Lecture 3: Detailed Diagnostics of Cool Core Clusters

1. Observational Evidence Against Classical Cooling Flows
2. Shock Wave Heating of the ICM
3. Metallicity as Diagnostics
„Cooling Flows“
Scheme of an inhomogeneous Cooling Flow

Multiphase cooling flow model:

\[ \tilde{M}(r) = \frac{d\tilde{M}}{dr} \]

[Thomas, Fabian, Nulsen (1987) MN 228, 873]

Typical cooling flow structure:

\[ \tilde{M}(T) \to f(T) \, dt \to f(n) \, dn \]

pressure equilibrium

\[ \Rightarrow \text{density distribution } f(n) \, dn \text{ (at } r_{cool}) \]
XMM Observations of the „Cooling Flow Region“ of M87

Böhringer et al. 2001
Spectral Model for Cooling Flows

- Spectrum of one temperature phase:

\[ L_v(T) dT d\nu = \frac{\text{emissivity}(\nu) d\nu}{\text{emissivity}(bol)} \frac{dT}{dt} \left( \text{enthalpy}(T) \right) dT \]

\[ L_v(T) dT d\nu = \frac{\Lambda_v(T) d\nu}{\Lambda_{bol}(T)} \frac{5k_B}{2\mu m_p} \dot{M} dT \]

- Full cooling flow spectrum:

\[ L_v d\nu = \frac{5k_B}{2\mu m_p} \dot{M} \int_{T_{cutoff}}^{T_{hot}} \frac{\Lambda_v(T') d\nu}{\Lambda_{bol}(T')} dT' \]
The Fe-L-Shell-Line Complex as a Thermometer

$T_X = 0.4 \text{ keV}$

Temperature
The Fe-L-Shell-Line Complex as a Thermometer

\[ T_X = 0.6 \text{ keV} \]
The Fe-L-Shell-Line Complex as a Thermometer

$T_X = 0.8 \text{ keV}$
The Fe-L-Shell-Line Complex as a Thermometer

\[ T_X = 1.0 \text{ keV} \]
The Fe-L-Shell-Line Complex as a Thermometer

\[ T_X = 1.2 \text{ keV} \]
The Fe-L-Shell-Line Complex as a Thermometer

\[ T_X = 1.4 \text{ keV} \]
The Fe-L-Shell-Line Complex as a Thermometer

\[ T_X = 1.6 \text{ keV} \]
The Fe-L-Shell-Line Complex as a Thermometer

\[ T_X = 1.8 \text{ keV} \]
The Fe-L-Shell-Line Complex as a Thermometer

$T_X = 2.0 \text{ keV}$
The Fe-L-Shell-Line Complex as a Thermometer

\[ T_X = 2.4 \text{ keV} \]
The Fe-L-Shell-Line Complex as a Thermometer

\[ T_x = 2.8 \text{ keV} \]
The Fe-L-Shell-Line Complex as a Thermometer

The iron l-shell line blend as a function of temperature
A detailed Spectral Investigation of the „Cooling Flow“ Region in M87

\[ N_H = 1.8 \times 10^{20}\text{cm}^{-2} \text{ (fix)} \]
\[ T_{\text{high}} = 2.0 \text{ keV (fix)} \]
\[ T_{\text{low}} = 1.44 \text{ keV (free)} \]
\[ \dot{M} = < 2.4 \text{ M}_{\odot}/\text{yr} \]

[Böhringer et al. 2001, 2002; Matsushita 2002 a]

almost isothermal plasma

Classical „cooling flow“

\[ N_H = 1.8 \times 10^{20}\text{cm}^{-2} \text{ (fix)} \]
\[ T_{\text{high}} = 2.0 \text{ keV (fix)} \]
\[ T_{\text{low}} = 0.01 \text{ keV (fix)} \]
\[ \dot{M} = \sim 10 \text{ M}_{\odot}/\text{yr} \]
Reflection Grating Spectrometer (RGS)
Spectrum of Abell 1835
ICM Heating
Requirements for a Heating Model for CCCs

