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Hot and cold gas accretion and feedback in radio-loud active galaxies

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ABSTRACT
We have recently shown that X-ray observations of the population of 'low-excitation' radio galaxies, which includes most low-power, Fanaroff-Riley class I sources as well as some more powerful Fanaroff-Riley class II objects, are consistent with a model in which the active nuclei of these objects are not radiatively efficient at any waveband. In another recent paper Allen et al. have shown that Bondi accretion of the hot, X-ray emitting phase of the intergalactic medium (IGM) is sufficient to power the jets of several nearby, low-power radio galaxies at the centres of clusters. In this paper we combine these ideas and suggest that accretion of the hot phase of the IGM is sufficient to power *all* low-excitation radio sources, while high-excitation sources are powered by accretion of cold gas that is in general unrelated to the hot IGM. This model explains a number of properties of the radio-loud active galaxy population, and has important implications for the energy input of radio-loud active galactic nuclei into the hot phase of the IGM: the energy supply of powerful high-excitation sources does not have a direct connection to the hot phase.

Key words: galaxies: active – X-rays: galaxies

1 INTRODUCTION

In the conventional picture of active galactic nuclei (AGN), accretion of cold matter on to the central supermassive black hole of a galaxy proceeds by way of a luminous accretion disc: the disc provides the radiation field that photoionizes the broad-line region (BLR) and narrow-line region (NLR) in the optical and gives rise to the X-ray emission via Compton scattering. Without radiatively efficient accretion via the disc, none of these standard features of such an AGN would be observed. Unified models propose that a direct view of the BLR, the optical continuum, and the soft X-rays may be obscured (e.g. in Seyfert 2s) by a dusty 'torus': but in this case the torus re-radiates strongly in the mid-IR band, while the hard X-rays are still detectable, so that the presence of a luminous AGN can still be inferred. Heavily obscured nuclear X-ray emission combined with mid-IR radiation is strong evidence for an obscuring torus.

Although this simple picture is broadly consistent with observations of radio-quiet AGN, it has been known for some time (Hine & Longair 1979) that it is not sufficient to explain the properties of radio-loud objects – the radio galaxies and quasars. By analogy with radio-quiet objects, we would expect that face-on radio-loud objects (the broad-line radio galaxies and radio-loud quasars) would show optical continuum emission, unabsorbed X-rays, and broad and narrow optical lines, while edge-on radio-loud objects (narrow-line radio galaxies, NLRG) would show narrow lines only in the optical, would have heavily absorbed nuclear X-rays, and would have a clear mid-infrared signature of the absorbing torus. This radio-loud unified picture does indeed seem to describe the nuclei of many of the most powerful radio sources (e.g. Barthel 1989; Haas et al. 2004), although an additional jet-related X-ray component must be present to explain the nuclear soft X-ray detections of the radio galaxies (e.g. Hardcastle & Worrall 1999; Belsole et al. 2006). However, Hine & Longair observed, in work more recently confirmed by others (e.g. Laing et al. 1994; Jackson & Rawlings 1997), that many radio galaxies do not have the strong high-excitation narrow-line optical emission that is expected from a conventional AGN. The objects lacking these narrow lines, which we shall refer to here as low-excitation radio galaxies (LERGs) are commonest at low radio luminosities: indeed, almost all low radio power (Fanaroff-Riley class I, or FRI) radio galaxies are LERGs. But in samples of radio galaxies the LERG phenomenon persists to high radio luminosities; many powerful FRII radio sources are LERGs as well. LERGs in general show no evidence in the mid-IR for an obscuring torus, either at low or high luminosities (Whysong & Antonucci 2004; Ogle et al. 2006) and their optical nuclei are consistent with being dominated purely by jet-related emission (Chiaberge et al. 2002). The relation between their emission-line and radio properties is also different (Baum, Zirbel & O'Dea 1995). Most recently, we have argued (Evans et al. 2006; Hardcastle et al. 2006, hereafter H06) that both low-power FRI and high-power FRII LERGs show no evidence for accretion-related X-ray emission, absorbed or unabsorbed, over and above what is likely to originate in the nuclear (pc-scale) jets. It seems most likely that the LERG population simply does not have a radiatively efficient accretion flow, and so produces none of the optical or X-ray characteristics of a conventional AGN. In other words, we and others have argued that *LERGs may be a class of luminous active galaxies that accrete radiatively inefficiently, with almost all the available energy from accretion being channelled into the jets*.

In this paper we take this argument a step further. We show that it is possible that these apparently different accretion modes may be a result of a different *source* for the accreting gas, building on the recent result of Allen et al. (2006), who showed that some low-luminosity radio galaxies in the centres of clusters could be powered by Bondi accretion from the hot, X-ray emitting medium, and supporting arguments about the nature of the accretion mode in low-power radio sources recently made by Best et al. (2006). We propose that the low-excitation objects are fuelled by accretion from the hot phase, while the high-excitation objects require fuelling from cold gas. If different types of radio sources do have different accretion modes, then a number of features of the radio-loud AGN population can be explained; there are also important implications for the so-called 'feedback' process in which radio-loud AGN do work on their hot-gas environments. We begin (Section 2) by using some simple quantitative tests to show that it is at least plausible that accretion from the hot phase can fuel even powerful low-excitation radio sources, but that it is hard to see how it can power the most powerful FRIIs. In Section 3 we discuss some of the wider implications of this model. We summarize our results and discuss future tests of the model in Section 4.

