Radio-Mode Feedback in Massive Galaxies at Redshift $0 < z < 1$

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Abstract. We have carried out a large observational study of the radio luminosities, stellar populations, and environments of massive galaxies over the redshift range $0 < z < 1$. Radio jets powered by an accreting central black hole are common in massive galaxies, and there is a large class of "optically quiet AGN," with radio emission but no optical/IR signature of black-hole accretion. The central black holes in these galaxies are probably accreting in a radiatively inefficient mode, and our results suggest that "radio-mode feedback" as described by Croton *et al.* is likely to occur in all massive early-type galaxies at $z < 0.8$. While it appears that radio-loud AGN occur episodically in all massive early-type galaxies, we also identify a sub-population of galaxies with powerful radio sources and a prominent younger ($\sim 10^8$ yr) stellar population that may have undergone recent mergers.

Keywords. galaxies: active, galaxies: evolution, radio continuum: galaxies

1. Introduction

The kinetic energy of radio jets powered by supermassive black holes is typically 100–1000 times higher than the observed radio luminosity (Bicknell 1995), and can be as high as 10^{45} ergs s^{-1} in nearby radio galaxies (Birzan *et al.* 2004). As a result, the energy input by radio jets into the interstellar medium can profoundly affect the evolution and star-formation history of massive galaxies (Binney & Tabor 1995; Rawlings & Jarvis 2004; Springel *et al.* 2005).

X-ray observations of the cavities created by radio lobes in the hot gas surrounding massive galaxies provide a direct estimate of the radio jet power (Birzan *et al.* 2004, 2008), and hence an empirical calibration between radio luminosity and jet power in nearby galaxies. Feedback mechanisms based on "radio-mode heating" have recently been incorporated into semi-analytic models of galaxy evolution (Bower *et al.* 2006; Croton *et al.* 2006), and allow these models to reproduce the observed colors and luminosity function of massive galaxies in the local universe.

While detailed X-ray imaging is possible only for relatively nearby radio galaxies, the radio emission from active galaxies can be detected out to high redshift. The radio luminosity function of galaxies therefore allows us to estimate how the energy input into the ISM by radio jets has varied over cosmic time.

2. Radio Jets and Galaxy Evolution

Paradoxically, radio jets are invoked both to *trigger* star formation and to *inhibit* star formation in massive galaxies.

In *jet-induced star formation* (e.g., van Breugel *et al.* 2004), the passage of a radio jet triggers star formation within the host galaxy. This happens when interactions between a radio jet and dense clouds of gas within the interstellar medium trigger shocks which induce star formation (Bicknell *et al.* 2000). Evidence for jet-induced star formation is seen both in high-redshift radio galaxies (Klamer *et al.* 2004) and in nearby galaxies like Centaurus A (Mould *et al.* 2000). Conversely, in *radio-mode feedback*, radio jets can inhibit late-time star formation by heating the interstellar medium and preventing the onset of cooling flows from the surrounding halo of hot X-ray gas (e.g., Ciotti *et al.* 2009; Cattaneo *et al.* 2009).

In studying the role played by radio jets in galaxy evolution, we need to keep in mind that both these mechanisms could operate in the same galaxy at different cosmic epochs. It is likely that jet-induced star formation occurs mainly at high redshift ($z > 2$), when massive galaxies contained substantial amounts of cold interstellar gas, while "negative" AGN feedback dominates at late time ($z < 1$) when the interstellar medium (ISM) of most massive galaxies is mainly in the form of a hot X-ray corona.

3. Black-Hole Accretion in Radio Galaxies

There is growing evidence that two separate modes of black hole accretion can power radio jets (Hardcastle *et al.* 2007). In *hot-mode accretion*, the central black hole is fueled inefficiently by accretion of gas from the hot ISM. In this case, there is no thin accretion disk and the optical spectrum of the galaxy may look like that of a normal passive galaxy, with no strong emission lines. In *cold-mode accretion*, the black hole is fueled by accretion of (originally) cold gas in an accretion disk. In this case, the radio galaxy is expected to show strong optical emission lines.

