Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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Reproducing the entropy structure of clusters and groups

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Abstract. We describe a semi-analytic model for the X-ray emitting gas in clusters and groups in which the gas is preheated before halo formation. The model relies on physically sound prescriptions for the formation and evolution of halo structure. For a gas temperature gradient corresponding to a polytropic index of 1.2 and an energy injection of 0.6 keV per gas particle, this model successfully reproduces the observed correlations between gas luminosity, gas temperature and halo mass. We use the model to investigate the detailed entropy structure of groups and clusters of galaxies and compare the results with the observational data.

1. Dark-matter model

We assume that the formation of halos, as well as their internal structure and dynamics following virialization, is dominated everywhere by the dark-matter (DM) component. The evolution of DM halos is computed according to the model developed by Salvador-Solé *et al.* (1998) and Raig *et al.* (1998, 2001). This model self-consistently includes a distinction between minor and major mergers in the usual extended Press-Schechter formalism by means of a phenomenological frontier Δ_{mer} for the fractional mass increase separating two basic mass aggregation regimes for halos: gentle mass accretion, where the halo structure is assumed to evolve undisturbed inside-out through the continuous aggregation of small clumps, and major merger events, where participant halos are disrupted giving rise to the formation of a completely new system. The epoch of formation of a given halo can be naturally defined as the redshift at which the halo experiences its last major merger. From this definition one can derive a probability distribution of formation times as well as a typical mass-accretion evolution for halos of any given mass, both in agreement with the predictions of N-body simulations (Raig *et al.* 2001). In this work we adopt the median of the formation time distribution as the typical halo formation time t_f, while the corresponding upper and lower quartiles will measure the dispersion associated to t_f. As shown by Manrique *et al.* (2003), taking the appropriate value of Δ_{mer} the model is able to reproduce the universal density profile and the mass-density correlation of halos predicted by N-body simulations.

In the present study, we consider the following cosmological context: a flat universe with $\Omega_M = 0.3$ and $\Lambda = 0.7$, a cold dark matter power spectrum of density fluctuations with normalization $\sigma_8 = 1$, a baryon content $\Omega_b = 0.04$ and a normalized Hubble constant $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 2/3$. For our DM model we adopt the empirical correlation between halo mass and halo concentration proposed by Bullock *et al.* (2001) to fit their N-body simulations (this requires a value of $\Delta_{mer} = 0.2$). In this way, the DM evolution is determined without free parameters.

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2. Gas model

Instead of considering a detailed model for the shock-heating of gas accreted by halos we adopt a set of physically motivated and simplified hypotheses with the aim of describing the expected post-shock conditions of virialized gas into halos even if there is an extra energy injection previous to halo virialization (which we refer as preheating). In the present model preheating is assumed to be universal, i.e., independent of halo mass. However, we do not need to assume that preheating occurs at any concrete redshift or even at a single redshift since we simply consider that the gas has been preheated before the time of halo formation (or last major merger). On the other hand, it must be noticed that our halo model predicts redshifts of formation which are not greater than 1.5 for halo masses greater than 10^{12} solar masses.

After halo formation and relaxation we consider that the hot diffuse gas is in thermal pressure-supported hydrostatic equilibrium within the gravitational potential well of the halo created by the DM distribution (we neglect gas and galaxy contributions to the gravitational halo mass in a first approximation). The distributions of gas and DM are taken to have the same total radius at any time. The gas mass fraction at the virial radius of present day halos is taken to be equal to the cosmological baryon fraction Ω_b/Ω_M. It is assumed that the gas is in a single phase, behaves as a monoatomic ideal gas, has a null metallicity gradient, and its density, ρ_g, and temperature T_g, are related through a polytropic equation $\rho_g \propto T_g^{1/(\gamma-1)}$. The polytropic index, γ, is left as a free parameter within the range $1 \leqslant \gamma \leqslant 5/3$. Finally, we take into account the balance between the specific energies of gas and DM that must hold for a virialized halo (in absence of mass losses during formation and any subsequent loss of energy). According to this energy balance, the specific energy of gas should be equal to the specific energy of DM plus any form of specific energy increment caused by preheating, $\Delta E/\bar{\mu}_{\rm ph}$, where $\bar{\mu}_{\rm ph}$ is the mean mass per gas particle when the preheating takes place (we assume a gas with zero metallicity at that time) and ΔE is the energy per gas particle due to preheating which is left as a free parameter.

