefficient radio sources, however, only low gas accretion rates are required. Best et al. (2005b) argue that the fuelling source is hot gas, cooling out of the hot X-ray haloes that surround the massive galaxies. They show that this provides a natural explanation for the steep power-law dependence of the radio-loud AGN fraction with black hole mass, due to the higher Bondi accretion rates in these systems. This picture for two physically distinct mechanisms of radio-loud AGN triggering has been widely adopted by other authors (e.g. Hardcastle et al. 2007 and references therein). A common mistake, however, is to assume that this distinction in triggering mechanism has the same origin as the dichotomy in radio morphological class of extended radio sources. This is not true: as discussed above there are many examples of radiatively-inefficient FR2 sources, and there are also examples of FR1 sources with clear quasar nuclei (e.g. Heywood, Blundell & Rawlings 2007). Instead the radio morphology differences appear to be more connected with the environment and evolution of the radio sources; this will be discussed in Sect. 5.

4 The heating-cooling balance in elliptical galaxies

Radio-loud AGN are believed to live for only 10^7 to 10^8 years, and yet in Fig. 1 it was shown that the fraction of the highest mass galaxies that are radio-loud is $>25\%$. This implies that radio source activity must be constantly re-triggered. If this re-triggering is indeed by the cooling of gas from the hot X-ray haloes surrounding the galaxy, then this offers the prospect for feedback control of the growth of galaxies: the AGN activity is regulated by the gas properties of the hot-phase gas, and in turn the energetic output of the AGN is fed back into that phase, providing a closed-loop system.

In this picture, Fig. 2 can then be interpreted *probabilistically* as the *fraction of its time* that a galaxy of given black hole mass spends as a radio source brighter than a given radio luminosity. To determine the heating effects of radio-loud AGN, what is then needed is an estimate of the mechanical energy output of radio sources. Although the

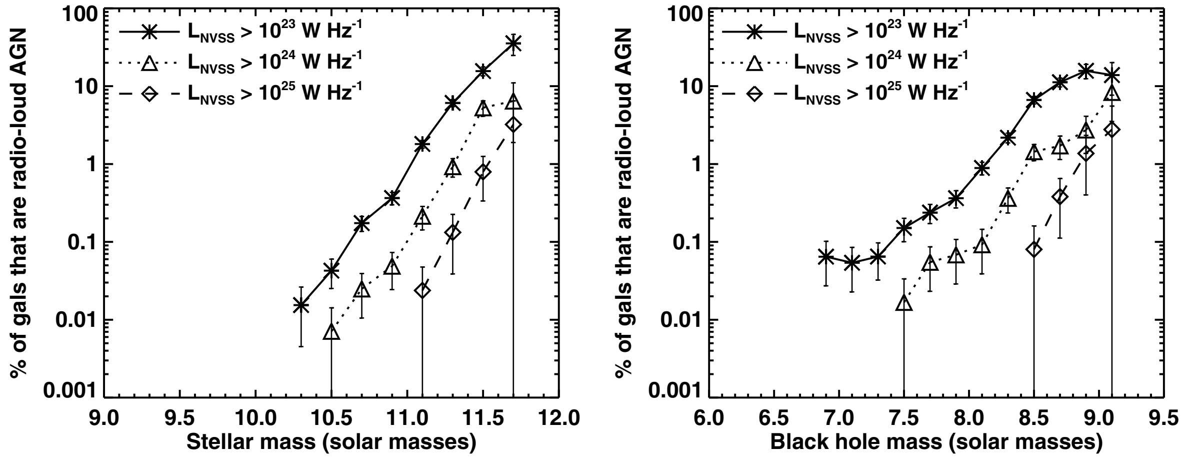

Fig. 1 The fraction of galaxies which are radio-loud AGN, as a function of stellar mass (*left*) and black hole mass (*right*), for different cuts in radio luminosity.

