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The Form and Evolution of Cluster Correlations In Numerical Samples of Galaxy Clusters

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Abstract

We examine the form and evolution through time of correlations between fundamental cluster observables such as the X-Ray luminosity, mean temperature, and mass in catalogs of simulated clusters. Our sample catalogs are constructed through high-resolution, Eulerian adaptive mesh refinement hydrodynamic simulations using a ΛCDM cosmological model. The volume-limited cluster sample is derived from a cosmological volume 256 h^{-1} Mpc on a side and contains approximately 70 clusters ranging in mass from 2×10^{15} $M_{\odot}$ to 4×10^{14} $M_{\odot}$. We obtain different realizations of our cluster sample by varying the physical processes acting and present results from our baseline adiabatic sample (treating the gravitational collapse of material into clusters with associated shock heating) and samples that are evolved with radiative cooling by the cluster medium and also including star formation (with and without thermal feedback).

1.1 Simulations

We have constructed samples of simulated galaxy clusters using a sophisticated, Eulerian adaptive mesh refinement cosmology code. The simulations evolve dark matter particles and utilize the piecewise parabolic method to evolve the baryonic component. Our samples are drawn from a computational box 256 Mpc on a side and our peak spatial resolution is 15.6 kpc (for seven levels of refinement). In our baseline adiabatic sample our simulations trace the gravitational heating as clusters assemble. At the next level of complexity, we include radiative cooling by the cluster gas. We use a tabulated cooling curve assuming a metal abundance of 0.3 solar. We have also generated samples using a star formation algorithm similar to the scheme developed by Cen & Ostriker (1992) that transforms rapidly cooling, collapsing gas into collisionless "star" particles. For the star formation simulations we consider both the case of only star formation and the case where the stars deposit thermal energy back into the neighboring gas. For the star formation with feedback simulations we assume a fraction 4.1×10^{-6} of the star particle rest mass energy is available to heat the gas. The four different realizations of our cluster sample were all computed assuming a ΛCDM cosmological model with the following parameters: $\Omega_b = 0.026$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, h = 0.7, and $\sigma_8 = 0.928$. The sample contains approximately 75 clusters in the mass range from 4×10^{14} $M_{\odot}$ to 2×10^{15} $M_{\odot}$.

