AGN Feedback in Nearby Clusters

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With much help from Jeremy Sanders, Gary Ferland and many others
AGN Feedback in Nearby Clusters

Feedback in the central galaxies of the Perseus and Centaurus
X-ray surface brightness of typical clusters of galaxies
Duty cycle is $\sim$100\%  

See also Birzan+04, Rafferty+06+08, Dunn+F07
Issues

• Total Energy not an issue.
• How does energy get distributed?
• How close is the heating/cooling balance? Feedback too good?
• Observations suggest better than 10% for many Gyr in some objects.
• HOW DOES THE AGN DO THIS?
• Moreover, (how) is coolest X-ray gas (ie $T<5 \times 10^6 K$ with radiative cooling time $\sim 10^7$yr) prevented from cooling?
Optical  Fabian+08
Perseus
~3.5PV measured in thick rims (Graham+08)
Power in ripples (sound waves) ~ X-ray luminosity within 70 kpc

Also seen in Centaurus, Virgo...
Buoyant radio lobes in a viscous intracluster medium

Christopher S. Reynolds, Barry McKernan, Andrew C. Fabian, James M. Stone and John C. Vernaleo
NGC1275 with HST   Fabian+08
X-ray image of M87 / Virgo
Forman+07
Centaurus
Fabian+05
Cen cluster: Abundance profile implies little diffusion/mixing

Graham+06 (following method of Rebusco+05)
Cool X-ray gas in Centaurus

200 ks Chandra observation

Shows feedback (cavities) and cool gas (~0.7 keV) in CCD spectra

How much gas is there at low X-ray temperatures?
Faraday RM and T map

Taylor+07 B~25uG in 5e6K gas 10% thermal pressure
Inner 60 arcsec width (16 kpc)

Flux (10^{-3} photon cm^{-2} s^{-1} Å^{-1})

Wavelength (Å)

FeXIX, FeXVIII, FeXVII, O VIII, Fe XVII, Fe XVII, Fe XVIII, Fe XVII, O VIII, Fe XVII, Fe XVII, O VIII, Fe XVIII, N VII

strong

missing
Abell 1835

$v_{\text{turb}} < 274 \text{ km/s}$

Sanders+09
Spectral fitting limits on gas kT

$\dot{t}_{\text{cool}} \sim 10^7 \text{ yr}$!
1.2Ms stack of XMM RGS spectra
Sanders+Fabian+10
1.2Ms stack of XMM RGS spectra
Sanders+Fabian+10
Coronal line emission [FeX] from $10^6$K gas in Centaurus

Canning + 10

VLT 10.5hr
Canning+11

Vel

FWHM
Perseus SFR~20 Msunpyr  Canning+10
Figure 12. Optical structure of the BCG of MACS J1931.8-2634. (a): SuprimeCam BRz image of the central 30 arcsec × 30 arcsec. (b): For this image, the SFR~170 Msunpyr.
Herschel observations of FIR emission lines in brightest cluster galaxies *


$L$(CII)$\sim5\times10^{42}$ erg/s $\sim6 \times L$(Ha)
## Dust

### Herschel points

<table>
<thead>
<tr>
<th>Cluster</th>
<th>A1068</th>
<th>A2597</th>
<th>Zw3146</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dust Temperatures</strong></td>
<td>24±4K 57+12 K</td>
<td>21±6K 48+17 K</td>
<td>23±5K 53+22 K</td>
</tr>
<tr>
<td><strong>Cold Dust Mass</strong></td>
<td>5.1×10^8 M_⊙</td>
<td>2.3×10^7 M_⊙</td>
<td>5.4×10^8 M_⊙</td>
</tr>
<tr>
<td><strong>Warm Dust Mass</strong></td>
<td>3.9×10^6 M_⊙</td>
<td>2.9×10^5 M_⊙</td>
<td>1.9×10^6 M_⊙</td>
</tr>
<tr>
<td><strong>Total FIR Luminosity</strong></td>
<td>3.5×10^{11} L_⊙</td>
<td>8.8×10^{9} L_⊙</td>
<td>2.5×10^{11} L_⊙</td>
</tr>
<tr>
<td><strong>Star Formation Rate</strong></td>
<td>60±20 M_⊙ yr^{-1}</td>
<td>2±1 M_⊙ yr^{-1}</td>
<td>44±14 M_⊙ yr^{-1}</td>
</tr>
<tr>
<td><strong>SFR Spitzer</strong></td>
<td>188 M_⊙ yr^{-1}</td>
<td>4 M_⊙ yr^{-1}</td>
<td>70±14 M_⊙ yr^{-1}</td>
</tr>
<tr>
<td><strong>SFR optical/UV</strong></td>
<td>20–70 M_⊙ yr^{-1}</td>
<td>10–15 M_⊙ yr^{-1}</td>
<td>47±5 M_⊙ yr^{-1}</td>
</tr>
<tr>
<td><strong>CO gas mass</strong></td>
<td>4.1×10^{10} M_⊙</td>
<td>2.0×10^{9} M_⊙</td>
<td>7.7×10^{10} M_⊙</td>
</tr>
<tr>
<td><strong>Hα Slit Luminosity</strong></td>
<td>8×10^{41} erg s^{-1}</td>
<td>3×10^{41} erg s^{-1}</td>
<td>3×10^{42} erg s^{-1}</td>
</tr>
</tbody>
</table>

