The host galaxies of AGN and radio-AGN feedback

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Overview of talk

• Part 1: AGN accretion modes
  - Two observed types of AGN
  - Evidence for radiatively inefficient accretion
  - Relative importance of the two accretion modes

• Part 2: AGN host galaxies
  - Differences in host galaxies of different AGN classes
  - Implications for triggering and fuelling of AGN

• Part 3: Radio-AGN feedback
  - Energetics of radio sources
  - Controlling the growth of massive elliptical galaxies
  - Evolution of radio-AGN feedback
What I won’t discuss

Radio Quiet AGN

- significant component of sub-mJy source counts
- allows radio to detect *all* black-hole accretion
- detects Type-2 AGN: best way to quantify population of obscured AGN before hard X-ray capabilities

Radio source counts simulation
(Wilman et al 2008)
Part 1:
AGN accretion modes
"Standard" picture of AGN

"Standard" AGN have:

- Luminous accretion disk (with X-ray corona)
- Bright line emission (ionised by disk)
- Dusty obscuring torus (emits in IR/sub-mm)
- Orientation-dependent observed properties
- Sometimes, extended radio jets
Another class of AGN

Other AGN, exemplified by weak radio sources, don’t fit this scheme:
Another class of AGN

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Laing et al 1994
Another class of AGN

Other AGN, exemplified by weak radio sources, don’t fit this scheme:

"Accretion-related" X-ray luminosity

Hardcastle et al 2007

178MHz Radio Luminosity (W/Hz)
Aside: not same as FR-split

Fanaroff & Riley Class 2 (FR2)
- “edge brightened”
- high $L_{\text{rad}} (P_{1.4\text{GHz}} > \sim 10^{25} \text{ W/Hz})$
- jets remain well-collimated
- optical host quasar or galaxy
- mostly, but not always, strong-lined, quasar-like sources
- 3C223

Fanaroff & Riley Class 1 (FR1)
- “edge darkened”
- low $L_{\text{rad}} (P_{1.4\text{GHz}} < \sim 10^{25} \text{ W/Hz})$
- jets decelerate & entrain
- usually no optical / X-ray AGN
- mostly, but not always, weak-lined, inefficient sources
- 3C31

Aside: not same as FR-split

3C31

3C223
Low excitation vs FR class?

The high / low excitation state of radio galaxies is a fundamental property of the active nucleus

- radiatively efficient vs radiatively inefficient
- triggering mechanism?
- accretion rate / mode?
- black hole spin?

The FR1/2 classification is something entirely different

- large scale environmental effects?
  - “hybrid sources”
  - host galaxy dependences
- all sources begin as FR2s, but jet disrupts to FR1 in dense environments? (cf. Kaiser & Best 2008)
More jet-dominated AGN?

Deep X-ray surveys have discovered a population of X-ray bright but optically normal galaxies ("XBONGs")

- Powered by AGN
- No or very weak emission lines
- No evidence for X-ray absorption (so unlikely to be heavily absorbed)
- X-ray to radio ratios a factor ~100 higher than weak radio sources

AGN with jet only, Doppler-boosted X-rays, but not radio-boosted BLLacs?

Hart et al 2009
Why different AGN?

Accretion models predict a change in the nature of the accretion flow at low fractions of Eddington:

- low accretion - most energy comes out as jets in “kinetic mode”
- high accretion - strong radiative emission, sometimes also with radio jets

Merloni & Heinz 2008
Testing accretion models

- Cross-matched SDSS DR7 with radio catalogues
  - sample of >18,000 radio sources
- Classify all radio galaxies as high- or low excitation
  - use SDSS emission line ratios (where possible)
  - use [OIII] 5007 line equivalent width
- Estimate black hole masses from velocity dispersions
- Calculated radiative luminosity, scaling from [OIII] 5007
  - corrected for reddening using Hα/Hβ line ratio
- Estimated mechanical (jet) luminosity from radio luminosity
Energetics of radio sources

Most of the energy of radio sources is in mechanical (jet) form. Simple arguments suggest $L_{\text{mech}} \approx 100-1000 \, \nu L_{\nu}$

- One estimate uses cavities blown in hot X-ray gas by radio sources, $E_{\text{cav}} = f \, p \nu V$ (where best estimate is $f \sim 4$)

$$L_{\text{mech}} = 8 \times 10^{37} \, f \left( L_{1.4 \, \text{GHz}} / 10^{25} \, \text{W Hz}^{-1} \right)^{0.70} \, \text{W} \quad (\text{Cavagnolo et al 2010})$$
Energetics of radio sources

