Accretion modes and feedback in radio-loud AGN

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Overview

• The puzzle of LERGs
• Unified models and X-ray emission
• The X-ray properties of radio galaxy nuclei
• Invisible or Compton-thick? The multi-wavelength view
• Accretion modes and accretion origin
• Consequences for feedback
LERGs

- Radio galaxies’ optical spectra can be classed as ‘Low-excitation’ vs ‘High Excitation’ (Hine & Longair 79; Laing et al 94; Jackson & Rawlings 97). Based on strength of high-excitation lines like \([\text{OIII}]\).
- *Most FRIs are low-excitation and most FRIs is high-excitation* – but substantial overlap.
LERGs and unification

- LERG cannot unify with quasars/BLRG since NLR cannot be hidden => beamed versions of LERG must be lineless, e.g. BL Lac objects.
- FRI and (probably) LERG FRIIs unify with BL Lacs – part of standard picture (e.g. Browne 83; Urry & Padovani 95; MJH et al 03)
- But why are the nuclear emission lines of these systems so different? Look at other properties to find out…
The X-ray view of radio galaxy nuclei

Torus obscures ‘coronal’ X-ray emission from nucleus => narrow-line radio galaxies should have heavily absorbed nuclei, as shown by early hard X-ray results (e.g. Ueno et al 1994)
X-rays from the nuclear jet

- Soft X-ray work (Feigelson et al 1984; Worrall & Birkinshaw 1994; Edge & Röttgering 1995; MJH & Worrall 1999...); an unabsorbed power-law component is present in nearly all RGs.
- Correlation between radio, optical, and X-ray cores => jet origin (from outside torus if present).
- FRIs, NLRG and LERG FRIs lie on same correlation
- Quasars and BLRG lie above it (we see additional unabsorbed accretion-disc related emission).
- (Required for unification with BL Lacs to work, so no surprise!)

Unabs. X-ray/radio core correlation (updated from MJH et al 06)
Search for absorbed X-rays

- What classes of objects have X-ray evidence for an obscuring torus?
- We need to look for absorbed X-rays in a sample containing significant numbers of both low-excitation and high-excitation objects and both FRIs and FRIIs.
- Archival XMM and Chandra on 3CRR sample (Laing, Riley & Longair 83) with z<1.0.
- Include sources from Evans et al 2006 (z<0.1), Hardcastle et al 2006 (0.1 < z < 0.5) and Belsole et al 2006 (0.5 < z < 1.0) plus some new observations and archive data since 2006 (e.g. Harris et al in prep.).
- In total 90/137 (66%) of the z<1.0 3CRR sources have Chandra or XMM data – almost all used in the current analysis.
Example FRII spectra

NLRG

LERG
Sample results

- Almost all of the NLRG (mostly FRIIs) show evidence for an absorbed nuclear component with $N_H \sim 10^{22} - 10^{24}$ cm$^{-2}$ – as expected if all have tori + large angle to LOS.
- BLRG and quasars generally unabsorbed or at most small absorption columns.
- Almost all the LERGS (FRIs and FRIIs) show no evidence for an absorbed component (exceptions not true LERGs?) although all show the jet-related, unabsorbed component.
- Can put upper limits on the absorbed, ‘accretion-related’ luminosity for sources where no absorbed component is detected by assuming a column density.
Luminosities

White = LERG
Red = NLRG
Green = BLRG
Blue = quasar

For quasars and BLRG the luminosity plotted is the total luminosity if no absorbed component is required in the fit.

Circle => FRI
Line goes through FRII NLRG

Limits assume $N_H = 10^{23} \text{ cm}^{-2}$
Invisible – or not there?

