Cluster Assembly and Non-Equilibrium in the Outer ICM

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SZ Observations of outer ICM

- SZ experiments measuring electron pressure in outskirts directly and indirectly through projection

- Less sensitive to complex baryon physics operating in cluster cores.

- Electron pressure may deviate from equilibrium in two ways: turbulence/bulk motion (incomplete kinetic dissipation) and incomplete thermal equilibration
Electron Equilibration: Physical Picture

Heavy ions carry bulk of kinetic energy ($\sim m_i/m_e$) through shock due to weak coupling between species (long mfp)

Two major uncertainties:
- amount of electron heating at the shock (min adiabatic compression)
- rate of temperature equilibration downstream from the shock front (min due to Coulomb collisions)

Simulations implicitly assume instant equilibration and may overestimate electron temperature

Electron gas equilibration due to shock dispersion

Total gas pressure downstream from shock given by standard jump conditions

$$T_{\text{gas}} = \frac{n_e T_e + n_i T_i}{n_e + n_i}$$

Rudd & Nagai (2009), Fox & Loeb (1997), see also Bykov et al (2008)
Numerical Scheme

Separately track electron internal energy which is advected with the fluid (not subject to shocks) with source terms:

\[
\frac{dT_e}{dt} = \frac{T_i - T_e}{t_{ei}} - (\gamma - 1) T_e (\nabla \cdot \mathbf{v})
\]

Coulomb equilibration timescale:

\[
t_{ei} \sim T^{3/2}/n_e \sim K^{3/2}
\]

\[
\approx 6.3 \times 10^8 \text{ yr} \ (T_e/10^8\text{K})^{3/2} \ (n_i/10^{-5} \text{ cm}^{-3})^{-1}
\]
Cosmological Simulations

Modified the distributed Adaptive Refinement Tree (ART) code to simulate several samples of galaxy clusters using this scheme (without cooling and feedback physics)

16 galaxy clusters and groups from Nagai et al (2007)

\[ M_{500} = 0.31 \times 7.3 \times 10^{14} \, h^{-1} \, M_\odot \]

Hydro resimulation of Bolshoi N-body simulation (Klypin et al 2010)

250 \, h^{-1} \, Mpc \, 1024^3 \, particles

\sim 130 \, clusters \, M_{500} > 10^{14} \, h^{-1} \, M_\odot

High resolution (\sim few kpc) in cluster core, degrading to several \sim 10s kpc in outskirts

Rudd & Nagai (2009)
Nagai '07 Sample

Range of temperatures and shock morphologies leads to qualitatively different distribution of "cold" electrons.

Expected mass trend broadly reproduced with some scatter due to formation history.

Only self-consistent simulations can model the full distribution of accretion histories.
Spherically averaged electron temperature profiles reach minimum relative to mean gas temperature near shock radius.

Rudd & Nagai (2009); see also Fox & Loeb (1997)
Two of the most massive clusters in our sample have similar mean gas temperatures (~6 keV) but dramatically different distribution of non-equilibrium electrons.

Understanding effect of cluster assembly history is critical to predicting the SZ signal from cluster populations.
Effect on SZ Flux

Effect is strongest for more massive clusters (up to ~6% in the projected SZ flux). Lower electron temperature in outer regions leads to lower flux when computed in projection.
Mass scale moves to lower mass with redshift (combination of evolution in age-mass relation and entropy-mass relations)
Summary

- Electron temperatures may be suppressed by up to 60% in the outskirts of massive clusters if equilibration proceeds through Coulomb collisions.

- Effect stronger in hotter and more massive clusters; projected SZ flux suppressed by ~6% at $8\times10^{14} M_\odot$ at $z = 0$

- Effect grows to lower mass with increasing redshift due partly to evolution of mass-entropy relation

- Unfortunately unlikely to be directly constrained by observations in the near future

Rudd, Shaw & Nagai (2010, in prep)