Little evidence for entropy and energy excess beyond \( r_{500} \) - An end to ICM preheating?

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ABSTRACT

Non-gravitational feedback affects the nature of the intra-cluster medium (ICM). X-ray cooling of the ICM and \textit{in situ} energy feedback from AGN’s and SNe as well as preheating of the gas at epochs preceding the formation of clusters are proposed mechanisms for such feedback. While cooling and AGN feedbacks are dominant in cluster cores, the signatures of a preheated ICM are expected to be present even at large radii. To estimate the degree of preheating, with minimum confusion from AGN feedback/cooling, we study the excess entropy and non-gravitational energy profiles up to \( r_{200} \) for a sample of 17 galaxy clusters using joint data sets of \textit{Planck} SZ pressure and \textit{ROSAT}/PSPC gas density profiles. The canonical value of preheating entropy floor of \( \gtrsim 300 \) keV cm\(^2\), needed in order to match cluster scalings, is ruled out at \( \approx 3\sigma \). We also show that the feedback energy of 1 keV/particle is ruled out at 5.2\( \sigma \) beyond \( r_{500} \). Our analysis takes both non-thermal pressure and clumping into account which can be important in outer regions. Our results based on the direct probe of the ICM in the outermost regions do not support any significant preheating.

Key words: cosmology: cosmological parameters — clusters: formation — galaxy clusters: general

1 INTRODUCTION

Galaxy clusters are the largest and most massive virialized objects in the universe, which make them ideal probes of the large scale structure of the universe and, hence, of cosmological parameters that govern the growth of structures (see Gladders et al. (2007) and references therein). However, in order to obtain robust estimates of these parameters, using X-ray techniques, one requires precise knowledge about the evolution of galaxy clusters with redshift and the thermodynamical properties of intracluster medium (ICM). In the simplest case, where one considers pure gravitational collapse, cluster scaling relations are expected to follow self-similarity (Kaiser 1986; Sereno & Ettori 2015). X-ray scaling relations have been widely used to test the strength of correlations between cluster properties and to probe the extent of self-similarity of clusters (Morandi et al. 2007). These observations show departure from self-similarity; for example, the luminosity-temperature (\( L_x - T \)) relation for self-similar models predict a shallower slope (\( L_x \propto T^{-2} \)) than observed (\( L_x \propto T^{-3} \)). Similarly, Sunyaev-Zel’dovich (SZ) scaling relations also show similar departure (Holder & Carlstrom 2001).

Such departures point towards the importance of complex non-gravitational processes over and above the shock heating of the ICM. The first idea aimed at explaining departure from self-similar scaling relations is that of \textit{preheating}, first proposed by Kaiser (1991) and later extended by others (Evrard & Henry 1991; Babul et al. 2002). In this scenario, the cluster forms from an already preheated and enriched gas due to feedback processes (such as galactic winds or AGN) heating up the surrounding gas at high redshifts. Preheating models require constant entropy level of \( \gtrsim 300 \) keV cm\(^2\) in order to explain the break in
the self-similarity scaling relations (Tozzi & Norman 2001; Babul et al. 2002; McCarthy et al. 2002). In terms of ICM energetics, this typically translates into feedback energy of \( \sim 1 \text{ keV per particle} \) (Tozzi & Norman 2001; Pipino et al. 2002; Finoguenov et al. 2003). However, there is an ambiguity in defining preheating energy/particle since it depends on the density at which gas is heated (less dense gas requires smaller energy to raise it to a particular entropic state). Therefore, preheating is best expressed in terms of entropy. Although, early preheating models could describe the scaling relations in clusters, it had drawbacks with regard to details. For example, these models predicted isentropic cores particularly in the low mass clusters (Ponman et al. 2003) and an excess of entropy in the outskirts of the clusters (Voit et al. 2003) which are not consistent with observations. The idea of preheating has endured and has found resurgence recently (see Pfrommer et al. (2012); Lu et al. (2015) and references therein). Pfrommer et al. (2012) suggested time dependent entropy injection due to TeV blazars which provide uniform heat at \( z \sim 3.5 \) peaking near \( z \sim 1 \) and subsequent formation of CC (NCC) clusters by early forming groups (late forming groups) while Lu et al. (2015) explored preventative scenario of feedback in which the circum-halo medium is heated to finite entropy.

