High-redshift radio galaxies: at the crossroads

Steve Rawlings\textsuperscript{a}

\textsuperscript{a}Astrophysics, Oxford University, Keble Road, Oxford, OX1 3RH, UK

Abstract

The next generation of surveys of extragalactic radio sources will be dominated by different types of objects than the jetted-AGN that dominate surveys like 3C, 6C and 7C. Before radio astronomy becomes concentrated on the new types of object, it is vital that we understand the cosmological importance of the jetted-AGN that have been studied for many years. I argue that, as observational manifestations of Eddington-tuned outflow events, these objects may have more significance for galaxy/cluster formation and evolution than is typically appreciated. Outstanding problems in galaxy formation may be solved by cosmological simulations in which this type of outflow, as well as other types associated with weaker jets, are properly taken into account. I will highlight areas of ignorance which are currently hindering attempts to do this.

Key words: galaxies: active - radio continuum: galaxies - cosmology: observations

1 Introduction

Radio astronomers are approaching an important crossroads (Fig. 1). The sensitivity of surveys with next-generation instruments like LOFAR and the SKA will be such that, as illustrated in Fig. 2, the radio emission from a typical survey object will have its origin in star formation (SF) rather than black-hole-related processes. There will be a dramatic increase in the areal density of ‘radio galaxies’, and, with HI surveys with the SKA, direct access to 3D maps of the large-scale structure (LSS). Radio observations may eventually lead the way in areas of astrophysical research traditionally dominated by observations in other wavebands.

This paper has a simple purpose – to make the case that much work still needs to be done if we are to claim to understand the jetted-AGN that dominate existing, classical radio surveys, as well as other types of jetted-AGN that are likely to be common in future surveys. I will argue that, despite their perceived
rare and exotic nature, jetted-AGN may have an important influence on the Universe, and must therefore be included in cosmological simulations. I will highlight some important, but as yet unresolved, questions concerning these seemingly well-studied objects.

2 The relevance of radio sources

Some astronomers have been heard to argue that extragalactic radio sources are irrelevant to the energy budget of the baryons in the Universe. Such arguments are commonly based on two misconceptions: (i) that radio luminosity gives a reliable measure of the ‘power’ required to generate radio emission; and (ii) that all power outputs associated with AGN couple with comparable efficiency to the baryons. The first misconception is typified by the use of a sharp drop in the spectral energy distribution (SED; the plot of $\nu L_\nu$ versus $\nu$) of AGN at radio wavebands to argue that radio emission is energetically unimportant. In fact, the bolometric radio luminosity of a radio source is typically $\lesssim 1$ per cent of the bulk kinetic power in its jets$^1$ (Willott et al., 1999). If one could plot the SED of a radio source including both mechanical and radiative outputs, then the mechanical output might well dominate. The second misconception arises because radiative outputs tend to be far more obvious than mechanical outputs. However, the fact that we see QSO radiative output so easily, e.g. to very large cosmological distances, implies that radiative outputs
Fig. 2. 151-MHz luminosity \( L_{151} \) versus redshift \( z \) diagram for various existing radio source redshift surveys: filled symbols are radio quasars, and open symbols are radio galaxies from 3C, 6CE and 7CRS; other dotted lines show loci of the flux-density limits of TOOT (Hill & Rawlings, 2003); TONS (Brand et al., 2003); radio follow-up of the Subaru/XMM-Newton Deep Survey (SXDS; Simpson et al., in prep.). QSOs like 1821 + 643 are also found in the ‘intermediate-\( L_{151} \)’ zone between the plotted radio quasars and radio-quiet quasars which tend to have detections or limits in between the TONS and SXDS lines. Also plotted are bands representing approximate limits (depending on issues like effective exposure time and confusion limits) for surveys with LOFAR and the SKA. Various critical values of \( L_{151} \) are marked: the break in the RLF (Willott et al., 2001); the FRI/FRII break; the starburst (SB) / AGN break and the radio luminosity of the Milky Way. Because the RLF is steep, a typical ‘high-\( z \) radio galaxy’ in a LOFAR survey will be a starburst rather than an AGN, and, in SKA surveys, it will be a normal galaxy rather than a starburst.

are often rather inefficiently absorbed by the baryons in the Universe.