Throughout the paper we use a cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$.

2 BONDI ACCRETION AND POWERFUL RADIO SOURCES

Without committing ourselves to a particular model of the way in which the accreted material actually powers the jets, we may use the Bondi accretion rate to estimate the amount of power that the central supermassive black hole can extract from accretion of the hot phase of the IGM, following the analysis of Allen et al. (2006). The Bondi rate is given by

$$\dot{M} = \pi \lambda c_{\rm s} \rho_{\rm A} r_{\rm A}^2 \qquad (1)$$

where λ is a constant which has the value 0.25 for an adiabatic index $5/3$, $c_{\rm s}$ is the sound speed in the medium ($c_{\rm s} = \sqrt{\Gamma kT/\mu m_{\rm p}}$), $r_{\rm A}$ is the Bondi accretion radius and $\rho_{\rm A}$ is the density at that radius. $r_{\rm A}$ is given by

$$r_{\rm A} = \frac{2GM_{\rm BH}}{c_s^2} \qquad (2)$$

so that, for $\lambda = 0.25$, we have the simple form

$$\dot{M} = \pi \rho_{\rm A} G^2 M_{\rm BH}^2 / c_s^3 \qquad (3)$$

and we assume, again following Allen et al., that all material that accretes across the Bondi radius is accreted on to the black hole, so that the available power for AGN activity, $P_{\rm B} = \eta \dot{M} c^2$, where η is an efficiency factor. To show that the jet can be powered by accretion of the IGM, we require that the jet power $Q \lesssim P_{\rm B}$.

Allen et al. (2006) were able to show that Bondi accretion could supply enough energy to power the radio sources they studied because they were able to estimate the power in the jets Q from the timescales and energies required to inflate observed cavities in the external medium, and the density at the Bondi radius $\rho_{\rm A}$ and the temperatures kT by extrapolation from observations. They obtained black hole masses from the mass-velocity dispersion relation ($M_{\rm BH}$ - σ relation) of Tremaine et al. (2002), except in the case of M87 for which a direct $M_{\rm BH}$ measurement was available. For powerful, distant radio galaxies in poorer environments, we generally do not have either a direct measurement of Q, an $M_{\rm BH}$ measurement, a galactic velocity dispersion σ, or a particularly good estimate of the density at the Bondi radius $\rho_{\rm A}$, and so more indirect methods must be used.

It is well known that radio observations alone cannot be used to measure Q for a given radio galaxy without making numerous assumptions about the particle and field content of the lobes, the validity of conventional spectral ageing techniques and the fraction of the jet power that has gone into doing work on the external medium. However, there is a class of low-power objects where a model-dependent but robust jet power measurement can be made. These are the twin-jet FRI sources, where the behaviour of surface brightness and polarization in the (presumed intrinsically symmetrical) jet and counterjet can be used to model jet dynamics (Laing & Bridle 2002a; Canvin et al. 2005; Laing et al. 2006). When combined with X-ray information on the pressure gradient surrounding the jets the dynamical model allows a jet power to be derived. The only source to have a published jet power derived from this method is 3C 31 (Laing & Bridle 2002b) but since 3C 31 is one of the archetypes of its class, and has a relatively powerful jet for an FRI, we begin by considering it in more detail.

To derive black-hole masses for radio galaxies we use the relationship between $M_{\rm BH}$ and K-band absolute bulge magnitude derived by Marconi & Hunt (2003) for nearby sources:

$$\log_{10} M_{\rm BH} = 8.21 + 1.13 \times (\log_{10} L_{\rm K} - 10.9) \qquad (4)$$

where $L_{\rm K}$ is the K-band luminosity in solar units. We choose to use this particular relation because it is well calibrated against an $M_{\rm BH}$ - σ relation – indeed, Marconi & Hunt argue that the dispersion in the $M_{\rm BH}$ - K relation is as small as that for the $M_{\rm BH}$ - σ relation for objects with well-determined black hole masses – and because K-band magnitudes for powerful radio sources are readily available. Marconi & Hunt carried out a bulge-disc decomposition for their objects, which included a number of spirals, but we assume that the total K-band magnitude is the appropriate number to use for the elliptical galaxies that host radio sources. The observed scatter in the $M_{\rm BH}$ - K relation is about 0.5 dex, implying (eq. 3) an uncertainty of about one order of magnitude in the available Bondi power. It should be noted that if Bondi accretion *is* responsible for powering radio jets, so that radio luminosity is correlated with Bondi power, then objects taken from a flux-limited radio sample are likely to be biased in the sense that their black hole masses will be above the expected value for galaxies of their observed properties, given the strong dependence of $P_{\rm b}$, and thus Q, on $M_{\rm BH}$ (eq. 3). We make no attempt to correct for this, but it should be borne in mind in what follows.

