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Interpreting radiative efficiency in radio-loud AGN

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Abstract

Radiative efficiency in radio-loud AGN is governed by the scaled accretion rate on to the central black hole rather than directly by the type of accreted matter; while it correlates with real physical differences, it does not give us unambiguous information about particular objects.

Active galactic nuclei (AGN) selected by observations in the optical, infrared (IR) or X-ray are almost always ‘radiatively efficient’: they show evidence of a luminous accretion disc, which produces optical and UV emission directly, photoionizes ambient material to produce broad and narrow emission-line regions, and drives strong X-ray emission from a ‘corona’ above the disc. Their radiation may be absorbed and re-radiated in the mid-IR by a warm, dusty structure referred to as the ‘torus’. The diversity of observed properties in these AGN is well explained on the whole by a combination of intrinsic luminosity differences and orientation-dependent obscuration [1].

AGN selected in radio observations can behave very differently. The evidence is overwhelming that these ‘radio-loud’ AGN (RLAGN) can operate in both radiatively efficient and inefficient modes [see e.g. 2, 3, 4, and refs therein]. The radiatively inefficient (RI) objects — known variously as low-excitation radio galaxies, weak-line radio galaxies or ‘jet-mode’ objects — have active jets, which drive the radio emission, but no evidence for a luminous accretion disc, torus, corona, or accretion-driven emission lines; by contrast, radiatively efficient (RE) radio-loud objects — high-excitation radio galaxies, narrow-line radio galaxies, broad-line radio galaxies, radio-loud quasars, or ‘quasar-mode’ objects — behave like conventional AGN with the addition of a jet. Nuclear emission in RI objects comes from the jet only. In terms of their number, RI objects are the dominant population by a very large factor in the local universe [5] and so it is important to understand their nature and their effects on their environments.

How does this RE/RI dichotomy come about? A long-standing proposal [6, 7] is that its basic driver is the Eddington-scaled accretion rate: objects whose total radiative luminosity and jet power fall below a few per cent of the estimated Eddington rate, $L_{\rm Edd} = \frac{4\pi G M_{\rm BH} c m_p}{\sigma_{\rm T}}$, are RI, while objects above this limit are capable of sustaining a conventional RE accretion disc. This is as expected from theory [8], though the exact threshold expected depends on details of the accretion disc model. This picture has recently received strong observational support from large-sample studies. [5] estimated total radiative luminosity from the optical emission-line luminosity of a large sample of RLAGN drawn from SDSS, NVSS and FIRST, and found a clear division between RI and RE objects in Eddington-scaled accretion rate, while studies using X-ray and mid-IR emission as proxies of radiative power instead [9, 10] have come to very similar conclusions, albeit with smaller samples. The basic picture is that all RLAGN have accretion flows that drive jets of varying powers, but only a small minority have accretion rates high enough (relative to Eddington) to also power a RE disc. In RI objects, the estimated kinetic jet power may exceed upper limits on the radiative luminosity from the accretion flow by many orders of magnitude.

Ten years ago my collaborators and I [11] proposed that there was a one-to-one relationship between the two accretion modes and the two obvious sources of fuel available to AGN in general: RE sources would be fuelled by cold gas (which could be carried into the mostly elliptical hosts of RLAGN by mergers, or produced by cooling) and RI sources by hot gas (directly from the hot phase of the intergalactic or intracluster medium). A consequence would be that RI objects are capable of participating in the feedback loop between AGN and hot gas in cluster centres, while RE sources, which get their fuel from other sources, may input far more energy into their hot-gas environments than is required to offset cooling.

This 'hot-mode/cold-mode' picture, though widely adopted, has partly been superseded by our improved understanding over the past decade. If the Eddington-scaled accretion rate controls the radiative efficiency, there is no reason why a RI source cannot be produced by accreting at a low level from a cold gas reservoir, or why rapid accretion from the hot phase (now widely thought [12] to be mediated by cooling-instability driven 'chaotic accretion' rather than Bondi accretion) should not be capable of sustaining high accretion rates. Indeed, we can point to individual AGN, such as NGC 1275 in the Perseus cluster, that clearly show signatures of RE accretion from cold material while also being (presumably) fundamentally regulated by cooling from the hot phase. Thus at first sight one might imagine that the 'hot-mode/cold-mode' model has no further role to play. But it is surprising, given these facts, that it has proved so *successful* in predicting or incorporating the known observational differences between RE and RI objects at low z. Observationally we see that RI objects in general tend to lie in rich environments, prefer massive quiescent galaxies, and have little star formation, all as expected if they are fuelled by hot gas; RE objects tend to lie in poorer environments, prefer smaller galaxies often with major mergers, and can be strongly star-forming, as would be expected if there were a copious cold gas supply.