In contrast to preheating, there can also be in situ effects such as injection of energy feedback from AGN, radiative cooling, supernovae and star formation, influencing the thermal structure of ICM (Roychowdhury et al. 2005; Pratt et al. 2010; Eckert et al. 2013a). There is growing evidence that AGN feedback mechanism provides a major source of heating for the ICM (McNamara & Nulsen 2007; Fabian 2012; Chaudhuri et al. 2013) in the cluster cores. Outside cluster cores, however, the estimates of entropy floor and feedback energy (particularly in massive clusters) are more reflective of preheating of gas since (i) the effect of central sources is unlikely to be significant and (ii) the loss of energy through radiation is negligible.

It is worth noting that irrespective of the nature of feedback, the thermodynamic history of the ICM is fully encoded in the entropy of the ICM. The ICM entropy profile is defined as \( K(r) = k_B T n_\text{e}(r)^{-2/3} \), where \( k_B \) is the Boltzmann constant. Non-radiative AMR/SPH simulations, which encodes only gravitational/shock heating, predict entropy profiles of the form \( K(r) \propto r^{1.1} \) (Voit et al. 2005). Apart from slightly larger normalization, it has been found that there is significantly higher (flatter) core entropy in AMR case as a result of the hydrodynamical processes that are resolved in the code (e.g. shocks and mixing motions) (Mitchell et al. 2009; Vazza 2011; Power et al. 2014). On the other hand, observations find deviations from the predicted entropy profile at small radii (Pratt et al. 2010; Eckert et al. 2013a) as well as large radii (Eckert et al. 2013a; Su et al. 2015).

A meaningful comparison of recent observations with theoretically expected entropy profiles can thus be used to determine the nature and degree of feedback. This idea was developed and used recently by Chaudhuri et al. (2012, 2013) who estimated the non-gravitational energy deposition profile in the cluster cores. They compared benchmark non-radiative AMR/SPH entropy profiles (Voit et al. 2005) with observed entropy profiles for the REXCESS sample of 31 clusters (Pratt et al. 2010) and found the excess mean energy per particle to be \( \sim 1.6 - 2.7 \text{ keV} \) up to \( r_{500} \). Further, they showed that the excess energy is strongly correlated with AGN feedback in cluster cores (Chaudhuri et al. 2013).

In the present study, we extend their work by going beyond \( r_{500} \) and estimate entropy floor and feedback energetics at large cluster radii. The effect of clumping and non-thermal pressure, especially at large radii, has been shown to be important (Eckert et al. 2015; Battaglia et al. 2015; Shaw et al. 2010; Shi et al. 2015) and we incorporate both in our analysis.

We study the joint data set of Planck SZ pressure profiles and ROSAT gas density profiles of 17 clusters (Eckert et al. 2012; Planck Collaboration V 2013) to estimate entropy profiles up to \( r_{200} \) and beyond\(^2\). As detailed in Eckert et al. (2013a), we use the parametric profiles which are obtained by fitting a functional form to projected emission-mass density and Planck SZ pressure data (Vikhlinin et al. 2006; Nagai et al. 2007)\(^3\). The parametric profiles have less cluster-to-cluster scatter and errors; however, they are consistent with the non-parametric deprojected profiles. Below 0.2 \( r_{500} \), the resolution of both Planck and ROSAT is insufficient to obtain reliable constraints.

In the last 25 years since its proposal, the evidence for- or-against preheating has been mainly circumstantial. In this Letter, we show that a direct estimate of entropy floor and non-gravitational energy in the outer regions is insignificant enough so as to rule out preheating scenarios. Throughout this work, we will assume \((\Omega_m, \Omega_\Lambda, h_0) = (0.3, 0.7, 0.7)\).