An alternative estimate uses minimum energy condition for radio synchrotron \((\text{cf Willott et al 1999})\)

\[
L_{\text{mech}} = 1.4 \times 10^{36} \, f_W^{3/2} \left( \frac{L_{1.4\text{GHz}}}{10^{25} \text{W Hz}^{-1}} \right)^{0.85} \, \text{W}
\]

where \(f_W \sim 10\) incorporates the uncertainty factors (nature of jet plasma; low energy synchrotron cutoff)

Comparing the two, for best-estimate values:

\[
L_{\text{mech, sync}} \sim 4 \times 10^{37} \left( \frac{L_{1.4\text{GHz}}}{10^{25} \text{W Hz}^{-1}} \right)^{0.85} \, \text{W}
\]

\[
L_{\text{mech, cav}} \sim 3 \times 10^{37} \left( \frac{L_{1.4\text{GHz}}}{10^{25} \text{W Hz}^{-1}} \right)^{0.70} \, \text{W}
\]

Agreement between two estimates is well within scatter.
Accretion modes of low-z RGs

Given all uncertainties on estimates, the agreement with a dichotomy at accretion rate $\log(L/L_{\text{edd}}) \sim -1.5$ is quite good.
A word on nomenclature

“Standard” AGN:

- High-excitation
- Strong-lined
- Quasar-mode
- Cold-mode
- Radiative mode
  [but RLQs also kinetic mode]

⇒ Radiatively efficient
  (standard accretion disk)

“Non-standard” AGN:

- Low-excitation
- Weak-lined
- Radio-mode
- Hot-mode
- Kinetic mode

⇒ Radiatively inefficient
  (ADAF/RIAF/ADIOS)
Jets & the cosmic energy budget
(Cattaneo & Best 2009)

Convolving the relations between radio and mechanical luminosity with the radio LF gives total bolometric heating rate of AGN in a kinematic mode, as a function of redshift.

This can be compared with estimates of the radiated AGN bolometric luminosity.

Typically at least an order of magnitude lower.....

[Figure: white line = QSO BLF; blue,red = kinetic LF from cavities, min energy]
Jets & the cosmic energy budget

Integrating over L gives total energetic output.

Jets produce 2-5% of local AGN energetic output, and their importance decreases further at higher-z (as in galaxy formation models).

Radio-jet energetics are therefore cosmically unimportant, but all jet energy is deposited locally and may go into feedback, whereas most radiated energy passes through nearby ellipticals.
Details of cosmic jet heating - and what will be seen by next-generation radio surveys - depend on the details of the radio LF evolution.

Rigby et al. (2011) give strong evidence that this is luminosity-dependent.
Part 2:
AGN host galaxies
“Optical AGN” hosts

The host galaxies of optically-selected (ie. radiatively efficient) AGN:

- are found at all BH masses

Best et al 2006
“Optical AGN” hosts

The host galaxies of optically-selected (ie. radiatively efficient) AGN:

- are found at all BH masses
- are often star-forming

Kauffmann et al 2003
“Optical AGN” hosts

The host galaxies of optically-selected (ie. radiatively efficient) AGN:

• are found at all BH masses
• are often star-forming
• have ‘down-sized’: low-mass black holes are still rapidly growing but high-mass BHs are typically switched off.

Heckman et al 2004
“Radio-AGN” hosts

In contrast, low-luminosity radio-AGN:

- are hosted by old, passive early-type galaxies, with a strong preference for the most massive systems.

\[ f_{\text{radio-loud}} \propto M_*^{2.5} \]

\[ f_{\text{radio-loud}} \propto M_{\text{BH}}^{1.6} \]
“Radio-AGN” hosts

In contrast, low-luminosity radio-AGN:

• are hosted by old, passive early-type galaxies, with a strong preference for the most massive systems.

• show completely the reverse of down-sizing.
Interpretation

Radiatively efficient AGN activity:
- Generally galaxies with relatively low mass black holes
- Fuelled by cold gas in standard thin accretion disk
- Gas source may be secular, or from interaction/merger
- Associated star formation - from same cold gas supply
- Significant mass growth during accretion
  • Important phase of black hole and galaxy growth

Radiatively inefficient (low-luminosity radio) AGN activity:
- Predominantly in massive black holes
- BH growing slowly at low accretion rate
- Gas supply is likely to be the hot halo of gas surrounding gal.
  • Re-fuelling of already well-formed massive black holes.
Part 3:
Radio-AGN feedback
AGN feedback

“AGN feedback” is currently postulated to explain many issues in galaxy evolution:

- Black-hole - bulge mass relation
- Avoidance of over-production of massive galaxies
- “Old, red and dead” appearance of massive ellipticals

I will argue the case that recurrent radio-loud AGN activity is responsible for the latter two.
Recurrent radio activity, and energetics

Radio sources live for only $10^7$-$10^8$ yrs. Nevertheless, the radio-loud fraction suggests that at least 25% of the most massive galaxies are radio-loud.