Why does the model make such good predictions if its basic premise is wrong? I suggest that the best explanation is that there is a strong *association* between the conditions needed to make a RI system and accretion from the hot phase. The RI/RE threshold can be recast as a ratio $\dot{M}/M_{\rm BH}$ between the accretion rate and the black hole mass; for the elliptical hosts of RLAGN $M_{\rm BH}$ scales well with galaxy mass. Galaxies that are the dominant (most massive) systems in a group or cluster environment, for a given jet power, will be more likely to be RI than galaxies in the field both because they will have high $M_{\rm BH}$ and because the main source of fuel will be cooling at relatively low $\dot{M}$ from the hot phase; merger-driven accretion of large quantities of cold gas in these systems is disfavoured because of ram-pressure stripping or strangulation of satellite galaxies in the hot-gas environment. By contrast, powerful RE AGN, where high accretion rates, close to Eddington, are required, can most easily be produced in systems with high $\dot{M}$ and relatively low $M_{\rm BH}$ and are expected to favour lower-mass galaxies in field environments. All that is required for this preference to give rise to significant differences between the two populations in large samples (as illustrated in Figure 1) is for there to be a wide range in $\dot{M}/M_{\rm BH}$ and in RLAGN environment, both of which we know to be true for powerful sources. Thus, although the fundamental basis of the model of [11] has changed, the predictions *on a sample basis* can remain correct.

There are two important consequences of this revised picture. Firstly, unlike in the 'hot-mode/cold-mode' model, the RI/RE observational classification of any given RLAGN does not *necessarily* tell us anything very fundamental about the source. If a source is close (in terms of $\dot{M}/M_{\rm BH}$) to the boundary between the two classes, it may change type repeatedly over its lifetime as a result of comparatively small changes in the accretion rate; there is a great deal of evidence that RLAGN and AGN in general can undergo large-amplitude long-timescale variation of the accretion power. Treating the current RI/RE status of a RLAGN as though it were an immutable property of the system over its lifetime is incorrect and may lead to other errors. More generally, it is never safe to conclude that a *particular object*'s fuel source is hot gas or cold gas based on its RI/RE classification; the model predicts a statistical preference that may be over-ridden by other factors. Secondly, the results on the cosmological evolution of the two populations now becoming available [5] need to be interpreted with caution, because it is not clear that the associations between fuel source and accretion mode will operate in *quantitatively* the same way in the earlier Universe; for example, the evolution of black-hole masses will mean that sources are more likely to be classed as RE for the same physical accretion rate $\dot{M}$ in the earlier Universe, so environments of similar richness might be expected to produce more RE sources.

In the picture presented here, RE/RI classification is a proxy of a specific quantity (accretion rate per unit black hole mass) that may not be particularly relevant to the purpose of a given study. Dividing observationally generated samples by their radiative efficiency certainly captures some real physical differences, but other methods of classifying them might provide more understanding. The ideal situation would be one in which we had direct estimates of the physically relevant quantities (jet kinetic power, radiative power, black hole mass...) and could divide up our samples according to these rather than simply according to the RI/RE class, but these parameters, particularly jet power which is fundamental to all studies of RLAGN, are hard to estimate uniformly and reliably. Developing techniques to extract jet power from radio observations using Bayesian inference based on detailed models of the evolution of radio sources [13, 14], and so moving away from the use of one well-studied but fundamentally limited AGN property, will be one of the key challenges for RLAGN science in the era of the SKA and its precursors.