2 ANALYSIS

2.1 Cluster modeling

The total hydrostatic mass profile \( M(r) \) of the galaxy clusters is given by \( M(r) = -\frac{2}{G \Omega_m(vir)} \frac{dP_r}{dr} \), where \( \rho_g \) and \( P_r \) are the parametric forms of the density and thermal pressure of the ICM respectively (Eckert et al. 2013a; Planck Collaboration V 2013). The radii \( r_{500} \) and \( r_{200} \) are obtained by first interpolating the \( M(r) \) profile and then iteratively solving \(^4\) for \( m_{500} = (4/3) r_5^3 \Delta \rho_c(z) \). The virial radius, \( r_{vir} \), is calculated with spherical collapse model \( r_{vir} = \frac{M_{vir}}{\Delta \rho_c(z) \rho_c(z)} 1/3 \) where \( \Delta_c(z) = 18\pi^2 + 82(\Omega_m(z) - 1) - 39(\Omega_m(z) - 1)^2 \).

Since the “actual” total mass is also partially supported

\(^1\) Thermodynamic definition of specific entropy being \( S = \ln K^{3/2} + \text{constant} \)

\(^2\) We have left out cluster “A2163” from Eckert et al. (2013a,b) in this work as its estimated feedback profile was found hugely different from others. This cluster is in the perturbed state and presumably out of hydrostatic equilibrium (Soucail 2012).

\(^3\) www.isdc.unige.ch/~deckert/newsite/Dominique_Eckerts_Homepage.html.

\(^4\) \( \Delta \) is defined such that \( r_\Delta \) is the radius out to which the mean matter density is \( \Delta \rho_c \), where \( \rho_c = 3H^2(z)/8\pi G \) being critical density of the universe at redshift \( z \).
by non-thermal pressure, we model the non-thermal pressure fraction using the form given in Shaw et al. (2010),

\[ \frac{P_{\text{nt}}(r, z)}{P_{\text{tot}}(r, z)} = \frac{f(r, z)}{1 + f(r, z)} \frac{P_\gamma(r)}{P_{\text{tot}}}, \]

where \( P_{\text{nt}} \) is total gas pressure, \( f(r, z) = a(z) \left( \frac{r}{r_\text{200}} \right)^{n_{\text{nt}}} \), \( a(z) = a_0(1 + z)^\beta \) with \( a_0 = 0.18 \pm 0.06, \beta = 0.5 \) and \( n_{\text{nt}} = 0.8 \pm 0.25 \) (Shaw et al. 2010). We also study the effect of different non-thermal pressure fraction by varying \( a_0 \). For our sample, the fiducial \( P_{\text{nt}} \) is \( 50\% \) of the thermal gas pressure, \( P_{\text{r}} \), around \( r_{\text{500}} \), and corresponds to a mass difference of \( 20\% \) at \( r_{\text{500}} \). This is in good agreement with simulations/theoretical predictions (Shi et al. 2015). The value of \( r_{\text{500}} \) obtained from the resultant mass profiles are consistent with the Planck Collaboration XI (2011). With the addition of the non-thermal pressure, the value of \( r_{\text{500}} \) typically increases by 50 – 150 Kpc; however, this difference is degenerate with the value of the normalization of \( P_{\text{nt}} \).

2.2 Initial entropy profile
Models of the formation of the large scale structure, where gas is shock heated as it falls in the cluster dark matter potential well, predict that the gas entropy \( K_{\text{th}}(r) \) has a power-law behavior with radius outside of cluster cores. For non-radiative AMR simulations, Voit et al. (2005) entropy profile is well described in the range \((0.2 - 1) \times r_{\text{200}}\) by

\[ K_{\text{th}}(r) = \left( \frac{r}{r_{\text{200}}} \right)^{1.1}, \]

plus a flatter core below \( 0.2 r_{\text{200}} \) with \( K_{\text{200}} = 144 \left( \frac{m_{\text{200}}}{10^{14} M_\odot} \right)^{2/3} \left( \frac{1}{\tau} \right)^{2/3} \left( h(z) \right)^{2/3} \) keV cm\(^2\).