• We see that the limits for LERGs generally lie below the radio/X-ray correlation for NLRG; however, some NLRG lie in the same region of parameter space.
• A crucial question is whether the undetected sources are just absorbed by columns $>> 10^{23}$ cm$^{-2}$ – i.e., whether they are just Compton-thick.
• Infra-red data give us the answer: Compton-thick sources will be luminous in the IR.
• Spitzer IRS photometry is available for many of our targets. We use the 15-micron luminosities ($\nu f_{\nu}$) given by Ogle et al (2006) and Cleary et al (2007), supplemented by our own analysis of other 3CRR sources with $z>0.1$ (following the method of Ogle et al). 47 objects in our sample.
X-ray vs 15-micron luminosity

White = LERG
Red = NLRG
Green = BLRG
Blue = quasar

Circle => FRI

Line goes through all detected points

Limits use $N_H = 10^{23} \text{ cm}^{-2}$. Compton-thick sources would lie far below/right of the correlation.
IR interpretation

• The only source to lie in the Compton-thick region of parameter space is the NLRG 3C244.1. This may be a genuine example of a Compton-thick radio-loud AGN – a column density of $> 3 \times 10^{24} \text{ cm}^{-2}$ would be required to bring it back onto the regression line.

• Other X-ray detected NLRG lying below the line may provide evidence for more complex absorption structure (clumpy torus models?).

• The two LERGs with detected heavily absorbed X-rays also have IR nuclei at a level that puts them on the correlation – at least one of these lies in a region of high Galactic reddening and is probably really a NLRG.

• No LERG lies in the Compton-thick region. Detections are all low-luminosity and may be affected by host-galaxy emission.
Multi-wavelength interpretation

• No single indicator tells us what is going on:
  – X-ray cannot alone distinguish between Compton-thick and unabsorbed sources because of jet X-ray emission
  – Single-band IR is contaminated by galactic emission at the low-luminosity end and possible jet-related emission at the high end (see Cleary et al); division into mid-IR weak and strong too simplistic since some ‘mid-IR weak’ AGN (Ogle et al) really do have absorbed nuclei in the X-ray.
  – Emission line classification may be wrong because of reddening, poor spectroscopy, extended emission-line regions, photoionization by jet (e.g. Chiaberge et al 2002) etc.

• When all this is taken into account there still seems to be a real LE/HE dichotomy in the data: LERG seem to be accreting in a radiatively inefficient mode (for details see HEC 2006).
Origin of the dichotomy

- There are two obvious sources of gas for AGN to accrete: cold neutral material and the hot, X-ray emitting phase of the IGM.
- Allen et al 06 and, more recently, Balmaverde et al 08 have shown that accretion from the hot phase (shorthand – Bondi accretion) can power nearby low-luminosity objects.
- Best et al 06 argue that Bondi accretion can explain the observed tendency of low-power radio sources to favour massive host galaxies.

Bondi accretion vs. jet power in nearby cluster-centre radio galaxies (Allen et al 06)
Origin of the dichotomy

- Accretion directly from the hot phase (w/o cooling) would not form a conventional AGN – thin disk, torus and NLR/BLR all require a cold fuel supply. Hot phase accretion could therefore be radiatively inefficient, as we suggest for LERG.

- Could all LERG be powered by ‘hot-mode’ accretion and all HERG by ‘cold-mode’?

Bondi accretion vs. jet power in nearby cluster-centre radio galaxies (Allen et al 06)
Testing hot-mode accretion model

- Bondi accretion is spherically symmetric – not realistic in many situations but possibly the centres of giant ellipticals are better than most.
- Bondi accretion rate is given by
  \[ \dot{M} = \pi \lambda c_s \rho_A r_A^2 \]
  where the accretion radius is
  \[ r_A = \frac{2GM_{\text{BH}}}{c_s^3} \]
  so we need black hole mass and central physical conditions, and compare with jet power.
- We assume a fixed accretion efficiency – 10%. Spin not included!
Bondi estimates

- Black hole mass from galaxy K-band luminosity – dominant source of scatter
- Central parameters of the hot phase from observations of nearby FRIs
- First compared Bondi rate with jet power from models of Laing et al in a few nearby cases. => OK
- Then looked at all 3CRR objects using jet powers from the Willott et al 1999 relation normalized using these known jet powers.
Bondi rates for all 3CRR sources with K-band mag assuming $f = 10$, central electron density $5 \times 10^5 \text{ m}^{-3}$, central temp $0.7 \text{ keV}$, and Bondi accretion efficiency 0.1.

