Are Galaxy Clusters Precise Cosmology Probes?
Cool Cores, Merger Shocks, Cosmic Rays & Radio Relics

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National Radio Astronomy Observatory
September 17, 2008
Me at 22!

NRAO Summer Student Class of 1975

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September 12, 2008
Are Clusters Accurate Probes of Cosmological Parameters?

- 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).
- Above used only cool core clusters.
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 ~30% of total pressure)
  - Magnetic fields (~1-3 \( \mu \)G)

- **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.


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\[ \text{=> Use numerical simulations to model and correct for these biases and errors.} \]
Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution

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

- $\Lambda$CDM with $\Omega_m = 0.3$, $\Omega_b = 0.04$, $\Omega_\Lambda = 0.7$, $h = 0.7$, and $\sigma_8 = 0.9$.
- AMR achieves 8-16 h$^{-1}$ kpc resolution in dense regions.
- (256-512 h$^{-1}$ Mpc)$^3$, 7 levels of refinement $\Rightarrow$ 1500 clusters with $>10^{14}$ $M_\odot$ for $z < 1$
- Dark matter mass resolution is $10^{10}$ h$^{-1}$ $M_\odot$.
- Baryon physics includes radiative cooling, star formation, & feedback.
  $\Rightarrow$ Approximate balance of heating and cooling.
- First simulation to produce both cool and non-cool cores in same volume.
Movies
Simulations

$\text{r}_{\text{core}}$ vs. beta

CC – closed
NCC - open

Gas fraction vs. temperature

Gas mass vs. temperature

Cool core clusters avoid major mergers with high fractional mass changes early in their histories.

NCC clusters suffer major mergers early in their evolution, destroying embryonic cool cores.
Comparison of Temperature & Hardness Ratio Profiles

- Simulated temperature profiles for CC & NCC clusters have notable differences beyond the cores.
- Normalized Hardness Ratio profiles reflect this difference between CC & NCC clusters in both simulations and observed (Chandra) samples.
CC clusters are biased low by ~15%, just like NCC clusters. Kinetic energy of bulk gas motions contributes ~10% of total energy.

- Burns et al. 2008.
Large Scale Structure Shocks: Generating Cosmic Rays

- Thermalization
- Dynamic Effects of Cosmic Rays
- Mass Estimates of Clusters
  - Can we trust hydrostatic equilibrium?
  - Effects on the Dark Energy Eq. of State
- Origin of high-energy Cosmic Rays
Shock-Finding in AMR

- Previous studies used coordinate-split analysis
- We allow for any orientation of the shock
- Rankine-Hugoniot Jump Conditions

\[
\nabla \cdot \vec{v} < 0 \\
\nabla T \cdot \nabla S > 0 \\
T_2 > T_1 \\
\rho_2 > \rho_1,
\]

\[
\frac{T_2}{T_1} = \frac{(5M^2 - 1)(M^2 + 3)}{16M^2},
\]
Numerical Results of Diffusive Shock Acceleration Simulations


- Two Models:
  - With and Without pre-existing CRs (30% Pressure)
Mach Number Evolution

- Accretion shocks onto clusters.
- Accretion shocks onto filaments.
- Turbulent Flow/merger shocks.
Simulated Radio Relics

- Sort for images where extended CR Rate(outside 200 $h^{-1}$ kpc) is high ($E_{CR, \text{extended}}/E_{CR, \text{total}} \sim 0.9-1.0$)

Bagchi et al. 2006, Science, 314, 791
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Distribution as $F(M, z)$

- About 15-20% have obvious merger shocks outside 200 kpc radius
Conclusions

• Galaxy clusters have potential to be the most precise tools for cosmological parameter estimation but are limited by our understanding of the astrophysics.
• Cool core (CC) clusters are assumed to be dynamically relaxed and, thus, best choice as dark energy probes. But, CC clusters are biased 15% low in mass assuming hydrostatic equilibrium.
• Shock-generated cosmic rays and B-field amplification are underappreciated nonthermal pressure components in the ICM that must be understood to realize full potential of clusters as precision probes.
• Shock morphologies look similar to radio relics. 15-20% of clusters expected to have relics.
• Future directions: MHD (with H. Li, LANL); model radio relics (including luminosity function) & gamma-ray emission.
LUNAR: Lunar University Node for Astrophysics Research

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