⇒ Radio sources must be constantly re-triggered

We can then interpret the “fraction of gals of given mass that are radio-loud at a given luminosity” probabilistically as “the fraction of time that a galaxy of given mass spends emitting at a given radio luminosity”
Time-averaged radio AGN heating

Combining the $L_{\text{mech}}$ vs $L_{\text{rad}}$ relation with the mass-dependent radio luminosity function gives the time-averaged heating rate due to radio sources, as a function of black hole mass:

$$H = 10^{21.4} f \left( \frac{M_{\text{BH}}}{M_{\odot}} \right)^{1.6} \text{ W}$$

Normalisation comes from radio LF and $L_{\text{mech}}$-$L_{\text{rad}}$ conversion

Mass dependence comes from mass-dependence of radio-loud fraction

Uncertainties in $L_{\text{mech}}$ vs $L_{\text{rad}}$ relation only lead to a change in the normalisation of the relation (accounted for in “f” factor)
Heating versus Cooling

Compare:

- Bolometric X-ray luminosity (rate at which energy is radiated from the host haloes)
- Derived radio-AGN heating rate for ellipticals, as a function of galaxy mass (luminosity)

Figure: Bolometric X-ray luminosity vs optical luminosity of elliptical galaxies (from O'Sullivan et al 2001).
Heating versus Cooling

Compare:

- Bolometric X-ray luminosity (rate at which energy is radiated from the host haloes)
- Derived radio-AGN heating rate for ellipticals, as a function of galaxy mass (luminosity)

Heating from radio-loud AGN (over-?) balances gas cooling for elliptical galaxies of all masses
Interpretation

- For all ellipticals, the time-averaged heating due to radio sources balances the radiation losses from the hot gas.

- Therefore the radio source may prevent gas cooling, and control the rate of growth of the galaxies.

⇒ Energetically this can solve problems of semi-analytic models of galaxy formation.

⇒ To understand this physically (e.g. a feedback cycle) we still need to understand which radio source populations are involved and how they are triggered......
High vs low-excitation sources

- Low-luminosity radio source population (below $\sim 10^{25.5}$ W/Hz), which dominate energetic output, is predominantly low-excitation.
- Radio-loud fraction vs mass relation (high masses) also dominated by low-excitation RGs.
- Hence, it’s low-excitation sources that are involved in feedback
- These require low accretion rates, as provided by Bondi accretion or low cooling rates from hot halos
- => possibility of feedback cycle
Cosmic evolution of the low-excitation radio population

A key observational requirement is determine the evolution of radio-AGN feedback (cf. models)
This requires us to determine the cosmic evolution of the low-excitation radio source population

Merloni & Heinz 2008
Croton et al 2006
Cosmic evolution of the low-excitation radio population

A key observational requirement is to determine the evolution of radio-AGN feedback (cf. models). This requires us to determine the cosmic evolution of the low-excitation radio source population. RLF does evolve positively (albeit weakly) at low power, but this is a mix of high & low excit. sources.

Sadler et al 2007
The high/low excitation ratio

If there’s differential evolution of the high and low radio source populations, the ratio of high/low excitation sources should change with redshift.

Using the SDSS sample (with spectroscopic data) a trend is seen, but S/N is low because at high-z a growing fraction of sources can’t be classified with SDSS data.
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Compare with data from our CENSORS low-luminosity radio sample (150 sources to 7mJy, with deep spectroscopy)
The high/low excitation ratio

Clear increase in the high-excitation fraction at low luminosity, from 10-20% at $z=0$ to 40-50% at $z\sim 0.5-1.0$.

(Weak) evolution of faint low-luminosity end of the RLF does not directly translate to evolution of "radio-mode" feedback.

Louise Ker is working to use CENSORS and complementary surveys to measure the evolution of the RLF of low excitation sources (= "radiatively inefficient" feedback). Results soon...
Evolution of the mass fraction

Look at how the fraction of galaxies hosting radio-loud AGN as a function of mass evolves with redshift:

- Using large SDSS Mega-Z LRG sample (Donoso et al 2009)
- Using deeper radio sample in XMM-LSS (Tasse et al 2009)

At high masses essentially the same relation is found out to z~1 as in the local Universe
Summary

- Not all AGN follow the "standard" accretion disk picture.
- A population of low accretion rate, radiatively inefficient, radio sources, dominates the low-luminosity end of RLF.
- This is not the same as the FR1/FR2 split!
- These sources are in massive galaxies, and are probably fuelled directly or indirectly from the hot gas halo.
- Low luminosity radio source activity is highly-recurrent with a fast duty cycle, especially in the most massive gals.
- Energetic output (over-?) balances cooling rates, leading to feedback cycle.
- Radio-AGN vs mass relation doesn't evolve much to z~1. RLF of these sources also evolves little (better measure needed).