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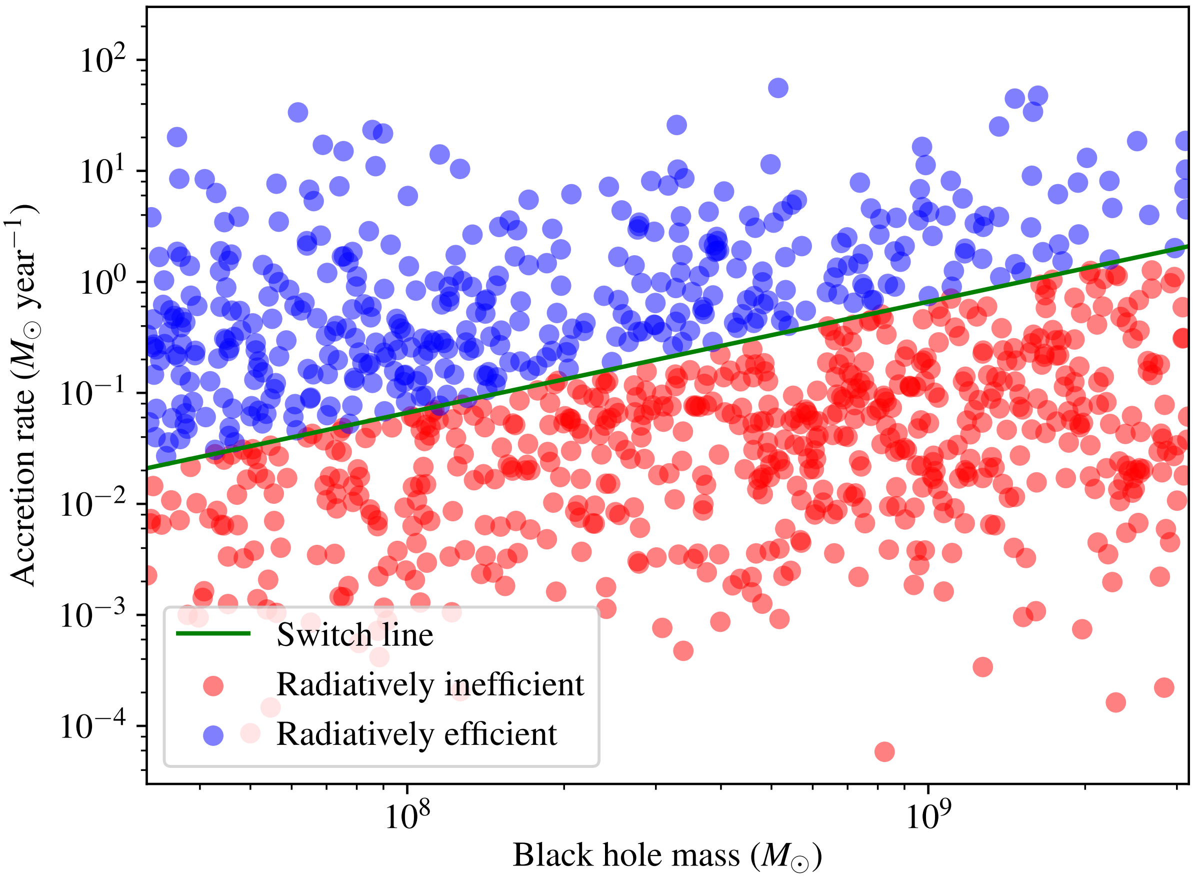

Figure 1: Black hole mass and accretion rate in a Monte Carlo simulation of a toy model in which black hole mass is uniformly distributed in log space between $10^{7.5}$ and $10^{9.5} M_\odot$ while intrinsic accretion rate, which is unrelated to $M_{\rm BH}$, has a lognormal distribution centred on $0.1 M_\odot$ year^{-1} with a dispersion of 1 dex. The RE/RI division is a straight line in this plot corresponding to 3% of the Eddington rate (assuming 10% conversion efficiency of accreted matter). Even in this toy model, RE sources on average have black hole masses a factor 3 less than RI sources and available (radiative/kinetic) luminosities, accounting for the Eddington limit, 1.2 decades higher, although there is essentially no difference between RE and RI sources close to the green line. In reality, the accretion rate is likely not uncorrelated with the black hole mass, but the details of this relationship need to be fleshed out observationally.

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