\footnote{All statements in this paper concerning the jet powers of radio sources ignore the considerable uncertainties associated with issues such as jet composition (Willott et al., 1999).}
Having established that the mechanical output of radio sources must be consid-
ered, it is also worth emphasising that making any estimate of the heating
effect of the radio source population is observationally difficult. The radio lu-
minosity function (RLF) has a pronounced break, and the luminosity density,
and hence the total heating effect of the population, is dominated by objects
at or near that break. We see from Fig. 2 that it is only the most recent gen-
eration of radio source redshift surveys, like TOOT (Hill & Rawlings, 2003),
that are sensitive to sources near the break in the younger high-z Universe,
where the heating effect probably peaked [Fig. 3 of Rawlings, 2000]. Such
sources can be thought of as being ‘typical’ of powerful-jetted-AGN in the
same, luminosity-weighted, sense that $L^*$ galaxies are typical of the normal
galaxy population.

Some astronomers have also been heard to argue that radio sources are ir-
relevant to galaxy formation. The basis of this argument, is that only a tiny
fraction of galaxies are, at any cosmic epoch, powerful radio sources. The hole
in this argument is that the low space density of radio-selected objects needs
to be corrected for the finite and short ($\lesssim 10^8$ yr) lifetimes of radio outbursts.
Accounting for this it seems likely that a large fraction, and possibly all, of
the most massive ($\gtrsim 3L_*$) galaxies have developed powerful radio jets on one
or more occasions during their history (Willott, Rawlings & Blundell, 2001).

So, my contention is that radio sources may be an important, and an as-
vect missing, ingredient in ‘semi-analytic’ models [e.g. Somerville & Primack,
1999] for galaxy formation. Powerful radio sources are ‘Eddington-tuned’ en-
gines (Rawlings, 2000) with jet powers $Q \sim f L_{\text{Edd}}$, with $f \sim 0.1$ (Willott et al.,
1999), and TOOT is beginning to tell us (Hill & Rawlings, 2003; Rawlings, Hill & Willott,
2003a) that this is true for objects dominating the luminosity density, and
hence the integrated heating effect, of the population at high redshift.

3 What problems might radio sources help solve?

One example of a problem potentially solved by considering radio sources is
the rough calculation (Rawlings, 2000) that, although most of the thermal
energy in cluster baryons came from gravitational collapse, powerful radio
sources may have injected heat at the $\sim 10$ per cent level. This may go at
least some way towards explaining the ‘excess’ entropy inferred in the central
regions of clusters (Ponman, Cannon & Navarro, 1999).

Including radio sources in cosmological simulations may solve other problems.
The tight relation between black hole mass and stellar luminosity, and/or stel-
lar velocity dispersion (McLure, 2003), is nicely explained by AGN feedback
(Silk & Rees, 1998; Fabian, 1999). According to feedback models, it is the
coupling of the mechanical power of AGN to the baryonic component of the forming galaxy that explains the normalization and slope of these relations. In essence these models balance the mechanical power, delivered presumably by winds and/or jets at some unknown fraction $f_{\text{mech}}$ of the Eddington luminosity $L_{\text{Edd}}$, with the power required to push out a shell of gas at a speed $V_{\text{shell}}$. So,

$$f_{\text{mech}} L_{\text{Edd}} \sim V_{\text{shell}} (\rho V_{\text{shell}}^2)^{4\pi r^2} \propto \frac{\sigma^2}{G r^2} r^2 V_{\text{shell}}^3,$$

where the proportionality follows from the assumption that the gas density $\rho$ follows the density profile of the dark matter, characterized by a velocity dispersion $\sigma$. If the shell is to be pushed away from the galaxy then $V_{\text{shell}}$ must exceed $\sigma$, yielding a relation close to that seen in the data (McLure, 2003). Including rough estimates of the normalization, the relation can be written as