If radio-mode feedback plays an important role in preventing late-time star formation in massive galaxies at $z < 1$, then we would expect to see a large population of radio galaxies fueled by "hot-mode" accretion. These galaxies should also have a dominant old stellar population, and show weak or no optical emission lines. Since the accreting black hole in these objects manifests itself mainly at radio rather than optical wavelengths, we can think of these galaxies as "optically quiet AGN."

On the other hand, if the infall of cold gas (either directly from the intergalactic medium or through an interaction or merger with a gas-rich galaxy) plays an important role in triggering radio galaxies, then we should see a population of radio galaxies fueled by "cold mode" accretion. These would be expected to show strong optical emission lines, as well as evidence for a young or intermediate-age stellar population if the merger also triggered a starburst (Hopkins *et al.* 2005).

4. Radio-Source Populations at $z \sim 0$

The radio luminosity function of galaxies in the local universe has been accurately measured from large-area optical redshift and radio continuum surveys (Sadler *et al.* 2002; Best *et al.* 2005; Mauch & Sadler 2007). As shown in Figure 1, radio emission powered by the central black hole is both more common and more luminous in more massive galaxies. Only about 10% of nearby radio galaxies show strong optical emission lines (Sadler *et al.* 2002), implying that the overwhelming majority are powered by "hot-mode" accretion. The optical spectra of most of these galaxies are also characteristic of passively evolving early-type galaxies, with little or no evidence of recent star formation. Evidence from the local universe is therefore consistent with a picture in which radio-mode feedback operates in almost all early-type galaxies with absolute magnitudes brighter than $M_K \sim -23$ mag.
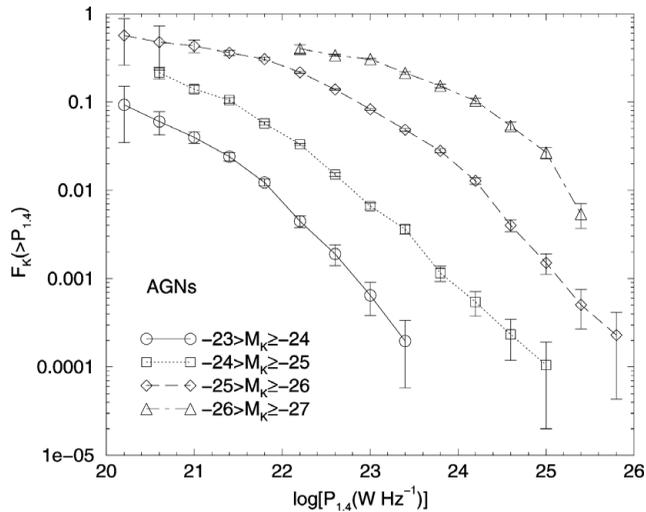
Figure 1. The fractional luminosity function of radio-loud AGN, from Mauch & Sadler (2007). The galaxies are binned in K-band absolute magnitude M_K, which is roughly proportional to the total stellar mass (and so is indicative of the black hole mass of the galaxy, as noted by Marconi & Hunt 2003). The vertical axis shows the fraction of all galaxies with radio luminosity above $P_{1.4}$.

To learn more about the likely role of radio-mode heating in massive galaxies beyond the local universe, we can look at the radio luminosity function of massive early-type galaxies at $0.4 < z < 0.8$.

5. Radio Sources in Luminous Red Galaxies at $z \sim 0.5$

The 2SLAQ redshift survey (Cannon *et al.* 2006) obtained optical spectra and redshifts for a sample of 15,000 luminous red galaxies (LRGs) in a $150\,\mathrm{deg}^2$ area of sky, using the 2dF spectrograph on the Anglo-Australian Telescope. The target objects were color-selected (Eisenstein *et al.* 2001) to be luminous early-type galaxies at redshift $0.4 < z < 0.8$. These galaxies lie well above the "knee" in the optical luminosity function, and have r-band luminosities in the range 2–15 L^* (Wake *et al.* 2006). As at $z \sim 0$, most of the radio-detected 2SLAQ galaxies show absorption-line optical spectra typical of early-type galaxies. Around 15% of the radio-detected 2SLAQ LRGs show strong emission lines in their optical spectra.

The rapid cosmic evolution of the most powerful radio galaxies was deduced in the 1960s from radio source counts (Longair 1966). Radio source counts also imply that low-power radio galaxies must evolve less strongly, if at all (Jackson & Wall 1999), but until recently almost no low-power radio galaxies have been observed at redshifts beyond $z \sim 0.3$.