We fix \( f_\text{th} = 0.156 \) from the recent Planck results (Planck Collaboration XVI 2013). It has been found that the entropy profiles after taking cooling into account differ with Eq. 2 significant only up 300 Kpc for 10\(^{15}\) solar mass cluster (McCarthy et al. 2008) which corresponds to \( 0.2 r_{\text{500}} \approx 0.1 m_{\text{500}}/m_{\text{200}} \) for our sample.

The hydrostatic equation, now including both thermal and non-thermal pressure, can be rewritten in terms of the entropy as

\[ \frac{d(P_g + P_{\text{nt}})}{dr} = - \left( \frac{P_g}{K_{\text{th}}} \right)^{3/5} m_p \mu_e^{2/5} \mu_g \frac{G M_{\text{tot}}(< r)}{r^2}, \]

where \( M_{\text{tot}} \) is the total mass which is equated to \( M_{\text{thermal}} + M_{\text{non-thermal}} \). For boundary condition, we fix the gas fraction \((f_g)\) to be 0.9\( f_\text{th}\) at virial radius (Crain et al. 2007). Initial profiles for density and temperature are found using Eqs. 2 & 3.

Recently, both simulations and observations have found significant clumping beyond \( r_{\text{500}} \), which by definition is measured as \( C < \langle \rho_g^2 \rangle / \langle \rho_g \rangle^2 \) (Eckert et al. 2013a, 2015; Battaglia et al. 2015). Eckert et al. (2015) found azimuthal median is a good tracer of the true 3D density (clumping factor) and showed from both hydrodynamical simulations and synthetic simulations that their method recovered the true 3D density profiles with deviations less than 10% at all radii. They found that the average \( \sqrt{C} = 1.25 \) at \( r_{\text{200}} \), consistent with the numerical simulations. Since clumping in the ICM is a plausible reason for the observed flattening of the entropy profiles in the outer regions, we estimate the observed entropy profiles by incorporating clumping using the recent parametric form of the clumping profile given in section 4.1 of Eckert et al. (2015).

2.3 Estimates of total feedback energy
To estimate the feedback thermal energy, we need to relate the entropy change (i.e., \( \Delta K = K_{\text{obs}} - K_{\text{th}} \)) with change in energy. Considering isobaric approximation, thermal energy change per unit mass is given by \( \Delta Q = \frac{k_{\text{th}}}{m_p} \frac{p^{5/2}}{\gamma - 1} \Delta K \left( \frac{r}{r_{\text{th}}} \right)^{\gamma-1} K_{\text{obs}} \) (see Chaudhuri et al. (2012) for details), where \( \beta = T_{\text{obs}}/T_{\text{th}} \) and \( \gamma = 5/3 \). Most importantly, in order to take into account the redistribution of gas mass due to the feedback one should compare entropy profiles for the same enclosed gas mass (i.e., \( \Delta K(m_i) \)) instead of the same radii (\( \Delta K(r) \)) as commonly done in the literature (Li et al. 2010; Nath & Majumdar 2011; Chaudhuri et al. 2012, 2013). The corresponding mechanical feedback energy per particle \( \Delta E_{\text{ICM}} \) can be written in terms of change in thermal and potential energies as

\[ \Delta E_{\text{ICM}} = \mu m_p \Delta Q + G \mu m_p \left( \frac{M_{\text{obs}}(r_{\text{th}})}{r_{\text{th}}} - \frac{M_{\text{tot}}(r_{\text{obs}})}{r_{\text{obs}}} \right), \]

where \( r_{\text{th}} \) and \( r_{\text{obs}} \) are theoretical and observed radii respectively enclosing the same gas mass. The total amount of feedback energy available in the ICM is \( E_{\text{ICM}} = \int \Delta E_{\text{ICM}} m_g \).

Since clusters lose energy due to X-ray cooling, we estimate total feedback energy deposited in the ICM by adding this lost energy to \( E_{\text{ICM}} \); thus \( \Delta E_{\text{feedback}} = \Delta E_{\text{ICM}} + \Delta L_{\text{tot lag}} \), where \( \Delta L_{\text{tot lag}} \) is the bolometric luminosity in a given gas shell which is obtained by using the approximate cooling function \( L_N \) given by Tozzi & Norman (2001) and \( t_{\text{age}} \) is the average age of the cluster which we have approximated to be 5 Gyr based on the results of Smith & Taylor (2008). Finally, we estimate the mean non-gravitational energy per particle, \( \langle \Delta E \rangle \), from total energy divided by the total number of particles in the ICM (i.e., \( \mu m_p \)).