For 3C 31 Laing & Bridle (2002b) quote a jet power $Q \approx 10^{37}$ W. From the K-band 2MASS observations (here and subsequently we use the total K-band magnitude provided by the NASA Extragalactic Database, NED) and the $M_{\rm BH}$ - K relation we infer a black hole mass of 1.1×10^9 M$_\odot$. Hardcastle et al. (2002, hereafter H02) studied the small-scale X-ray halo of the host galaxy of 3C 31 (the dominant galaxy of a rich group) and measured a central gas temperature of 0.66 keV. If we assume an efficiency of conversion of accretion power to jet power of $\eta = 0.1$ [following Allen et al.: Nemmen et al. (2006) have recently argued that efficiencies of this order are possible in various jet-formation models provided that the central black hole is rapidly spinning] then we can infer that an electron density at the Bondi accretion radius (assuming $\rho = 1.13 n_{\rm e} m_{\rm p}$ as Allen et al. do) $n_{\rm e,A} \approx 6 \times 10^5$ m^{-3} is required to power the jet. H02 give a central density from their β-model fit of $n_{\rm e} \approx 2 \times 10^5$ m^{-3}, which is already consistent within the uncertainties on $M_{\rm BH}$: however, we know from the H02 fits to the inner 1.5 arcsec (0.5 kpc) of the 3C 31 X-ray emission that the density is higher in that region than the β-model would predict, and in fact the mean density inferred from spectral fitting is around 5×10^5 m^{-5}, while clearly if there is any density gradient in this inner region of the source the density at the Bondi accretion radius ($r_{\rm A} = 50$ pc) will be higher than the mean value. Thus there is no difficulty in producing the jets of 3C 31 by accretion of the hot phase of the IGM. We have repeated this calculation for several other FRI radio galaxies for which both X-ray estimates of the central density (e.g. 3C 296, Hardcastle et al. 2005) and jet power estimates from jet modelling (Laing, private communication) are available, and find that this conclusion is generally true: the central densities in the galaxy-scale components of these sources, even those in considerably poorer large-scale environments than 3C 31, are sufficient for Bondi accretion at a nominal 10 per cent efficiency to power the jet.

We next investigate whether there are sources that *cannot* be powered by Bondi accretion under these conditions. A widely used estimator of jet power is that derived by Willott et al. (1999):

$$Q_W = 3 \times 10^{38} f^{3/2} L_{151}^{6/7}\ \mathrm{W} \qquad (5)$$

where L_{151} is the observed radio luminosity in units of 10^{28} W Hz^{-1} sr^{-1}. The factor f parametrizes our ignorance of true jet powers, and is likely to depend in practice on the type of source and its environment, as discussed by Willott et al.. However, Blundell & Rawlings (2000) estimate that f may be ~ 10 for FRII sources, while we find by normalizing this relation to jet powers of FRIs (Laing, private communication) that f lies in the range 10–20 for these objects as well. If we adopt a common f value for all sources then an object's jet power Q and available Bondi power $P_{\rm B}$ *for given density and temperature at the Bondi radius* can be calculated simply from its redshift, radio flux density and K-band apparent magnitude (using the $M_{\rm BH}$ - K relation as discussed above). In Fig. 1 we plot the observational quantities, radio luminosity and K-band luminosity, for radio galaxies from 3CRR (Laing, Riley & Longair 1983) with available K-band magnitudes, which are taken from the compilation[1] of Willott et al. (2003) for sources with $z > 0.05$ and from 2MASS for nearby objects. The figure also shows the conversion of the observational quantities to Bondi power and jet power, assuming values of the central density and sound speed appropriate for nearby FRI sources. Sources are divided according to their emission-line classifications in the manner discussed by H06. Quasars and BLRG are not plotted, as they have a substantial AGN-related contribution to the observed K-band magnitude, but we would expect them to behave similarly in unified models. For reference, we also plot the position of the high-excitation, powerful non-3CRR object Cygnus A (3C 405), using the black hole mass determined by Tadhunter et al. (2003).

