A Physical Model for Baryons in Clusters of Galaxies

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ABSTRACT

The X-ray emission from clusters of galaxies is one of the best observational probe to investigate the distribution of dark matter at intermediate and high redshifts. Since the disposition of the intracluster plasma (ICP) responsible of the emission is crucial to link X-ray properties to the global properties of the dark matter halos, we propose a semi-analytical approach for the diffuse baryons. This comprises the following blocks: Monte Carlo “merging histories” to describe the dynamics of dark matter halos; the central hydrostatic disposition for the ICP; conditions of shock, or of closely adiabatic compression at the boundary with the external gas, preheated by stellar energy feedbacks. From our model we predict the $L - T$ correlation, consistent with the data as for shape and scatter.

1. Introduction

Groups and clusters of galaxies constitute cosmic structures sufficiently close to equilibrium and with sufficient density contrast ($\delta \approx 2 \times 10^2$ inside the virial radius $R$) as to yield definite observables. They are dominated by dark matter (hereafter DM), while the baryon fraction is observed to be less than 20%. The great majority of these baryons are in the form of diffuse plasma (ICP) with densities $n \sim 10^{-3} \text{ cm}^{-3}$ and virial temperatures $kT \sim GMm_H/10R \sim 5 \text{ keV}$, and are responsible for powerful X-ray luminosities $L \sim 10^{44} \text{ erg/s}$ by optically thin thermal bremsstrahlung. As the plasma is a good tracer of the potential wells, much better than member galaxies, the X-ray emission is a powerful tool to investigate the mass distribution out to moderate and high redshifts. The ICP temperature directly probes the height of the potential well, with the baryons in the role of mere tracers; on the other hand, the luminosity, with its strong dependence on density ($L \propto n^2$), reliably probes the baryonic content and distribution. Statistically, a definite $L - T$ correlation is observed (albeit with considerable scatter), and this provides the crucial link to relate the X-ray luminosity...
functions with the statistics of the dark mass $M$ or with that of the corresponding $T$.

Many numerical experiments, using hydrodynamical N–body (see especially Gheller, Pantano & Moscardini 1997, Bryan & Norman 1997), provide a comprehensive tool to model the ICP distribution in the potential wells. However, such numerical experiments still do not have enough dynamic range to describe DM and ICP over the full range from $\sim 50$ Mpc associated with the large scale structures (which guide the ongoing mergers of DM halos), to the inner 50 kpc where the ICP yields a substantial contribution to $L$, and moreover do not include properly non–gravitational effects, which instead cannot be ignored.

The simplest semi–analytical approach is constituted by the Self Similar model (Kaiser 1986) which include only gravity and assumes the ICP amount to be proportional to the DM at all $z$ and $M$. This leads to a relation $L \propto T^2$ conflicting with the observed correlation for rich clusters, which is close to $L \propto T^3$ (David et al. 1993; Mushotzky & Scharf 1997). A missing ingredient is thought to be the stellar energy feedback by supernovae.

The above features motivate us to develop a comprehensive semi–analytical model for the ICP which include the effects of stellar energy scales. First we assume that such energy input is efficient in depleting the potential wells of the clusters progenitors, at $z \simeq 1 \div 2$, and in pre-heating the intergalactic medium to temperatures in the range $T_1 = 0.1 \div 0.8$ keV as recently evidentiated in the outer cluster atmosphere (Henriksen & White 1996). Then we describe clusters evolution as a sequence of hierarchical merging episodes of the DM halos, associated in the ICP to shocks of various strengths (depending on the mass ratio of the merging clumps), which provide the boundary conditions for the ICP to re–adjust to a new hydrostatic equilibrium. In §3 we shall show that our predictions for the X-ray properties of clusters are consistent with recent data (see also Cavaliere, Menci & Tozzi 1997, hereafter CMT97).

2. A physical model for the ICP

The mass growth of dark halos leading to the formation of groups and clusters, develop through the accretion of diffuse matter or massive merging events between virialized halos. In our approach the history of such episodes is followed in the framework of the hierarchical clustering by Monte Carlo simulations. During the mass growth, the pre–heated ICP is recovered through shocks of variable intensity, depending on the temperature ratio between the accreted gas and the virialized plasma contained in the main progenitor. The ICP is reset to a new equilibrium after each episode of accretion or merging.

In this framework it is possible to check the reliability of the assumption of equilibrium. Roettiger, Stone & Mushotzky (1997) show that after a major merging event, i.e., with a mass ratio less than 2.5, the non thermal contribution to the pressure
Figure 1: Fraction of groups and clusters which have experienced at least one massive merging event with a mass ratio less than 2.5 in the last 2 Gyrs. Solid line: tilted CDM, dotted line: Open CDM, dashed line: ΛCDM (see N. Menci this volume).

lasts less than two Gyrs. Adopting this as a conservative rule to identify disturbed objects, we can compute the fraction of clusters at redshift $z = 0$ for which the hydrodynamical equilibrium does not fully apply. As is shown in fig. 1 this fraction is less than 20% at cluster scales in most FRW universes. Of course the situation is better for small objects, as they are in average older than rich clusters.

