THE INTRACLUSTER PLASMA: A UNIVERSAL PRESSURE PROFILE?

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ABSTRACT

The pressure profiles of the intracluster plasma in galaxy clusters show a wide variance when observed in X-rays at low redshifts, \( z \lesssim 0.2 \). We find the profiles to follow two main patterns, featuring either a steep or a shallow shape throughout both core and outskirts. We trace these shapes back to a physical dichotomy of clusters into two classes, marked by either low entropy (LE) or high entropy (HE) throughout. From X-ray observations and Sunyaev–Zel’dovich (SZ) stacked data at higher redshifts \( 0.2 \lesssim z \lesssim 0.4 \), we obtain evidence of an increasing abundance of HEs relative to LEs. We propose this to constitute a systematic trend toward high \( z \); specifically, we predict the pressure profiles to converge into a truly universal HE-like template for \( z \gtrsim 0.5 \). We submit our physical templates and converging trend for further observational tests, in view of upcoming measurements of individual, stacked, and integrated SZ signals.

Key words: cosmic background radiation – galaxies: clusters: general – methods: analytical – X-rays: galaxies: clusters

Online-only material: color figures

1. INTRODUCTION

A keen interest is focusing on the radial pressure profiles \( p(r) \) that prevail in the hot intracluster plasma (ICP) filling up galaxy clusters. Specifically, the degree of their “universality” among rich clusters is debated on the following grounds.

On the upside, the profile of the ICP thermal pressure \( p \equiv n k_B T/\mu \) (with the mean molecular weight \( \mu \approx 0.59 \) for cosmic abundances) is expected to score off the components: temperature \( T(r) \) and number density \( n(r) \equiv \rho(r)/m_p \), on account of its prompt equilibration at sound speed in the absence of forcing stresses. The equilibrium gradient is simply linked by

\[
\frac{dp}{dr} = -\frac{GM(<r)}{r^2} \rho
\]

(1)

to the gravitational force from the dark matter (DM) distribution \( M(<r) \) on the ICP mass density \( \rho \).

On the downside, one may worry that the equilibrium pressure profiles might be affected by the complexities found for redshifts \( z \lesssim 0.2 \) in the X-ray observations. These probe \( n \) from the surface brightness \( S_X \propto n^2 T^{1/2} \) emitted by the ICP via thermal bremsstrahlung, while the temperatures \( k_B T \) in the keV range are measured from spectroscopy.

In fact, in the cluster cores for \( r \lesssim 0.2 R_{500} \),5 the radiation observed in X-rays is to erode the ICP thermal content on the cooling timescale \( t_c \approx 30 (k_B T/\text{keV})^{1/2} (n/10^{-3} \text{ cm}^{-3})^{-1} \) Gyr (e.g., White & Rees 1978; Voit & Bryan 2001). The process tends to speed up as \( n \) rises and \( T \) lowers, with the effect of steepening the inner pressure gradient as per Equation (1). A catastrophic runaway is conceivably offset by the energy fed back from self-regulated active galactic nucleus (AGN) activities (see discussions by Cavaliere et al. 2002; Lapi et al. 2003, 2005; Ciotti & Ostriker 2007; Churazov 2010) or is even forestalled by strong energy injections from deep mergers (see McCarthy et al. 2007; Markevitch & Vikhlinin 2007).  

In the cluster outskirts for \( r \gtrsim R_{500} \), a pressure jump is forced by shocks driven by the supersonic inflow of cold external gas. Thus, the gravitational infall energy is mainly thermalized at the virial boundary (see Lapi et al. 2005, 2010; Voit 2005); meanwhile, part of it drives the outer subsonic turbulence contributing to the equilibrium so as to require lower thermal pressures (see Lau et al. 2009; Cavaliere et al. 2011b).