3. Comparison with observational results

Since we have fixed the cosmological context of our study, the model has only two free parameters, the polytropic index, γ, and the energy injected to the system by preheating, ΔE. We derive the model luminosities using the Sutherland & Dopita (1993) cooling function table for a gas with one third solar metallicity, whereas model temperatures are emission weighted within the halo virial radius. Then, by comparing our model predictions with the X-ray luminosity-temperature correlation observed for real systems with temperatures in the range from 0.5 keV to 10 keV, we find that the best fit to the real data is achieved for $\gamma = 1.2$ and $\Delta E = 0.6$ keV per particle. These values also fit quiet well the observed mass-temperature correlation. In Figure 1 we show the comparison between the model results from the previous best-fit parameters and the observational measurements of the gas entropy at various distances from the system center. One can see that our model again reproduces quite well the real data and, in particular, it predicts a minimum entropy close to the value observed for systems with gas temperature around 1 keV (Lloyd-Davies *et al.* 2000). However, for temperatures below 1 keV the inner entropy increases when the gas temperature decreases. More extended data samples are required in order to determine wether this trend is certainly present in real systems (see, e.g. , the recent work of Osmond & Ponman 2004). In the case that the observations of real systems with temperatures below 1 keV confirm that the entropy significantly decreases

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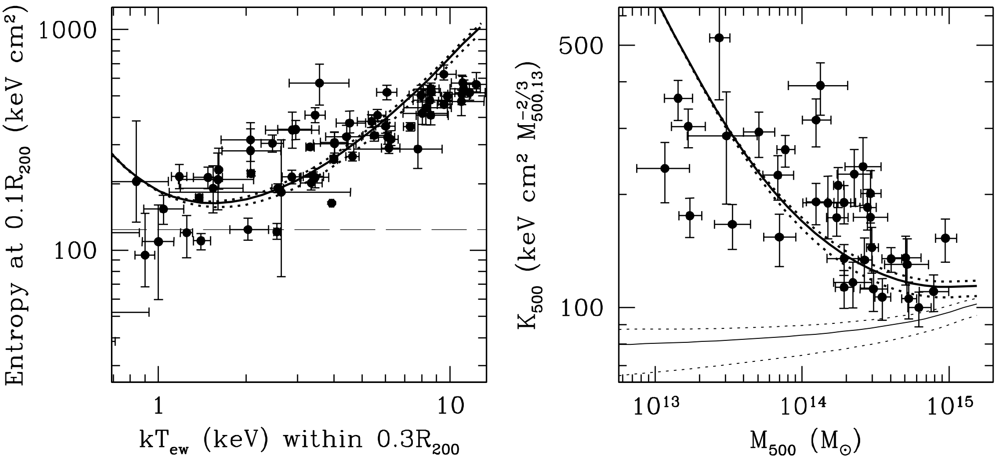

Figure 1. Comparison of the model predictions for the best-fit values of γ and ΔE in §3 with the measured gas entropy in the inner and outer regions of systems with different gas temperatures. Left panel: entropy at $0.1R_{200}$ vs emission-weighted temperature, where R_{200} is the radius enclosing a halo overdensity equal to 200. The points with error bars are taken from Ponman *et al.* (2003). The horizontal long-dashed line is the observed entropy floor from Lloyd-Davies *et al.* (2000). The thick solid line is the model prediction when halos are formed at t_f while the dotted lines indicate the dispersion corresponding to the halo formation time distribution function (see §1). Right panel: entropy at the radius enclosing a halo overdensity of 500 vs mass within such radius ($M_{500,13}$ is the latter mass in units of 10^{13} $M_\odot$). Points with error bars are from the observational study of Finoguenov *et al.* (2002). Again thick solid an dotted lines are the model predictions. To illustrate the effects of preheating we also plot the model results for $\Delta E = 0$ and $\gamma = 1.2$ in thin solid and dotted lines.

with gas temperature, then our model results would imply that a universal preheating of gas is inconsistent with observations.

References

Bullock, J.S., Kolatt, T.S., Sigad, Y. *et al.* 2001 *MNRAS* **321**, 559
Finoguenov, A., Jones, C., Böhringer, H. & Ponman, T.J. 2002 *ApJ* **578**, 74
Lloyd-Davies, E.J., Ponman, T.J. & Cannon, D.B. 2000 *MNRAS* **315**, 689
Manrique, A., Raig, A., Salvador-Solé, E. *et al.* 2003 *ApJ* **593**, 26
Osmond, J.P.F. & Ponman, T.J. 2004 *MNRAS* in press, astro-ph/0402439
Ponman, T.J., Sanderson, A.J.R. & Finoguenov, A. 2003 *MNRAS* **343**, 331
Raig, A., González-Casado, G. & Salvador-Solé, E. 1998 *ApJ* **508**, L129
Raig, A., González-Casado, G. & Salvador-Solé, E. 2001 *MNRAS* **327**, 939
Salvador-Solé, E., Solanes, J.M. & Manrique, A. 1998 *ApJ* **499**, 542
Sutherland, R.S. & Dopita, M.A. 1993 *ApJSup* **88**, 253

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