2.1. Hydrodynamical equilibrium

To compute the disposition of the ICP in equilibrium in a DM potential well, we have just to solve the hydrostatic equilibrium equation

$$
\frac{1}{n} \frac{dP}{dr} = -G \frac{M(< r)}{r^2},
$$

where $n(r)$ is the gas density profile, $M(< r)$ is the mass contained within the radius $r$ (dominated by DM) and $P$ is the pressure. To solve the equation we need the boundary condition, i.e. the density of the gas at the virial radius $n(R)$, and the state equation, that we write for a polytropic gas:

$$
P(r) = \frac{kT(r)}{\mu m_H} n^\gamma(r),
$$

where $m_H$ is the proton mass, $\mu \sim 0.6$ is the mean molecular weight of the ICP, and $\gamma$, ranging from 1 to 5/3, is the polytropic index treated as a free parameter. The resulting profile is:

$$
n(r) = n(R) \left[ 1 + \beta \left( \frac{\gamma - 1}{\gamma} \right) (\phi(R) - \phi(r)) \right]^{1/(\gamma-1)},
$$
where \( \phi \equiv V/\sigma_r \) is the adimensional gravitational potential and \( \beta \equiv \mu m_H \sigma_r / kT_2 \), with \( \sigma_r \) the line-of-sight velocity dispersion of the DM particles. Here \( T_2 \) is the temperature at the virial radius. The above equation can be considered a generalized \( \beta \)-model (Cavaliere & Fusco–Femiano 1978), which reconduces to the usual isothermal case for \( \gamma \to 1 \). Before computing the ICP distribution, we then need the boundary condition \( n(R) \).

2.2. Physics of shocks

The key boundary condition is provided by the dynamic stress balance \( P_2 = P_1 + m_H n_1 v_1^2 \), relating the exterior and interior pressures \( P_2 \) and \( P_1 \) to the inflow velocity \( v_1 \) driven by the gravitational potential at the boundary. Here \( n_1 \) is the baryon density external to the virial radius, and it is assumed to be unbiased respect to the universal value, i.e. \( n_1 = \Omega_B \rho \) where \( \rho \) is the total matter density. We expect the inflowing gas to become supersonic close to \( R \), when \( m_H v_1^2 > 2kT_1 \). In fact, many hydrodynamical simulations of loose gas accretion into a cluster (from Perrenod 1980 to Takizawa & Mineshige 1997) show shocks to form, to convert most of the bulk energy into thermal energy, and to expand slowly remaining close to the virial radius for some dynamical times. So we take \( R \) as the shock position, and focus on nearly static conditions inside, with the internal bulk velocity \( v_2 << v_1 \).

The post-shock state is set by conservations across the shock not only of the stresses, but also of mass and momentum, as described by the Rankine-Hugoniot conditions (see Landau & Lifshitz 1959). These provide at the boundary the temperature jump \( T_2/T_1 \), and the corresponding density jump \( g \equiv n(R)/n_1 \) which reads

\[
g\left( \frac{T_2}{T_1} \right) = 2 \left( 1 - \frac{T_1}{T_2} \right) + \left[ 4 \left( 1 - \frac{T_1}{T_2} \right)^2 + \frac{T_1}{T_2} \right]^{1/2} \tag{4}
\]

for a plasma with three degrees of freedom. Eq. 4 includes both weak (with \( T_2 \approx T_1 \), appropriate for small groups accreting preheated gas, or for rich clusters accreting comparable clumps), and strong shocks (appropriate to "cold inflow" as in rich clusters accreting small clumps and diffuse gas). From clusters to groups, the density jump \( g(T) \) lowers from the maximum value of 4 towards unity.

Given the inflow velocity \( v_1 \) and the nearly static post-shock condition \( v_2 << v_1 \), it is possible to work out the explicit expression of the post-shock temperature \( T_2 \) in the form:

\[
kT_2 = \frac{\mu m_H v_1^2}{3} \left[ \frac{(1 + \sqrt{1 + \epsilon})^2}{4} + \frac{7}{10} \epsilon - \frac{3}{20} \frac{\epsilon^2}{(1 + \sqrt{1 + \epsilon})^2} \right], \tag{5}
\]

where \( \epsilon \equiv 15kT_1/4\mu m_H v_1^2 \). For \( \epsilon \gg 1 \) the shock is weak and \( T_2 \approx T_1 \) is recovered as expected. In the case of strong shocks, \( \epsilon \ll 1 \) and the approximation \( kT_2 \approx
Figure 2: a) The $\beta(T)$ parameter entering equation 3. b) Baryonic fraction respect to the universal value $\Omega_B$ for different values of $\gamma$. Continuous line: $\gamma = 1$; dotted line: $\gamma = 1.1$; dashed line: $\gamma = 1.2$.

\[-V(R)/3 + 3kT_1/2\] holds, where the second term is the contribution from the non–gravitational energy input.