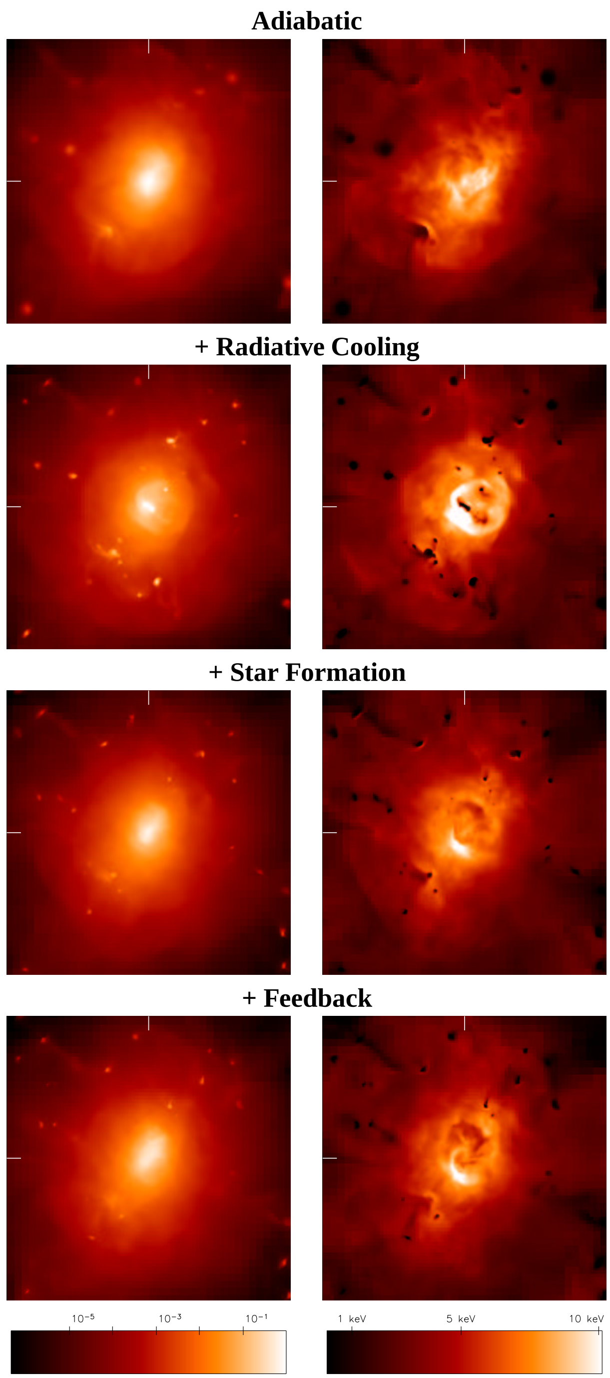

Fig. 1.1. The normalized, X-Ray surface brightness (left column) and projected, emission-weighted temperature (right column) at the current epoch for an identical cluster evolved in the adiabatic limit, with radiative cooling, star formation and finally star formation + feedback. The field of view is 5 Mpc on a side and the image color tables are scaled to the range of values in the adiabatic simulation.

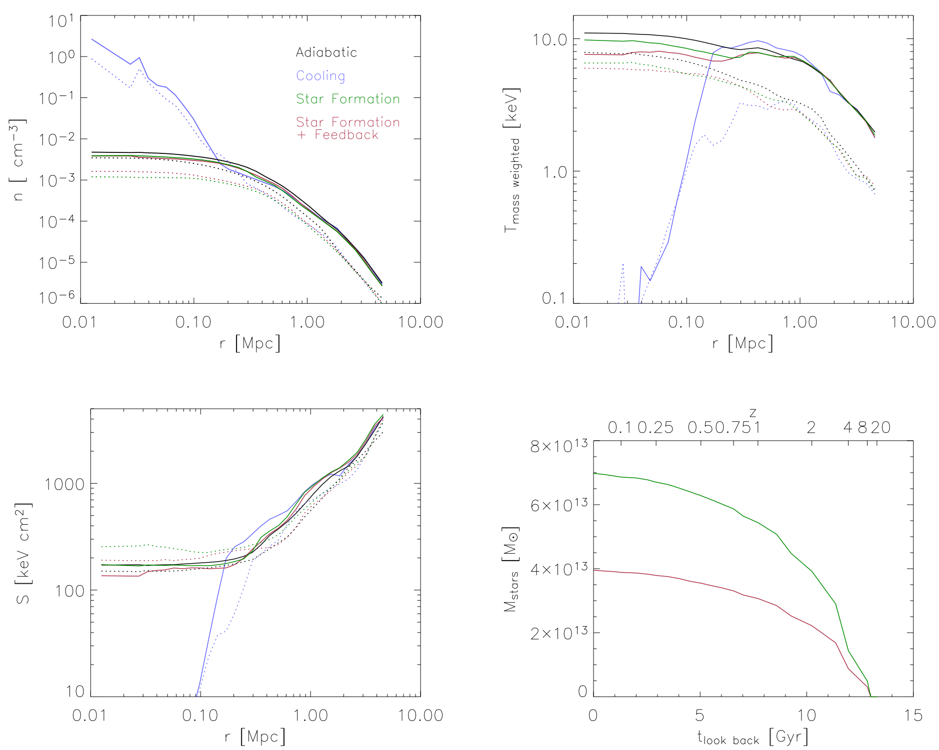

Fig. 1.2. Profiles of density, temperature and entropy for two example clusters at the present epoch. The results for a 1.5×10^{15} $M_\odot$ cluster are shown as solid curves and the dotted curves are from a 5×10^{14} $M_\odot$ cluster. The curves are color coded according to the input physics. Note the cool, dense core in the radiative cooling sample. For runs with star formation, the cool central material is converted into star particles. In the bottom right panel we show the mass in star particles versus time for a typical cluster run both with and without supernova feedback. Without feedback 28% of baryons are in stars at $z = 0$ and with feedback 17% are in stars for this particular cluster.

