Bubbles or Sound Waves - How do Super-Massive Black Holes heat the ICM?

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ABSTRACT

Context. Galaxy clusters are promising probes of precision cosmology. Their ability to deliver precise, unbiased, results depends on a better understanding of the intracluster medium (ICM). Active galactic nuclei (AGN) powered by the central Super-Massive Black Holes (SMBHs) play a major role in modifying the thermal properties of the ICM. Therefore, understanding the AGN feedback mechanism is essential for cluster cosmology.

Aims. In this work, we implement two AGN heating models: (i) by buoyant cavities rising through stratified ICM (Effervescent model) and, (ii) by viscous and conductive dissipation of sound waves (Acoustic model). Our aim is to determine whether these heating models are consistent with ICM observables and if one is preferred over the other.

Methods. We study the evolution of ICM thermal profiles with effervescent and acoustic models of AGN heating. We assume an initial entropy profile of ICM expected from the purely gravitational infall of the gas in the potential of the dark matter halo. We then incorporate heating, radiative cooling, and thermal conduction over the age of the clusters.

Results. Our results are: (i) We find that both heating processes match well with observations, with some tuning of relevant parameters. (ii) Thermal conduction is crucially important, even at the level of 10% of the Spitzer values, in transferring the injected energy beyond the central regions, and without which the temperature/entropy profiles do not match with observations. (iii) We show that the required injected AGN power scales with cluster mass as $M_{\text{vir}}$ for both models. (iv) Moreover, the required AGN luminosity is comparable with the observed radio jet power, reinforcing the idea that AGNs provide the most dominant heating sources in clusters. (v) Finally, we estimate that the fraction of the total AGN luminosity available as the AGN mechanical luminosity at 0.02r$_{\text{500}}$ is less than 0.05%.

Key words. Galaxy clusters, AGN feedback, Intracluster medium, Cluster cosmology

1. Introduction

Galaxy clusters are promising cosmological probes. Current and future X-ray and CMB missions (like eROSITA, Athena, Simons Array, CMB-S4, CMB-HD, etc) have cluster cosmology and cluster physics as two of their main drivers. The synergy of cosmology and cluster gas physics, intertwined through the nature of the ICM, lies at the core of realizing the science goals. The physics of the ICM is complex due to the multiple energetic physical processes, having both temporal and spatial dependence, involved in it. With the advent of the current X-ray satellites, Chandra, XMM-Newton and eROSITA, it is now believed that the energetics of the ICM is regulated by heating from non-gravitational sources like AGN and SNe in galaxies, in addition to the heating at the accretion shock due to gravitational collapse (White & Rees 1978) and radiative cooling. One of the most important implications of these observations is that the central gas must experience some kind of heating plausibly due to the same feedback mechanism that prevents cool cores from establishing significant cooling flows that were predicted by earlier, low-resolution, X-ray observations (see Fabian (1994); Peterson et al. (2001, 2006) and references therein). Establishing the source of this heating, and understanding when and how it takes place, has become a major topic of study in extra-galactic astrophysics. In addition to the cooling flow problem, another important issue that came into focus recently is the existence of an enhancement in the entropy profile within the core (< 100 kpc) of the cluster (see Pratt et al. (2010) and references therein). This entropy enhancement is found to be more pronounced in non cool-core (NCC) clusters compared to the cool-core (CC) clusters.

The complexities of ICM also manifest in the so-called “cluster scaling relations”. The theory of hierarchical structure formation predicts cluster scaling relations to be self-similar (Kaiser 1986; Sereno & Ettori 2015). However, 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 ($L_x \propto T^3$) (Pratt et al. 2009). Similarly, Sunyaev-Zel’dovich (SZ) scaling relations also show similar departure (Holder 2001; Andrade-Santos et al. 2021).