Now we can compute the ICP distribution, assuming a specific choice for the potential well (in the following we use forms given by Navarro, Frenk & White 1996, but of course this is not mandatory). First, we compute $\beta(T)$, which decline from $\sim <1$ for rich clusters, to $\sim 0.4$ for poor groups, where the stellar competes with the gravitational energy, as shown in fig. 2a.

In fig. 3a,b we show the emission–weighted temperature and density profile for two different values of $\gamma$ in the case of a rich cluster with $M \sim 10^{15} M_\odot$. A temperature profile with a mild decrease out to $r \sim 1$ Mpc is in agreement with the observations (Markevitch et al. 1997), pointing toward a value $\gamma \lesssim 1.2$. The corresponding baryonic fraction lowers down with the mass scale by a factor of three from clusters to groups (see fig. 2b).

3. The $L$-$T$ correlation

The X-ray luminosity of a cluster with temperature profile $T(r)$ and density profile $n(r)$ can be written:

$$L \propto \langle g^2(T) \rangle \int d^3r \frac{n^2(r)}{n^2(R)} T^{1/2}(r).$$

In fact, before computing the $L$–$T$ relation, the statistical effect of the merging histories has to be taken into account. For a cluster or group of a given mass (or temperature), the effective compression factor squared $\langle g^2 \rangle$ is obtained upon averaging eq. 4 over the sequence of the DM merging events; in such events, $T_2$ is the
virial temperature of the receiving structure, and \( T_1 \) is the higher between the stellar preheating temperature and that from “gravitational” heating, i.e., the virial value prevailing in the clumps being accreted. All that is accounted for in our model using Monte Carlo simulations; these are based on merging trees corresponding to the excursion set approach of Bond et al. (1991), consistent with the Press & Schechter (1974) statistics (see CMT97). The averaged \( \langle \gamma^2 \rangle \) is lower than the \( \gamma^2 \) computed with a single temperature \( T_1 \), because in many events the accreted gas is at a temperature higher than the preheating value. In addition, an intrinsic variance is generated, reflecting the variance intrinsic to the merging histories (see fig. 4a).

The net result is shown in fig 4b. In agreement with the observations (David et al. 1993; Ponman et al. 1996), the shape of the average \( L - T \) relation flattens from \( L \propto T^5 \) at the group scale (where the nuclear energy from stellar preheating competes with the gravitational energy) to \( L \propto T^3 \) at the rich cluster scales. At larger temperatures the shape asymptotes to \( L \propto T^2 \), the self-similar scaling of pure gravity. Notice the intrinsic scatter due to the variance in the dynamical merging histories, but amplified by the \( n^2 \) dependence of \( L \). We note that the shape of the \( L - T \) relation is little affected by change of \( \gamma \). The average normalization formally rises like \( \rho^{1/2}(z) \), where \( \rho \) is the effective external mass density which increases as \( (1 + z)^2 \) (Cavaliere & Menci 1997) in filamentary large scale structures hosting most groups and clusters. This implies, e.g., an increase of 30% at \( z = 0.3 \), consistent with the observations by Mushotzky & Scharf (1997).

4. Conclusions

The ICP state in the hierarchically evolving gravitational wells constitutes the
focus of our new approach. We propose that such state follows suit, passing through a sequence of equilibrium condition that we compute semi-analytically. These computations comprise: the merging histories of the DM potential wells, obtained with a large statistics from Monte Carlo simulations of the hierarchical clustering; the inner hydrostatic equilibrium disposition, updated after each merging episode; and the boundary conditions provided by strong and weak shocks, or even by a closely adiabatic compression, depending on the ratio of the infall to the thermal energy in the preheated external medium.

The results of our model depend on two parameters, the external temperature $T_1$ and density $n_1$, which are not free. Specifically, we use for $T_1$ the range $0.1 \div 0.8$ keV provided by the literature on stellar preheating. The value of $n_1$ for rich clusters is related to the DM density by the universal baryonic fraction. The expression of the bolometric luminosity is proportional to $g^2 = (n_2/n_1)^2$, the square of the density jump at the bounding shock. The average of such factor over the merging histories coupled with $\beta(T)$ is what gives to the statistical $L - T$ correlation the curved shape shown in fig. 4b. In addition, our approach predicts an intrinsic variance of dynamical origin due to the different merging histories, and built in the factor $g^2$. Moreover the decreasing temperature profiles are in agreement with the published data and with the results from advanced simulations. A straightforward application is the prediction for the X-ray statistics in different FRW universes (see N. Menci, this volume, and Cavaliere, Menci & Tozzi 1998).
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