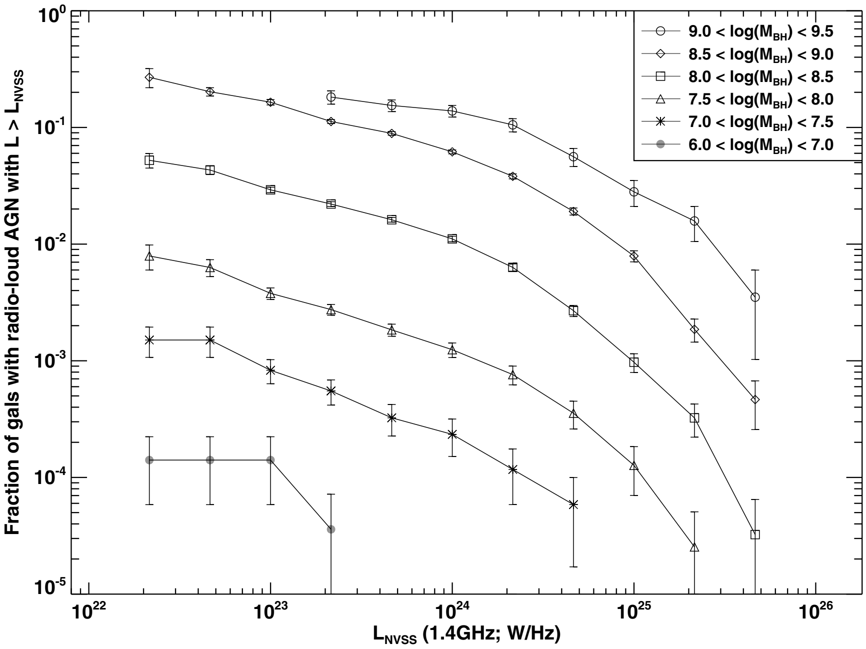

Fig. 2 The fraction of radio-loud AGN brighter than a given radio luminosity, as a function of black hole mass.

monochromatic radio luminosity accounts for typically less than 1% of the radio source energy, it is possible to use this to make a good first-order estimate of the mechanical energy. Bîrzan et al. (2004) studied a large sample of cavities and bubbles produced in clusters and groups of galaxies due to interactions between radio sources and the surrounding hot gas. They derived the (pV) energy associated with each cavity, and also estimated the cavity ages. Best et al. (2006) showed that although there is no single scaling factor between the mechanical luminosities so derived and the radio luminosities of the radio sources producing the bubbles, it is nonetheless possible to obtain a reasonable fit to the data using a simple power-law relation: $L_{\rm mech}/10^{36}\,{\rm W} = (3.0 \pm 0.2)\,(L_{\rm 1.4GHz}/10^{25}\,{\rm WHz}^{-1})^{0.40\pm0.13}$.

Using this conversion, the probability function for the time that a galaxy of given black hole mass spends as a radio source with a given radio luminosity can be converted into a probability function for mechanical luminosity. Integrating across this gives the time-averaged heating rate for black holes due to radio-loud AGN activity (for details see Best et al. 2006, 2007): $\bar{H} = 10^{21.4}(M_{\rm BH}/M_{\odot})^{1.6}$ W. Note that the black hole mass dependence of this heating rate arises entirely from the variation of the radio-loud fraction with black hole mass (which is well determined from the observations) whilst the normalisation term encompasses the shape of the radio luminosity and the radio to mechanical luminosity conversion. Uncertainties in these can therefore be accounted for by introducing an uncertainty factor f

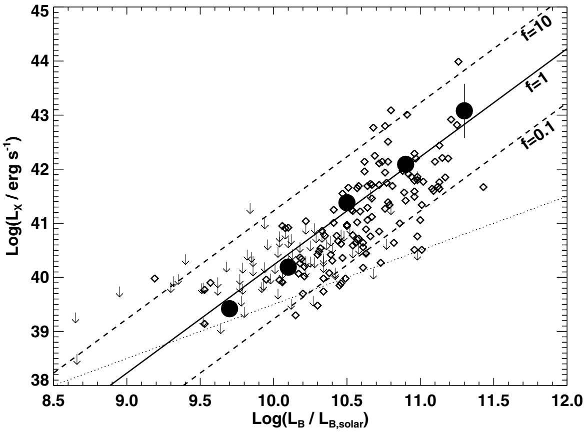

Fig. 3 A plot of $L_{\rm X}$ versus L_B for the elliptical galaxies in the sample of O'Sullivan et al. (2001). The large filled circles show the mean values of $L_{\rm X}$ for galaxies in 5 bins of L_B. The solid and dashed lines shows the predicted X-ray emission from the hot haloes of the ellipticals, assuming that heating from radio-loud AGN balances the cooling, for different values of f. The dotted line gives the expected contribution towards the X-ray luminosities from the sum of discrete X-ray sources within the galaxies.

