Heating, Cooling and Polluting the Gas in Clusters of Galaxies

C. Jones, W. Forman, E. Churazov, A. Vikhlinin, M. Markevitch

Temperature structure and distribution of heavy elements in the ICM

OUTLINE
Basic cluster properties - baryons in clusters

How is the gas heated?
  Cluster mergers -- cold fronts and shocks

How is the cooling gas in cluster cores reheated?
  Outbursts from supermassive black holes

Is there non-thermal pressure support for the gas?
Is the gas turbulent?
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Family of increasing mass, temperature, and luminosity

- **E/S0 Galaxies**
  - $L_x$ (ergs/sec): $10^{40-42}$
  - Gas Temp: 0.5-1.0 keV
  - $M_{\text{gas}}/M_{\text{stellar}}$: 0.02

- **Groups**
  - $L_x$ (ergs/sec): $10^{42-43}$
  - Gas Temp: 1-2 keV
  - $M_{\text{gas}}/M_{\text{stellar}}$: 1

- **Clusters**
  - $L_x$ (ergs/sec): $10^{43-46}$
  - Gas Temp: 2-15 keV
  - $M_{\text{gas}}/M_{\text{stellar}}$: 5

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**Early type Galaxy**

**Group**

**Cluster**
Census of Baryons in clusters and groups

Clusters form from such large volumes that their baryonic mass to dark matter should be representative of the Universe.

Gonzalez et al include intracluster light as well as galaxies. Fraction of stars in ICL grows with decreasing cluster mass.

In massive clusters, most of the baryons are in the hot gas.

In poor clusters/groups, near equal amounts of baryons in stars and gas.

Decrease in star formation efficiency in more massive environments - hot cluster gas does not cool to form stars.

Baryon fraction is constant and near WMAP value - no significant, undetected baryonic component

From Gonzalez et al. 2007
arXiv 0705:1726
X-ray emission from clusters

The hotter the cluster gas, the more X-ray luminous is the cluster.

Good correlation between gas temperature and cluster velocity dispersion (mass).

From Markevitch et al. 1998
Clusters grow hierachically through mergers

“relaxed” systems may be elliptical, but do not have significant structure in their X-ray surface brightness or temperature maps.

A399 & A401

A754

A2029
Clusters grow through gravitational infall and mergers of smaller subclusters

\textbf{A3667} -- \textit{mach} = 1 merger - example of cold front

Cold fronts are sharp in terms of both their temperature and density jumps.

Measure pressure jump across edge to determine Mach number of cloud.

For A3667, Mach number is 1.0 (0.2) which is 1400 (300) \text{ km/s}

\textit{Vikhlinin, Markevitch \& Murray 2001a,b} \linebreak \textit{Markevitch \& Vikhlinin} review \textit{arXiv 0701821}
Cluster gas is heated through mergers

Mathis et al. 2005

Almost core passage

Dark matter

14 Mpc

Compressed shock heated gas

GasTemperature

6 Mpc

Cold fronts
The bullet cluster
The temperature profile through the nose of the shock shows a strong shock and a cold front.

X-RAY TEMPERATURE PROFILE FROM CHANDRA OBSERVATIONS

Markevitch et al. (2006)
Fitting the density jump in the X-ray surface brightness profile allows a measurement of the shock's Mach number

*Markevitch et al. (2006)*

**Shock strength:**

\( M = 3.0 \pm 0.4 \)

**Shock velocity:**

\( v_s = 4700 \text{ km/s} \)

![Graph showing X-ray surface brightness profile with line indicating \( \rho_1/\rho_0 = 3.0 \) and data points at 30 keV and 9 keV.]
New weak lensing mass reconstructions have confirmed an offset between mass peaks and X-ray emission.
1E 0657-56: NASA Finds Direct Proof of Dark Matter
Volker Springel’s simple toy merger model of two NFW halos on a zero-energy collision orbit

PARAMETERS OF THE BASIC TOY MODEL

Mass model from Clowe et al. (2006):

\[ M_{200} = 1.5 \times 10^{14} \, M_\odot \]

\[ R_{200} = 1.1 \, \text{Mpc} \]

\[ c = 7.2 \]

\[ V_{200} = 780 \, \text{km/sec} \]

\[ M_{200} = 1.5 \times 10^{15} \, M_\odot \]

\[ R_{200} = 2.3 \, \text{Mpc} \]

\[ c = 2.0 \]

\[ V_{200} = 1680 \, \text{km/sec} \]
VIDEO OF THE TIME EVOLUTION OF A SIMPLE BULLET CLUSTER MODEL - Volker Springel
Drawing the observed X-ray map and the simulation images with the same color-scale simplifies the comparison

SPRINGEL SIMULATED X-RAY MAP COMPARED TO OBSERVATION
Relaxed Clusters

Temperatures and abundances -- radial profiles
Cluster radial temperature profiles for “relaxed” systems

Chandra

Vikhlinin et al.