Bypassing such complexities, a “universal” fitting formula for the pressure profiles has been proposed by Nagai et al. (2007) to interpret the outcomes of hydrodynamical simulations of relaxed clusters (see also Battaglia et al. 2011), and applied by Arnaud et al. (2010) to render with empirically adjusted parameters the X-ray data out to \( R_{500} \) for \( z \lesssim 0.2 \). Actually, these analyses led us to recognize an average profile along with a considerable variance.

On the other hand, the actual pressure profiles can be directly probed with the thermal Sunyaev & Zel’dovich (1980; hereafter SZ) effect that occurs as CMB photons are inverse Compton scattered by the hot ICP electrons and change the radiation temperature \( T_{\text{cmb}} \approx 2.73 \) K by an amount \( \Delta T = g_{\nu} y T_{\text{cmb}} \sim -0.5 \) mK. This provides a linear, intrinsically \( z \)-independent probe of the thermal electron pressure \( p_e = \mu p/\mu_e \approx 0.52 p \) (with the mean molecular weight per electron \( \mu_e \approx 1.15 \) for cosmic abundances), since its strength is given by the Comptonization parameter \( y \equiv (\sigma_T/m_e c^2) \int d\ell p_e(r) \sim 10^{-4} \) integrated along the line of sight. The spectral factor \( g_\nu \) approaches the value \( \approx 2 \) at low frequencies (see Rephaeli 1995); its positive signature for \( \nu > 217 \) GHz offers a powerful cross-check for the SZ nature of the signals.

The SZ observations now start to probe the radial profiles in nearby individual clusters, and in more distant stacked samples (South Pole Telescope (SPT) Collaboration, Plagge et al. 2010; Wilkinson Microwave Anisotropy Probe (WMAP) Collaboration,
Komatsu et al. 2011; Planck Collaboration, Aghanim et al. 2011a, 2011b). They are also addressing the cluster contribution to the CMB power spectrum at multipoles \( \ell \gtrsim 2000 \) (see Lueker et al. 2010; Dunkley et al. 2011; Reichardt et al. 2011). Extensive data at higher resolutions and sensitivities are expected from current and upcoming instrumentation, and eventually from ALMA (see Birkinshaw & Lancaster 2007). All such actively pursued observations call for a reliable template to interpret and assess their astrophysical and cosmological import.

Here we take advantage of the effective formalism provided by the Supermodel (SM; Cavaliere et al. 2009; Fusco-Femenia et al. 2009, see http://people.sissa.it/~lapi/Supermodel/) to show that the complex ICP thermal states still allow a neat physical description of the spherically averaged pressure profiles. In response to the intriguing challenge posed by Arnaud et al. (2010), we find two basic shapes that span the observed variance in the pressure profiles for low \( z \lesssim 0.2 \) and predict that they are to converge into a closely universal one for high \( z \gtrsim 0.5 \).

2. A PHYSICAL APPROACH TO PRESSURE PROFILES

In singling out the ICP disposition and evolution we use the updated paradigm for the hierarchical formation of the containing DM halos (e.g., Zhao et al. 2003; Genel et al. 2010; Wang et al. 2011). The paradigm comprises an early collapse punctuated by major mergers, building up the core over a few crossing times; this occurs at redshifts \( z_f \approx 1.5–0.5 \) weakly depending on the mass \( M \sim 10^{14}-10^{15} M_\odot \). Slow, dwindling inflows of external matter follow over several gigayears and accrete in the outskirts out to the current virial \( R \) in closely stationary conditions described by the Jeans equation. In the process, the core scale radius \( r_{-2} \) stays put while \( R \) expands, and the “concentration” parameter \( c \equiv R/r_{-2} \) correspondingly grows.