$$\left( \frac{f_{\text{mech}}}{0.1} \right) \left( \frac{L_{\text{Edd}}}{10^{40} \text{ W}} \right) \sim k_1 \left( \frac{\sigma}{1000 \text{ km s}^{-1}} \right)^5,$$

or alternatively as

$$\left( \frac{f_{\text{mech}}}{0.0001} \right) \left( \frac{L_{\text{Edd}}}{10^{40} \text{ W}} \right) \sim k_2 \left( \frac{\sigma}{250 \text{ km s}^{-1}} \right)^5,$$

where $k_1$ and $k_2$ are constants of order unity, accounting for the numerous uncertainties.

The implication is that Eddington-tuned outflows may be more than just ‘fireworks’ – they may be an integral part of galaxy formation. Despite at least one astronomer at the meeting saying they never wanted to see the phrase again, I stubbornly suggest we start thinking about powerful radio sources less as discrete objects and more as Eddington-tuned feedback events. Such events may be ubiquitous in the life histories of the most massive ellipticals and their associated clusters. Since nearly all clusters of galaxies contain one or more ultramassive ($\gtrsim 3L^*$) elliptical galaxy, it may be impossible to fully understand the properties of clusters, and the elliptical galaxies they contain, without understanding the effects of these dramatic, short-lived events.

4 Radio sources as Eddington-tuned feedback events

AGNs almost certainly drive more than one type of outflow. In fact theories predict at least two types: (i) the narrow-beam, relativistic radio jets we all know and love, for which the power source is often assumed to be rotational
energy stored in the ergosphere of the black hole as the result of previous episodes of accretion \cite{Cattaneo2003}; and (ii) wider-beam, sub-relativistic winds driven off the accretion disk, for which the power source is more directly linked to the release of gravitational potential energy \cite{Blandford1999}. These fundamentally different processes seem likely to have widely different values of $f_{\text{mech}}$, with theories suggesting a significantly higher value in the case in which the outflow is a powerful, narrow jet.

Binary black hole merger becomes a possibility for the $\gtrsim 3L_*$ products of the mergers that are likely to form the most massive elliptical galaxies \cite{Cattaneo2003}. This provides an attractive mechanism both for heating the stellar core via orbital decay \cite{Faber1997}, and for the formation of a single spinning supermassive black hole \cite{Wilson1995}. The subsequent emergence of a powerful jet would be expected to yield a step-increase in $f_{\text{mech}}$. This could drive a dramatic feedback event in which the gas is expelled on the timescale of the radio source expansion, terminating black hole growth as well as star formation in the circum-nuclear regions. This would be in line with suggestions that powerful jet outflows come at the end of significant periods of black hole growth and associated star formation \cite{Willott2002,Rawlings2003,Jarvis2003}. Massive elliptical galaxies probably underwent this formative phase in the young ($z \gtrsim 4$) Universe when the gas could have been given more energy than its binding energy within the associated dark-matter halo (c.f. Equation 1). This gas, enriched by the short-lived, merger-driven burst of star formation, could be driven to large ($\sim \text{Mpc}$) radii, where it might form an intracluster medium. One interesting, but highly speculative, possibility is that the fast clear out of recently enriched material may be important in explaining the puzzling metal, i.e. [Mg/Fe], abundances of elliptical galaxies \cite{Thomas2002}.

This all sounds reasonable. Physical models suggest that $\approx 1/2 \sim 1$ of the jet power of radio galaxies finds its way into the gaseous surroundings whether it is mediated by bubbles, at low $Q$ \cite{Bruggen2002}, or strong bow shocks, at high $Q$ \cite{Blundell1999}. Comparisons of $Q$ with the bolometric (radiative) luminosity $L_{\text{bol}}$ suggest that for powerful sources $Q \sim L_{\text{bol}} \sim 0.1 L_{\text{Edd}}$ \cite{Willott1999}, so given a roughly unit coupling efficiency to the gaseous environment, we get $f_{\text{mech}} \sim 0.1$ for Eddington-tuned radio jets. Any shocks driven by the radio sources will have radiative luminosities much less than $Q$ because of the long cooling times of the low-density material passing through the shocks. From Equation 1, we see that Eddington-tuned jets from $\gtrsim 10^9 \text{M}_\odot$ black holes have sufficient power to expel all the gas from a proto-cluster-like potential.

