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Group Scaling Relations From a Cosmological Hydrodynamic Simulation: No Pre-heating Required?

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Abstract. We investigate the X-ray vs. optical scaling relations of poor groups to small clusters ($\sigma \approx 100-700$ km/s) identified in a cosmological hydrodynamic simulation of a ΛCDM universe, with cooling and star formation but no pre-heating. We find that the scaling relations between X-ray luminosity, X-ray temperature, and velocity dispersion show significant departures from the relations predicted by simple hydrostatic equilibrium models or simulations without cooling, having steeper $L_X-\sigma$ and L_X-T_X slopes and a "break" at ≈ 200 km/s (≈ 0.3 keV). These departures arise because the hot (X-ray emitting) gas fraction varies substantially with halo mass in this regime. Our predictions roughly agree with observations. Thus radiative cooling is a critical physical process in modeling galaxy groups, and may present an alternative to *ad hoc* models such as pre-heating or entropy floors for explaining X-ray group scaling relations.

1. Introduction

The simplest view of a cluster is as a sphere of Virial-temperature gas punctuated by old galaxies, with perhaps a cooling flow onto the cD galaxy. Within this model, the gas cooling time is longer than a Hubble time everywhere except near the center, and thus it is predicted that clusters should follow simple "self-similar" scaling relations derived from the Virial theorem combined with an assumption of hydrostatic equilibrium, namely: $L_X \propto T_X^2$, $L_X \propto \sigma_{\rm gal}^4$, and $T_X \propto \sigma_{\rm gal}^2$, where L_X is the total X-ray luminosity, T_X is the gas temperature (presumed to be the halo Virial temperature), and $\sigma_{\rm gal}$ is the velocity dispersion of cluster galaxies (presumed to trace the system's total mass).

While observations of the most massive clusters follow these relations, as one progresses to smaller systems, the self-similar model fails. The failure is most striking when one extends observations to poor groups, where Helsdon & Ponman (2000; HP) found that the luminosity of their poorest groups declined much faster than expected ($L_X \propto T_X^{4.9}$), a fact also interpreted as an "entropy floor" of ~ 100 keV cm^{-2} (Ponman, Cannon & Navarro 1999). One model that successfully accounts for these observations postulates that the gas is "pre-heated" by some unknown physical process (possibly supernovae or winds) with

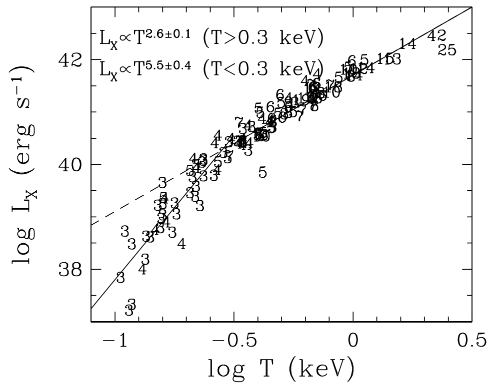

Figure 1: $L_X - T_X$ relation, showing a break at $T \approx 0.3$ keV.

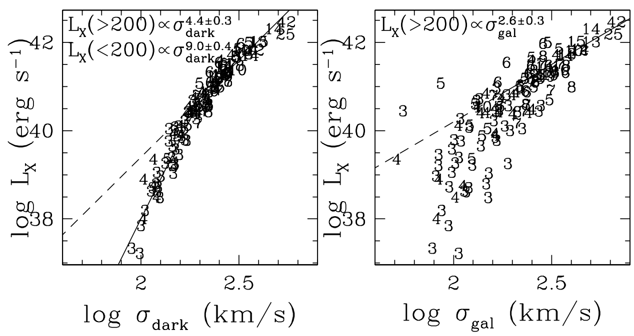

Figure 2: $L_X - \sigma_{\rm DM}$ (left) and $L_X - \sigma_{\rm gal}$ (right) relations.

an energy of ~ 1 keV/baryon. However, the success of this model relies on the assumption that groups are self-similarly scaled-down versions of large clusters.

In these proceedings we present a preliminary test of whether self-similar scaling relations arise naturally in a cosmological hydrodynamic simulation of galaxy formation. We find that on group scales, the self-similar scaling relations are not followed, and that features can arise that quantitatively mimic a pre-heating model. The breaking of self-similarity from clusters to groups is due to an increased cooling efficiency in smaller systems, and does not imply additional heat or entropy input at early times (see also Bryan 2000).

2. Simulation and Group Identification

Our simulation is of a $50h^{-1}$Mpc random volume in a ΛCDM universe with $\Omega_m = 0.4$, $H_0 = 65\ \mathrm{km\,s^{-1}\ Mpc^{-1}}$, and $\sigma_8 = 0.8$. There are 144^3 dark matter and 144^3 SPH particles. It includes cooling, star formation, and thermal feedback. We identify galaxies using SKID, and halos using a spherical-overdensity criterion on friends-of-friends halos, as described in Murali et al. (2001). Our 64-particle galaxy mass resolution limit ($5 \times 10^{10} M_\odot$) corresponds to $\approx L_\star/4$. Halos that contain three or more galaxies are identified as "groups"; we find 128 at $z = 0$.

