Self-similarity Breaking in Galaxy Clusters

The Birmingham-CfA Cluster Scaling Project

Alastair Sanderson

with
Trevor Ponman, Alexis Finoguenov, Ed Lloyd-Davies & Maxim Markevitch
Outline

● Background & introduction to project
● Gas mass fraction
● ICM entropy
● Optical results
● Summary
Introduction

- Virialized systems comprise 3 distinct mass components. On average:
  - 2–5% Stars
  - 10–15% Hot gas
  - 80–85% Dark matter
  \((H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1})\)

- Useful cosmological probes; yield important information on feedback & interaction processes

- Under simplest assumptions, expect such systems to be *self-similar* — i.e. optical light & gas trace mass, which simply scale with halo mass

- Observational evidence reveals simple scaling *not* obeyed for X-ray emitting IGM

- Extra physics needed e.g.
  - heating via energy injection
  - radiative cooling
The cluster scaling sample

- Detailed X-ray study, as majority of baryons reside in gaseous intergalactic medium ($\sim 10^{7-8}$ K, $\sim 10^{-3}$ cm$^{-3}$)

- Main (X-ray) sample comprises 66 rich clusters, groups & individual galaxies (median $z = 0.035$) with $kT \sim 0.4 - 17$ keV
  \[ \rightarrow \sim 200 \text{ kpc} - 3 \text{ Mpc} \]

- Have determined deprojected gas $T(r)$ & $\rho(r)$, corrected for effects of central cooling

- Optical sub-sample comprises 32 groups & clusters, with deprojected optical luminosity profiles

- Assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$

  (See Sanderson et al, 2003 for details)
Data Analysis

- *ASCA & ROSAT* data – combining Markevitch, Finoguenov & Lloyd-Davies samples + new analysis

- Use beta model for gas density and either linear or polytropic temperature profile:

\[
\rho(r) = \rho(0) \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-\frac{3}{2} \beta}
\]

\[
T(r) = T(0) \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-\frac{3}{2} \beta(\gamma - 1)}
\]

- Derive gravitating mass, assuming hydrostatic equilibrium:

\[
M_{grav}(r) = -\frac{kT(r)}{G\mu m_p} \left[ \frac{d \ln \rho}{d \ln r} + \frac{d \ln T}{d \ln r} \right]
\]

- Virial radius, mean temperature etc., all derived *self-consistently*
Gas fraction vs temperature

![Graph showing gas fraction vs temperature with error bars.]

Gas fraction at $0.3R_{200}$ as a function of emission-weighted temperature

- 6σ trend: groups have significantly less gas at $0.3R_{200}$ than clusters—reflects their flatter gas density profiles
- Where is missing gas in cooler systems?
Gas fraction profiles

Mean gas fraction profiles, grouped by X-ray temperature.

- $f_{\text{gas}}$ rises monotonically with radius ($> 0.03R_{200}$), normalization increases with temperature
- Hot gas is most extended mass component
  \[ \Rightarrow \text{Most influenced by heating/cooling mechanisms} \]
- Rising $f_{\text{gas}}$ profile predicted by simulations, \textit{even without heating/cooling} (e.g. Santa Barbara comparison project – Frenk et al., 1999)
- Does group $f_{\text{gas}}$ “catch up” with clusters within $R_v$?
Gas entropy: an overview

- For an ideal gas, ignoring constants & logs, defined as

\[ S = \frac{kT}{n_e^{2/3}} \]

- Entropy conserved in any adiabatic process
  \( \Rightarrow \) Powerful probe of non-gravitational physics

- Entropy must rise monotonically with radius for convective stability

![Graph showing entropy vs temperature](image)

Entropy at 0.1\( R_V \) vs emission-weighted temperature (Lloyd-Davies et al., 2001)
Entropy vs temperature

Entropy at $0.1 R_{200}$ vs emission-weighted temperature

- Slope ($0.65 \pm 0.05$, excluding the 2 galaxies) flatter than self-similar prediction of $S(r) \propto kT$

- Good agreement with simple cooling model of Voit & Bryan, 2001

- Excess entropy – more apparent in cooler systems, but no evidence of entropy “floor”
Simulated entropy profiles

Entropy profiles for a rich cluster ($M = 10^{15} h^{-1} M_\odot$, upper panel) and a small cluster ($M = 10^{14} h^{-1} M_\odot$, lower panel).


- Solid curves show external heating case (pre-heating)
- Predict $S(r) \propto r^{1.1}$ within shock region
- Predict flat entropy core from pre-heated IGM
Scaled entropy profiles

Mean entropy profiles (scaled by $kT$), grouped by temperature (from Ponman, Sanderson & Finoguenov, 2003: PSF03).

- Entropy rises monotonically with radius
- Cooler systems have a greater entropy excess
- Asymptotic logarithmic slope consistent with accretion shock entropy
  - e.g. Tozzi & Norman, 2000 model predicts $S(r) \propto r^{1.1}$
- No evidence of large isentropic core
  ⇒ Incompatible with standard preheating
**XMM-Newton** observation of the poor cluster A1983

From Pratt & Arnaud, 2003

- A1983 $kT \sim 2$ keV ; A1414 $kT \sim 7$ keV
- No isentropic core present in A1983
- Right: Scaled with $S \propto (1 + z)^{-2}T_X^{0.65}$ from PSF03
- Right: Dashed line is $S \propto r^{1.1}$ (shock heating) normalized to scaled entropy of a 10 keV cluster from PSF03
Optical Luminosity vs Halo Mass

Optical luminosity within $R_{200}$ ($B_J$ band) as a function of Total mass within $R_{200}$ for the optical sample.

- Surface density fits to APM data
- Derive normalization from aperture luminosities in literature (Mainly Girardi et al., 2002)
- Red line is best fitting power-law: $L_{B,J} \propto M^\alpha$, where $\alpha = 0.93 \pm 0.10$
- Logarithmic slope consistent with self-similar prediction of 1
Summary

- The intergalactic medium is less dense & more extended in smaller halos
  ⇒ heating and/or cooling

- No evidence of isentropic cores or entropy floor

- Stellar properties broadly self-similar
  ⇒ Star formation only slightly enhanced in groups

- Need both heating and cooling

- Preheating may act mainly to reduce gas density along accreting filaments