XMM-Newton

Pratt et al.
Cool cluster cores

- Cool X-ray gas and short cooling times were found in cluster cores
- **Estimated mass deposition rates were large (100 -1000 M/yr)**
- But large amounts of cool gas were not detected in HI, IR-optical-UV
- True test for cool gas came from X-ray spectroscopy showed little cool gas (Peterson et al. 2001)
Cool cluster cores

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Gas Heating Mechanisms

- Cluster-subcluster mergers – plenty of energy ($10^{64}$ ergs), but not dependable (plus cooling flow clusters appear relaxed)
- “Sloshing” of gas in the core (Markevitch et al 2001)
- Thermal Conduction – from hot outer cluster gas to cool centers; see Tucker & Rosner 1983, Bertschinger & Meiksin 1986, Gaetz 1989, Narayan and collaborators, probably not effective at center
  - Bubbles
  - Shocks

- Chandra image shows evidence for repeated outbursts
- Processed image (unsharp masking) shows faint ripples
- Sound waves (weak shocks)? Driven by expansion of radio bubbles
  - Sound speed = 1170 km/sec, separation = 11 kpc, t = 9.6 x 10^6 yr
  - Dissipate energy (high ion viscosity) over a distance < 100 kpc
- Energy of bubbles/shocks balances cooling
M87 with Chandra

- ACIS observations
  - 100 ksec in 2002
  - 500 ksec in 2005
- Bright central region
- X-ray-Radio arms
- Shocks

- Forman et al. 2005, 2007

1′=4.5 kpc
Eastern Arm - classical buoyant bubbles
Sequence of small buoyant bubbles
• $PV \sim 10^{54} - 10^{55}$ ergs
• $\tau_{\text{rise}} \sim 10^7$ year

Southwestern arm - overpressured and “fine”
(∼300pc, like bubble rims)
Central Region of M87 - the driving force

- Nucleus, jet (knots)
- Cavities surrounding the jet and the (unseen) counterjet
- Bubble breaking from counter jet cavity
  - Perpendicular to jet axis;
  - Radius \(~1\) kpc.
  - Formation time \(~4 \times 10^6\) years
- **Piston driving shock**
  - X-ray rim is low entropy (cool) gas uplifted/displaced by relativistic plasma

SMBH \(3 \times 10^9 M_{\text{sun}}\)

6cm VLA
Density and Pressure Maps

Central Piston

Shock

Filamentary arms

Measure temperature & pressure jumps across shock to determine shock speed
Shock Model - the M87 surface brightness profiles

Hard (3.5-7.5 keV) pressure (red)
Soft (1.2-2.5 keV) density profiles

Projected

Deprojected
Deprojected M87 Gas Temperature

Mach 1.2 shock - transfers energy to cooling gas
M87 “arms”

- Eastern arm - classical buoyant bubble; bubbles lose 50% of energy by adiabatic expansion (Churazov et al 2001)
- XMM-Newton shows both arms are cool: uplifting cool gas from the core (Belsole et al 2001; Molendi 2002)
Cavities filled by radio plasma $\sim 200$ kpc diameter PV work to create each $10^{61}$ ergs

Energy driving shock $6 \times 10^{61}$ ergs (requires BH accretion $3 \times 10^8 m_{\text{sun}}$)

Age of shock $1 \times 10^8$ years

Average power $1.7 \times 10^{46}$ ergs/sec (weak radio, X-ray, opt nucleus)
Outbursts from Clusters to Galaxies