In the rest of the paper, we refer to the case where the energy lost due to cooling is not added to energy estimated from entropy differences as final (after cooling), i.e.,
ΔE_{ICM}. In contrast, where the energy lost due to cooling is also added is referred to as initial (before cooling), i.e., ΔE_{feedback}. The latter represents the non-gravitational energy/particle required to heat the gas in a collapsed system from the initial theoretical model to the observed state. However, if the change in configuration is solely due to preheating of gas much before the collapse of system then the amount of energy required would be less than ΔE_{feedback} (McCarthy et al. 2008). This implies that ΔE_{feedback} represents upper limit on the preheating energy.

3 RESULTS AND DISCUSSION

3.1 Feedback beyond r_{500}

Once the individual profiles are found, we study the mean properties of the sample. The magnitude and profiles of ΔK and ΔE, estimated following the method laid down, provide clue to the feedback on the ICM. In Fig. 1, we see the weighted average (Louis 1991) ΔK profile is close to 100 keV cm² for most of the cluster region. There are four cluster marked with * in Fig. 1, which are not included in the sample for which ΔK profiles have comparatively large value (and hence large positive change in thermal energy) in outer regions. However, after accounting for the change in potential energy along with change in thermal energy, the ΔE profiles for these clusters become close to zero (or even negative). Moreover, for the sub-sample, the ΔK = 0 is always consistent at 1σ beyond r_{1000}. Fig. 3 shows ΔK with and without including clumping in calculations.

In Fig. 4, we show the corresponding average ΔE_{feedback} (solid red line) for the full sample and compare it with the average of ΔE_{ICM} (dotted red line). These are indistinguishable beyond r ≈ r_{500} since, unlike in the inner region (as explored in Chaudhuri et al. (2013)), cooling plays subdominant role beyond r_{500}. There is clear evidence of the feedback up to ≈ r_{500} with the feedback peaking centrally (also found by Chaudhuri et al. (2013)). However, the average ΔE profile is close to zero beyond r_{500}. Since, more than 70% of the cluster volume lies between r_{500} – r_{200}, one can confidently claim insufficient or complete lack of feedback over most of the cluster volume.

3.2 Discussion

It is now amply clear that both non-thermal pressure and clumping are important at large radii. The addition of non-thermal pressure increases the initial entropy profile “K_{0} m_{a}” due to the increase in the normalized K_{200}. This in turn leads to the decrease in ΔK and hence ΔE (see Iqbal et al. (2016) for details). Considering the clumpiness in gas density (and assuming that no fluctuations exist in temperature distribution), however, results in increase in the observed entropy and hence increase in the ΔE. The importance of clumping (K ≈ C^{-5/8} m_{a}) is highlighted in Fig. 3, where we show the average ΔK profile before and after correcting for the clumping bias. While the estimated entropy...
excess is unrealistically negative when no correction is applied, it attains a positive value close to zero when the effect of clumping is taken into account following the parametrization of Eckert et al. (2015). Note that this determination is consistent with the expectation of numerical simulations (Battaglia et al. 2015), see the inset of Fig. 3. We find, preheating value of entropy floor $\geq 300 \text{ keV cm}^2$ is ruled out at $3\sigma$ for full sample and at $4.2\sigma$ for sub sample.

To study the impact of non-thermal pressure on the estimate of non-gravitational energy, we show the $\Delta E$ profiles for the pure thermal case along with the non-thermal case with three different normalization ($a_0 = 0.10, 0.18, 0.26$) in Fig. 4. These correspond to mass differences of $\sim (10\%, 20\%, 30\%)$ at $r_{500}$ for the average profile. The mean excess energy is still far below 1 keV/particle and consistent with zero beyond a specific radius which depends on the choice of $a_0$. However, neglecting non-thermal pressure overestimates the feedback energy, though still staying less than 1 keV in the outer regions.

