Toward a Universal Scaling Relation between Jet Power and Radio Power

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Cooling Flow Clusters and Heating Mechanisms

- Density rises inwardly
- The cooling time: \( t_{\text{cool}} \propto n^{-1}T^{1/2} \)
- Cooling radius, \( r_{\text{cool}} \) where \( t_{\text{cool}} < t_H \)
  \( \rightarrow \) Cooling flow cluster
    (Fabian et al. 1994)
- Chandra and XMM-Newton did not find gas below \( \sim 2 \) keV.
  \( \rightarrow \) Heating mechanisms

- Heating by AGN:
  - Convective core (Binney & Tabor 1993)
  - Cosmic rays (Gou & Oh 2008)
  - X-ray bubbles
    (e.g., MS 0735+7421, McNamara et al. 2005)

X-ray data (McNamara et al. 2005); 327 MHz VLA radio data (Birzan et al. 2008)
What Do the Cavities Tell Us?

- The cavities demonstrate the **strong coupling** between the AGN radio lobes and the hot, cooling atmosphere
- Enthalpy gives **estimate of energy** required to create them
- Buoyancy arguments allow **estimate of age**
  ➔ Used together, we can estimate the AGN mechanical power

- From the X-ray data:
  - Measure $p, V$
    \[ E_{\text{cav}} = pV + \frac{1}{\gamma - 1} pV, \quad \gamma = \frac{4}{3} \]
  - **Ages:** $t_{\text{cav}} (t_{\text{buoy}}, t_{\text{refill}}, t_{\text{cs}})$
    \[ P_{\text{cav}} = \frac{E_{\text{cav}}}{t_{\text{cav}}} \]

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*X-ray: Rafferty et al. 2010 (in preparation); poster*

*Radio (325 MHz, GMRT): Gitti et al. 2010*
Balancing Cooling with Cavities in Cooling Flows

- Bîrzan et al. 2004; Dunn et al. 2004, 2005; Rafferty et al. 2006
- >50% of the systems with cavities can balance cooling, considering the enthalpy (Rafferty et al. 2006).
The Sample

24 systems from Chandra Data Archive which show X-ray cavities (Rafferty et al. 2006).

- Redshift range: $0.0035 < z < 0.545$
- All have radio sources associated with the central galaxy.
- Follow-up VLA observations in 2004–2007 at 300 MHz, 1400 MHz, 4500 MHz and 8500 MHz.
What Can We Learn?

• **Radio data alone tell us about:**
  
  – Cavity contents:
    • Relativistic electrons
    • Magnetic fields
  
  – Synchrotron ages

• **Radio and X-ray data together (Bîrzan et al. 2008):**
  
  – Radiative efficiencies
  
  – Scaling relations (see also Cavagnalo et al. 2010)
  
  – Cavity contents:
    • Distribution of energy between electrons and other particles (see also Dunn et al. 2004, 2005)
    • Magnetic field strengths
Raditive Efficiencies of AGNs in the Radio Mode

\[ P_{\text{cav}} = 4 p V / t_{\text{cav}} \]

\[ L_{\text{radio}} = L_{\text{bolometric}} \]

\[ P_{\text{cav}} \propto L_{\text{radio}}^{0.59}, \text{ for the entire sample} \]

\[ P_{\text{cav}} \propto L_{\text{radio}}^{0.69}, \text{ for the 5 radio-filled sources} \]


⇒ Ghost cavities generally have lower efficiencies.
Scaling Relation

• Accounting for aging gives tighter scaling relation:

\[
\log P_{\text{cav}} = 0.53 \log L_{\text{radio}} - 0.74 \log \nu_C + 2.12
\]

• Scatter = 0.3 dex

Bîrzan et al. 2008
Monochromatic Scaling Relations

- $P_{327}$: Scatter = 0.75 dex
  0.61 dex
- $P_{1400}$: Scatter = 0.83 dex
  0.78 dex

\[
\log P_{\text{cav}} = 0.51 \pm 0.07 \log P_{327} + 1.51 \pm 0.12 \\
\log P_{\text{cav}} = 0.64 \pm 0.09 \log P_{200-400} + 1.54 \pm 0.12 \\
\log P_{\text{cav}} = 0.35 \pm 0.07 \log P_{1.4} + 1.85 \pm 0.10 \\
\log P_{\text{cav}} = 0.75 \pm 0.14 \log P_{1.4} + 1.91 \pm 0.18
\]
Cavity Particle Content, $k (=E_{\text{part}}/E_e)$ and Aging

- $p_{\text{X-ray}} = p_{\text{part}} + p_B \rightarrow B_p(k)$,
  
  $B_{eq} = B_p \Rightarrow k_{eq}$

  where $p_{\text{part}} \propto (1 + k)B^{-3/2}$,

  $p_B \propto B^2, B_{eq} \propto (1 + k)^{2/7}$

- Is the wide range in $k$ due to aging?
  - $t_{\text{syn}} \propto \nu_{\text{break}}^{-1/2}$
  - Young sources tend to have smaller $k$.
  - But, range in age can not fully account for the range in $k$.