### Edge+10
Spectrum of these filaments is unlike anything in Galaxy, other than Crab and due to energetic particles (the hot gas?) Ferland+08/9
10.8hr WHT spectra of Perseus
Nina Hatch

Horseshoe
Almost $10^{11}$ Msun of cold gas in Perseus
P. Salomé et al.: A very extended molecular web around NGC 1275

Distance [kpc]

Position [kpc]

Velocity [km/s]

FWHM = 130

r1

FWHM = 118

r2

FWHM = 140

r3

FWHM = 117

r4
What heats and ionises the cold gas?

Energetic particles

(not photons)
- Energetic particles produce Ionized gas
  - Heating
- Neutral gas
  - Shower of suprathermal electrons
  - Secondary excitation and ionization
  - less heating

Ferland+08/09
Observed / predicted spectrum

H I, [N I], He I, [O I], [N II], [S II], H$_2$, H$_2$, [Ne II]

Ferland+09
Properties of filaments

• Densities $\sim 10^3 \text{ cm}^{-3}$ or more
• Pressure $nT \sim 10^{6.5} \text{ cm}^{-3} \text{ K}$
• Magnetic Fields $B \sim 70 \text{ uG}$
• Diameter $\sim 70 \text{ pc}$, length many kpc
• Mass usually dominated by molecular gas
• Reconnection diffusion allows

• Hot ICM particles penetrate cold gas, providing secondary ionization

• Rate about right
  
  (obs flux~0.01 erg cm\(^{-2}\) s\(^{-1}\)~20\% sat. cond. flux)

• Filament mass growing at
  
  10-100 M\(\odot\) yr\(^{-1}\)
Figure 1. Chandra image of the Northern filament from which the spectrum is measured (right). The long box is 4.1 x 24.3 arcsec (1.5 x 9 kpc). The base of it is about 24.4 kpc from the nucleus of NGC 1275.
In other words

- Innermost hot gas cools radiatively through X-ray emission to \( \sim 10^7 \) K, then plunges to \(< 10^4 \) K by mixing with cold filaments

(cf Fabian+01,02, Soker04)
Summary

• Kinetic mode feedback operates in most massive galaxies, those with hot atmospheres, maintaining stellar mass. Parts of feedback loop observed (bubbles, sound waves, warm, cool and cold gas)

• Inner parts of hot atmosphere cooling radiatively and by mixing into cold gas
Allen+06  Implies Jet Power is 2% Bondi rate
Bondi flow from a rotating hot atmosphere
(Feeding the central black hole with a giant ADAF)
Narayan & Fabian 2011

\[ \mathcal{L} \equiv \frac{\ell_{\text{out}}}{\ell_{\text{ms}}} = \frac{\Omega_{\text{out}} r_B^2}{\ell_{\text{ms}}} = 0.136 \Omega_{\text{out}} \left( \frac{c}{c_{\text{out}}} \right)^4 \]
RXCJ1504  Ogrean+10  z=0.2

SFR\sim140 \, M_{\sunpyr}
Photograph of a spherical cap bubble rising in water (from Davenport, Bradshaw, and Richardson 1967).

Figure 5.13 Flow visualizations of spherical-cap bubbles. On the left is a bubble with a laminar wake at Re≈180 (from Wegener and Parlange 1973) and, on the right, a bubble with a turbulent wake at Re≈17000 (from Wegener, Sundell and Parlange 1971, reproduced with permission of the authors).
Bubbling long lived
Ripples in Centaurus Cluster
Sanders+Fabian 08

![Graph showing relative surface brightness vs. radius in kpc and fractional difference vs. radius in arcmin.]

South west
Sanders, Fabian, Smith 10 in prep
The Physics of Cool Cluster Cores

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Thermal content of bubbles?

For volume filling factor $>50\% \quad kT>50$ keV
Stability of bubbles

The stability of a large gas bubble rising through liquid†

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The stability of buoyant bubbles in the atmospheres of galaxy clusters

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Dynamics, viscosity and magnetic draping help to stabilise bubbles and make them long-lived
The weak shock