Finally, we list the average energy/particle in Tab. 1. We find, beyond $r_{200}$, the $\Delta E_{\text{feedback}}=1 \text{ keV/particle}$, is ruled out at $5.3\sigma$ for the full sample, and by $4.8\sigma$ for sub sample. Since, $\Delta E_{\text{feedback}}$ is roughly the upper limit of preheating energy/particle, this in turn rules out preheating scenarios which require 1 keV/particle to explain the break in scaling relations. At regions below $r_{200}$, $\Delta E = 1 \text{ keV/particle}$ is allowed within $3\sigma$. It may be also noted from the table that our results are insensitive to the choice of the boundary conditions, particularly for the sub sample. Thus, our constraint on extra heating refers to the inner regions ($< r_{1000}$) only, which strongly corroborate with the results of Gaspar et al. (2014). Our results can be compared to the value obtained by Chaudhuri et al. (2013) who studied the regions inside the core ($r < 0.3r_{500}$) and obtained $1.7 \pm 0.9 \text{ keV/particle}$ which they showed to be strongly corroborate to the central AGN feedback. The feedback energy left in the ICM is much lower for the entire radial range with cooling influencing the average energy per particle mainly in the range $0.2 - 1 r_{200}$.

### Table 1. Average feedback energy per ICM particle (in keV) after including non-thermal pressure and clumping.

| Sample          | final average feedback energy/particle | initial average feedback energy/particle |
|-----------------|----------------------------------------|-----------------------------------------|
|                 | $(0.2 - 1) r_{500}$ | $r_{500} - r_{200}$ | $(0.2 - 1) r_{500}$ | $r_{500} - r_{200}$ |
| Full Sample     | $0.35 \pm 0.17$  | $0.03 \pm 0.18$  | $0.72 \pm 0.17$  | $0.05 \pm 0.18$  |
| Sub Sample      | $0.60 \pm 0.21$  | $0.11 \pm 0.18$  | $1.00 \pm 0.21$  | $0.13 \pm 0.18$  |

Columns (2) & (3): Average energy per particle in the range $(0.2 - 1) r_{500}$ and $r_{500} - r_{200}$ respectively without taking into account energy lost due to cooling (i.e., $\Delta E_{\text{ICM}}$). Columns (4) & (5): Average energy per particle in the range $(0.2 - 1) r_{500}$ and $r_{500} - r_{200}$ respectively after taking into account energy lost due to cooling (i.e., $\Delta E_{\text{feedback}}$). The numbers in brackets show the average energy per particle for boundary condition $f_g = 0.9 f_b$ at the last observed radius instead at virial radius. Error bars are given at $1\sigma$ level. Clearly, there is little evidence of feedback energy beyond $r_{500}$ for all cases.

### 4 CONCLUSIONS

Our analysis shows that the estimated entropy excess and energy input corresponding to this excess of the ICM is much less than required by preheating scenarios to explain the break in scaling relations. While the feedback energy estimates rely on some assumptions (isobaric and cooling energy approximations) and refer to energy deposition after the collapse of cluster, the constraints on the $\Delta K$ shows that preheating scenarios that require $\Delta K$ much less than 300 keV cm$^2$ can be ruled out. This result holds good whether or not the effects of non-thermal pressure and clumping are taken into account. At large radii, the effect of central sources is unlikely to be significant (Hahn et al. 2015), and the loss of energy through radiation is also negligible. While some previous workers have cast doubts on the simple preheating scenario arguing that no single value of energy input can explain the observations (Younger & Bryan 2007), one can in principle construct variations in the scenario (Fang & Haiman 2008) in order to explain observations that are dominated by processes in the inner regions. However, our analysis directly probes the entropy floor and energetics of the cluster gas at the outermost regions and shows that any significant preheating that can manifest as a property of the ICM is absent.

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5 Note, that Chaudhuri et al. (2013) did not consider $P_{\text{et}}$ or clumping.
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