Galaxy Clusters at the Edge: Temperature, Entropy Structure, & Gas Dynamics at the Virial Radius

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JILA Seminar
March 19, 2010
Are Clusters Accurate Probes of Cosmological Parameters?

Cluster Mass Function


Fig. 10.— Dark energy constraints in flat universe from combination of all cosmological datasets. We find $w_0 = -0.991 \pm 0.045$ (±0.04 systematic) and $\Omega_X = 0.740 \pm 0.012$, see Table 2 and § 8.3.
Are Clusters Accurate Probes of Cosmological Parameters?

Cluster Gas Fraction

- Angular diameter distance (depends on Dark Energy model) $d_A \sim f_{\text{gas}}^2$ (assume $f_{\text{gas}}$ is constant and ICM is in hydrostatic equilibrium).
Galaxy clusters have “the statistical potential to exceed the baryon acoustic oscillations and supernovae techniques but at present have the largest systematic errors. Its eventual accuracy is currently very difficult to predict and its ultimate utility as a dark energy technique can only be determined through the development of techniques that control systematics due to non-linear astrophysical processes.”
What are the systematics?

• **Gastrophysics**
  – Cooling
  – Heating/feedback from SN and AGNs

• **Cluster dynamics** (hydrostatic equilibrium?)
  – Mergers
  – Turbulence & bulk flows (“sloshing”)

• **Nonthermal component of ICM**
  – Cosmic rays (possibly ~10% of total pressure)
  – Magnetic fields (~1-3 μG)

• **Cluster sample selection effects**
  – Use of cool core clusters
  – Non-statistically complete samples

=> Use numerical simulations to model and correct for these biases and errors.
Potential to use Cluster Mass Function for cosmology is challenging because mass is not a directly observable quantity. Instead, we measure:

- X-ray luminosity or X-ray temperature.
- Sunyaev-Zeldovich Effect ($Y \sim \int nT \, dl$).
- Weak lensing shear.
Hydrostatic Equilibrium

\[ \nabla \Phi = -\frac{\nabla P}{\rho} \]

Applying Gauss’ Law to the above:

\[ M(< r) = \frac{1}{4\pi G} \int -\frac{\nabla P}{\rho} dA \]

If cluster is spherical & \( P = nkT \), then,

\[ M(< r) = -\frac{r^2 k}{\rho G \mu m_p} \left[ T \frac{d\rho}{dr} + \rho \frac{dT}{dr} \right] \]

=> Need to measure \( T, \rho \) and their gradients
Are CC clusters in Hydrostatic Equilibrium?

- Burns et al. 2008.

CC clusters are biased low by ~15%, just like NCC clusters. Kinetic energy of bulk gas motions contributes ~10% of total energy.
A Universal Temperature Profile for Galaxy Clusters?

ΛCDM AMR Cosmology Simulations compared to X-ray observations from BeppoSAX

\[ T = 1.3T_0(1 + 1.5r / r_{vir})^{-1.6} \]
Suzaku is a game-changer for measuring cluster temperatures

<table>
<thead>
<tr>
<th>S/C</th>
<th>Orbit apogee</th>
<th>568 km</th>
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<tbody>
<tr>
<td></td>
<td>Orbital period</td>
<td>96 minutes</td>
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<tr>
<td></td>
<td>Observing efficiency</td>
<td>~ 45%</td>
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<tr>
<td>XRT</td>
<td>Focal length</td>
<td>4.75 m</td>
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<tr>
<td></td>
<td>Field of view</td>
<td>17' at 1.5 keV</td>
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<tr>
<td></td>
<td></td>
<td>13' at 8 keV</td>
</tr>
<tr>
<td></td>
<td>Plate scale</td>
<td>0.724 arcmin/mm</td>
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<tr>
<td></td>
<td>Effective area</td>
<td>440 cm² at 1.5 keV</td>
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<tr>
<td></td>
<td></td>
<td>250 cm² at 8 keV</td>
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<tr>
<td></td>
<td>Angular resolution</td>
<td>2' (HPD)</td>
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<tr>
<td>XIS</td>
<td>Field of view</td>
<td>17.8' × 17.8'</td>
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<td>Bandpass</td>
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<td>Pixel grid</td>
<td>1024×1024</td>
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<tr>
<td></td>
<td>Pixel size</td>
<td>24 μm×24 μm</td>
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<tr>
<td></td>
<td>Energy resolution</td>
<td>~ 130 eV at 6 keV</td>
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<tr>
<td></td>
<td>Effective area</td>
<td>340 cm² (FI), 390 cm² (BI) at 1.5 keV</td>
</tr>
<tr>
<td>(incl XRT-I)</td>
<td></td>
<td>150 cm² (FI), 100 cm² (BI) at 8 keV</td>
</tr>
<tr>
<td></td>
<td>Time resolution</td>
<td>8 s (Normal mode), 7.8 ms (P-Sum mode)</td>
</tr>
</tbody>
</table>

Low and stable backgrounds!
**X-ray Observations of PKS 0745-191**

$z=0.103$, $M_{200}=6.4\times10^{14} \, M_{\odot}$, $T\approx 7 \, \text{keV}$, $r_{200} = 1.7 \, h_{70}^{-1} \, \text{Mpc}$

**Suzaku X-ray Observations**

Suzaku Observations of Abell 1795

$z=0.063$, $M_{200}=8.6 \times 10^{14} \, M_\odot$, $T=5.3 \, \text{keV}$, $r_{200} = 1.9 \, h_{70}^{-1} \, \text{Mpc}$

Bautz et al. 2009, PASJ, 61, 1117
Suzaku Observations of Abell 1413

$z=0.143$, $M_{500}=7.8 \times 10^{14} \, M_{\odot}$, $T=7.4$ keV, $r_{200} = 2.2 \, h_{70}^{-1} \, \text{Mpc}$

Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution

- $\Lambda$CDM with $\Omega_m = 0.27$, $\Omega_b = 0.04$, $\Omega_\Lambda = 0.73$, $h = 0.7$, and $\sigma_8 = 0.9$.
- AMR achieves $15.6 \, h^{-1} \, \text{kpc}$ resolution in dense regions.
- $(128 \, h^{-1} \, \text{Mpc})^3$, 5 levels of refinement $\Rightarrow$ 80 clusters with $>10^{14}$ $M_\odot$ for $z = 0$.
- Dark matter mass resolution is $3.1 \times 10^9 \, h^{-1} \, M_\odot$.
- Adiabatic gas physics.

Enzo (e.g., O’Shea et al. 2004, http://lca.ucsd.edu/portal/software/enzo)

Mass $= 1.7 \times 10^{14} M_\odot$

$T = 1.4 - 4.4$ keV

$z = 0$
Accretion onto clusters is not spherical!
Summary & Conclusions

• Galaxy clusters exhibit a universal outer temperature profile.
• However, this T profile suggests some deviation from hydrostatic equilibrium, especially in the outer regions of clusters. Why?
  – Clusters accrete gas non-spherically via linear filaments.
  – Bulk gas motions in ICM are important, especially in outer parts of cluster.