Cluster Entropy Profiles

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Why entropy?
Entropy: A Review

Definition of S: \[ \Delta S = \Delta(\text{heat}) / T \]

Equation of state: \[ P = K \rho^{5/3} \]

Relationship to S: \[ S = N \ln K^{3/2} + \text{const.} \]

Convective Stability: \[ d \left( \frac{S}{dr} \right) \geq 0 \]

Useful Observable: \[ Tn_e^{-2/3} \propto K \]

Only heat loss can reduce \( Tn_e^{-2/3} \)

Only heat input can raise \( Tn_e^{-2/3} \)
Fundamentals of Cluster Structure

Properties of relaxed cluster determined by:

- shape of halo
- entropy distribution of intracluster gas

MS 1054-0321 / Donahue et al. (1998)
Clusters without Feedback

Self-similar entropy profiles in absence of galaxy formation scale with

\[ K_{200} = \frac{T_{200}}{(200 f_b \rho_{cr})^{2/3}} \]

Also,

\[ K(r) \sim r^{1.2} \]

Voit, Kay, & Bryan (2005)
Allow baseline profile to cool for a Hubble time in an NFW potential, and remove gas at $r = 0$ when $K = 0$. 

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**Chandra Entropy Profiles**

- Pure cooling model is lower limit to observed profiles
- Most profiles are well fit with:
  \[ K(r) = K_0 + K_{100}\left(\frac{r}{100 \text{ kpc}}\right)^\alpha \]
  - \( K_{100} \sim 150 \text{ keV cm}^2 \)
  - \( \alpha \sim 1.2 \)
Distribution of Core Entropy

Distribution of $K_0$ is bimodal with deficit at $K_0 \sim 30$-50 keV cm$^2$ corresponding to a cooling time $\sim 1$ Gyr.

Cavagnolo et al. (2008, 2009)
See also:
Sanderson et al. (2009)
Hudson et al. 2010
(HIFLUGGS)
Cool cores have steeper entropy slopes than non-cool core clusters.
Cool cores have steeper entropy slopes than non-cool core clusters.

Sanderson et al. 2009
How is core entropy related to feedback signatures?
Central galaxy of a $z < 0.2$ cluster can be a strong radio source only if

$$K_0 < 30 \text{ keV cm}^2$$

Radio data from NVSS+SUMMS within 20” of X-ray peak

Cavagnolo et al. (2008)
$K_0$ and $H\alpha$ Emission

Central galaxy can have emission-line nebulosity only if

$$K_0 < 30 \text{ keV cm}^2$$

$H\alpha$ data from many diverse sources

Cavagnolo et al. (2008)
$K_0$ and Central Blue Gradient

Central galaxy can have blue gradient indicating star formation only if

$$K_0 < 30 \text{ keV cm}^2$$

Rafferty et al. (2008)
K₀ and UV color

124 BCGs
GALEX-2MASS colors

Hoffer, Donahue et al. 2011, in prep
$K_0$ and Spitzer 24 micron excess

Hoffer, et al. 2011, in prep

83 BCGs with Chandra + MIPS 24 micron
$K_0$ and $L_K$
$K_0$ and $L_K$

Extra $L_K$ for some BCGs with $K_0 < 30$ keV cm$^2$

K-band luminosity inside $r=10$ kpc does not depend on $K_0$ ($K_0 > 30$ keV cm$^2$)
Multiphase Gas in REXCESS BCGs
REXCESS Cooling Times

REXCESS cool-core classification based on $t_{\text{cool}}$ at 0.003 $R_{500}$
Entropy profile depends on cluster morphology.

Pratt et al. 2010
BCGs in REXCESS

• Haarsma et al. 2010: no correlation with BCG luminosity and central cooling time or K0.

• Donahue et al. 2010: only BCGs in REXCESS CC’s exhibited excess UV and/or Hα emission ($f_{H\alpha} = 70\%$ of REXCESS CCs)
Cooling–Time Threshold for $\text{H}\alpha$

Donahue et al. (2010)
Spitzer studies of emission-line BCGs
Spitzer IRS Spectra of 9 cool-core BCGs

- Show PAHs, [Ne II], strong H2 lines
- PAH/IR and PAH/PAH ratios similar to star forming galaxies (Donahue et al. 2011)
- H$_2$ consumption timescales 1 Gyr or less, similar to star-forming galaxies and starbursts
H$_2$ depletion $\sim$ Gyr

diamond: Leroy et al. 2008
triangle: Solomon & van den Bout 2005
speculations about the distribution of $K_0$
Distribution of Core Entropy

Distribution of $K_0$ is bimodal with deficit at $K_0 \sim 30-50$ keV cm$^2$ corresponding to a cooling time $\sim 1$ Gyr.

Cavagnolo et al. (2008)
See also Hudson & Reiprich
No consensus from simulations on distribution of $K_0$ without cooling & feedback
Distribution of Core Entropy

If conduction is inefficient, cooling causes clusters with $t_c < \text{few Gyr}$ to migrate to lower $K_0$. 

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Distribution of Core Entropy

Episodic AGN feedback can plausibly maintain clusters in a quasi-steady state with

\[ K_0 \sim 10-20 \text{ keV cm}^2 \]

Voit & Donahue (2005)
See also Kaiser & Binney
Distribution of Core Entropy

Raising $K_0$ by a large factor requires an implausibly large AGN outburst.

Mergers are also ineffective at producing large $K_0$ jumps.
Distribution of Core Entropy

If conduction is operating, mergers can more easily cause clusters with $K_0 > 30$ keV cm$^2$ to migrate to greater $K_0$. 

![Histogram of Core Entropy Distribution](image)
Distribution of Core Entropy

How many clusters with $K_0 > 100$ keV cm$^2$ are mergers in progress that will eventually relax to a low $K_0$ state?
Summary

• Cluster population is bimodal (may include an intermediate mode)
• Central AGN and BCG star formation activity responds to state of ICM
• ICM is multiphase for low $K_0$
• High $K_0$ seems more common in disturbed clusters