Using the 2SLAQ LRG data, Sadler *et al.* (2007) were able to show that the radio luminosity function of low-power radio galaxies undergoes significant cosmic evolution over the redshift range $0 < z < 0.7$, with radio-loud AGN in massive galaxies being more common and more luminous in the past. This was confirmed by Donoso *et al.* (2009), using a larger LRG sample with photometric redshifts. These results imply that the energy input into massive galaxies by "radio-mode" heating was probably significantly higher in the past than it is now.
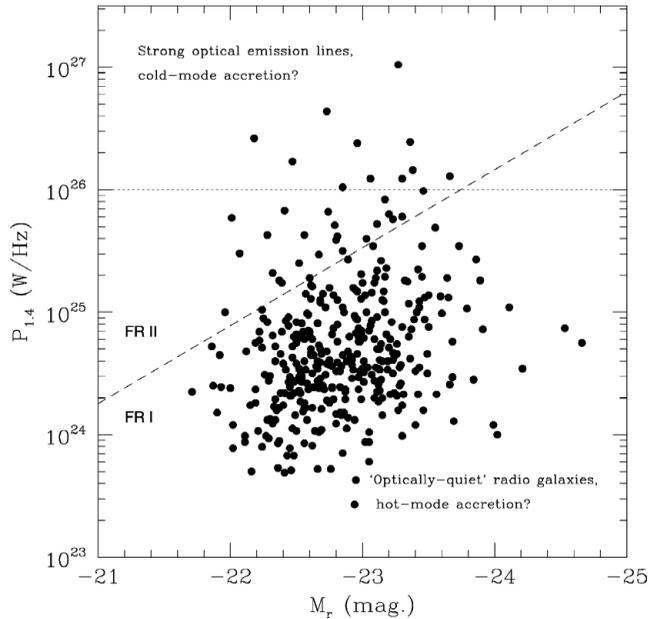
Figure 2. Comparison of 1.4 GHz radio luminosity and *r*-band absolute magnitude for 2SLAQ radio galaxies at $0.4 < z < 0.8$, adapted from Sadler *et al.* (2007). The diagonal dashed line represents the division between FR-I and FR-II radio galaxies found by Ledlow & Owen (1996).

6. The Stellar Populations of Radio Galaxies at $0 < z < 1$

To look for differences in the stellar populations of radio-loud and radio-quiet massive galaxies, Johnston *et al.* (2008) studied composite spectra of the 2SLAQ LRGs at $0.4 < z < 0.8$. Both radio-loud and matched radio-quiet composites were fitted with single-age stellar population models (Bruzual & Charlot 1993). None of the composite spectra could be fitted by a single old stellar population, but satisfactory fits were obtained by combining a dominant old (7 Gyr) population with a smaller intermediate-age (~ 1 Gyr) single-burst population.

Johnston *et al.* (2008) found no difference in the stellar populations of radio-loud and radio-quiet LRGs, except for the most powerful radio galaxies (with $P_{1.4} > 10^{26}$ W Hz^{-1}) in the 2SLAQ sample. These powerful radio galaxies had both stronger optical emission lines and a younger stellar population than the other 2SLAQ LRGs, and the best fit to their composite spectrum was obtained with a ~ 100 Myr stellar population contributing about 40% of the stellar light at 4050 Å. This strongly suggests that the most powerful radio galaxies in the 2SLAQ sample are powered by "cold mode" accretion and may have been triggered in a past merger which also triggered a starburst (Hopkins *et al.* 2005).

