Exploring the Outskirts of Galaxy Clusters

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Clusters as Tools

- **cosmology**
  - formation of structure is governed by gravity; measuring *mass distribution* of clusters is a direct test of cosmology

- **astrophysics**
  - non-gravitational processes (AGN and SN heating, radiative cooling) change the thermodynamics

- **chemical evolution**
  - “beacons” that can trace production and distribution of elements
A Word About “Entropy”

Fundamental Relation of Thermodynamics

\[ dU = \delta Q - \delta W \]

- internal energy
- heat
- work

\[ dU = TD - PdV \]

entropy
A Word About “Entropy”

\[ dU = TdS - PdV \]

- entropy encodes the thermal history of the gas; only heat energy transferred in or out of the system can change the entropy
- shock heating, AGN heating, radiative cooling

From Cavagnolo+09:

“Thus, gravitational potential wells are giant entropy sorting devices: low entropy gas sinks to the bottom of the potential well, while high entropy gas buoyantly rises to a radius at which the ambient gas has equal entropy.”
The Power of Entropy

non-cool core

cool core

$K \propto r^{1.1}$

non-radiative, spherical accretion; only gravity (Voit+05)

Cavagnolo+09 (ACCEPT)
Entropy in the Outskirts

- AGN feedback
- merging mixing
- cool core vs. non-cool core
Entropy in the Outskirts

- hydrostatic equilibrium?
- low-entropy accreting halos?
- $EM \propto n_e^2$
  $\rightarrow$ inferred density may be enhanced by “clumping”
  $\rightarrow$ lower $K = kT n_e^{-2/3}$
Comparison with Simulations

Roncarelli+2006 (also Burns+2010, Nagai+2011)

Accretion onto clusters is clumpy!
Clusters to $R_{200}$ with Suzaku

PKS 0745-191  George+2009
              Walker+2012
Abell 2204    Reiprich+2009
Abell 1795    Bautz+2009
Abell 1413    Hoshino+2010
Abell 1689    Kawaharada+2010
Perseus       Simionescu+2011
              Urban+2013
Abell 2142    Akamatsu+2011
RXJ 1159+5531 Humphrey+2012
Centaurus     Walker+2013
ESO 3060170   Su+2013

...and more!
Clusters to $R_{200}$ with Suzaku

- differing azimuthal coverage
- heterogeneous analysis methods
- plan: systematic observations of well-defined sample
## Suzaku Cluster Outskirts Project

<table>
<thead>
<tr>
<th>Cluster</th>
<th>$z$</th>
<th>$R_{200}$</th>
<th>ksec</th>
<th>date obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A383</td>
<td>0.187</td>
<td>9.3</td>
<td>110</td>
<td>July 2010</td>
</tr>
<tr>
<td>A1413</td>
<td>0.135</td>
<td>14.8</td>
<td>170</td>
<td>May 2010 + archive</td>
</tr>
<tr>
<td>A1795</td>
<td>0.063</td>
<td>26.0</td>
<td>260</td>
<td>June 2009 + archive</td>
</tr>
<tr>
<td>A1914</td>
<td>0.174</td>
<td>14.5</td>
<td>160</td>
<td>June 2010</td>
</tr>
<tr>
<td>A2204</td>
<td>0.151</td>
<td>11.8</td>
<td>140</td>
<td>Sep 2010 + archive</td>
</tr>
<tr>
<td>A3378</td>
<td>0.137</td>
<td>12.2</td>
<td>150</td>
<td>May 2010</td>
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<tr>
<td>A773</td>
<td>0.216</td>
<td>9.5</td>
<td>200</td>
<td>May 2011</td>
</tr>
<tr>
<td>A2667</td>
<td>0.221</td>
<td>10.0</td>
<td>200</td>
<td>July 2011</td>
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<tr>
<td>A1068</td>
<td>0.147</td>
<td>10.8</td>
<td>200</td>
<td>Oct 2011</td>
</tr>
<tr>
<td>A665</td>
<td>0.179</td>
<td>11.7</td>
<td>200</td>
<td>April 2012</td>
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<tr>
<td>A2597</td>
<td>0.080</td>
<td>15.0</td>
<td>200</td>
<td>Dec 2012</td>
</tr>
</tbody>
</table>

- selected from Snowden et al. 2008 XMM cluster catalog
- “relaxed”, no substructure
- falling, flat, and rising $kT$ profiles
- full azimuthal coverage out to $R_{200}$
Background Systematics

\[ S_{\text{cluster}}(R_{200}) < 30\% \text{ of X-ray background} \]

