Simulating the Universe: Giant Light Cones & Cool Cores in Galaxy Clusters

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Sunyaev-Zeldovich Effect Light Cone 10° x 10°

Enzo simulation with (500 h^{-1} Mpc)^3 volume, 4 levels of refinement, 0<z<3, adiabatic physics, 10” resolution.

Same as left image but clusters with M>5x10^{13} solar masses have been removed.

=>Fully half of the SZE flux comes from very low mass halos and filamentary structures made up of gas in the Warm Hot Ionized Medium (WHIM) phase.
Power spectra of the Light Cone images including instrumental response for 4 upcoming experiments.
Cooling Core vs Non-Cooling Core Clusters

Abell 478

Coma

(slide courtesy of A. Fabian)
Chandra observations of a cool core cluster
THE COMA CLUSTER

DSS Image of Coma Core

Coma ROSAT PSPC 0.73-2.04 keV

~ 3 Mpc

Simple Cooling Flow Model

• Assumes an isolated, spherical cluster in quasi-hydrostatic equilibrium.
• Central gas thermally cools from $T_{\text{virial}}$ at constant pressure driving a subsonic accretion flow onto the central galaxy.
• Expect mass accretion rates of hundreds of solar masses per year.
Why “Cooling Flows” Don’t Work

• End-products of presumed 100 M⊙/yr infall are not seen:
  – Star-formation <1000 times of expected rate
  – Little or no HI
  – Molecules like CO not detected in abundance or over extended volume

• Central temperatures observed to be not less than \( \sim 0.3 \cdot T_{\text{virial}} \)

• Simple model does not account for on-going accretion/mergers from supercluster environment, producing turbulent, shock-filled ICM (i.e., stormy weather) \( \Rightarrow \) such clusters may be far from dynamical equilibrium
Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution

Enzo (e.g., O’Shea et al. 2006, http://cosmos.ucsd.edu/enzo)

- $\Lambda$CDM Cosmology with $O_m = 0.3$, $O_b = 0.026$, $O_\Lambda = 0.7$, $h = 0.7$, and $s_8 = 0.9$.
- Hydro + N-body code uses AMR to achieve high resolution (2.0 to 15.6 $h^{-1}$ kpc) in dense regions.
- Simulation volume is 256 $h^{-1}$ Mpc on a side, use 7 to 9 levels of refinement with cluster subvolumes.
- Mass resolution is $10^{10} h^{-1}$ $M_\odot$ (Dark Matter).
- Baryon physics includes thermal cooling, star formation, supernova (Type II) feedback, and AGN heating (in progress).
Formation of Cool Core Clusters

$z = 4.00$

$\text{Emission-Weighted Temperature}$

$\text{Projected Density}$

$t = 1.57 \text{ Gyr}$
Statistics of Cool Core Clusters

- White et al. (1997) sample of clusters from *Einstein* found cool cores in \(\approx 60\%\) of their 207 cluster sample.
- Peres et al. (1998) found over 70\% of their sample of clusters observed with *ROSAT* to have cool cores.
- Chen et al. (2006) identify 49\% of their HIFLUGCS sample, based on *ROSAT* and *ASCA* data, as having cool cores.

Why do only about half of clusters in flux-limited samples have cool cores?
Cool cores initially grow slowly.
Evolution of a Non-Cool Core Galaxy Cluster

Non-cool cores suffer early major mergers
X-ray Surface Brightness Profiles

- Non-cool core clusters are fit very well to beta-models, $S_x = S_0 [1 + (r/r_c)^2]^{1/2 - 3\beta}$.

- Cool core clusters are fit poorly by beta models between $r_{500}$ and $r_{200}$.

- Mass in CC clusters over-estimated by 3-5x.
Simulations predict more cold gas outside the cores in cool core clusters than in non-cool core clusters.
Hardness Ratio (2-8 keV/0.5-2 keV) Comparisons with Chandra Observations

Abell 478 (CC)

T = 6.8 keV

Abell 3158 (NCC)

T = 5.8 keV
Numerical CC clusters lie within denser, more crowded supercluster environment than NCC clusters.

Agrees with Loken et al. (1999) who find that CC Abell clusters are surrounded by a higher density of other Abell clusters than NCC clusters.
Conclusions

• Cool core clusters are complicated, generally non-equilibrium systems where nongravitational physics is important.
• Our simulations suggest that Non-cool core (NCC) clusters suffer early major mergers when embryonic cool cores are destroyed. Cool core (CC) clusters grow more slowly without early major mergers.
• X-ray surface brightness profiles for NCC clusters are well fit by single $\beta$-models whereas the outer emission for CC clusters is biased low compared to $\beta$-models (resulting in masses and densities too high by factors of 3-5).
• CC clusters have 40% more cool gas beyond the cores than do NCC clusters.
• CC clusters generally lie within higher density supercluster environments in comparison to NCC clusters.