Supermassive Black Holes & Mechanical Feedback

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Physical basis for “radio mode” (mechanical) feedback hot X-ray atmospheres

Evidence for self-regulating feedback: cooling, star formation, AGN

Consequences: quenching of cooling flows (Birzan), large scale structure (Schaye) recovery of galaxy properties in ΛCDM (Benson +, Croton +, Bower+, Springel+)

New development: metal-enriched, large-scale outflows in clusters

Issues: what powers radio AGN? How does feedback work?
Cooling flows (cores) in most clusters and all gEs

\[ T \approx 10^8 \text{ K} \]

NGC 1275 Perseus

X-ray cooling cusp

X-ray luminosity $10^{44-45} \text{ erg s}^{-1}$ exceeds radio synchrotron power $10^{40-42} \text{ erg s}^{-1}$

implies cooling flow: $n_e \sim 10^{-1} \text{ cm}^{-3}$ \( \dot{M} = 10-1000 \text{ M}_\odot \text{ yr}^{-1} \)

Cooling flow problem: star formation $\sim 1\% \ M$
Key X-ray observations of cooling flows

**Reduced cooling**

XMM-Newton 1999 -

Peterson, Kaastra, Paerels +03

Sanders +08, Peterson & Fabian 06

**AGN interactions**

Chandra 1999 -

Mc+00, Fabian +00

**Implication:** Heating, feedback by SMBHs
Mechanical Feedback in Cooling X-ray Halos

“radio mode” feedback

Even weak radio source are mechanically powerful

Radiative cooling - AGN heating of hot gas
thermostatically controlled accretion

==> feedback loop

Key evidence:

-AGN mechanical power matched to cooling rates
  Birzan+04, Rafferty+06, Dunn Fabian 06

-Short (<10^9 yr) cooling times in all systems
  Voigt & Fabian 04

consequences

- heat hot halos; regulates growth of galaxies & SMBHs

See McNamara & Nulsen 07 ARAA
Abell 2052
Chandra 500 ksec unsmoothed
Blanton + 11

X-ray

E\sim 10^{59} \text{ erg}

2nd shock
1st shock
N filament
NW loop
NW bubble
S bubble
SE outer bubble

30 kpc
Measuring Jet Power using X-ray Cavities

- energy & age measured directly
- measure mechanical (not synchrotron) power

1) Cavity enthalpy (pV work + internal energy)

\[ E_{\text{cav}} = \frac{\gamma pV}{\gamma - 1} = 2.5 pV - 4 pV \]

\[ t_{\text{cav}} = \frac{r_{\text{nuc}}}{v_{\text{buoy}}} \]

2) Shock energy

\[ E_{\text{shock}} \approx \Delta pV \]

\[ t_{\text{shock}} \approx \frac{r_{\text{shock}}}{c_s} \]

\[ E_{\text{tot}} = E_{\text{cav}} + E_{\text{shock}} + (E_{\text{photon}}) = 10^{55} - 10^{62} \text{ erg} \]

McNamara + 00,01; Birzan + 04

Theory: Ruszkowski, Heinz, Bruggen, Begelman, Voit, Churazov, T. Jones, etc.

slow gas motions < c_s, gentle heating
Jet (cavity) power vs radio power

Key breakthrough: even weak radio sources mechanically powerful enough power to regulate or quench cooling, X-ray atmospheres
AGN heating balances cooling in gE’s & Clusters

\[ \langle \text{heating} \rangle \approx \text{cooling} \]

Trend shows:
cooling, jet power are correlated
cooling, heating know about each other!
Despite large AGN heating rates, central cooling times are short < Gyr
AGN outbursts & cooling on comparable timescales

Conditions for feedback

See Voit & Donahue 05, Peterson & Fabian 06, McNamara & Nulsen 07 ARAA
UV emission from star formation in molecular-gas-rich BCGs

- Fuel directly linked to cooling hot halo (not mergers) - Rafferty+08, Cavagnolo+08, Kirkpatrick + 08

\[ \text{A1664 SFR} \sim 20 \, M_\odot \, \text{yr}^{-1} \]
\[ \text{A1835 SFR} > 100 \, M_\odot \, \text{yr}^{-1} \]
\[ P_{\text{cav}} \sim 10^{45} \text{erg s}^{-1} \]

Edge & Frayer 02

\~10^{10} - 10^{11} M_\odot \text{of gas}
Star formation rates comparable to X-ray cooling Rates

Pre-XMM cooling rates: cooling flow problem

~100x

post-XMM

Rafferty + 06
O’Dea + 08
star formation cooling time threshold: $t_{\text{cool}} \sim 500$ Myr

Cool gas & Star formation linked to cooling, X-ray atmospheres
"Leaky" Mechanical Feedback

- Jet Power
- X-ray cooling luminosity

- gE & groups
- cD clusters
- quenched "red, dead"

- quenching ~ 4pV
- cD clusters ongoing star formation
- \( t_{\text{cool}} < 5 \times 10^8 \) yr
- \( \text{sfr} \sim \text{cooling rate} \)
- \( L_{\text{AGN}} \sim L_{\text{cool}} \)

McNamara & Nulsen 07 ARAA and McNamara + 07 arXiv:0708.0579 for reviews
AGN Feedback on Cluster Scales

re. J. Shaye’s review

New stuff...
Hydra A Cluster $z=0.05$

$E_{\text{jet}} > 10^{61}$ erg AGN outburst: swiss cheese morphology to hot atmosphere

380 kpc
6 arcmin

Wise + 07
Nulsen + 05
McN + 00

320 MHz + 8 GHz
MS0735 Cool, metal-enriched outflow

McN+11

500 ks Chandra image
VLA, HST

\[ P_{\text{jet}} \sim 3 \times 10^{46} \text{ erg s}^{-1} \]

\[ E_{\text{jet}} \sim 10^{62} \text{ erg} \]

\[ R_{\text{Fe}} \sim 300 \text{ kpc} \]
iron outflow limiting radius correlates with Jet power

\[ R_{Fe} \propto P_{jet}^{0.42} \]

Orientation of outflow correlates with radio and cavity orientation: jet driven outflows
Problem: How are AGN outbursts powered?

**Powering Mechanisms**

- Hot gas *Bondi Accretion* – ok for low power systems
  (Churazov + 02, Allen 06, Narayan & Fabian 11); won’t work in high power systems
  (McN+11, Rafferty +06)

- Cold *Gas Accretion* likely, short supply in some systems

- Black Hole Spin- potentially important
  (McN+11)

  ALMA will lead to great progress

Other issues:

Must understand heating, microphysics: conduction, transport processes

AGN Heating of hot atmospheres *significant* in distant clusters (Ma + 11)
Summary

Relatively weak radio AGN can be mechanically powerful

Powerful enough to suppress cooling hot halos

Strong evidence for a self-regulating feedback loop

Star formation, jets linked to central X-ray cooling time

Suppress star formation, disperse metals throughout LSS

Questions:

Why do powerful AGN live in gas-poor hosts?

What powers AGN: cold accretion, hot accretion, spin?

How does AGN feedback work and heat the gas?