Radio-loud AGN feedback: how and when does it work?

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Outline

• Introducing radio-loud AGN
  – radio structures
  – active nuclei
• How do lobes and jets interact with their environments?
  – or, what physics do you need to put into your models?
• Problems and puzzles of 'feedback'
No need to look for evidence for outflows here!

Bulk LF ~ 10 at least on pc scales, certainly >~2 on kpc scales.
Straw man model #1: radio-loud AGN are exactly the same as RQ AGN but with the addition of a jet.
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Straw man model is wrong!

There are RGs with powerful ($Q \sim 10^{44}$ erg/s or more) jets that have no optical continuum above what is jet-related, no X-ray emission above what is jet-related (Varano+04), and no heavily obscured X-ray (MJH+06), and no mid-IR emission from a torus (Ogle+06, MJH+09).

Low and even comparatively high-power jet activity may come with none of the conventional trappings of an AGN.
AGN properties

Straw man model #2: **all** radio-loud AGN are operating in this radiatively inefficient way.

This model is **also** wrong. There are radio-loud AGN that do have NLR, BLR, optical-UV continuum, a torus, and coronal X-rays. These are the radio-loud quasars and BLRG/NLRG (Evans+06, MJH+06, 09).

Why the 'radio mode' terminology is bad; also a problem for the XRB/AGN analogy.
AGN properties

• XRB analogy does not seem to work:
  – No obvious analogue of the jetted, disky HERGs
  – No obvious 'switch' as a function of accretion rate...
An Eddington switch?

$M_{\text{BH}}$ from K-M relationship; K-z relation for radio galaxies means this is similar for all our objects.

Willott jet power (i.e. scaling of radio luminosity) normalized to known jet powers.

Bolometric correction from 2-10 keV assumed to be 10.
AGN properties

• We proposed that the radiatively efficient/inefficient RL AGN activity may be related to source of accreting material (MJH+07, 09). This is the 'hot mode' – 'cold mode' picture.
• Testable predictions – environments, population evolution (see Philip's talk).
• Does XRB analogy disfavour this? – not clear to me
• Not necessary to buy into this to realise that some RL AGN can be radiatively coupled to their environment while others may not.
• Hence in the second part of the talk we will neglect AGN radiation and discuss how kinetic power of RLAGN is coupled to their environments.
RLAGN-environment interactions

• Every time you see a bright radio structure you are seeing **direct** evidence for interaction with environment.
How can RLAGN affect environment?

- Jet plasma is low density but high pressure => interactions with gas, not stars.
- Most jets will form lobes anyway (see later).
- Lobe boundaries appear to be impermeable (why?).
- => RG-env interactions are mostly interactions between hot, low-density bubbles and cooler, denser external medium.
- Highest-pressure phase of external medium is X-ray-emitting, so start there.
Lobe dynamics + interactions

- Newly formed lobes will expand supersonically, driving shocks.
- Internal lobe pressure drops as lobe expands and (observationally) lobes can come into rough pressure balance.
- Once jet activity terminates, lobe continues to expand and move out buoyantly (relic).
- Finally, lobes must dissipate (mixing).
- Each phase will deposit energy in the hot gas, but not all will change the entropy.
Supersonic expansion – where are the shocks?

- Strongly overpressured sources will drive shocks throughout their lifetime (Scheuer 74).
- Used to be an article of faith in the FRII modelling community (e.g. Begelman & Cioffi 89, Kaiser & Alexander 97, and many more).
- Numerical models of FRII environment impact may make this assumption (e.g. Basson & Alexander 03) although more recently some have allowed it to vary (Vernaleo & Reynolds 07).
Where are the shocks?

- So far best *direct* evidence for shocks in hot phase is around the small-scale lobes of some nearby FRIs.
- Evidence for shocks around FRIIs is weak even in the best cases (e.g. Cyg A).

Cen A lobe shock, Croston+ 09
Where are the shocks?

- At the same time, growing evidence that the internal pressures of typical 100-kpc-scale FRIIs are comparable to the internal pressures from inverse-Compton (e.g. MJH+02).
- => lobe dynamics more complex (MJH+Worrall 00)
- => most FRIIs are not driving strong elliptical shocks (may still be supersonic at far end)
- => effect of shocks is limited for these sources.
- NB 'relic' shocks may still be detectable in X-ray observations
**pdV work**

- Typical radio-selected AGN where jets are embedded in lobes will spend most of their lives doing *pdV work*.
- We know that lobes expand without much mixing from observations of cavities, so $p = p_{\text{ext}}$ and $V = V_{\text{lobe}}$. Can use this to calculate jet power (e.g. Birzan+08).
- *Direct* evidence for *pdV work* limited, but see Croston+ 05. Recently we have been trying to use RG host groups as calorimeters – watch this space.
- This type of energy input does not solve entropy problems.
Buoyancy

- Disconnected lobes will continue to rise and expand – this can drag out cold material and continues to do $pdV$ work, tapping the internal energy of the lobe.
Mixing

• The elephant in the room – very large amount of energy in internal energy of lobes, which will be released at some point (changes entropy too).

