The X-ray foundation for AGN Feedback

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Outline:

• cooling flows
• X-ray cavities, shock fronts: gauges of AGN power
• Implications: clusters, radio sources, SMBH growth & fueling, galaxy formation & cosmic feedback

Cooling Flows

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

observer’s Cooling flow problem: star formation $\sim 1\%\ \dot{M}$
**Key X-ray observations of cooling flows**

**Reduced Cooling**

XMM-Newton 1999 -

Peterson, Kaastra, Paerels + 03

Sanders + 08 & this conference

**AGN Interactions**

Chandra 1999 -

Mc+00, Fabian +00

Hydra A

...Results foreshadowed by ASCA & Rosat

**Implication:** Heating, feedback by SMBHs
Key Insights from XMM & Chandra

• weak FR I radio sources can be as powerful as Quasars
• AGN in the “radio mode” must heat gently over large volumes
• conditions conducive to operational feedback loop

These insights have lead to significant progress in understanding cooling flows and the role of AGN feedback in galaxy formation.
Galaxy-scale AGN Outbursts

$E \sim 10^{57-59}$ erg

Perseus

 ghost cavity

$1' = 20$ kpc

weak shock

Abell 2597

cool rims

Blanton + 01

Fabian + 05
Cluster-scale AGN outbursts “preheating” events

$E = 10^{61-62}$ erg

$\sim 1/4$ keV per baryon

Hydra A

MS0735.6+7421

$3' = 190$ kpc

$1' = 200$ kpc

$M=1.3$ shock

Nulsen + 05
Wise + 07

McN + 05
Gitti + 07

Optical, radio, X-ray
Hydra A  X-rays + 327 MHz + 8 GHz
Taking the measure of AGN (jet) power

Cavity Enthalpy

\[ H = \frac{\gamma p V}{(\gamma - 1)} \]

\[ H = 2.5 - 4 \, pV \]

McN +00, Churazov +02

Measure total energy, age independently

but \( H \) could be > 4\( pV \) (Binney + 07, Nusser +07 Li + 08)

Shocks

\[ P = \frac{\Delta p V}{t_{\text{shock}}} \]

\[ t_{\text{shock}} \sim \frac{r_{\text{shock}}}{c_s} \]
How Powerful are Extragalactic Radio Sources?
What are they made of?

Cygnus A (radio)

Burbidge 56, Scheuer 74, Blandford & Rees 74, Begelman, Blandford, Rees 84,
FR Is: low radiative efficiency, mechanically-dominated, powerful

\[ P_{\text{cav}} \propto L_{\text{rad}}^{1/2} \]

Nulsen, Jones + 08

see also Merloni & Heinz 07 for core power relation
Implications for Clusters

- Cluster "preheating" ~ 1 keV per baryon needed (Wu+ 00, Voit 04)
- Quenching of cooling flows
- Scaling relations eg. $L-T$ (Nusser & Silk 2007, Gitti + 07)
- S-Z relation (Pfrommer + 06, Colafrancesco 08)
- Stripping galaxies by large-scale sonic booms (Fujita 07)
- UHE particle & photon accelerators (Hinton + 07, Benford + 08)

Implications for Extragalactic Radio Sources

- Heavy jets: ratio of energy in protons to electrons, $k >> 1$
- Radio lobes out of equipartition
  - De Young 06 Dunn + 04, 05
  - Birzan + 04,08, Hinton + 08
- Magnetic (Poynting) jets? (Diehl + 08, Li + 08)
...potential implications for galaxy formation:

The broken hierarchy of galaxy formation
standard CDM fails …Bower + 06

SMBH-bulge mass relation

K-band luminosity function

fossil evidence for self-regulation or feedback

ongoing feedback in clusters: does it work?
Heating & Cooling Diagram

\[ \langle L_{ICM}(< r_{cool}) \rangle = 6.45 \times 10^{44} \text{ erg s}^{-1} \]

Rafferty + 06
Birzan + 04

\[ \Phi = \frac{P_{cav} \times f}{\langle L_{ICM}(< r_{cool}) \rangle} = 1.1 \]

\[ f = 0.7 \]
(Dunn & Fabian 06)

heating ~ cooling

upper limits

jet power

jet power

X-ray cooling luminosity
Star formation is prevalent in cooling flows
connection between feedback & galaxy formation

Fabian, Conselice & co
star formation threshold: $t_{\text{cool}} \sim 500$ Myr

suppressed by active feedback

- star formation rates nearing XMM cooling limits
- “observer’s cooling flow problem” nearing resolution

Rafferty + 06, O’Dea + 08
Significant SMBH growth at late time!