Several processes have been proposed to explain the observations: pre-heating of the infalling gas due to early feedback processes in high-redshift galaxies (Babul et al. 2002), Active
Galactic Nuclei (AGN) feedback from quasars or radio jets (Binney & Tabor 1995; Rephaeli & Silk 1995; Nath & Roychowdhury 2002), conduction of thermal energy from the outer shock-heated regions carried by electrons (Voigt & Fabian 2004; Rasera & Chandran 2008), and gas sloshing from minor and major mergers (Fabian & Daines 1991). While the verdict is still out for early pre-heating and thermal conduction, the ability of AGN feedback to stem cooling flows, and to break self-similarity in scaling relations, has been demonstrated in several hydrodynamical simulations (Sijacki & Springel 2006; Khlatyan et al. 2008; Puchwein et al. 2008; Fabjan et al. 2010; Dubois et al. 2010; McCarthy et al. 2010; Teyssier et al. 2011). It seems, therefore, natural to consider such an AGN feedback mechanism as a key ingredient to account for the excess energy or entropy in the ICM. However, one still needs to understand the exact physical process that helps evolve the excess entropy with time and distance from the SMBHs powering the central AGN.

In earlier work, Iqbal et al. (2017a, b) found that the presence of non-gravitational energy per particle, related to excess entropy beyond \( r_{500} \) is almost negligible thereby ruling out pre-heating models at a large confidence level. Subsequently, Iqbal et al. (2018) showed that AGN feedback and radiative cooling are jointly responsible for the state of the ICM in the central regions, \( r \lesssim 0.3r_{500} \). Similarly, Gaspari et al. (2014) showed that AGN feedback can naturally regulate the thermodynamical state of ICM up to \( r \approx 0.2r_{500} \). Given the importance of AGN feedback and radiative cooling in the inner regions and the lack excess energy in the outer regions, it is natural to investigate the radial dependence of the feedback energetics.

Two models of mechanical heating by central AGN have been widely discussed in the literature. One concerns the work done by bubbles (cavities) blown by the AGN jet and carried towards the outer regions of the cluster by the pressure gradient in the ICM (Ruszkowski & Begelman 2002; Roychowdhury et al. 2004). The other model explores the possibility of heating via viscous dissipation and thermal conduction of the energy by sound waves generated by some other phenomena related to the jet (Fabian et al. 2005; Zweibel et al. 2018). Although other possibilities exist for dissipation of energy (such as turbulence or cosmic rays), the two proposals mentioned above have been analytically worked out in detail and hence can be compared to X-ray and SZ observations. Note, that it is important to consider the heating models together with radiative cooling and thermal conduction so as to check whether the final ICM thermal profiles tally with observations. The time scale over which both heating and cooling would contribute is decided by the age of a given cluster, which would depend on the cluster mass.

In this paper, we compare these two dominant modes of energy deposition into the ICM by AGN, combined with radiative cooling and thermal conduction, for clusters of different masses. We trace the evolution of the thermal properties of the ICM over its lifetime. Given that the ICM is not affected by feedback far from the core, we consider feedback models that affect the thermal structure of ICM up to 0.1\( r_{500} \) and 0.3\( r_{500} \). Finally, we estimate the relation between the mechanical energy injected by the AGN and the cluster mass and compare it with scaling relations derived from the complementary observations.

Throughout this work, we adopt a cosmology with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \). Further, \( E(z) \) is the the ratio of the Hubble constant at redshift \( z \) to its present value, \( H_0 \) and \( h_70 = H_0/70 = 1 \).

### 2. Cluster Model

#### 2.1. The dark matter profile

We work with the Navarro-Frenk-White (NFW) density profile (Navarro et al. 1996; 1997) of galaxy clusters given by

\[
\rho_{\text{tot}}(r) = \frac{\rho_\Sigma}{y(1 + y)^2},
\]

(1)

where \( y = r/r_s, \) \( r_s \) is the scale radius and \( \rho_\Sigma \) is the normalization of the density profile. The concentration parameter is defined by \( c_\Delta = r_A/r_s \), where \( \Delta \) is defined such that \( r_A \) is the radius out to which mean matter density is \( \Delta \rho_c, \) \( \rho_c \) being critical density of the universe at redshift \( z^1 \). We adopt the expression for the concentration parameter from N-body simulations (Duffy et al. 2008) which relates \( c_{\text{vir}} \), the concentration parameter at virial radius, to the cluster virial mass \( M_{\text{vir}} \),

\[
c_{\text{vir}} = 7.85\left(\frac{M_{\text{vir}}}{2 \times 10^{12} M_\odot}\right)^{-0.081} (1 + z)^{-0.71}
\]