1.2 Conclusions

- Star formation removes cores of cool, dense gas present in the radiative cooling simulations resulting in clusters similar to the adiabatic sample though with more small-scale substructure than in the adiabatic case.
- Star formation does not appear to introduce an entropy floor.
- The $L_X - T$ and $L_X - M$ relations are steepest for the radiative cooling sample at all redshifts considered while the adiabatic and star formation sample relations steepen at higher redshift.
- All physics realizations considered produce similar $T - M$ relations and all are slightly less steep than the self-similar scaling.

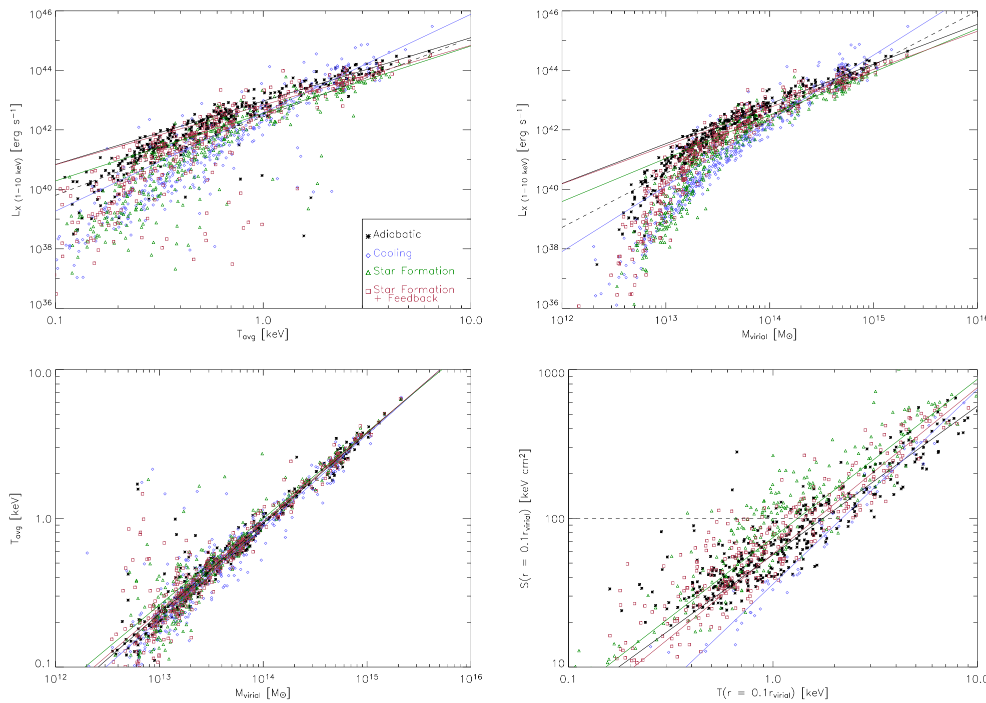

Fig. 1.3. Correlations at the present epoch for sample clusters. The luminosity is integrated out to the virial radius (for $\delta\rho/\rho_{crit}$ = 200) in the 1 - 10 keV energy band assuming 0.3 solar metallicity. T_{avg} is the average, emission weighted temperature within the virial radius. The data points and fit lines are color coded with black corresponding to the adiabatic sample, blue for the cooling sample, green for the star formation sample and red for the sample with star formation feedback. The fits were computed for the 100 most massive clusters only. For the L_X-T relation the dashed curve is from Markevitch (1998) and the dashed curve overlaid on the L_X-M relation is from Reiprich & Böhringer (2002). The observed "entropy floor" (Ponman *et al.* 1999) in low mass systems is indicated by a the horizontal dashed line.