1. Enough energy input $10^{60}$-$10^{61}$ erg (in $10^{10}$ yr)
2. Self-regulated energy input (not too much – but enough!)
3. Global heating (non-localized energy transfer to thermal plasma - to avoid thermal instabilities)
4. Heating process has to reproduce the observed entropy structure with decreasing entropy towards the center (convection is inconsistent with observed entropy structure)
5. Heating process has to preserve observed metallicity gradients
6. Cosmic ray pressure should not exceed thermal pressure
Suggested Heating Models

1. **Heating from a central AGN** (e.g. Rosner & Tucker 1989, Böhringer & Morfill 1989, Binney & Tabor 1995, David & Tucker 1997, Churazov et al. 2001)

2. **Heat conduction from the outer region** (e.g. Tucker & Rosner 1983, Bertschinger & Meiksin 1986, Geatz 1989)

3. **Magnetic reconnection** (e.g. Soker & Sarazin 1990, Norman & Meiksin 1996, see also Makishima et al. 2001)
X-ray Holes Associated with Radio Lobes in the Center of the Hydra-A and Perseus Clusters

Hydra A Cluster

NGC 1275 in the Perseus Cluster

Fabian et al. 2001

Rising Bubble in the „Horseshoe“

Fabian et al.
2003
Age of the Structures in the Radiohalo of M87

Energy input into the Radio halo around M87 on three different time scales with $\sim 10^{44}$ erg/s

- Few $10^6$ yr in the jets (Bicknell & Begelman 1996)
- Few $10^7$ yr in the inner radio lobes (Churazov et al. 2001)
- Few $10^8$ yr in the outer radio lobes (Owen et al. 2000)

Extent $r \sim 40$ kpc, total energy $\sim 3 \times 10^{59}$ erg
Interaction of the Radio Lobes with the ICM

- Radio bubbles loose > 60% of the internal relativistic energy by adiabatic expansion (~25% during inflation, 45% during rise)
- Further energy loss by uplifting ambient material
- Smaller fraction of the energy is lost by direct interaction: ionization, reconnection etc.

[Scenario by Churazov et al. 2001]
Estimation of the Kinetic Power of the Radio Jets

Subsonic expansion and rise of bubbles of relativistic plasma from the radio jets

\[ L_{\text{rel}} = 10^{45} \text{ erg/s} \ (r/13 \text{ kpc})^2 \ (P_0/2 \times 10^{-10} \text{ erg cm}^{-3}) \ (v_K/700 \text{ km/s}) \]

[ Churasov et al. 2000 ]
Estimated Power Input from Radio Jets

NGC 1275 – Perseus: \( r_b = 15 \text{ kpc}, \ P_0 = 2 \times 10^{-10} \text{ erg cm}^{-3}, v_K = 600 \text{ km s}^{-1} \)

\[ L_{\text{rel}} \sim 10^{45} \text{ erg s}^{-1} \ (\tau \sim 3 \times 10^7 \text{ yr}) \]

M87 – Virgo: \( r_b = 8 \text{ kpc}, \ P_0 = 10^{-10} \text{ erg cm}^{-3}, v_K = 460 \text{ km s}^{-1} \)

\[ L_{\text{rel}} \sim 1.2 \times 10^{44} \text{ erg s}^{-1} \ (\tau \sim 3 \times 10^7 \text{ yr}) \]

3C218 – Hydra A: \( r_b = 40 \text{ kpc}, \ P_0 = 5.5 \times 10^{-11} \text{ erg cm}^{-3}, v_K = 550 \text{ km s}^{-1} \)

\[ L_{\text{rel}} \sim 2 \times 10^{45} \text{ erg s}^{-1} \ (\tau \sim 10^8 \text{ yr}) \]

There is plenty of mechanical jet energy to heat the cooling flows!
Powering the AGN by Bondi Accretion

Bondi accretion occurs inside the radius where gravitational influence of the black hole dominates over the thermal velocity

\[ v_{\text{escape}} > v_{\text{thermal}} \]

For the parameters in the case of M87:

\[ M_{\text{BH}} \sim 3 \times 10^9 M_{\odot}, \quad T \sim 1 \text{keV}, \quad n_e \sim 0.1 \text{ cm}^{-3} \]

we find:

\[ \frac{dM}{dt} = 0.01 M_{\odot}/\text{yr}, \quad r_{\text{Bondi}} \sim 50 \text{pc} (0.6\arcsec), \]

\[ P = 7 \times 10^{43} \text{ erg/s} \]
Conclusions

• Observational evidence points towards much lower mass deposition rates in CCCs than previously derived in standard cooling flow models

• Mass deposition seems to be observed on small scales in the very center – no large scale flow required !!