While of course we do not claim that this plot gives the accurate position of any given source on the Q - $P_{\rm B}$ plane – it is essentially just a version of the well-known magnitude/radio-power plot of Ledlow & Owen (1996) – it is instructive in several ways. Firstly, it shows that the nearby FRI radio galaxies (for which the adopted densities and temperatures are comparable to those directly measured where X-ray observations exist) almost all lie within a factor of a few of the line of $Q_W = P_{\rm B}$, as we would expect for the more detailed analysis carried out above. Secondly, it shows that the majority of low-excitation FRII radio galaxies in our sample also lie close to this line, within the uncertainties due to the scatter in the $M_{\rm BH}$ – K relation. And thirdly, it shows that there is a population of FRII sources, encompassing most of the narrow-line FRII sources (and therefore, presumably, all high-excitation sources), that have jet powers exceeding the available Bondi powers (for our choice of central gas properties) in some cases by more than two orders of magnitude. For these sources to be powered by accretion of the hot IGM they would have to have a much higher central density than nearby FRIs, f factors much lower than the values appropriate for the twin-jet FRIs, or central black holes an order of magnitude more massive than the local $M_{\rm BH}$-K relation predicts. While we cannot rule out high central gas densities for distant objects, nearby FRII sources in group environments with detailed *Chandra* observations show that the luminosities and masses of any central hot-gas component in these objects are typically much *lower* than in those of nearby FRI sources (Croston et al., in prep.). Thus, for these sources at least, we feel confident in the claim that Bondi accretion of hot gas almost certainly cannot be responsible for powering the jet.

We note that several powerful low-excitation radio galaxies (with estimated jet powers $Q \sim 10^{39}$ W) lie more than an order of magnitude away from the line of $P_{\rm B} = Q_W$ on Fig. 1. One or two of these may not be true low-excitation objects (H06). Setting that aside, though, we already know that these powerful FRII LERGs tend to trace cluster environments, much richer than those of NLRGs, BLRGs and quasars of comparable power (Hardcastle 2004), and so it is possible that for these objects our choice of central density (comparable to those in group-centre FRIs) is too low, which would move them up on Fig. 1: at the same time, their denser environment would tend to lead to higher radio luminosity for a given jet power (Barthel & Arnaud 1996), moving them to the left. Both these effects would bring them closer to the region of parameter space where accretion from the hot phase could power the jets. While this picture needs to be tested by detailed X-ray studies of the environments of powerful LERGs, we do not feel that these objects present an insuperable problem for the model at present.

Finally, it is worth commenting on one observational point that could be used to argue against the picture we present here – the widespread detection of nuclear dust features in the host galaxies of nearby FRI sources (e.g. Martel et al. 1999). In some cases these structures have even been described as being related to the accretion disc itself (e.g. Jaffe et al. 1993), and, although they are clearly on scales much too large to be directly related either to any true accretion disc or to the larger-scale torus, it is possible that they represent a reservoir of cold gas accreting on to the central black hole. However, as we know the central cooling rates of the hot gas in these objects are high (e.g. H02) and the jet in classical twin-jet systems at least is likely to be a relatively inefficient source of heating for this central hot gas component, it is possible that small-scale cold material will naturally appear as a result of cooling, mirroring the processes seen on a larger scale in massive central cluster galaxies. Tan & Blackman (2005) argue that formation of a cold disc with a scale comparable to the Bondi radius is in fact a natural consequence of Bondi accretion in massive ellipticals. Given these possibilities, we do not consider that the observations are inconsistent with the picture presented here.