(which should have a value close to unity) into the equation $\bar{H} = 10^{21.4} f (M_{\rm BH}/M_\odot)^{1.6}$ W.

This heating rate due to radio-loud AGN activity can be compared with the radiative cooling rates of the haloes of hot gas surrounding elliptical galaxies, as determined using X-ray observations. Figure 3 shows the bolometric X-ray luminosities ($L_{\rm X}$) of the 401 early-type galaxies from the sample of O'Sullivan et al. (2001), compared with their optical luminosities (L_B). Also shown are the predicted radio-loud AGN heating rates for three different assumed values of f. It is remarkable how well the predicted radio-loud AGN heating rates for $f = 1$ match the radiative cooling rates at all optical luminosities. Provided that all or most of the energetic output of the radio-loud AGN can be coupled effectively to their host galaxy then recurrent radio-loud AGN activity provides a sufficient feedback effect to suppress the cooling of gas and thus control the rate of growth of massive elliptical galaxies.

It is important to highlight that this feedback mechanism only works for those radio sources triggered by accretion from hot-phase gas. For the higher-luminosity radiatively-efficient sources, the radio jet power is controlled by the supply of cold gas, which may have nothing to do with hot gas halo (e.g. in the case where it is brought in by galaxy mergers or interactions). Such radio sources can (and frequently do, e.g. Best, Longair, Röttgering 1996; Kraft et al. 2007) have a large impact on their host galaxies, but in an unregulated and possibly catastrophic way, rather than forming part of a controlled feedback loop.

5 The Fanaroff-Riley radio morphology dichotomy

FR1 (Fanaroff-Riley class 1) sources are 'edge-darkened', have low radio powers and usually display weak optical emission lines; their radio jets quickly decelerate as they advance through the interstellar medium. FR2 jets retain relativistic speeds over kpc or even Mpc scales, ending in bright hotspots ('edge-brightened' sources); these sources have higher radio luminosities and the majority show strong, high-excitation emission lines. The dividing line between FR1s and FR2s occurs more or less at a monochromatic power of $P_{\rm 1.4GHz} \sim 10^{25}$ WHz^{-1}, close to the break in the radio luminosity function.

There has been much debate as to whether the FR dichotomy relates to intrinsically different properties of the central black hole (different accretion mechanisms, or black hole spin; e.g. Baum, Zirbel & O'Dea 1995), or whether it depends on extrinsic factors, such as the interactions of the radio jets with the interstellar medium of the galaxy. Recent evidence supports the latter. Ledlow & Owen (1996) studied the location of radio sources in the plane of radio luminosity vs optical absolute magnitude, and showed that the FR1-FR2 division occurs at higher radio luminosity in more optically-luminous galaxies; this is interpreted as jets being more easily disrupted in more massive galaxies. Gopal-Krishna & Wiita (2000) discovered a population of 'hybrid' sources, with one lobe showing FR1-like morphology and the other FR2-like, which would be difficult to explain in intrinsic-difference models. Also, as discussed in Sect. 3, the existence of (low-excitation) FR2 sources with emission line and X-ray properties similar to the bulk of the FR1 population, and FR1 sources with quasar-like nuclei, dictates that the radio morphology does not directly correlate with fundamental black hole differences.

Instead, as argued above, although there are two different accretion mechanisms, the division between which occurs over a similar range of radio luminosities to the FR1-FR2 morphology transition, these two dichotomies have distinct origins. If the triggering fuel supply is the origin of the accretion property differences, the question then is "what is the precise origin of the FR-dichotomy, and how do GPS and CSS sources relate to this?" Ledlow & Owen (1996) provided significant insight on this, with their demonstration that FR1 and FR2 radio sources divide cleanly in the radio vs optical luminosity plane. However, this study had a significant short-coming: the sample studied was highly heterogeneous, being comprised of different sub-samples drawn from the literature to cover the entirety of the $L_{\rm rad}$ vs. $L_{\rm opt}$ plane. This leads to a number of potential biases: for example, the majority of the FR1 sources lie at redshifts $z < 0.1$, while the FR2s typically have $z > 0.25$.