The ICP forms from intergalactic gas with pressure \( \lesssim 10^{-3} \) eV cm\(^{-3} \) (see Ryu et al. 2008; Nicastro et al. 2010) that—along with the DM—inflows at supersonic Mach numbers \( M \gtrsim 10 \). The gas is shock-heated at about \( R \), and its pressure jumps by factors of \( 4 M^2 \gtrsim 500 \) up to the ICP values \( p_R \gtrsim 1 \) eV cm\(^{-3} \). Inward of \( R \), the pressure rises to balance the DM gravitational pull as described by Equation (1), with the following universal features: the rise will be monotonic within a smooth potential well; the gradient will vanish at the center when the gravitational force does, as implied by the Jeans equilibrium and found in simulations and real data (see Lapi & Cavaliere 2009a, 2009b; Navarro et al. 2010; Newman et al. 2011); and the rise terminates with a finite central value, proportional to the thermal energy density.

Within such universal constraints, a full description of the pressure profile is keyed to the specific “entropy” (adiabat) run \( k(r) \equiv k_R T/n^{3/5} \) embodying the ICP thermal state. In fact, using \( n \propto (p/k)^{3/5} \) Equation (1) can be solved to yield

\[
p(r) = \left[ \frac{p_R}{p_{kr}} + \frac{2}{5} \int R_d x \frac{m_p G M(<x)}{x^2 k^{3/5}(x)} \right]^{5/2} \tag{2}
\]

in the context of the SM (see also Lapi et al. 2005; Cavaliere et al. 2009). For the DM mass distribution \( M(<r) \) we use our \( \alpha \)-profiles; these solve the Jeans equations under physical boundary conditions and agree well with \( N \)-body simulations (see Lapi & Cavaliere 2009a).

The key role is played by the entropy run \( k(r) \) over scales larger than some \( 10^2 \) kpc, for which physical insight is provided by the above picture of cluster formation. The latter indicates the basic shape (see also Voit 2005)

\[
k(r) = k_c + k_R (r/R)^{a}; \tag{3}
\]

this involves the boundary value \( k_R \) at \( R \), and features two intrinsic parameters: the central level \( k_c \) and the average outer slope \( a \). These are evaluated as follows.

In the cluster core \( r \lesssim 0.2 R_{500} \) a level \( k_c \sim 10^2 \) keV cm\(^2 \) is set by the early collapse; this results from densities \( n \sim 10^{-3} \) cm\(^{-3} \) compressed by the standard contrast factor 200 over the average background’s and from temperatures impulsively raised to values \( k_B T \sim GM(<r)/10 r \sim \) a few keV. Thereafter, radiative cooling competes with energy injections from AGNs or mergers to the effect of stabilizing or even raising the time-integrated \( k_c \) at levels that gather around \( 10^4 \) or \( 10^5 \) keV cm\(^2 \) (see Cavagnolo et al. 2009; Pratt et al. 2010; Hudson et al. 2010).

From Equations (1) and (2) the central pressure is seen to follow the basic scalings \( p_c \propto k_c^{-5/3} \) and \( dp^{5/3}/dr \propto k_c^{-5/3} \).

At the other end, \( r \gtrsim R_{500} \), an entropy ramp rises with slope \( a \lesssim 1.1 \) originating from the continuously shocked infall and the progressive stratification of the accreted shells during the slow outskirt’s growth (see Tozzi & Norman 2001; Lapi et al. 2005). The ramp ends up at the boundary \( R \) with the value \( k_R \gtrsim 10^3 \) keV cm\(^2 \) set by strong shocks (see Cavaliere et al. 2011a). From Equations (1) and (2) the outer pressure profile follows the basic scaling \( p(r) \sim p_R (r/R)^{5+2a} \); see Cavaliere et al. 2011a). We stress that \( p(r) \) will decrease monotonically outward even when the temperature \( T(r) \sim p^{2/5}(r)k^{3/5}(r) \) features a middle peak at \( r \approx 0.2 R_{500} \) due to the entropy rising steeply from a low \( k_c \); the peak is the defining mark of cool-core clusters (see Molendi & Pizzolato 2001; Leccardi et al. 2010).