(2)

The \( c \sim M \) relation from Duffy et al. (2008) has been found to be consistent with the Subaru weak lensing estimates of Okabe et al. (2010). The virial radius, \( R_{\text{vir}}(M_{\text{vir}}, z) \) is found using

\[
R_{\text{vir}} = \left(\frac{M_{\text{vir}}}{4\pi/3\Omega(z)}\right)^{1/3} \left(\frac{P_{\text{tot}}}{c(z)}\right)^{1/2},
\]

(3)

where \( x = r/r_{500}, \) \( P_{\text{tot}} = c(z), \) \( \alpha, \beta \) are the model parameters and

\[
P_{\text{tot}} = 1.65 \times 10^{-3} E(z)^{8/3} \times \left[\frac{M_{500}}{3 \times 10^{14} h_{70}^{-1} M_\odot}\right]^{2/3} h_{70}^2 \text{keV cm}^{-3}.
\]

(4)

\( P_{\text{tot}} \) reflects the self-similar dependence with mass and redshift. Moreover, simulations have shown no significant evolution outside of the cluster core (Battaglia et al. 2012; Planz et al. 2017), which has been also confirmed observationally (McDonald et al. 2014; Adam et al. 2015). In the present work, we consider Planz et al. (2017) best fit non-radiative pressure profile \( (P_0 = 6.85, c_{500} = 1.09, \gamma = 0.31, \alpha = 1.07 \) and \( \beta = 5.46) \) as our baseline pressure profile. It is worth mentioning here that the Planz et al. (2017) did not find additional mass dependence of pressure profile like in Arnaud et al. (2010). Given an initial non-radiative pressure, temperature \( T_g \) and density \( \rho_g \) profiles of the ICM can be determined using hydrostatic equation,

\[
\frac{dP_g}{dr} = -m_p h_e^{2/3} \mu_e^{1/2} \frac{P_g}{K_g} \left(\frac{1}{r^2}\right) GM_{\text{tot}}(< r),
\]

(5)

where \( K_g = T_g \rho_g h_e^{2/3} (m_p \mu_e)^{2/3} \) is entropy of the ICM, \( M_{\text{tot}} \) is the total mass enclosed within radius \( r, \) \( \gamma = 5/3 \) is the adiabatic

\[1^1 \Delta m = 4/3 r_\Delta^3 \Delta \rho_c(z) \]
index, $m_p$ is the mass of the proton, $\mu_q = 0.59$ and $\mu_e = 1.14$. Similar to the pressure profiles, we also scale the entropy and temperature profiles by $K_{500}$ and $T_{500}$ respectively,

$$K_{500} = 106 \left( \frac{M_{500}}{h_{500}^2 10^{14} M_\odot} \right)^{2/3} \left( \frac{1}{F_0} \right)^{2/3} E(\epsilon)^{2/3} \text{keV cm}^2,$$

$$T_{500} = 8.71 \left( \frac{M_{500}}{h_{500}^2 10^{15} M_\odot} \right)^{2/3} E(\epsilon)^{2/3} \text{keV}.$$  

Finally, note that the the overall conclusion of this work is independent of the choice of the initial ICM profile used, for example using non-radiative profile from Voit et al. (2005) would have made no significant change.

### 2.3. Central AGN heating

To recapitulate, there are two leading models of AGN heating of the ICM: acoustic model and effervescent model. Here we discuss these two models briefly.

#### 2.3.1. Effervescent heating model

The central AGN is responsible for inflating buoyant bubbles of relativistic plasma in the ICM in the effervescent heating model (Churazov et al. 2001; Begelman 2001; Ruszkowski & Begelman 2002; Roychowdhury et al. 2004). The timescale for bubbles to cross the cluster, which is of the order of the free-fall time, is found to be shorter than the cooling timescale. It is assumed that the number flux of bubbles is large such that the flux of bubble energy through the ICM approaches a steady state. This, in turn, implies that the details of the energy injection process such as the number flux of bubbles, the bubble radius, filling factor and the rate of rise do not affect the average heating rate.