- Entrainment of heavy particles may play a role (Dunn & Fabian 2006, Croston et al. 2008).
Scaling Relation Applications

- **Best et al. 2006:** radio heating mode can balance cooling for a sample of 401 elliptical galaxies (O’Sullivan, Forbes & Ponman 2001).
- **Best et al. 2007:** radio heating mode does not balance cooling in the most massive systems; an additional source of heat, such as conduction, is invoked there (using a sample of 625 nearby BCGs selected from SDSS).
- **Magliocchetti & Bruggen 2007:** suggested a transition between radio-mode AGN heating and thermal conduction mode, using 145 selected clusters from REFLEX and NORAS surveys plus NVSS data.
- **Hart et al. 2009:** low power AGNs may be responsible for heating the ICM.
- **Sun 2009:** discussed the accretion mechanism for lower-mass haloes (using a sample of 145 BCGs selected from Chandra).
- **Smolcic et al 2009:** radio-luminous AGNs play an important role in galaxy formation (COSMOS field).
- **Giodini et al. 2010:** mechanical input by radio AGN can be enough to unbind a significant fraction of baryons from the potential well (using a sample of 16 groups from COSMOS field).
Future Work

• Extend observations to lower frequencies (with LOFAR, for example), particularly for older sources, to better constrain break frequencies and better understand how a radio source is aging.

• Use the scaling relations and current radio surveys to investigate AGN feedback across a wide range of environment.

• Use the scaling relations and future radio surveys to further investigate AGN feedback (to higher redshifts and lower frequencies).
Complete Samples; Subsamples of Cooling Flow Clusters

• **B55** (the brightest 55 clusters of galaxies): a 2-10 keV flux-limited sample based on ROSAT data (Edge et al. 1990).
  – *Dunn & Fabian 2006* (ROSAT estimates for cooling times); *Rossetti & Molendi 2010* (XMM-Newton data; pseudo-entropy ratio);

• **HIFLUGCS** (HIghest X-ray FLUx Galaxy Cluster Sample): a flux limited sample based on ROSAT and ASCA observations (Reiprich 2001).
  – *Sanderson et al. 2006, 2009* (temperature ratio); *Chen et al. 2007* (mass deposition rate ratio); *Hudson et al. 2009* (central cooling time).
B55 Subsample of Cooling Flow Clusters

- **Dunn et al. 2006**: 14/20 clusters that require heating ($t_{\text{cool}} < 3 \times 10^9$ yr using ROSAT estimates, and a large temperature drop, $T_{\text{outer}} / T_{\text{center}} > 2$) have clear bubbles.

- **Using Chandra data**: 34/55 are cooling flow systems ($t_{\text{cool}} < 3 \times 10^9$ yr; Dunn et al. 2006, Rafferty et al. 2008); 20 systems have X-ray cavities.
  - For the remaining 14 systems we performed simulations.
Heating vs. Cooling for B55 Sample

- For the B55 sample, 20 (~36%) have detected cavities
  - Lower than Dunn et al. 2010 finding for a sample of ellipticals (~50%; 9/18).
- Most systems could have bubbles with enough power to balance cooling and remain undetected
- One system (Ophiuchus) can not have such bubbles, unless they are at $\theta<30^\circ$
- Some (or all) could have no bubbles, and may be in a cooling stage having high star formation rates.
- Also, the actual exposure time may be too short, such that signal-to-noise ratio of bubbles is low.

The figure shows a scatter plot with the following labels:
- Black circles: Cool-cores with detected bubbles (20 systems)
- Red circles: Cool-cores without detected bubbles (14 systems)
Problems with CC/NCC separation

- The separation based on central cooling time → which cooling time value is physically right?
- The need for a complementary way of separation (such as the cluster thermal stability; Sanderson et al. 2009).
- Try to understand the influence of AGN heating, conduction, turbulence and mergers on cluster formation and evolution (O’Hara et al. 2006; McCarthy et al. 2008; Poole et al. 2006; Burns et al. 2006; Guo & Mathews 2010; Ruszkowski & Oh 2010; Parrish et al. 2010).
Summary

- The radiative efficiency of radio sources in cavity systems is around 1%, but can be much lower.
- By accounting for differences in age (break frequency), scatter in \( L_{\text{radio}} - P_{\text{cav}} \) scaling relation is reduced by \( \approx 50\% \).
  - The scaling relations are useful for studying feedback across a wide range of environment and redshift
- \( k (=E_{\text{part}}/E_{\text{e}}) \) ranges between a few and a few thousand (for equipartition assumptions).
  - Again, aging and entrainment may contribute to large range in \( k \).
- For the B55 sample, 20 systems (~36%) have detected cavities.
  - Of the other 14 cooling flow systems, most could have significant cavity power yet remain undetected in existing images (under simple assumptions).
- The results from the complete sample need to be further investigated in radio (Burns et al 1990, Mittal et al. 2009): ~70% of systems have a central radio source, (~100% for cooling flow systems; ~45% for non-cooling flow).