When the X-ray data on brightness and temperature at \( z \lesssim 0.2 \) are analyzed with the SM, a direct correlation between \( k_c \) and \( a \) emerges (see Cavaliere et al. 2011a). This implies that clusters can be divided into two main classes: low entropy (LE) or high entropy (HE), featuring low or high entropies, respectively, throughout cores and outskirts. The LEs (e.g., A2204, A1795) are marked by low central entropies \( k_c \sim 10^1 \) keV cm\(^2 \) along with shallow entropy slopes \( a \lesssim 0.7 \); the HEs (e.g., A1656, A399) are marked by higher central values \( k_c \sim 10^2 \) keV cm\(^2 \) along with steeper slopes \( a \sim 1 \).

Then from the above inner and outer scalings \( dp^{5/3}/dr \propto k_c^{-5/3} \) and \( p \propto r^{-5+2a} \), we find the pressure profiles to differ from HEs to LEs, with the former featuring quite shallower gradients both in the core and in the outskirts. Our picture is substantiated by the data presented in Figure 1.

3. PROBING PRESSURE WITH X-RAYS AND THE SZ EFFECT

In Figure 1, we compare the pressure profiles computed with our SM to data from X-ray and SZ observations, and from numerical simulations. In the plot, the radial scale is normalized to \( R_{500} \), while the pressure is normalized to the standard value \( p_{500} \approx 1.8h^3 \) \( (M_{500}/5 \times 10^{14} M_\odot)^{3/5} \) eV cm\(^{-3} \) in terms of the Hubble parameter \( h_c \equiv H(z)/H_0 \) (e.g., Ettori et al. 2004; Arnaud et al. 2010).

Our pressure templates provided by Equation (2) for HE and LE clusters are illustrated by the red and blue solid lines. These are computed from Equations (2) and (3) with the parameter values discussed in Section 2, and consistent with the outcomes from detailed fits to X-ray observations of nearby clusters carried out by Fusco-Femenia et al. (2009) and
Cavaliere et al. (2011a). Specifically, for typical HEs we adopt $k_c = 100 \text{ keV cm}^2$, $k_R = 3 \times 10^6 \text{ keV cm}^2$, and $a = 1.1$, while for LEs we adopt $k_c = 10 \text{ keV cm}^2$, $k_R = 10^3 \text{ keV cm}^2$, and $a = 0.7$; for both we set $R = 2 \text{ Mpc}$.

The yellow shaded area illustrates the region covered by the low-redshift ($z \lesssim 0.2$) clusters of the REXCESS X-ray sample analyzed by Arnaud et al. (2010); the dotted blue and red lines refer to their average profiles for the subsamples of cool-core and non-cool-core clusters, respectively. The cyan shaded area illustrates the region covered by hydrodynamical simulations of relaxed clusters. The cyan shaded area represents the region covered by hydrodynamical simulations of relaxed clusters (Borgani et al. 2004; Nagai et al. 2007; Piffaretti & Valdarnini 2008; Battaglia et al. 2011).

The dashed line represents the joint fit by Arnaud et al. (2010) to the observational and virtual data in terms of their “universal” pressure profile. For $r \lesssim R_{500}$ the X-ray data show that such a profile yields only an average but incomplete description. In the fact, the partial averages over the cool-core and non-cool-core subsamples deviate upward and downward by a large amount exceeding their internal variance; thus, a bimodal description constitutes both a closer and a more effective representation. This is just what is provided by the above SM templates for HE or LE clusters, which in the core recover the non-cool-core or cool-core behaviors. Moreover, for $r \gtrsim R_{500}$ where only scarce X-ray data are available, the SM template for LE clusters agrees well with the results of hydro-simulations of relaxed clusters. In the way of a prediction, beyond $R_{500}$ we expect for HEs considerably higher pressure profiles relative to LEs, as represented in Figure 1.