1.3 Acknowledgments

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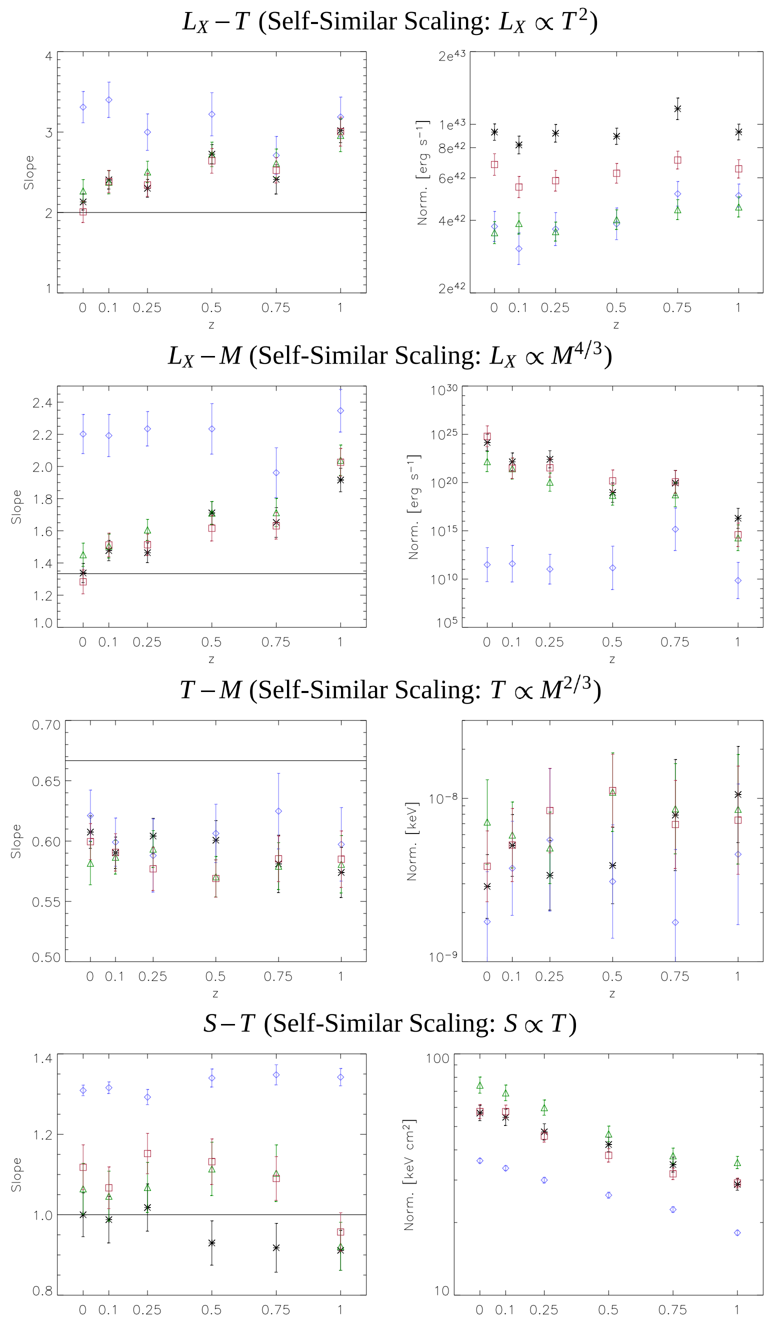

Fig. 1.4. Fitted least squares parameters for the $L_X - T$, $L_X - M$, $T - M$, and $S - T$ relations as a function of redshift. The 100 most massive clusters at each epoch were used in the fits and the heavy, solid lines show the expected exponents for self-similar scaling. The different realizations are represented with black stars for the adiabatic sample, blue diamonds for the radiative cooling sample, green triangles for clusters with star formation and red squares for the star formation + feedback models. The error bars indicate the 67% confidence interval for the fitted parameters.