[1] Data available online at
http://www-astro.physics.ox.ac.uk/∼cjw/kz/3ckz.html

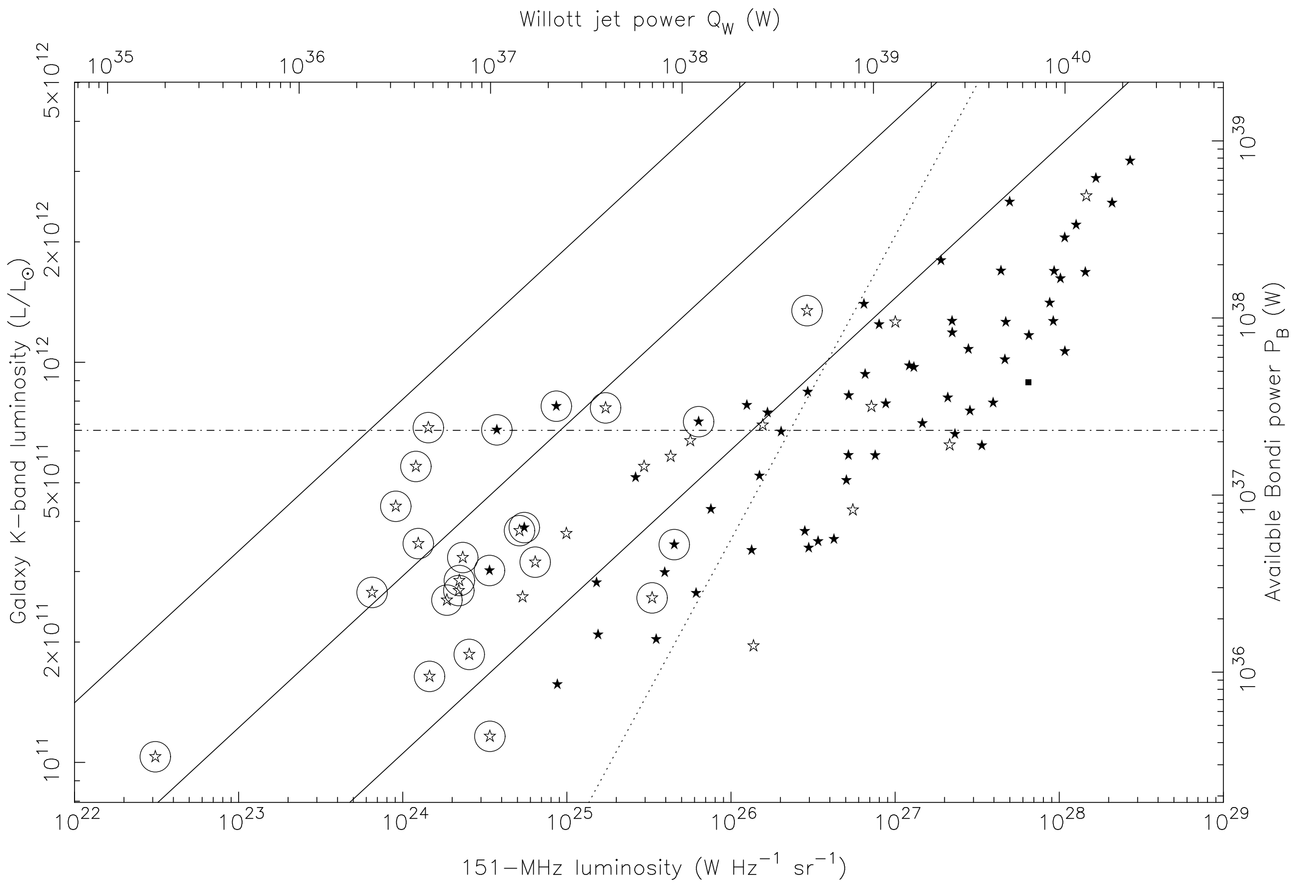

Figure 1. K-band host galaxy luminosity against 151-MHz luminosity for 3CRR narrow-line and low-excitation radio galaxies with available K-band magnitudes. The top and right-hand axes show the conversion of these observational quantities into jet power derived from the Willott et al. (1999) relation ($Q_{\rm W}$) and available Bondi power ($P_{\rm B}$) respectively, derived from eqs 3 and 5 using a single density at the Bondi accretion radius, ($\rho_{\rm A} = 5 \times 10^5$ m^{-3}), a single temperature at that radius ($kT = 0.7$ keV), a single factor f in the Willott et al relation ($f = 10$) and a single Bondi efficiency ($\eta = 0.1$). Black hole masses are inferred from the K-band magnitudes as described in the text. Open stars are low-excitation radio galaxies and filled stars are narrow-line objects. A circle round a data point indicates an FRI. The filled square marks the position of the powerful NLRG Cygnus A, as discussed in the text (note that here the adopted K-band luminosity is derived from the known black hole mass rather than vice versa). The central solid line shows equality between the predicted Bondi power and the Willott et al jet power. The lines on either side are separated from the solid line by one order of magnitude, and so give an idea of the scatter expected on the Bondi luminosity from the observed dispersion in the $M_{\rm BM}$ - K relation. The horizontal dash-dotted line shows the galaxy luminosity (corresponding to a black hole mass) at which the Bondi accretion rate $\dot{M}$ for our chosen gas parameters is equal to 0.01 times the Eddington rate (so that $P_{\rm B} = 10^{-3} L_{\rm Edd}$), while the dotted line shows the line at which the Willott jet power $Q_{\rm W}$ equals 0.015 times the Eddington luminosity, both (for clarity) assuming the nominal $M_{\rm BM}$ - K relation. See the text for discussion of these lines.

3 IMPLICATIONS OF THE MODEL

The analysis of the previous section has shown that it is possible that all the low-power low-excitation radio galaxies are powered by accretion from the hot phase, consistent with the fact that their nuclear spectra show no evidence for cold material close to the nucleus (i.e., no evidence for the ‘torus’). On the other hand, we have seen that narrow-line radio galaxies (and therefore also broad-line radio galaxies and radio-loud quasars) which have clear evidence for accretion discs and tori, cannot be powered in this way — the large amounts of cold material in the nucleus and the radiative efficiency of accretion are naturally explained if these objects are powered by accretion of cold material via a thin disc in the standard manner.

Does accretion from the hot phase necessarily imply a radiatively inefficient accretion flow? We know that, by definition (eq. 2) the sound speed of the gas exceeds the Keplerian velocity v_k at the Bondi radius. For $\gamma = 5/3$, this condition is maintained throughout the Bondi flow (Bondi 1952). Thus true spherical Bondi accretion is incompatible with the formation of a thin disc, which requires $c_s \ll v_k$. However, the effects of a two-temperature plasma and of viscous dissipation must be considered, the assumption of spherical symmetry must break down at some point, and adequate radiatively inefficient cooling models close to the black hole should probably resemble a quasi-spherical accretion-dominated advection flow (ADAF: Narayan & Yi 1995a,b) or one of the numerous variants discussed in the literature. We know that these solutions in general are inconsistent with accretion rates of order of or greater than the Eddington rate, which we define as $L_{\rm Edd}/c^2$, i.e.

