Electron and Ion Equilibration by Coulomb Collisions in the Envelopes of Galaxy Clusters

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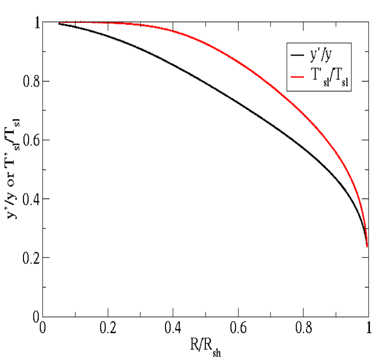
ABSTRACT: Cosmological studies using clusters of galaxies require a detailed understanding of cluster physics (e.g., the baryon fraction). Recent X-ray and SZ observations suggest that a significant fraction of the thermal energy and/or baryons in the intracluster medium are missing, which is not expected from hydro simulations. In fact, the physical state of the hot gas in outskirts of clusters is poorly known. To do precision cosmology, systematic uncertainties at the percent level must be addressed. We present a study of X-ray and SZ signatures of nonequipartition between electrons and ions in the cluster outer regions. We address the bias to cosmological studies introduced by such nonequilibrium processes.

INTRODUCTION: The collisionless accretion shock at the virial radius of a cluster should primarily heat the ions since they carry most of the kinetic energy of the infalling gas. Assuming that cluster accretion shocks are similar to those in supernova remnants, the electron temperature (T_e) immediately behind the shock would be lower than the ion temperature. The equilibration between electrons and ions would then proceed by Coulomb collisions. Near the virial radius, due to the low density, the Coulomb collisional time scale can be comparable to the age of the cluster, and the electrons and ions may not achieve equipartition in these regions (Fox & Loeb 1997). In fact, non-equipartition of ions and electrons is also known in various astrophysical shocks. Since X-ray and SZ observations measure the properties of the electrons in the ICM, the net effect is to underestimate the total thermal energy content within clusters. This might account for some or all of the missing thermal energy in the ICM derived by recent X-ray and SZ observations (Afshordi et al. 2007, Evrard et al. 2008).

Modeling Electron and Ion Equilibration in Galaxy Clusters:

- For our ΛCDM Universe, at high enough redshift where Ω_M dominates over Ω_Λ, the dynamics of our Universe should be similar to that of the Einstein-de Sitter Universe, and cluster profiles might follow the self-similar solution (Bertschinger 1985). Numerical simulations show that clusters are close to self-similar down to $z(\Omega_M = \Omega_\Lambda)$ at least for the outer regions (Ryu & Kang 1997). Hence, we assume self-similar solutions can be applied to clusters at redshift $z(\Omega_M = \Omega_\Lambda) \gtrsim 0.33$.
- Under the self-similar model, the effect of non-equipartition depends entirely on the cosmic time (age of the cluster) and the equipartition time scale just inside the shock radius (Fox & Loeb 1997).
- After scaling the time scales to our ΛCDM cosmology to a high enough redshift ($z \gtrsim 0.33$), we calculated the biases in X-ray and SZ observables, e.g., T_{sl}'/T_{sl}, y'/y, and Y'/Y (Figures 1 & 2). The prime and un-prime quantities correspond to clusters in non-equipartition and in fully equipartition, respectively.
- At low redshift where self-similar solutions may break down, numerical simulation is indeed needed to address the degree of non-equipartition. In the second part of this work, we studied four models by simply assuming the degree of non-equiparition (e.g. Y'/Y) at low redshift ($z \approx 0$) to be:
  1) the same as the self-similar solution (Model M1 below),
  2) the same as the high redshift ($z\approx0.33$) value (Model M2 below),
  3) a half of the high redshift value (Model M3 below),
  4) in fully equipartition (Model M4 below).