There is much observational evidence in support of the notion that powerful radio sources should be viewed as Eddington-tuned feedback events, important in the history of some, arguably all, the most massive elliptical galaxies.
Although subtle cosmic-evolution and black-hole-mass effects are present [Willott et al. 2003], the main message from the remarkably tight relation between stellar luminosity and redshift (the $K - z$ relation) for radio galaxies remains that a massive ($\gtrsim 3L_*$) elliptical galaxy seems a necessary prerequisite for powerful-jet production.

Evidence for the importance of halo-halo mergers in the production of powerful jets is growing. There are now several clear examples [e.g. Simpson & Rawlings, 2002] of powerful outflows being triggered by interpenetrating collisions of galaxies, yielding accretion onto pairs of black holes; in other cases of AGN activity, these black holes may have already coalesced. There are hints that these collisions are orchestrated by the collapse of larger-scale structures which, on cluster scales, may be viewed as double, merging X-ray sources [Crawford et al., 2003] and which on supercluster scales may give rise to conspicuous aggregations of radio sources [Brand et al., 2003].

Evidence that a powerful radio outbursts terminate star formation comes from anti-correlations between various quantities and the linear sizes of radio sources [Baker et al., 2002; Willott et al., 2002; van Ojik et al., 1997; Jarvis et al., 2003]. Taking linear size to be related to the time since jet triggering, sub-mm luminosity (which traces heated dust), nuclear reddening (which traces all dust) UV absorption (which traces ionized gas) and HI absorption (which traces neutral gas) are only high in the most recently-triggered systems. Together, these results make a compelling case that radio source expansion is clearing the central regions of the gas and dust needed to fuel starbursts.

Evidence for significant heat input by radio sources into their environments is also mounting. A bow shock is readily visible in the CHANDRA image of Cygnus A [Smith et al., 2002], but it is a minor contributor to the total X-ray luminosity. In higher-$z$ systems, the expectation is that bow shocks will radiate a greater fraction of the energy they receive, largely because the densities in collapsing systems will be higher [by a factor $\approx (1 + z)^3$], and the cooling times shorter. Such strongly radiative bow shocks, totalling $\gtrsim 10^{38}$W, may well have been detected at high redshift both directly as extended soft X-ray emission [Carilli, 2003] and indirectly as the source of photoionizing photons for low-density gas in and around the lobes of $\sim$ 100-kpc-scale radio sources [Inskip et al., 2002].

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2 At this meeting, Crawford argued that the latest X-ray data on the high-$z$ radio galaxy 3C294 support an inverse-Compton rather than thermal origin for its double X-ray structure. Simpson & Rawlings (2002) have already considered this possibility, and argued that confinement of the CMB-up-scattering electrons would still require an underlying double structure in the gas and dark-matter distributions.
5 Other types of Eddington-tuned feedback event?

Initial results from the TOOT survey (Rawlings, Hill & Willott, 2003a) suggest that typical high-redshift radio sources appear to be Eddington-tuned outburst events. However, not all Eddington-tuned events, for example ‘radio-quiet’ quasars, seem to produce powerful jets. This begs the question of whether jets are important only for a sub-class of galaxies, e.g. the most massive (>3L*) ones. This question is linked to two old results: (i) that some sort of jet activity is common, possibly ubiquitous, in radio-quiet QSOs (Miller, Rawlings & Saunders, 1993); and (ii) that radio-quiet quasars are known to reside in both spiral and elliptical galaxies (McLure, 2003).