$$\dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_p}{\sigma_{\rm T} c} \qquad (6)$$

where $\sigma_{\rm T}$ is the Thomson cross-section and m_p is the mass of a proton. Therefore an important check on whether our picture is consistent with ADAF-type solutions is to ask whether it requires accretion rates of the order of the Eddington rate. Comparing eqs 3 and 6 it can be seen that $\dot{m} = \dot{M}_{\rm B}/\dot{M}_{\rm Edd}$ is linear in black hole mass for given parameters of the external gas, and that the black hole mass required to give $\dot{m} \sim 1$ is high for plausible external thermal parameters. In fact, all of the black hole masses for the low-excitation sources give $\dot{m} \ll 1$ for our choice of Bondi parameters. The maximum value of $\dot{m}$ for a low-excitation source close to the line of $P_{\rm B} = Q_{\rm W}$ in Fig. 1 is ~ 0.02, and most lie below $\dot{m} = 0.01$. To illustrate this we have plotted the black hole mass (and therefore galaxy mass) corresponding to $\dot{m} = 0.01$ for our hot-gas parameters as the dash-dotted line in Fig. 1. Thus all the low-excitation objects consistent with being powered by Bondi accretion (i.e. within the solid lines in Fig. 1) also have significantly sub-Eddington accretion rates, as required by ADAF-type solutions. In addition, we have plotted (dotted line) the line of $Q_{\rm W} = 0.015 L_{\rm Edd}$ for the inferred black hole masses. This line of jet power vs. Eddington luminosity was used to divide FRI and FRII sources by Ghisellini & Celotti (2001). In the present plot we would argue that, while it does indeed separate FRIs and FRIIs reasonably well, it (or any variant on it represented by shifting the line to right or left) separates the low-excitation and high-excitation objects less well than the Bondi lines: in particular, there is a class of high-excitation low-power FRIIs with low $Q_{\rm W}/L_{\rm Edd}$ that could not lie to the right of such a line without also including a number of low-excitation FRIIs. Although the sample size is very small, this provides some weak evidence that it is genuinely the origin of the accreting material, and not simply the value of $Q_{\rm W}/L_{\rm Edd}$, that determines the accretion mode of radio galaxies (cf. section 5.2 of Narayan & Yi 1995b).

In the rest of this section of the paper we therefore explore some of the consequences of a picture in which there is a causal connection between the origin of the accreting gas and the accretion mode, as indicated by the emission-line type of the galaxy. We know that most, though not all, low-power radio galaxies are low-excitation objects, while essentially all the high-power radio galaxies (and of course all powerful radio-loud quasars) are high-excitation objects. Thus it is not too much of a simplification to say that low-power radio galaxies (roughly in the FRI regime, but including a handful of less powerful FRIIs) are likely to be powered by 'hot-mode' accretion, while powerful FRII radio galaxies and quasars in general will trace 'cold-mode' accretion. This allows us to interpret some previous results that have been stated in terms of luminosity differences, or FRI/FRII differences, as being more naturally understood in terms of a dichotomy in accretion mode, bearing in mind that the FRI/FRII difference, in our picture, is a result of the jets' interaction with the large-scale environment rather than a direct consequence of the nature of the accretion.

3.1 Feedback

Feedback from AGN outbursts is now thought to be an important ingredient in galaxy formation models (e.g. Croton et al. 2006), enabling successful reproduction of the high-mass end of the galaxy luminosity function and solving the 'cooling flow' problem in the centre of massive clusters. An important feature of current models in which AGN heating prevents cooling of the ICM in the centre of massive clusters is that the AGN should both be able to influence, *and should be influenced by*, the X-ray emitting phase. Direct accretion of the hot phase provides an elegant way of ensuring that the AGN activity is regulated by the gas properties at the cluster centre, which was of course the motivation for the work of Allen et al. (2006). It is clear, though, that this is only possible for a 'hot-mode' radio source. Radio galaxies and quasars accreting in the cold mode do not have this direct connection between the hot phase and the rate of fuelling of the AGN: instead, the jet power is controlled solely by the accretion rate of cold gas, which may have nothing to do with the state of the hot phase. It is thus possible for cold-mode sources to inject catastrophic amounts of energy into the hot phase of the IGM. This is borne out by recent studies of the poor environments of nearby NLRG FRIIs (Kraft et al. 2007; Hardcastle et al. 2007) that show that the work done by the radio sources plus the internal energy in their lobes of the radio sources is comparable to the entire thermal energy of their host poor-group environments. Cold-mode systems can nevertheless play some role in feedback models. Churazov et al. (2005) suggest an evolutionary feedback model in which elliptical galaxies go through an early stage of rapid black hole growth at high accretion rates, until the black hole becomes sufficiently massive that radio-mode feedback turns on, slowing the rate of black hole growth. The radio outbursts of cold-mode systems may occur at an intermediate stage in this evolution, rather than forming part of an eventual feedback loop; the un-self-regulated energy input from this type of outburst into the ICM may instead be responsible for the "entropy excess" observed in galaxy groups and clusters (e.g. Pratt, Arnaud & Pointecouteau 2006).