Figure 2 plots the radio and optical luminosity of 2SLAQ LRGS detected as radio sources at 1.4 GHz in the NVSS (Condon *et al.* 1998) and FIRST (Becker *et al.* 1995) radio surveys. The currently available radio images do not have high-enough resolution to distinguish reliably between the FR-I and FR-II classes often used to classify radio-galaxy morphologies (Fanaroff & Riley 1974), but the dashed line shows the FR-I/FR-II division found by Ledlow & Owen (1996) for radio galaxies in the local universe. "Cold mode" radio galaxies with strong optical emission lines dominate the radio-galaxy population at radio luminosities typical of FR-II systems, though some emission-line galaxies are also found at lower radio luminosities.
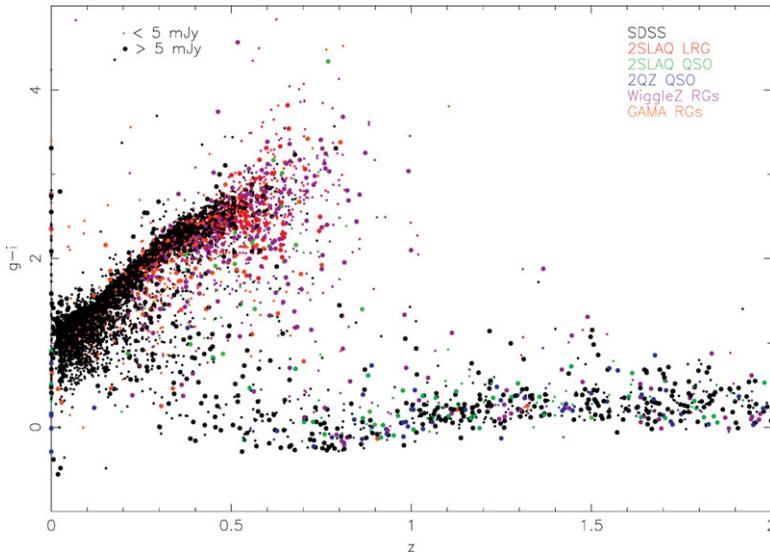
Figure 3. Plot of optical $g - i$ color versus redshift for radio-detected galaxies and QSOs from several recent redshift surveys. Objects in this plot are optically identified FIRST radio sources with $i < 20.5$ mag, but no color selection has been applied. The data points include observations of radio-selected "additional target" objects by the WiggleZ and GAMA survey teams. Large dots show objects with 1.4 GHz flux density $S_{1.4} > 5$ mJy and small dots those with $S_{1.4} < 5$ mJy.

As in the local universe, the great majority of radio galaxies at $0.4 < z < 0.8$ appear to be "hot-mode" accretion systems in which radio-mode feedback can operate. In this redshift range, we also start to see the appearance of very powerful radio galaxies with strong optical emission lines and a younger stellar population, which may have undergone a recent major merger. Powerful radio galaxies with recent star formation are extemely rare in the $z \sim 0$ radio-galaxy samples, but they appear to evolve with redshift much more rapidly than the larger population of "optically quiet" radio galaxies with radio luminosities below 10^{26} W Hz^{-1} (Sadler *et al.* 2007; Donoso *et al.* 2009).

7. Blue Radio Galaxies at $0 < z < 1$?

Although the LRG studies have advanced our knowledge of radio source populations and evolution, they leave a number of questions unanswered. In particular:

(*a*) Since the 2SLAQ LRG survey selected only optically luminous galaxies with red colors, have we excluded a population of blue radio galaxies with ongoing or very recent star formation?

(*b*) At redshift $0.4 < z < 1$, increasingly large samples of both radio galaxies and radio-loud QSOs are now becoming available. How are these two populations related?

To answer these questions we have begun a new spectroscopic study of radio-source populations at $0 < z < 1$, using a sample of radio-detected galaxies and QSOs which have $i < 20.5$ mag but are selected without applying any color cuts. Figure 3 shows the distribution of these objects in color and redshift. The ~ 1 mJy flux density limit of the FIRST radio survey (Becker *et al.* 1995) means that at $z > 0.1$ the radio emission from all the objects in Figure 3 is expected to arise from a radio-loud AGN.

Two main groups of points can be seen in Figure 3: luminous red galaxies are tightly clumped in color, with $(g - i) \sim 1$ mag at $z = 0$ and 3.5 mag at $z = 0.8$. Radio-loud QSOs form a second group of points, with $(g - i) \sim 0$ mag at all redshifts. There are

also a smaller number of objects which fall in between the LRG and QSO groups. Many of these appear to be radio galaxies with strong, narrow emission lines, but analysis of their stellar populations is still in progress.

We currently have around 3000 good-quality spectra of radio galaxies out to redshift $z \sim 1$, and we now plan to map out the relative numbers of hot-mode and cold-mode accretion systems as a function of both redshift and clustering environment out to $z = 1$.

Acknowledgements

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