The idea of Miller, Rawlings & Saunders (1993) – that all radio-quiet QSOs have low-Q, but initially relativistic, jets – seemed attractive as QSOs with intermediate radio luminosity could be explained as the favourably aligned, Doppler-boosted cases. The case of the quasar 1821 + 643, whose credentials as an intermediate-L151 quasars are clear from Fig. 2, has shown that the real situation is more complicated. Deep radio observations of 1821 + 643 (Blundell & Rawlings, 2001) reveal a radio structure akin to those of classical FRI radio galaxies, i.e. intrinsically weak non-Doppler-boosted jets. Blundell & Rawlings (2001) argue that similar low-radio-surface-brightness features may be present in a significant fraction of optically-selected QSOs, but they have not yet been properly looked for. Large-scale jets may be a far more common feature of QSO activity than is commonly recognised.

I believe, however, that a simple but powerful argument limits the power in such jets, and any associated winds, to a small fraction of the bolometric/Eddington luminosity of their associated highly accreting AGN. The radio source population can account nicely for the excess entropy seen in the cores of clusters (Rawlings, 2000). Radio sources dominate the heating budget (over ‘radio-quiet’ AGN) provided that they have typical ratios of jet power to bolometric luminosity that exceed the factor ~ 100 by which the (bolometric) luminosity density of the radio-quiet population exceeds that of the radio-loud population (Rawlings, 2001). This is in accord with the normal assumption (Miller, Rawlings & Saunders, 1993) that, to zeroth order, the bolometric output in jets scales with the total low-frequency radio luminosity. Reversing this argument, if the ‘radio-quiet’ population were postulated to have winds (or indeed jets) with similar f_{mech} to the radio-loud population, then the wind/jet input to the intracluster medium would be ~ 100-times greater than is observed in the form of the ‘excess’ entropy in clusters. I conclude that both jets and winds from Eddington-tuned radio-quiet quasars have f_{mech} ~ 0.0001, and hence are intrinsically weak.

It is important to note, however, that weak jets and winds can have very
important effects. There is already compelling evidence that fairly weak jets can limit the cooling of gas in present-day rich clusters (Brüggen & Kaiser, 2002), although in these cases the outflows are driven by AGN accreting at sub-Eddington rates. AGN-driven winds from highly accreting systems could lead to a different type of feedback event, tuned to a lower fraction of $L_{\text{Edd}}$, but still capable of removing gas from the central regions of the starburst/AGN, limiting black hole growth and star formation. From Equation 2, material can clearly be pushed out of the central regions of a galaxy even if it cannot reach the scales of the intracluster medium. This less-extreme mode of feedback may be ubiquitous during the formation of less massive ($\lesssim 3L^*$) spheroids. Since more massive spheroids are likely to grow hierarchically, their progenitors probably underwent such events. The fact that the so-called ‘radio-loud’ BALQSOs (Becker et al., 2001) also inhabit the intermediate-$L_{151}$ zone (around 1821 + 643 in Fig. 2) is very interesting in this regard. We (Grimes et al. in prep) are using sub-mm and radio observations to investigate the possibility that weak outflows are capable of disrupting star formation like their powerful-jet counterparts (Willott et al., 2002).