In addition, our picture envisages for decreasing $z$ an ICP evolution from HE to LE states. In fact, over lifetimes of several gigayears elapsed from the formation $z_f \approx 1$ to the observation redshift $z \lesssim 0.2$, the outer slope $a$ will flatten out from values $a \approx 1.1$ toward values $a \lesssim 0.5$ and correspondingly the boundary level $k_R$ decreases; such a trend is enhanced as $z$ approaches 0, when the cosmic timescale lengths considerably. This is because the entropy production by weakened virial shocks is reduced as inflows peter out, especially in the accelerated cosmology (see Lapi et al. 2010). Meanwhile, cooling erodes the central entropy $k_c$ over comparable times $t_c \approx 5 (k_c / 100 \text{ keV cm}^2)^{1.5}$ Gyr after Equation (2) and undergoes an accelerated drop toward the “attractor” level $k_c \sim 10 \text{ keV cm}^2$ set by competition with AGN feedback.

On the other hand, the evolution of the cluster DM halo is marked by the growth of the “concentration” $c \approx 3.5 h c_f / h_z$ from $z_f$ to $z$ (see Zhao et al. 2003; Prada et al. 2011). Since $a$ and $k_c$ decrease together, we expect them both to anticorrelate with $c$. In fact, such correlations $a, k_c$, vs. $c^{-1}$, have been quantitatively elicited with SM analyses of high-quality X-ray data concerning several clusters at $z \lesssim 0.2$ (see Cavaliere et al. 2011a).

As $z$ increases, our evolutionary trend envisages the HE/LE ratio to grow toward 1; in other words, we expect all pressure profiles to converge toward a truly universal template provided by the HE shape. Our picture is supported by comparison of the local data with stacked SZ observations of redshifts $0.2 \lesssim z \lesssim 0.4$; the pressure profiles from the SPT stacked data (Plagge et al. 2010) are represented in Figure 1 with the green squares. Although the uncertainties are still considerable in the outskirts, a departure from the “universal” profile stands out and the trend toward an HE-like template clearly emerges. The same trend is emerging from the analysis of a stacked cluster sample observed with WMAP (Komatsu et al. 2011). A similar trend is suggested by the sample of clusters detected by Planck for redshifts $0.3 \lesssim z \lesssim 0.5$ and followed up in X-rays with XMM-Newton (Aghanim et al. 2011a). Independent evidence is provided by the dearth of strong cool-cores found in X-rays by Santos et al. (2010) at high redshifts.

The next step to test the evolutionary trend from LEs to HEs will involve observing the SZ profile from individual clusters.

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**Figure 1.** Profiles of ICP pressure normalized to $p_{500}$; see Section 3 for details. The yellow shaded area illustrates the region covered by the low-redshift ($z \lesssim 0.2$) clusters of the REXCESS X-ray sample; the dotted blue and red lines refer to the average profiles for the subsamples of cool-core and non-cool-core clusters, separately. The cyan shaded area illustrates the coverage by hydrodynamical simulations of relaxed clusters. The dashed line represents the joint fit to the observational and virtual data with the “universal” pressure profile. The green squares represent stacked SZ observations of higher redshift (0.2 $\lesssim z \lesssim 0.4$) clusters with the SPT. Our SM templates for HE and LE clusters are illustrated by the red and blue solid lines, respectively.

(A color version of this figure is available in the online journal.)
over an extended range of redshifts. This is still challenging with the present instrumentation even at $z \lesssim 0.2$, but will become feasible out to high $z \gtrsim 0.5$ with new-generation instruments up to ALMA (see http://www.almaobservatory.org/). To illustrate the current status, in Figure 2 we report the recent data on the SZ profile for the Coma Cluster at $z \approx 0.023$ with WMAP (Komatsu et al. 2011). We also report the “universal” pressure profile (black dashed line) and the SM templates for HE and LE clusters (red and blue solid lines). These data allow us to recognize the HE nature of the Coma cluster, which is still more prominent in X-rays. On the other hand, the SZ data will become competitive once resolutions better than $1'$ are attained.