• Bondi accretion from the CCC-plasma provides a very natural self-regulated feeding model of the AGN

• The subsonically expending and rising radio bubbles – or shock wave heating - provide a suitable heating model for the CCC

• Most of the requirements can be met - the open question concerns the exact model of energy dissipation
Evidence for additional heating by shock waves
M87 X-ray Halo Morphology

[ Forman et al. 2005 ]

14 kpc ring: shock from outburst $1.1 \times 10^7$ yr ago with energy $\sim 8 \times 10^{57}$ erg, $M \sim 1.2$ shock; time average $2.4 \times 10^{43}$ erg/s (cooling $r<70$ kpc $\sim 10^{43}$ erg/s)
Blue: radio
Red: X-rays

Jet

Forman et al. 2005
Chandra Details of M87 X-ray Morphology

[ Forman et al. 2007 ]

Chandra image (0.5 – 1 keV) shows surprising amount of fine structure, filamentary structure, in the central region.
Details of Central M87 Morphology
X-ray, Radio, Optical

[ Forman et al. 2007 ]

- Counter Jet Rim
- Jet Cavity
- "Bud"
- Counter Jet Cavity

6 cm VLA image

0.5-2.5 keV Chandra image

SPITZER IRAC 4.5 μm Image divided by a β-model
Entropy and Pressure Diagnostics of the M87 X-ray Halo

Entropy excess over azimuthally symmetric model

High pressure ring of 14 kps shock

Low pressure region in the arms

[Simionescu et al. 2007a]

low entropy

high entropy
High entropy region is bounded by the outer radio lobes – signature of entropy production in the lobes.

[Simionescu et al. 2007a]
The Shock Wave in Hydra A

Simionescu et al. 2008 in prep.

Hans Böhringer

Varenna Summer School 15.-25. July 2008 - Lecture 1 38
Modeling the Shock Wave in Hydra A

<table>
<thead>
<tr>
<th>Sector</th>
<th>radius (arcsec)</th>
<th>Mach number</th>
<th>Shock energy (10^{61} ergs)</th>
<th>Shock age (Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>360</td>
<td>2.9</td>
<td>1.30 ± 0.05</td>
<td>6.0 ± 1.4</td>
</tr>
<tr>
<td>E</td>
<td>288</td>
<td>2.8</td>
<td>1.30 ± 0.05</td>
<td>3.8 ± 1.0</td>
</tr>
<tr>
<td>S</td>
<td>248</td>
<td>2.6</td>
<td>1.27 ± 0.05</td>
<td>3.1 ± 1.0</td>
</tr>
<tr>
<td>W</td>
<td>228</td>
<td>2.6</td>
<td>1.30 ± 0.05</td>
<td>3.2 ± 0.9</td>
</tr>
</tbody>
</table>

Surface brightness of Hydra A and best fit shock model for N and E sector.

Simionescu et al. 2008 in prep.
Simulations of the Shock wave in Hydra A
Simulations of the Shock wave in Hydra A

ICM flows deform the shock wave in a similar way as seen in Hydra A

Simulations by Elke Roediger and Marcus Brüggen - Simionescu et al. 2008 in prep.
Diagnostics of Cool Cores
Using the Metallicity Distribution
O & Si Abundance Profiles in M87

The O profile is almost flat (consistent with a flat profile within +/- 10%)

The O/Si ratio increases from about 0.4 to 0.7 (from r = 2 – 50 kpc)

- (using MEKAL models)

Matsushita, Finoguenov, Böhringer 2003
Fe and S also show strong abundance gradients
– Fe is approximately proportional to Si

Matsushita, Finoguenov, Böhringer 2003
• at $r = 10$ kpc : $M_{Fe} \sim 10^6 - 2 \times 10^7 M_{\odot}$ (large dispersion - differences in enrichment time $\sim 0.5 - 5$ Gyr)