The sample of radio sources drawn from the Sloan Digital Sky Survey offers an opportunity to repeat this investigation in a bias-free manner, and also to probe in much more

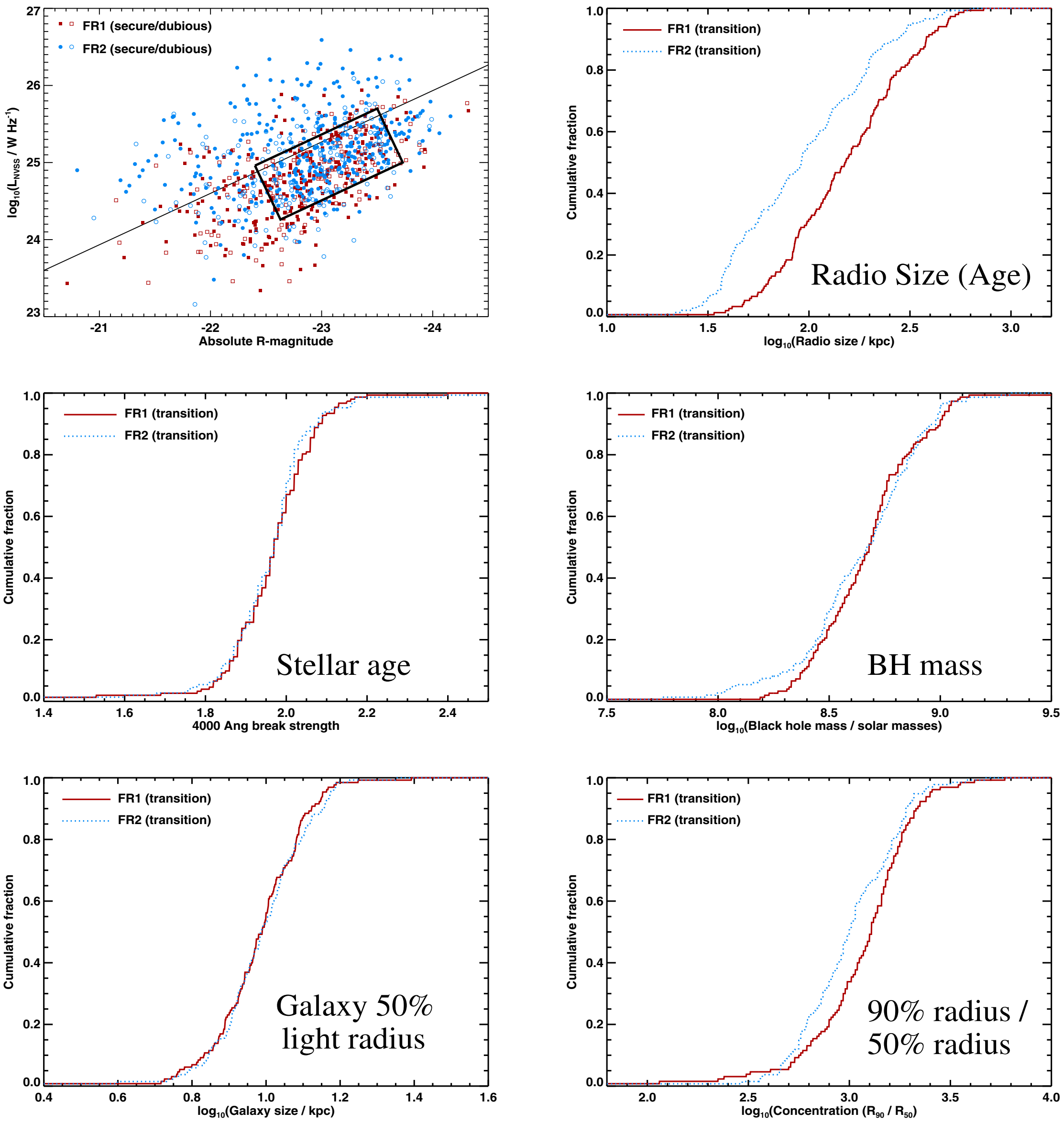

Fig. 4 (online colour at: www.an-journal.org) The top left plots shows the 'Ledlow & Owen' $L_{\rm rad}$ vs. $L_{\rm opt}$ diagram for the SDSS radio sources. The square box illustrates the "transition region" studied in the other plots. The remaining plots show cumulative distributions for FR1 and FR2 sources within this transition region, for the radio size, 4000Å break strength, black hole mass (estimated from the velocity dispersion), host galaxy half-light radius, and host galaxy concentration index.

detail any host galaxy differences between the FR1 and FR2 sources.