The X-ray luminosity of a group is computed from all particles with $T > 10^{4.5}$K that are members of that group. Only Bremmstrahlung emission is used;

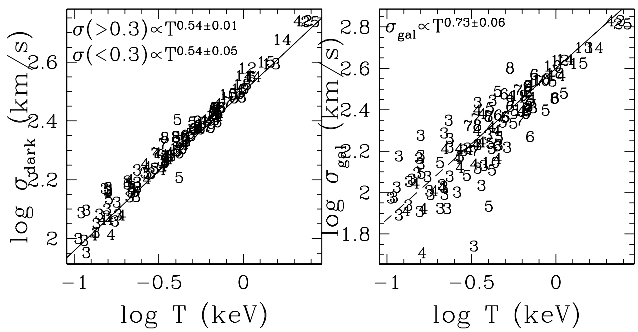

Figure 3: $T_X - \sigma_{\rm DM}$ (left) and $T_X - \sigma_{\rm gal}$ (right) relations.

metal emission is not included in this preliminary analysis to facilitate a straightforward comparison with the self-similar model, and also because intragroup gas metallicities are uncertain. In order to avoid the well-known problem of overestimation of X-ray luminosity due to SPH oversmoothing, we recalculate gas densities using only hot particles, ignoring all particles with $T < 10^{4.5}$K. This explicit decoupling of the hot and cold phases is shown to reproduce the correct X-ray luminosity in analytic cases (Croft et al. 2001). The X-ray temperature is given by the average luminosity-weighted temperature of group particles.

3. Results

Figure 1 shows the $L_X - T_X$ relation for our simulated groups. The plot symbols indicate the number of group members. Best fit power law relations above and below $T = 0.3$ keV are shown in the upper left. The slope, for groups with $T_X > 0.3$ keV, is steeper than predicted by the self-similar model, and steepens even more below ≈ 0.3 keV (the dashed line shows a continuation of the high-temperature slope). The latter slope is consistent with the HP data, and the former with results from clusters (White, Jones & Forman 1997). The break appears at a somewhat lower temperature than is suggested by HP, but more detailed modeling (i.e. including metal emission and aperture effects) may improve agreement. The crucial point is that a break occurs at all, when no physics has been input into the simulation that specifically picks out this temperature scale. This suggests that a straightforward extrapolation of cluster scaling relations (i.e. self-similarity) is an inappropriate model for poor groups.

Figure 2 shows the $L_X - \sigma_{\rm DM}$ (left panel) and $L_X - \sigma_{\rm gal}$ relations (right panel). The dark matter velocity dispersion faithfully traces the group mass. A break is seen in L_X at $\sigma_{\rm DM} \approx 200$ km/s. The slopes above and below the break are consistent with a compilation of $L_X - \sigma$ for clusters down to galaxies by Mahdavi & Geller (2001). Their break occurs at $\sigma \approx 350$ km/s, but given observational uncertainties it is roughly consistent with our prediction.

The galaxy velocity dispersion does *not* trace the group mass when small numbers of galaxies are used. The right panel of Figure 2 shows smaller groups shifted towards lower $\sigma_{\rm gal}$ compared to the left panel, and the best-fit slope is altered significantly. Thus we confirm Zabludoff & Mulchaey's (1998) result that a large number of galaxies ($\gtrsim 10$) must be used to accurately estimate

group velocity dispersions. HP find a slope consistent with our $L_X - \sigma_{\rm DM}$, but claim that their σ is lowered due to misestimation from using small numbers of galaxies. However, Zimer, Zabludoff & Mulchaey (these proceedings) find a similar slope using more than 20 galaxies per group.

Figure 3 shows the $T_X - \sigma$ relation for $\sigma_{\rm DM}$ (left panel) and $\sigma_{\rm gal}$ (right panel). Interestingly, the $T_X - \sigma_{\rm DM}$ relation shows no break at 200 km/s, indicating that the drop in L_X is not due to an additional heat source such as shock heating on filaments. The slope is in reasonable agreement with the self-similar model, indicating that these systems are Virialized. However, the misestimation of σ from using too few galaxies results in a steeper slope (right panel), bringing it more into agreement with HP; this can be misinterpreted as excess heat injection.

Since there is no excess heat, we conclude that the break in L_X arises from a drop in the hot fraction due to an increase in efficiency of galaxy formation in smaller systems. The fraction of hot ($T > 10^5$ K) gas for our simulated groups drops linearly from 50% at $\sigma > 500$ km/s to 20% at $\sigma \approx 100$ km/s. When placed on a logarithmic scale (cf. the L_X plots), the decline appears to steepen at lower σ; hence the appearance of a "break". While the large cold gas + stellar fraction may appear to contradict baryon estimates in clusters, there are indications that the hot gas fraction decreases in smaller systems (see Bryan 2000 for summary). In any case, the trend for a rapid decline of the hot fraction in this mass regime seems to be a generic feature of CDM-based galaxy formation, arising in semi-analytic models as well (Bower, these proceedings).

4. Summary

Using a cosmological hydrodynamic simulation, we have shown that group X-ray scaling relations are not expected to follow simple extrapolations from clusters. For rich groups, the scaling relations for the X-ray luminosity are somewhat different than predicted by self-similarity arguments, while for poor groups the scaling relations deviate dramatically. The trends of our predictions are in agreement with observations. The location of the predicted break predicted is slightly different than that observed, but more careful modeling and better data may improve the agreement. We conclude that cooling is responsible for breaking self-similarity, and hence it is premature to use observed poor group scaling relations as evidence for an excess injection of heat or entropy into these systems.

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