• at $r = 50$ kpc : $M_{Fe} \sim 1 - 2 \times 10^8 M_{\odot}$ (~ half of Fe from cD – only possible if strong increase in SN Ia rate with $z$ - and no losses due to condensation !)
Iron Mass Loss in Cooling Flows

\[ \dot{M}_{Fe} = \dot{M} \cdot z \frac{[Fe]}{[H]} \frac{m(Fe)}{m(H)} \]

<table>
<thead>
<tr>
<th></th>
<th>&lt; 10 kpc</th>
<th>&lt; 50 kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>M87</td>
<td>$8 \times 10^6$ M\text{sun}/Gyr</td>
<td>$1.4 \times 10^7$ M\text{sun}/Gyr</td>
</tr>
<tr>
<td>Perseus</td>
<td>$1.3 \times 10^7$ M\text{sun}/Gyr</td>
<td>$1.6 \times 10^8$ M\text{sun}/Gyr</td>
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<tr>
<td>Centaurus</td>
<td>$4.8 \times 10^7$ M\text{sun}/Gyr</td>
<td>$8.0 \times 10^7$ M\text{sun}/Gyr</td>
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<tr>
<td>A1795</td>
<td>$2.2 \times 10^7$ M\text{sun}/Gyr</td>
<td>$1.5 \times 10^8$ M\text{sun}/Gyr</td>
</tr>
</tbody>
</table>

Losses are much larger than the enrichment rates !!
Enrichment Times for the central Fe Excess

Enrichment time needed to produce Fe excess with constant SN Ia rate (as estimated for E galaxies)

Böhringer et al. 2004

\[
\begin{align*}
R_{SN} \propto t^{-2} \\
R_{SN} \propto t^{-1.1}
\end{align*}
\]
The Lobes regions have to be modeled with a multi-temperature plasma model. The low temperature distribution is only shown for regions where we have 3σ significance for multi-temperature.

[Simionescu et al. 2007b]
Cold Gas Mass Fraction in the M87 Halo

2-temperature modeling

\[ \text{Simionescu et al. 2007b} \]

The regions with a large, significant low T fraction follow very closely the radio lobes! \(\rightarrow\) low T gas probably uplifted by the radio bubbles.

[Simionescu et al. 2007b]
Abundance variations (between hot and cool phase) cannot simultaneously be constraint in 2-T modelling – we couple the abundance of both phases. The plot shows the apparent abundance variations with fraction of cool phase \( \Rightarrow \) subsequently modeled as abundance difference \( \Rightarrow \) [Fe] about 2.2 solar (~0.8 in the ambient medium), O about 0.9 solar in the cold phase.
Fe Mass Map of M87 Halo

Lower abundance in high entropy region

Higher abundance in low entropy region

[Simionescu et al. 2007b]
Total mass of cool (T<1.5keV) gas: $\sim 0.5 \times 10^9\, M_{\odot}$

Required uplift energy:
$\sim 4 \times 10^{57}\, \text{erg} \ (0.5 \text{ of explosion energy})$

Source of cold gas from stellar mass loss ($\sim 2.5\, M_{\odot}/\text{yr}$) requires 200 Myr replenishing time.

Metallicity roughly consistent with stellar mass loss, but not with cold gas having cooled from the cooling flow.

We would require no major outburst before the last one for 200 Myr, but then a more dramatic one before to get enough time averaged heating?
Conclusions

The modern X-ray observatories XMM-Newton and CHANDRA are providing a wealth of detailed diagnostics of the physics in cooling cores, that we are just starting to exploit in a few deep observations.

One obtains the impression that the feedback of energy of the AGN into the ICM is not one simple feedback model for all clusters, but there may be large diversities. We still have to compile more data to arrive at a general picture.

The next generation of X-ray observatories NEXT, XEUS, etc. equipped with high spectral resolution calorimeters will provide further important diagnostics by allowing a more unique determination of the multi-temperature structure of the ICM and by providing velocity diagnostics through line broadening. The latter will e.g. allow us to study the degree of turbulence associated to cool core regions.