- Galactic thermal BG + cosmic X-ray BG
- use outer regions, ROSAT

A2204 ROSAT PSPC
Background Systematics

\[ S_{\text{cluster}}(R_{200}) < 30\% \text{ of X-ray background} \]

- scattered X-ray flux from bright core
- restrict cluster sample
- simulations, cal obs: \( \sigma_{\text{SB}} < 3\% \text{ of X-ray BG} \)
Background Systematics

\[ S_{\text{cluster}}(R_{200}) < 30\% \text{ of X-ray background} \]

- point source Poisson noise

- with Chandra snapshots:
  \[ \sigma_{\text{SB}} < 5\% \text{ of X-ray BG (full annulus)} \]
Results
Temperature

$\frac{kT}{kT_{\text{ave}}}$ vs $\frac{R}{R_{200}}$

- XMM
- Suzaku

Data points for:
- A1413
- A2204
- A773
- A3378
- A1914
- A383
Temperature

The temperature profile suggests that clusters generally hold similar relation even near the center. The flatness of the temperature profile indicates that clusters may not be the only or the dominant source of the entropy. However, the presence of filament is not clear in the observed direction.

We note that the present A2142 profile shows a smooth temperature decline with radius, even though it is a merger of several clusters. We will refer to “entropy” of the ICM by the gas. We will refer to “entropy” of the ICM by the gas.

The entropy of ICM is used as an indicator of the energy available for the ICM. Researchers have found that the ICM is not in a steady state, but rather in a state of evolution.

Numerical simulations have shown that the ICM is not in a steady state, but rather in a state of evolution. Researchers have found that the ICM is not in a steady state, but rather in a state of evolution.

Table 8. Cluster samples and their properties

<table>
<thead>
<tr>
<th>Cluster</th>
<th>k,T</th>
<th>T</th>
<th>l &lt;m&gt;</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PKS 0745</td>
<td>7.0</td>
<td>2.21</td>
<td>19.6</td>
<td>George et al. 2008</td>
</tr>
<tr>
<td>Abell 1413</td>
<td>7.4</td>
<td>2.24</td>
<td>14.8</td>
<td>Hoshino et al. 2010</td>
</tr>
<tr>
<td>Abell 1795</td>
<td>5.3</td>
<td>1.96</td>
<td>26.9</td>
<td>Bautz et al. 2009</td>
</tr>
<tr>
<td>Perseus</td>
<td>6.5</td>
<td>2.22</td>
<td>103.1</td>
<td>Simionescu et al. 2011</td>
</tr>
<tr>
<td>A2142</td>
<td>8.6</td>
<td>2.46</td>
<td>24.6</td>
<td>This work</td>
</tr>
</tbody>
</table>

The entropy profile of A2142 shows a flatter slope than the average, which indicates a steeper slope than the average, even though all of them show an elliptical shape to some extent. The flattening of the entropy profile in such outer regions looks to be a common feature.

The entropy slope is consistent with this value derived from Henry et al. (2010). Two measurements close to (0.5–2.0) in the slope. Suzaku has extended the entropy measurements to a much larger radius range. The solid line indicates the Newton results on the entropy profiles of 31 clusters showed a flattening or even a decrease at r ∼ r/5000.

Results of Nagai (2011) show that the entropy profile flattens around r ∼ r/5000. The feature is not likely to be the only or the dominant source of the entropy. In order to see a suppression of entropy, the entropy profile would need to go negative near r ∼ r/5000. This feature is not seen in the profiles of the clusters on the right.

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$K \propto r^{1.1}$

non-radiative gravitational accretion

(Voit+05)

(A1413, A2204, A773, A3378, A1914, A383)
Entropy
Pressure

Planck

\( \frac{P}{P_{500}} \)

\( R_{500} \)

\( \frac{R}{R_{200}} \)

A1413
A2204
A773
A3378
A1914
A383
Pressure

A1413
A2204
A773
A3378
A1914
A383

Perseus

Urban+13

Centaurus

Walker+13

“clumping” corrected
Summary (1/2)

- 20+ clusters observed to $R_{200}$ with Suzaku
- our study: 6 of 11 clusters, full azimuthal coverage
  - support “universal” temperature, entropy, pressure profiles
- Suzaku background systematics addressed (PSF, stray light, point sources)
Summary (2/2)

- **entropy** encodes thermal history of gas
- *most clusters* have entropy decrement beyond $R_{500}$
  - low-entropy, clumpy (group- and galaxy-scale) infalling halos
- radius of turn-over varies greatly
  - mass?
    variations predicted in simulations (Nagai+11) but not yet constrained in observations
  - environment?
    two isolated fossil groups have no entropy decrement (Humphrey+12, Su+13)