The Millennium Gas Simulations

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Conclusions

• We show that feedback from SNR and AGN in the L-Galaxies SA model are consistent with the observed properties of the ICM in clusters of galaxies

• We have re-run the Millennium simulation with the WMAP-7 cosmology

• We have created merger trees and SA galaxy catalogues using the Guo 2011 version of L-Galaxies (contact me if you want to use them)

• We use the SA galaxies as input to a hydrodynamical simulation:
  ◦ SNR contribute metals (but are inconsequential for entropy generation in massive halos)
  ◦ AGN heat the gas (and can reproduce the entropy and metallicity profiles of clusters)
The old Millennium Gas Simulations

- Millennium Simulation:
  - Tracks CDM only (+SA galaxies)
  - $N=2160^3$ particles
  - $L=500 \, h^{-1}\text{Mpc}$ (comoving)
  - WMAP1 cosmology ($\sigma_8=0.9$)

- Millennium Gas Simulation
  - Same large-scale structure as MS
  - Same volume as MS
  - Same cosmology as MS
  - Fewer ($10^9$) particles than MS
  - But also tracks gas (using SPH)

- Three models:
  - GO: gravity only
    - entropy generation through shocks only
  - PC: preheating plus cooling
    - gas is pre-heated to entropy floor of 200 keV cm$^2$ at $z=4$
  - FO: feedback only (no cooling)
    - SN+AGN feedback using SA galaxies — for selected clusters only

- See papers by:
  - Hartley et al. 2008 (X-ray L-T relation)
  - Stanek et al. 2010 (Scaling relations)
  - Short et al. 2011 (Evolution of scaling rel.)
  - Young et al. 2011 (Baryon fractions)
  - Kay et al. in prep (SZ scaling relations)
Combining semi-analytics with simulations
The feedback model

- Type II supernova feedback:
  \[
  \Delta E_{\text{ejected}} = \frac{1}{2} \epsilon_{\text{halo}} v_{\text{SN}}^2 \Delta M_* - \frac{1}{2} \epsilon_{\text{disk}} v_{\text{vir}}^2 \Delta M_*
  \]
  Energy used to reheat cold disk gas
  Total energy available

- AGN feedback:
  - Adopt the Bower et al. (2008) AGN feedback prescription used in GALFORM
  - Available heating energy is given by:
    \[
    \Delta E_{\text{BH}} = \min \left\{ 0.1 \Delta M_{\text{BH}} c^2, \epsilon \Delta E_{\text{Edd}} \right\}
    \]
    Radio mode
    Quasar mode
    where $\epsilon = 0.02$ is the disk structure parameter

Feedback

Preheating
We resimulate clusters from the Millennium simulation using a variety of physical models for entropy generation.

Both preheating and feedback models match the gas fraction profiles of non-cool-core (NCC) clusters.
This figure shows the ratio of the observed to predicted gas fractions within $r_{500}$.

The feedback (FO) model is consistent with a constant value of unity. However, this is ruled out for the preheating (PC) model with high significance.

This argues strongly against a preheating model for entropy generation in the intracluster medium.
Entropic feedback scheme

Density feedback scheme

Entropy

Density

Temperature

Metallicity

An improved feedback mechanism
Chris Short, Peter Thomas

- Heating dominated by AGN.
- Radio jet/bubble affects only a fraction of particles
- Heating occurs with a duty cycle of $10^8$ yr

- SNR important for injection of metals
- In clusters most metals are accreted — so inject within $R_{\text{vir}}$

- Optimal parameters:
  - Heating efficiency = Bower model
  - Radial extent affected = $R_{\text{vir}}$
  - Heating fraction per duty cycle = 0.01
Entropy

Entropy values are plotted against the radius in units of the Sun's radius, $r/r_{\odot}$, for two different feedback schemes: Observed — CC and Observed — NCC. The graphs show the variation of entropy $K$ [keV cm$^2$] with radius.

Density

Density values are also plotted against the radius in units of the Sun's radius, $r/r_{\odot}$, for the two feedback schemes. The graphs show the variation of electron density $n_e$ [cm$^{-3}$] with radius.

Temperature

Temperature values are plotted against the radius in units of the Sun's radius, $r/r_{\odot}$, for the two feedback schemes. The graphs show the variation of temperature $T_e$ [keV] with radius.

Metallicity

Metallicity values are plotted against the radius in units of the Sun's radius, $r/r_{\odot}$, for the two feedback schemes. The graphs show the variation of metallicity $Z_{\text{met,ISM}}/Z_{\odot}$ with radius.

**Observations**

**Entropy slope**

**Entropy normalisation**

**Metallicity slope**

The new Millennium Gas Simulation

• Simulation details:
  ○ WMAP-7 cosmology
  ○ Full Millennium Simulation resolution
  ○ Guo et al 2011 semi-analytics
  ○ Improved AGN feedback scheme
  ○ Metal enrichment from Type II, Type 1a & AGB
  ○ Without and with radiative cooling

• Status:
  ○ Testing complete in smaller boxes
  ○ DM-only simulation complete
  ○ SA model catalogue constructed
  ○ Gas simulation started

• Data products:
  ○ SA galaxy catalogue
  ○ X-ray/SZ cluster catalogues
  ○ Maps and full datacubes for each cluster

• Science:
  ○ SZ scaling relations and power spectra
    ★ relative contribution of core/halo/filaments
    ★ evolution
    ★ radio source contamination
  ○ X-ray properties of galaxy clusters and groups
    ★ in the WMAP-7 cosmology
    ★ self-consistent stellar population
    ★ entropy profiles that resemble those of NCC clusters
    ★ realistic population of both NCC and CC clusters
  ○ Metal enrichment of ICM/IGM/WHIM from a self-consistent stellar population and feedback model
  ○ Holistic models for clusters extending to high redshift: X-ray, optical, SZ, radio
Simulating cool-core systems  Owain Young
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