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>SHOCK RADIUS (kpc)</th>
<th>ENERGY ((10^{61} \text{ erg}))</th>
<th>AGE (My)</th>
<th>MEAN POWER ((10^{46} \text{ erg/s}))</th>
<th>(\Delta M) ((10^8 M_{\odot}))</th>
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</thead>
<tbody>
<tr>
<td>MS0735.6</td>
<td>230</td>
<td>5.7</td>
<td>104</td>
<td>1.7</td>
<td>3</td>
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<tr>
<td>HerculesA</td>
<td>160</td>
<td>3</td>
<td>59</td>
<td>1.6</td>
<td>1.7</td>
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<tr>
<td>Hydra A</td>
<td>210</td>
<td>0.9</td>
<td>136</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>M87</td>
<td>14</td>
<td>0.0008</td>
<td>11</td>
<td>0.0024</td>
<td>0.0005</td>
</tr>
<tr>
<td>NGC4636</td>
<td>5</td>
<td>0.00006</td>
<td>3</td>
<td>0.0007</td>
<td>0.00003</td>
</tr>
</tbody>
</table>

Clusters to galaxies (5, 2.5, 0.7 keV gas)
Late growth of SMBH by accretion in “old” stellar population systems
Grow stellar mass as well - see moderate star formation
AGN outbursts deposit energy into gas through shocks and bubbles
$M_{\text{mol}}$ vs $M_{\text{dot}}$ -- David & Nulsen (in prep)

Correlation of molecular mass in the cluster (Edge et al.) and
X-ray vs optical potential profiles (Churazov et al. arXiv0711.4686)

Optical

X-rays

Stars: gravity

Gas: gravity, cosmic rays, magnetic fields, turbulence
Deprojected X-ray data: gas temperature and density

Gravitational potential depends only on measured quantities -- temperature & gas density

And hydrostatic equilibrium!

\[
\varphi = -\frac{k}{\mu m_p} \left[ \int T_e \frac{d \ln n_e}{d r} dr + T_e \right] + C
\]

\[
\frac{1}{\rho} \frac{dP}{dr} = -\frac{GM}{r^2}
\]

\[
\frac{1}{\rho} \frac{dP}{dr} = -\frac{d\varphi}{dr}
\]
N1399 \[ \phi_X (r) \approx 0.93 \phi_{opt} (r) \]

M87 \[ \phi_X (r) \approx 0.85 \phi_{opt} (r) \]
HEAVY ELEMENT ABUNDANCES IN THE ICM

Historical note - Although even Uhuru observations with a scanning collimated (0.5 x 5 deg) proportional counter showed clusters were extended (Forman et al 1972, Kellogg et al 1972), Ariel 5 (Mitchell et al 1976) and OSO-8 (Serlemitsos et al. 1977) detected Fe-K emission showing X-ray emission from clusters was due to thermal gas.

More iron mass in the ICM than in all the cluster galaxies! To produce this much iron required top heavy IMF at early epochs (Arnaud et al 1992, Elbas et al 1993) or higher rate of SNIa in the past (Rensini et al. 1993).

Outer cluster regions show iron-to-silicon typical of SN II.
Relaxed Clusters

Heavy element abundances -- radial profiles - peaked around brightest cluster galaxy - excess Fe from SN Ia

ASCA - Finoguenov et al.

XMM-Newton - Bohringer et al

Chandra
Vikhlinin et al.

A400

A133

A2029
cD Abundance Peaks

Average abundance profiles
- Centered on cD
- Fe mass $1-20 \times 10^{10} \, M_{\text{sun}}$
- Long accumulation time ($>5 \times 10^9 \, \text{yr}$)
- Excess Fe in center from cD
- Broader than cD stellar light
- BCG $L_{\text{opt}}$ correlates with $M_{\text{Fe}}$

12 cD (CC) clusters
10 non CC clusters
De Grandi et al. 2004

For Perseus - from Rebusco et al. 2005
The important (cool) stuff --

--Clusters grow through mergers, the primary heating of the ICM is by shocks. We can measure the space velocity of subclusters (or galaxies) by measuring temperature or pressure jumps across cold fronts; Dark Matter exists!
--Reheating of cool cores is by AGN outbursts, (+sloshing, mergers, conduction….)
Observe past history of AGN activity and measure how much a black hole grows to produce the required energy to make shocks and cavities
--Gas temperature profiles are similar outside the core. Use measurements of the gas temperature and density to measure total cluster mass
Compare X-ray and optical potential to determine non-thermal pressure support
--Measure element abundances in the ICM to determine mass & origin (SNII vs SNIa)
Compare Fe distribution to stars in the cD to search for gas turbulence

M87 X-ray & radio  The Bullet cluster  Temperature profiles
Confronting X-ray and Optical data: XO Project