It is further assumed that the relativistic gas inside the bubble does not mix with the ICM very efficiently. These bubbles push aside the X-ray emitting gas, thus excavating depressions in the ICM which should be detectable as apparent cavities in the X-ray images. Indeed, this scenario is vindicated through Chandra and XMM observations which have seen cavities far away from the central regions of the cluster Shin et al. (2016). In this scenario, the bubbles can expand and do pdV work on the ambient medium, as they rise in the cluster pressure gradient, thus converting the internal energy of the bubbles to thermal energy of the ICM within a pressure scale height of where it is generated. In steady state (assuming spherical symmetry), the energy flux carried by the bubbles, during adiabatic bubble inflation, is given by

$$F_b \propto \frac{P_b(\gamma_{\text{eff}} - 1)/\gamma_b}{r^2},$$

where $P_b(r)$ is the partial pressure of relativistic buoyant gas inside the bubbles at cluster radius $r$ and the relativistic adiabatic index of buoyant gas $\gamma_b = 4/3$. Assuming that the partial pressure inside these bubbles scales as the thermal pressure of the ICM, the volume heating rate $\dot{\epsilon}_{\text{heat}}(r)$ can be expressed as

$$\dot{\epsilon}_{\text{heat}}(r) \approx r^2 h(r) \nabla \cdot (\hat{r} F_b),$$

where $h(r)$ is given by

$$h(r) = \frac{L_{\text{inj}}^{\text{eff}}}{4\pi r^2} [1 - \exp(-r/r_0)] \exp(-r/r_{\text{cav}}) q^{-1}.$$  

In Eq. 9, $L_{\text{inj}}^{\text{eff}}$ is the time-averaged energy injection rate, $r_0$ represents the transition from bubble formation region to the buoyant (effervescent) phase and $r_{\text{cav}}$ is the outer heating cutoff radii. The term $h(r)$ thus takes into account the fact that the volume heating rate is maximum near the inner cut-off radius and falls off exponentially with increasing radius. In our calculations, we fix $r_0$ to be equal to 0.015 $R_{500}$. We note that our final results are not sensitive to the choice of $r_c$. The normalization factor $q$ is defined by

$$q = \int_{r_{\text{cav}}}^{r_0} \frac{1}{\nabla \cdot (\hat{r} F_b)} \frac{d \ln P_b}{d \ln r} [1 - \exp(-r/r_0)] \exp(-r/r_{\text{cav}}) dr$$

where we fix $r_{\text{cav}} = R_{\text{vir}}$.

#### 2.3.2. Acoustic heating model

In the acoustic heating model (Fabian et al. 2005, 2016; Yang & Reynolds 2016), the ICM is heated through the dissipation of adiabatic acoustic waves produced from the central AGN. Assuming the average acoustic luminosity $L_{\text{Aco}}^{\text{ff}}$, injected into the ICM at $r_0$, the acoustic luminosity surviving a given radius $r$ given by $L_{\text{Aco}}$ will depend on the dissipation length in the ICM $L_{\text{Aco}}$ as

$$L_{\text{Aco}}(r) = L_{\text{Aco}}^{\text{ff}} \times \exp \left( - \int_{r_0}^{r} \frac{1}{\nabla \cdot (\hat{r} F_b)} \frac{d \ln P_b}{d \ln r} dr \right).$$

As before, we fix $r_0$ to be 0.015 $R_{500}$. Assuming that heating is due to kinematic viscosity ($\nu$) and thermal conductivity ($\kappa$), the acoustic dissipation length in the ICM can be written as (Fabian et al. 2005)

$$L_{\text{Aco}}(r) = 697 \frac{n_e(T_r)^{1/2}(f_\nu)^{-2}}{(\xi_\nu + 11.8 (\xi_\kappa/36))^{1/2}} \text{kpc}$$

where $f_\nu$ is the frequency of the sound wave in the units of mega year ($f_\nu = f/(10^{-6} \text{yr}^{-1})$, $T_r$ is the temperature of the ICM in the units of 10$^7$ K ($T_r = T/10^7$) and $n_e$ is the electron number density in cm$^{-3}$, $\xi_\nu$ and $\xi_\kappa$ represent the viscosity and conduction fractions respectively of their Spitzer values in the absence of magnetic field