Another tested for our evolutionary picture will be provided by the power spectrum of the unresolved SZ effect integrated over redshift and over the evolving cluster mass distribution including groups (e.g., Shaw et al. 2010; Efstathiou & Migliaccio 2011). In Figure 2 we illustrate the outcome from the “universal” profile of Arnaud et al. (2010) and the SM templates for LE and HE clusters, compared with the constraints at $t \sim 3000$ set by current observations with the SPT (Reichardt et al. 2011). The latter are converging to indicate that the integrated SZ effect is to be both dominated by HEs at the relevant $z \gtrsim 0.5$ and reduced by the presence of a nonthermal contribution to the inner ICP equilibrium.

We find consistency of our HE template with the data when the standard scaling $p_{500} \propto h_z^{2/3}$ is decreased by a factor of $h_z^{-1/2}$; the latter renders how the inner nonthermal component mildly increases with $z$, as expected for the early HE equilibrium punctuated by major mergers with strong turbulent wakes (see Section 2 and Cavaliere et al. 2011b). Additional constraints on the detailed shape of the SZ effect will require high sensitivities at resolutions $\ell \gtrsim 5000$ with good control of the systematics, an effort actively pursued by the SZ community.

4. DISCUSSION AND CONCLUSIONS

As the observational uncertainties in the SZ measurements are shrinking below the theoretical ones, we have aimed at eliciting truly universal features in the pressure profiles of the intracluster plasma (ICP). These are described in terms of our SM, are tested at low $z$ against X-ray observations of brightness and temperature, and are proposed for probing at higher $z$ with the linear, $z$-independent SZ effect.

At low $z \lesssim 0.2$ we identify from X-ray data two main pressure patterns, each featuring related shapes at the center and in the outskirts. These are interpreted in terms of two cluster classes: HEs with high entropy throughout, i.e., high central levels $k_c$ along with a steep outer rise with slope $a$, leading to shallow pressure profiles; the converse holds for LEs.

For $z \gtrsim 0.2$ we expect the onset of an evolutionary trend in cosmic time from HE to LE, comprised of fast erosion of central entropy by radiative cooling, along with reduced outer entropy production by decreasing inflows (see Cavaliere et al. 2011a). Accordingly, the ratio HE/LE increases toward high $z$, implying, for $z \gtrsim 0.5$, convergence of the pressure profiles toward a truly universal, HE-like template.

Few intermediate instances are expected; these may occur when cooling is forestalled by an exceedingly high initial level $k_c > 10^5$ keV cm$^2$, while the outer entropy ramp is independently flattening (e.g., in A1689 and A2218 as discussed by Cavaliere et al. 2011a). On the other hand, Equation (2) implies our radial pressure profiles to be robust against overall asphericity and localized hot/cold imprints from recent mergers, even when the latter cause wiggles in temperature and marked flatness in the central brightness as often found from detailed fits to X-ray data in HEs (e.g., A2256 as discussed by Fusco-Femiano et al. 2009). This strengthens the case for universality of our asymptotic HE-like pressure template.

We have traced evidence for our evolutionary trend developing in the pressure profiles through stacked SZ signals due to $0.2 \lesssim z \lesssim 0.4$ clusters (see Figure 1). At higher $z$, further evidence will be difficult to pinpoint from X-rays alone, given their bias toward high central brightnesses proper to LEs; rather it will be provided again by SZ signals from individual or stacked clusters. In parallel, such an evidence will be tested with the integrated contribution from unresolved SZ signals to the CMB.
anisotropies at multipoles $\ell \gtrsim 5000$ (see Figure 2). All such observations require high-sensitivity data at resolutions below $1'$ that are currently pursued and will eventually culminate with ALMA.

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