3.2 Environments of active galaxies

In the model we have outlined we expect different types of active galaxies to be found in different environments. Cold-mode accretion requires a supply of cold gas: the easiest way for an elliptical galaxy to acquire this is by a merger with a gas-rich system. Samples of high-excitation radio galaxies should thus show evidence for mergers and interactions, consistent with many observations showing evidence for recent or ongoing mergers in the hosts of powerful sources (e.g. Heckman et al. 1986). Of course, since the timescale for transport of cold gas to the galactic centre may be much longer than the timescale for removal of the obvious optical signature of a merger, we do not expect a one-to-one correlation between observed elliptical-spiral mergers and AGN activity. We note, though, that this picture is consistent with observations of the few low-power, FRI, radio galaxies that we know to have heavily obscured nuclear X-ray emission, including Cen A (e.g. Evans et al. 2004) and NGC 3801 (Croston, Kraft & Hardcastle 2007). Host galaxies of cold-mode systems do not need a rich environment, or to be at the bottom of a deep potential well, so long as galaxy-galaxy mergers can take place.

By contrast, hot-mode accretion requires a supply of hot gas and a massive central black hole. Both the black hole mass and the mass of the galaxy-scale X-ray halo (e.g. Mathews & Brighenti 2003) are correlated with the mass of the host galaxy. Thus we expect hot-mode systems – which, observationally, include almost all FRI radio galaxies – to favour massive galaxies, and the most powerful radio sources to tend to be group- or cluster-dominant systems, as is observed (e.g. Longair & Seldner 1979; Prestage & Peacock 1988; Owen & White 1991). In samples that are not radio-selected, and in which the radio population (given the luminosity function) will therefore be dominated by low-luminosity radio galaxies accreting in the hot mode, we expect a strong correlation between radio activity and host galaxy/black hole mass, as found by Best et al. (2005). Best et al. (2006) have already pointed out the potential link between this observation and the fuelling of these radio sources by accretion of the hot phase, but in our picture their findings cannot be generalized to high-power, high-excitation, cold-mode radio sources.

3.3 AGN populations

The luminosity function of hot-mode radio galaxies will be determined by a combination of the black hole mass function and the distribution of properties of central hot gas. The cold-mode luminosity function, on the other hand, will be determined by the rate of accretion of cold material on to the central black hole, with no direct effect of the black hole mass until the Eddington luminosity is reached. We therefore expect the luminosity functions to be different, and the local radio luminosity function of radio-loud AGN, being the composite of two different luminosity functions, should have a break at a luminosity comparable to the transition between populations dominated by low-excitation and high-excitation radio sources, as is observed (e.g. Machalski & Godlowski 2000). The 'dual-population' unified model of Jackson & Wall (1999) proposes that the luminosity functions of FRI and FRII populations evolve differently with cosmic time. Since we know that the conditions for hot-mode and cold-mode accretion *must* vary with time, we would expect that this type of model would more properly be applied to the low-excitation and high-excitation sources.

3.4 Jet production and accretion history

We have so far not attempted to comment on the formation of jets in these systems. In our picture, the FRI/FRII difference is not in origin a function of accretion mode: the FRII LERG population provides the clearest evidence for this feature of the model. While the nuclear and large-scale properties are correlated in general (in 3C 31 and other twin-jet FRI sources, for example, the dense central concentration of hot gas required to fuel the active nucleus in the hot mode also provides the pressure gradient needed to collimate the jet and keep it stable to large distances: H02) they need not be in particular cases, which explains the lack of a one-to-one relationship between accretion mode and FR class. It is thus a requirement of the model that the two accretion modes must be capable of producing jets that are similar in most of their observable parsec-scale properties, as FRI and FRII jets are known to be (e.g. Pearson 1996). In models where the jet is produced from the accretion flow (Blandford & Payne 1982) it seems likely that this would require similar structure in the innermost regions of the accretion flow, but clearly we cannot distinguish between particular jet formation models.