6 The hidden variable – black-hole spin?

I sketch in Fig. 3 some possible evolutionary tracks for the most massive (elliptical) galaxies after their formation. As black-hole mass is essentially a constant along these tracks, it is clear that variations in black-hole mass and/or accretion rate cannot determine the wide variation in jet and accretion properties. This is exemplified by the cases of M87 (a sub-Eddington accretor with weak jets), Cygnus A (a much-closer-to-Eddington accretor with powerful jets) and 1821+643 (a close-to-Eddington accretor with weak jets). There must be a hidden variable, and this is normally ascribed to black-hole spin. Very crudely, this might work as follows. At some suitably high redshift (say $z \sim 7$), the first $3L^*$ galaxies formed from galaxy-size halo mergers, and they were born with spinning supermassive black holes. Some, but not all, of this spin was removed during the first Eddington-tuned feedback event. Orchestrated perhaps by the collapse of larger-scale structures, subsequent galaxy-size halo mergers (say at $z \sim 1 - 7$), and further Eddington-tuned feedback events could have extracted more and more of spin. So, a $\gtrsim 3L^*$ galaxy that was born in a rare dark-matter fluctuation may well have had such a turbulent history that by present times its black hole has little spin remaining. Now, situated perhaps in the core of a very rich, relaxed cluster like 1821 + 643 (Lacy, Rawlings & Hill, 1992), even when its black hole is strongly accreting, it has too little spin to power a powerful-jet outflow. On the other hand, a $\gtrsim 3L^*$ galaxy that was born within a less rare dark-matter fluctuation may well have lost little spin since its formation and its initial Eddington-tuned
Fig. 3. Sketch of possible evolutionary tracks in the black hole spin versus accretion rate plane. Eddington-tuned events during and after formation could spin-down the black hole either ‘slightly’ or ‘largely’. Objects similar to observed high-z radio galaxies (HzRG) were likely to be the young-Universe counterparts of diverse present-day objects like M87, Cygnus A and 1821+643. Hierarchical models predict that the progenitors of $> 3L^*$ ‘radio loud’ galaxies in the upper part of the Figure were two less massive galaxies (probably with two black holes and little spin) which merged at very high redshift.

Feedback event. Its large-scale environment might be dynamically young in the sense that it is part of a galaxy group which is only at present times falling into a massive relaxed cluster, such as appears to be the case for Cygnus A (Owen et al., 1997). Even moderate accretion onto such a black hole might stimulate a powerful radio jet.

This is certainly not the first time a plot such as Fig. 3 has been shown, and it just as certainly won’t be the last. My plea here is that we finally, collectively, make some observational progress on understanding it! The crude evolutionary scenario discussed above, and its potential relation to dark-matter fluctuations, is undoubtedly far too simplistic but it at least provides a framework which is testable via observations.
7 Concluding Remarks

- Let’s finish the job of understanding the Eddington-tuned outburst events that are observationally manifested as powerful radio galaxies. I have argued here that, when viewed at high redshift, these events may well be the terminal phase in the formation of $\gtrsim 3L^*$ elliptical galaxies. The triggering of powerful jets may well introduce a step-function change in $f_{\text{mech}}$ which delivers sufficient power to the environment that it influences the gas content, and hence star-formation history, of entire clusters (Equation 1). The fantastic results presented at this meeting identifying high-$z$ radio galaxies with forming proto-clusters (Venemans et al., 2003) is obviously in line with this sort of picture.

- Let’s finish the job of understanding the weaker jets, noting that we need urgently to determine why these are sometimes associated with sub-Eddington accretors (classical FRI radio galaxies) and sometimes with highly-accreting objects (‘radio-quiet’ quasars like 1821 + 643). This is vital because recent results suggest that even weak outflows can have important influences on the Universe, such as regulating cooling flows in galaxy clusters. Weak, but relativistic (i.e. jet-like) outflows may be just part of a second type of Eddington-tuned outburst event that may be the terminating feedback process during the formation of less massive ($\lesssim 3L^*$) spheroids. If there are associated wide-beam, sub-relativistic (i.e. wind-like) outflows, I have argued that they must carry at least a factor $\sim 100$-times less mechanical power per unit bolometric power than the powerful radio jets. This is still sufficient to remove gas from the central regions (Equation 2). We also need to understand how such outflows are linked to potential observational manifestations like the BALQSO phenomenon.

- Let’s devise methods for finally hunting down the ‘hidden’ variable in physical models for AGN which is normally, without much observational evidence, ascribed to black hole spin. Clues to this may come from studying the exact link between AGN triggering, star formation and the collapse of dark-matter fluctuations.

- Jetted-AGN, be they powerful-jetted-AGN like known high-redshift radio galaxies or weak-jetted AGN, may have much more cosmological importance than is typically recognised. They should not, therefore, be treated as just a nuisance for future surveys with LOFAR and the SKA.

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