White points are low-excitation radio galaxies, red points are NLRG. Circles show FRIs.

Lines indicate uncertainty due to scatter in M-K relation.
Bondi rates

- We see that
  - The FRI sources (circled) lie close to the line(s) of equality.
  - Many LERG FRIIs lie close to the line too.
  - The majority of FRII NLRG are a long way away from being able to be powered by hot-mode accretion, if parameters used are correct.
  - (All plausible corrections to environmental parameters move NLRG away from line and LERG FRIIs towards it.)
Consequences

- Possible that all low-excitation radio-loud AGN (i.e. the vast majority of nearby low-power sources) are powered by hot-mode accretion (consistent with work of Allen et al and Balmaverde et al).

- Almost certainly *impossible* that the high-excitation objects (including most powerful FRIIs) get their energy this way – probably powered by accretion of cold material instead (consistent with observations of torus, NLR and radiatively efficient accretion disk).

- Let’s suppose this is true, what follows?
Consequences – jet generation

• Sources with and without a conventional thin accretion disc must generate (very similar) jets.
• => constrains jet generation models. (Somebody else’s problem…)
• (XRB tell us that jets can be generated in a radiatively inefficient accretion state, though the analogy is not exact.)
Consequences: feedback

Radiatively inefficient accretion = hot mode?

Hot gas fuel?

Feedback with hot phase

Radiatively efficient accretion + torus = cold mode?

Cold gas fuel?

Unregulated heating of hot phase?
Consequences: feedback

- True ‘feedback’ between AGN and hot phase requires the AGN to be controlled by the hot phase.
- Only directly possible (w/o intermediate cooling) in hot mode.
- In cold mode accretion (e.g. fuel supplied by gas-rich merger) the radio source can blow away its atmosphere without affecting its fuel supply.
- Consistent with observations of nearby NLRG FRIIs in poor environments which show work done/energy stored comparable to total thermal energy of atmosphere.

Consequences: feedback

• Croton et al (2006) and many other papers use ‘quasar-mode’ and ‘radio-mode’ to describe the two types of feedback in which, respectively, the AGN drives cold gas out of the galaxy via winds and suppresses hot-gas cooling via radio lobes.

• Unsatisfactory terminology
  – because many quasars are also radio sources
  – because many powerful radio sources, while not quasars, are operating in the ‘quasar mode’

• In our picture the nature of the AGN (X-ray/IR/emission line...) allows us to establish what mode a given AGN is in.

• Plausibly, most powerful, distant radio sources are not telling us anything about the ‘radio mode’!
Consequences: environments

• Hot-mode sources need massive central black holes and a good supply of hot gas – they will tend to inhabit the most massive galaxies in relatively rich environments (cf Best et al 06) as observed (Longair & Seldner 79, Prestage & Peacock 88, Owen & White 91, &c).

• Cold-mode sources’ power comes from accretion of cold mass and is independent of black hole mass (modulo Eddington limit): so they can inhabit poorer systems, as observed (P&P 88, &c). Cold gas required => merger with gas-rich system (for ellipticals) => merger signatures in high-excitation sources, as observed (e.g. Heckman et al 86).

• Qualitatively good agreement with known facts. Further tests of model required (see Huub’s talk?).
Summary

- RG nuclear X-ray emission is complicated by the presence of a soft (jet-related) component, but we think we can detect/set limits on absorbed components with Chandra & XMM.
- Seems plausible that LERG (in the local universe, most FRIs and some FRIIs) are radiatively inefficient.
- Can be related to source of accreting material with important consequences for the types of radio source that engage in ‘feedback’.