A potentially more interesting question is whether hot-mode sources *necessarily* form a jet. Cold-mode sources can be divided into radio-loud and radio-quiet classes: is the same true for hot-mode accretion? At least some hot-mode sources at cluster centres require a more or less continuously active jet, to reproduce the nearly universal detection of radio galaxies in high cooling-rate cluster cores (e.g. Eilek & Owen 2006) and it may be this is true for hot-mode sources in general: that is, it may be that this mode of accretion always produces a jet. Certainly it has been argued (e.g. Ho 2002; Nagar et al. 2002) that low-power AGN (with low values of $L_{\rm bol}/L_{\rm Edd}$), where identified as AGN, tend to be dominated by jet emission. However, it would be hard to identify a class of AGN accreting in the hot mode in a radio-quiet manner, without powerful jets – we only know about the active nuclei in LERGs because of their jet-related radio, optical and X-ray emission. The only accretion-related radiation in this situation would be the extremely weak emission from the radiatively inefficient flow itself, but these sources would still contribute to black hole growth. Although it is generally argued that radiatively inefficient accretion has only a small effect on the evolution of the black hole mass function (BHMF), direct estimates of its effect (e.g. Merloni et al. 2004; Hopkins, Narayan & Hernquist 2006) are based on samples of AGN that are detectable as such, either by radio or optical emission, and so might not include jetless hot-mode objects. Sample-independent constraints on the effects of radiatively inefficient accretion independent of the population of objects being considered come from work like that of Cao (2007), who shows that radiatively inefficient accretion cannot be very important in the evolution of the BHMF if it is not to overproduce the hard X-ray background, but this relies on theoretical assumptions about the spectral energy distribution of a radiatively inefficient accretion flow, possibly still leaving some loophole for hot-mode objects. In any case, we would expect that if radiatively inefficient accretion does have any effect on the BHMF, it will do so primarily in sources where the Bondi accretion rate is high. This would predict an environmental dependence of the BHMF, though the effect is probably too weak to detect at present.

3.5 Analogy with X-ray binaries

Recently there has been considerable discussion of the relationship between the accretion modes and jet behaviour of X-ray binaries ('microquasars'; hereafter XRB) and those of AGN (e.g. Fender, Belloni & Gallo 2004, Körding, Jester & Fender 2006). Support for a connection between XRB jet/accretion states and those of various different types of AGN comes from the so-called 'fundamental plane of black-hole activity' (e.g. Merloni, Heinz & Di Matteo 2003, Falcke, Körding & Markoff 2004), and from similarities in their variability properties (e.g. McHardy et al. 2006). Radio-quiet AGN are usually associated with the high $\dot{M}$ high/soft spectral state of XRB, and low-power (FRI) radio galaxies with the low/hard state (e.g. Maccarone, Gallo & Fender 2003). Powerful FRII radio galaxies and radio-loud quasars have sometimes been associated with the radio outbursts seen as XRB transition between states (e.g. Körding, Jester & Fender 2006). Churazov et al. (2005) recently suggested that the central AGN of massive elliptical galaxies evolve through an early stage of radiatively efficient, high accretion rate black hole growth (analagous to the radio-quiet high/soft XRB state) to a state of stability regulated by feedback from radiatively inefficient feedback (analogous to the jet-dominated low/hard state).

In the picture of radio source activity we have presented, the two different modes of accretion (radiatively inefficient accretion of the hot medium and radiatively efficient accretion of cold gas) *both* have to operate to produce radio jets; in this model the jet properties are essentially independent of the accretion mode. There is a strong relationship between radio morphology and accretion mode in our picture, but this is likely to be due to the need for an accretion rate higher than that available from Bondi accretion of the hot phase (in most environments) in order to produce powerful jets. By removing the direct connection between accretion mode and radio-jet properties, our model causes some difficulties for a simple connection between XRB and AGN jet/disc states. In our picture, the low-excitation radio galaxies (including the FRIs) can be straightforwardly associated with the radiatively inefficient low/hard XRB state; however, it is unclear how the high-excitation sources fit into the picture, since they are clearly undergoing radiatively efficient accretion with steady jet emission. It remains possible that high-excitation sources are in some sense transitional objects (as discussed above, many such systems are associated with mergers, which plausibly cause a dramatic increase in accretion rate), but these systems can maintain steady jets for $\sim\, 10^7$ years in a radiatively efficient accretion mode, so that it is not clear whether a direct analogy with XRB behaviour can really be made for the high-power, cold-mode systems.

4 SUMMARY AND FUTURE WORK

The idea that low-excitation radio galaxies are fuelled by the accretion of the hot, X-ray emitting phase of the IGM, while high-excitation radio sources are powered by accretion of cold material, can be used (qualitatively) to explain

- their different optical and X-ray nuclear properties (H06, this paper)
- the close relationship between the power output of low-power radio galaxies and the energy needed to solve the cooling flow problem (Allen et al. 2006)
- the association of low-power radio galaxies with the most massive host galaxies (Best et al. 2006)
- the observed differences in cosmic evolution of low- and high-power radio-loud AGN (this paper), and
- the different environments of low- and high-excitation radio sources (this paper)

In this paper we have shown quantitatively that the required difference between low-excitation and high-excitation objects in the well-studied 3CRR sample is at least plausible. Clearly, though, further testing of this picture is essential. Observational tests would include a significant expansion of the available database of sensitive, high spatial resolution X-ray spectroscopic observations of nuclei of radio galaxies – our conclusions on the nature of low-excitation FRII sources in particular are based on small samples. Better constraints on the small-scale hot-gas environments of radio sources are vital, and forthcoming mid-infrared studies of the nuclei of radio-loud AGN will also provide important information. In future we expect studies of the evolution of the luminosity functions of the two populations, combined with cosmological simulations that give indications of the availability of fuel to the two accretion processes, to provide the most stringent tests of the model.

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