\[
\dot{M}_{BH} = \left( \frac{\varepsilon}{0.1} \right)^{-1} \left( \frac{P_{\text{cavity}}}{5.67 \times 10^{45} \text{ erg s}^{-1}} \right) M_\odot \text{yr}^{-1}
\]

\[
\langle \dot{M}_{BH} \rangle \approx 0.1 M_\odot \text{ yr}^{-1}
\]

(clusters)

sub-Eddington accretion

Does Bulge + SMBH growth follow Magorrian?
Feedback Sequence

Jet Power

X-ray cooling luminosity

McNamara & Nulsen 07 ARAA and McNamara + 07 arXiv:0708.0579 for reviews
Problem: How do jets heat?

- Thermalization of Enthalpy as cavity rises
  Begelman 01, Churazov+02, Bruggen & Kaiser 02, Reynolds, Heinz, Begelman 02

- Weak shocks, sound damping
  Fabian+03,05, McN+05, Forman+07, Ruszkowski, Bruggen, Begelman +04,05

- Cosmic rays (heavy jets)
  Sijacki, Pfrommer+08, Guo & Peng 08, Ruszkowski +08

- Hybrid models: AGN + Conduction
  Ruszkowski & Begelman 02 Voit & Donahue 05

gentle, distributed heating

see McNamara & Nulsen 07, ARAA

for a review
Problem: How are outbursts powered?

**Accretion Mechanisms**

- **Bondi** - low power systems (Churazov + 02, Allen 06); won’t work in high power systems.

- **Stars** - hard to regulate, hard to power - (Wang + 05, Syer + 99)

- **Gas** - very likely, short supply in some systems (Rafferty 06, Soker +07)

- **Hybrid** - good bet

**Spin & BH Mergers** - energetics ok, hard to regulate

**M87**: Note cold gas within $R_{Bondi}$

\[
\frac{\dot{M}_{Bondi}}{M_\odot \text{ yr}^{-1}} = 0.012 \times \left( \frac{n_e}{\text{cm}^{-3}} \right) \left( \frac{kT}{\text{keV}} \right)^{-3/2} \left( \frac{M_{BH}}{10^9 M_\odot} \right)^2
\]
Future of Feedback: enabling larger surveys

Goal: universal relationship between radio power and jet power

Radio probes feedback across the Universe

\[ P_{\text{jet}} \propto L_{\text{rad}}^\alpha \alpha \sim 0.35 - 0.75 \]

\[ \alpha \text{(frequency, radio age, etc.)} \]

Birzan + 08

Issues:
1) heating function for ellipticals not yet established
2) big scatter in cavity power-radio power: underestimates heating -- must model
3) heating function frequency dependent (Birzan + 08)
4) feedback is selective: knows about X-ray atmosphere (Dunn + 06)
Tighter scaling jet power and synchrotron power:

\[ \frac{P_{cav}}{L_{radio}} = (4.11 \pm 0.86)(\nu_c)^{-0.58 \pm 0.19} \]

Birzan + 08
Summary

Modern X-ray observations have lead to:

- Deeper understanding of cooling flows and AGN feedback
- Direct measurements of heating/cooling and SMBH growth
- Reliable measurements of mechanical efficiency (heating) and contents of extragalactic radio sources
- Motivated development of realistic jet & X-ray halo models
- Foundation for AGN feedback

“fundamental test” for jet heating and feedback models

Heinz, Bruggen, Reynolds, Croton, Springel, Li, and others…
Realistic Jet Models

Cygnus A

- Static jet/atmosphere models don’t heat
  Vernaleo, Reynolds 06

Realistic Jet models
In CDM context

Isotropic heating:
- a) jet precession
- b) weak shocks

“dentist drill”

Simulation
Heinz, Bruggen + 07

ripples
cold front

Kurosawa, Proga 07
Sternberg, Soker 08
Bondi accretion problem for clusters

Accretion Mechanisms

Bondi- low mass systems (Allen 06)
Stars - hard to regulate
Gas - very likely (Rafferty 06)

\[ \frac{\dot{M}_{\text{Bondi}}}{M_\odot \text{ yr}^{-1}} = 0.012 \times \left( \frac{n_c}{\text{cm}^{-3}} \right) \left( \frac{kT}{\text{keV}} \right)^{-3/2} \left( \frac{M_{\text{BH}}}{10^9 M_\odot} \right)^2 \]

M87’s gas disk
Galaxy Cluster at X-ray & Visual wavelengths

70%-80% dark matter, 20%-30% baryons, most baryons @~ 5 keV