Optical

X-rays

Stars: gravity

Gas: gravity, cosmic rays, magnetic fields, turbulence
Deprojection of X-ray data
\[ \frac{1}{\rho} \frac{dP}{dr} = -\frac{d\phi}{dr} \]

\[ P_{true} = P_{gas} + \ldots \]

25% in Cosmic Rays

\[ \varphi_X (r) \approx \alpha \varphi_{true} (r), \quad \alpha \leq 1 \]
\[ \phi_X (r) \approx 0.93 \phi_{opt} (r) + C \]

\[ U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.07 U_{thermal} \]
\[ \varphi_X (r) \approx 0.85 \varphi_{opt} (r) \]

\[ U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.15 U_{\text{thermal}} \]
\[ \phi_X(r) \approx 0.85 \phi_{opt}(r) \]

\[ U_{CR} + \frac{H^2}{8 \pi} + U_{turb} = 0.15 U_{thermal} \]
Cooling flow + AGN model: consistent!

\[
U_{\text{CR}} + \frac{H^2}{8\pi} + U_{\text{turb}} = 0.07 - 0.15 U_{\text{thermal}}
\]

Expected

\[
U_{\text{CR}} + \frac{H^2}{8\pi} + U_{\text{turb}} = 0.1 - 0.2 U_{\text{thermal}}
\]

AGN heating

\[
L_{\text{heating}} \approx L_{\text{cooling}}
\]

\[
\frac{U_{\text{CR+}}}{U_{\text{thermal}}} \approx \frac{t_{\text{cross}}}{t_{\text{cool}}}
\]

\[
t_{\text{cross}} \approx 0.1 - 0.2 t_{\text{cool}}
\]
Limits on the Cosmic Rays (protons) energy density in the past

Proton energy losses are small for $\gamma >> \text{few}$

Proton do not diffuse

Adiabatic evolution of protons

If the (core) gas was shock heated $\Rightarrow$ CR energy density $< 0.01$
How rare is the bullet cluster?

DISTRIBUTION OF VELOCITIES OF THE MOST MASSIVE SUBSTRUCTURE IN THE MILLENNIUM RUN

Hayashi & White (2006)

Adopted mass model from Clowe et al. (2004):

NFW-Halo with:

\[ M_{200} = 2.96 \times 10^{15} \, M_\odot \]
\[ R_{200} = 2.25 \, \text{Mpc} \]
\[ V_{200} = 2380 \, \text{km/sec} \]
\[ V_{\text{shock}} = 4500 \, \text{km/sec} \]

\[ \frac{V_{\text{sub}}}{V_{\text{shock}}} = 1.9 \]

chance: \[ 10^{-2} \]

But, revised data from Clowe et al. (2006) and Markevitch et al. (2006):

\[ M_{200} = 1.5 \times 10^{15} \, M_\odot \]
\[ V_{200} = 1680 \, \text{km/sec} \]
\[ V_{\text{shock}} = 4740 \, \text{km/sec} \]

\[ \frac{V_{\text{sub}}}{V_{\text{shock}}} = 2.8 \quad \text{chance: } 10^{-7} \]
Southwestern Arm

Southwestern arm exits core as narrow (10” – 0.8 kpc) filament.

- Inner southwestern X-ray arm seems uncorrelated with radio. Radio appears to spiral around X-ray filament magnetic tension confining X-ray gas?)}
Measuring non-thermal pressure in cluster cores
(XO project)

E.Churazov, W.Forman, A.Vikhlinin,
S.Tremaine, O.Gerhard, C.Jones

Chandra image, 0.5-2 keV
M87 – multiple radio/X-ray bubbles

- Three sets of bubbles
  - Inner lobes (youngest)
  - Rising mushrooms (arms)
  - Pancakes (oldest)
- Bubbles rise rapidly
  - ~400 km/sec
- Radio bubbles lose > 50% of the internal relativistic energy by adiabatic expansion
- Bubbles uplift ambient material from cool core

Churazov et al. 2001
Deprojected X-ray data: gas temperature and density

\[ n_e(r), T_e(r), P(r) \]

\[ \frac{1}{\rho} \frac{dP}{dr} = -\frac{GM}{r^2} \]

\[ \frac{1}{\rho} \frac{dP}{dr} = -\frac{d\varphi}{dr} \]

\[ \varphi = -\frac{k}{\mu m_p} \left[ \int T_e \frac{d \ln n_e}{dr} \, dr + T_e \right] + C \]

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