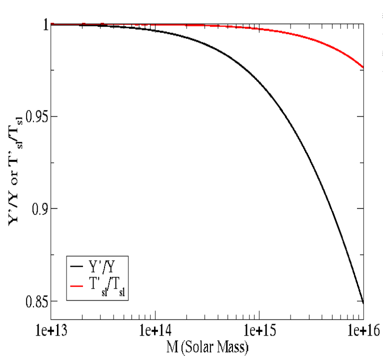


Figure 1 ***(left panel):*** Biases of Comptonization parameter and spectroscopic-like temperature, y'/y and T_{sl}'/T_{sl}, respectively, as a function of projected radius, R, in unit of shock radius, R_{sh}. A cluster mass of $2\times10^{15} M_\odot$ at z=0.33 is assumed.
Figure 2 ***(right panel):*** Biases of integrated Comptonization parameter and average spectroscopic-like temperature over the whole cluster, Y'/Y and T_{sl}'/T_{sl}, respectively, as a function of cluster mass, M, in unit of solar mass.

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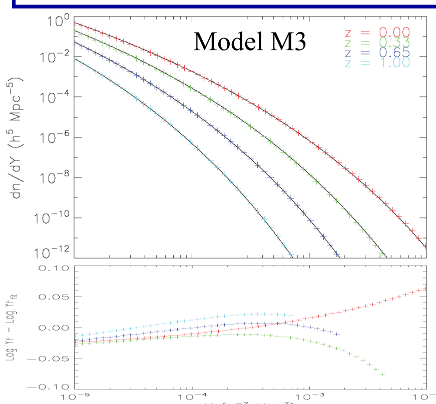
Impact of Non-equipartition on Cosmological Parameter Estimation from SZ Surveys:

- We followed the technique developed by Randall et al. (2002) to estimate the effect of non-equipartition on the distribution function, YF, determined from extended Press-Schechter (PS) theory.
- We assume a flat, ΛCDM cosmology with Ω_M=0.3, σ_8=0.8 and w=-1. We generated the PS distribution function, YF, in this underlying cosmology. This YF describes the distribution function of clusters in fully equipartition.
- We then applied the non-equipartition effect $(Y'/Y)_z/(Y'/Y)_{z=0}$ to generate a biased PS distribution function, YF'. We fitted the biased YF' by assuming the cosmology was flat with a constant w that is not necessarily equal to -1. The fitted cosmological parameters with different models assumed are given in Table 1. An example of the fitted YF' is shown in Figure 3.



Model	Ω_M	σ_8	w
M1	0.298(1%)	0.807(1%)	-1.05(5%)
M2	0.307(2%)	0.799(0%)	-1.02(2%)
M3	0.326(9%)	0.783(2%)	-0.93(7%)
M4	0.350(17%)	0.765(4%)	-0.84(16%)

Figure 3: Crosses: Biased PS distribution function, YF', generated by including the non-equipartition effect. Solid curves: Best-fitted PS function. Lower panel shows the log residual of the fits.
Table 1: Best-fit cosmological parameters if non-equipartition is not properly accounted for. Deviations from our underlying cosmology are shown in the parentheses. All models assume the bias, Y'/Y, follows the self-similar solution for redshift $z\gtrsim0.33$. The assumed biases, Y'/Y, at z=0 for models M1 to M4 were described above.

Conclusions:

- The spatially resolved X-ray spectroscopic-like temperature profile deviates significantly from equipartition value in the outer region of a cluster, while the deviation for the average temperature over the entire cluster is less than 3%. For X-ray temperature measured within a small projected radius (e.g. $\sim R_{500}$), non-equipartition effect should be negligible.
- At a high enough redshift where self-similarity might hold, the integrated SZ Comptonization parameter can be 5-10% biased low for massive clusters if the non-equipartition effect is not properly accounted for. Gas mass fraction measurement based on SZ observations can be biased by the same amount. Depending on model assumed, we have shown that cosmological parameters derived from SZ surveys can be biased at a 10% level; these calculations may overestimate the bias due to non-equipartition if the Y versus mass relation is determined empirically by the SZ surveys (e.g., by self-calibration).