6 The morphologies of SDSS radio sources

Following the technique of Best et al. (2005a), the DR6 catalogue of the SDSS has been cross-matched with the NVSS and FIRST radio catalogues, resulting in a much larger radio source sample of over 16,000 radio sources. From these, the subset of extended radio sources was selected, being those composed of multiple radio components (either from FIRST or NVSS). The radio morphologies of these 1083 extended radio sources have then been visually classified as either FR1 or FR2 (with a tiny fraction classified as hybrids, following Gopal-Krishna & Wiita 2000), with the classification additionally being declared as either "certain" or "dubious" based on the clarity of the morphological structure (Best, Kauffmann & Heckman 2009).

The top-left panel of Fig. 4 shows a version of the Ledlow & Owen plot, as constructed from the SDSS galaxies classified as FR1 or FR2. It is immediately clear that the sharp division between the two populations found by those authors is not replicated here. There is a tendency for the sources above the Ledlow & Owen dividing line to be FR2 sources, whilst those below it are more likely to be FR1s, but there is a large overlap between the two populations. To investigate this further, a "transition region", illustrated by the rectangle on the top-left panel of Fig. 2, is considered. This is located in the overlap region, and contains roughly equal numbers of FR1 and FR2 sources.

The top-right panel of Fig. 4 shows cumulative distributions of the radio source size for the FR1 and FR2 subsamples within this overlap region. The FR2 radio sources are systematically smaller than the FR1 sources. Interestingly, this difference is almost entirely due to about 20% of FR2 sources having radio sizes smaller than 40 kpc, whereas almost no FR1 sources are found at these sizes.[1] For sizes larger than 40 kpc the distributions of the two populations are similar. This result suggests that all radio sources begin life (in their GPS and CSS phases) as FR2 sources, with collimated jets, but that some sources do not survive as such to large sizes, getting disrupted into FR1s (see Kaiser & Best 2007 for a model of this process).

The final four panels of Fig. 4 show cumulative distributions of various properties of the host galaxies of the FR1 and FR2 radio sources. The host galaxies of FR1s and FR2s in this transition region are statistically indistinguishable in their effective stellar ages (as measured by the 4000Å break strength), their black holes masses (as estimated from the velocity dispersions) and their half-light radii, as well as many more properties. The one difference that is significant is their concentration index, defined as the ratio between the 90% and 50% light radii: FR1 host galaxies tend to be more extended. This again is consistent with the picture whereby more massive or more extended galaxies are more likely to disrupt the radio jets, and lead to an FR1.

7 Conclusions

In this contribution it has been shown that there are two methods of triggering and fuelling radio sources. Powerful radio sources have relatively high accretion rates, fuelled by cold gas in a standard thin accretion disk, and have properties similar to optical and X-ray selected AGN. In contrast, low luminosity radio sources are fuelled slowly, by the accretion of gas cooling from the hot halo, in a radiatively-inefficient mode. These low luminosity sources are preferentially located in the most massive elliptical galaxies. The repeated re-triggering of these sources provides a feedback mechanism which is able to control the growth of their host galaxy, thereby solving the long-standing problem of the overgrowth of massive elliptical galaxies in semi-analytic models of galaxy formation.

It is shown that this dichotomy in fuelling mechanisms is distinct from the well-known dichotomy in the morphologies of extended radio sources, although the two occur at similar radio powers. The radio morphology dichotomy is instead argued to be associated with the environment and evolution of radio sources: all radio sources begin life with collimated jets, but less powerful jets in denser environments are more easily disrupted as the source grows, leading to the production of FR1 sources. Thus, GPS/CSS sources will in general have FR2-like morphologies; the disruption of a subset of these to FR1s, with a consequent drop in radio luminosity, can help to explain the over-abundance of these sources compared to their larger counterparts.

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[1] Neither are any hybrid FR1-2 sources found at these sizes; the sizes of hybrid sources are intermediate between those of the FR1s and FR2s, as expected for the disruption model. These sources will be discussed in greater detail in Best et al (2009).