• When does lobe material start to mix?

• Some evidence for diffuse synchrotron emission in groups with RGs, plus radio haloes/relics in clusters.

• Timescale for thermalization of particle population very long (Coulomb losses). Hard to observe these processes!

A194, Sakelliou+ 08
Intermittency

• Many sources, and perhaps even most low-power radio galaxies, show evidence for recurrent activity.

• => Many (all) of these processes may be going on simultaneously!

• Both duty cycle and timescales will depend on jet power and environment (e.g. Perseus)

Jetha+ 08; shocks and rising, buoyant relic lobes in a low-power radio galaxy.
Interactions with cold gas

- Extended (10-100 kpc scale) emission-line regions seen in high-z objects imply some means of ionizing cool ($10^4$ K) gas.
- Shock ionization implies direct(ish) interaction between jets and cold gas (e.g. Nesvadba+ 08).
- Kinematics often imply outflow, but gas masses are not significant at low z. But...
- ... outflows of neutral hydrogen – necessarily at low z – imply higher mass outflow rates. Necessarily kinetically coupled (Morganti+05,10)
In 3C171 (MJH+10) we see radio (red), [OIII] (green) and X-ray (blue) are all aligned. [OIII] kinematics imply outflow: optical and X-ray properties imply shock ionization: taken together we have $3 \times 10^9$ solar masses moving out at $\sim 1000$ km/s.
Blowing hot and cold

- How do we get this jet-cold gas coupling?
- Not yet clear, but shock driven by jet through hot phase may be sweeping up and ionizing cold gas.
- Potentially important feedback mechanism, esp. at high z where more cold gas available; more work in progress.
Problems and puzzles of 'feedback'

- Following are some examples of problems in radio-loud feedback models.
- Not intended to be exhaustive.
- Scare-quotes highlight difference between X-ray astronomers' and galaxy-evolution modellers' feedback...
- I am mostly talking about the former (i.e. how to prevent catastrophic cooling of hot gas while not getting rid of the hot phase altogether).
Central heating

- Cooling rates are highest at the centre, but AGN heating can often be poorly coupled to the central gas.
- Rapid bubbling with many shocks may work in cluster centres (Fabian+) but most RLAGN outside cluster centres are not like this.
Central heating

- Particularly acute problem with the minority of powerful FRIs where powerful jets are embedded in the hot medium.
- Jets require high pressure gradients to collimate them => high central density => short cooling times (<< source lifetime).
- But jet energy is dissipated on scales >> the central few kpc. How are the central pressure and density gradients maintained?
Particle (& field) content

- What provides the lobe pressure?
- In FRIIs e+e- and fields close to equipartition can do it
- In FRIs, particularly jetted ones (Croston+09) large discrepancy between min and external pressure
- To understand these sources we need to know what particles provide the internal pressure. Entrainment may be implicated (Croston+10).
Over-reaction

- Often a good coupling between jet power and required heating, but some radio sources in group/cluster environments are way too powerful.
- We suggest that these are powered by accretion of **cold** material (these sources all have 'traditional' AGN) & so uncoupled from the hot phase.
- \(\Rightarrow\) **Unregulated** heating of the IGM is taking place.
- Bower's 'expulsive feedback'?

3C285, MJH+08
Closing the feedback loop

• For true (X-ray-astronomers') feedback we need the jet (AGN) output to be coupled to the properties of the hot phase, as well as the reverse.
• Direct accretion from the hot phase? Or intermediate cooling?
• What happens below the Bondi radius?
• Bondi rate is adequate for many RGs – if you can get high efficiency of jet formation – but some sources need more (see Brian's talk).
• Can we really infer accretion source from accretion mode?
Summary

- Interactions between radio-loud AGN and both hot & cold gas are present at all epochs, though best studied at low z.
- They are not associated with any particular accretion mode – but their effects may depend strongly on their fuel source.
- The 'microphysics' of energy transfer is extremely complex, poorly understood in places, and operates on a wide variety of timescales.
- Many remaining unresolved questions even for the 'solved' problem of radio-source suppression of cooling in clusters & groups.