$$\nu = 1.0 \times 10^{25} T_r^{3/2} n_e^{-1} \xi_\nu$$

$$\frac{k}{\rho g c_p} = 2.36 \times 10^{26} T_r^{5/2} n_e^{-1} \xi_\kappa$$

where $\rho g$ is the gas density and $c_p$ is the specific heat at constant pressure. The volume heating rate due to viscous and conductive dissipation is then given by

$$\dot{\epsilon}_{\text{heal}}(r) = \frac{L_{\text{Aco}}(r)}{4\pi r^2}.$$

Applying this idea to the Perseus cluster, Fabian et al. (2005) suggested energy dissipation due to frequencies in the range $f_\nu = 0.2 - 1$, with the slope $\zeta = 1.8$, to balance the radiative cooling at the cluster cores. In this work, we also consider heating by sound waves having frequency spectrum with $\zeta = 1.8$ such that acoustic luminosity in a frequency interval $(f, f + df)$ is given by,

$$L_{\text{Aco}}^{\text{spec}}(f) = A_{\text{norm}} f^{-\zeta}$$
where $\Lambda_{\text{norm}}$ sets the normalization such that total acoustic injected luminosity $L_{\text{Ac}}^{\text{inj}}$ is given by $L_{\text{Ac}}^{\text{inj}} = \Lambda_{\text{norm}} \int L_{\text{Ac}}^{\text{spec}}(f) \, df$. However, we will consider different frequency ranges, depending on the cluster mass, suitable for our analysis. The modified volume heating rate can then be written as

$$\epsilon_{\text{heat}} = \int L_{\text{Ac}}^{\text{spec}}(f) \left( \frac{4\pi r^2}{4\pi r^2} \right) \exp \left( - \int_{r_{\text{inj}}}^{r} \frac{1}{r_{\text{Ac}}} \, dr \right) \, df.$$  \hspace{1cm} (16)

Note, that the higher frequencies will produce a higher heating rate but are confined to a smaller region as opposed to lower frequencies which will produce relatively less heating but up to a larger area. The total heating is frequency averaged over the spectrum in the spectral range taken for a particular cluster.

2.4. Radiative Cooling and Conduction

In the case of galaxy clusters, the radiative cooling is dominated by the free-free emission. The emissivity per unit volume can be expressed as

$$\epsilon_{\text{cool}} = n_e^2 \Lambda_N \frac{\mu_e}{\mu_h} \, \text{erg s}^{-1} \text{cm}^{-3}$$  \hspace{1cm} (17)

where $\mu_h = 1.26$. We consider the cooling function $\Lambda_N$ from Tozzi & Norman (2001) given by

$$\Lambda_N = C_1 (kT)^{\alpha} + C_2 (kT)^{\beta} + C_3$$

where $\alpha = -1.7$ and $\beta = 0.5$. The constants $C_1 = 8.6 \times 10^{-25}$ erg cm$^{-3}$ s$^{-1}$ keV$^{-\alpha}$, $C_2 = 5.8 \times 10^{-24}$ erg cm$^{-3}$ s$^{-1}$ keV$^{-\beta}$ and $C_3 = 6.3 \times 10^{-23}$ erg cm$^{-3}$ s$^{-1}$ are for metallicity of 0.3 $Z_{\odot}$.

In the presence of a thermal gradient, the heat flux due to thermal conduction is given by

$$F_{\text{cond}} = -\kappa \nabla T.$$  \hspace{1cm} (19)

One can easily see from the above equation that the Spitzer thermal conductivity $\xi$ has a strong dependence on the temperature structure of the ICM. Finally, the heating (or cooling) rate due to thermal conduction is given by

$$\epsilon_{\text{cond}} = \frac{1}{r^2} \frac{d}{dr} \left[ r^2 F_{\text{cond}} \right].$$  \hspace{1cm} (20)

3. Evolution of the ICM

We assume quasi-hydrostatic evolution of the ICM (Roychowdhury et al. 2004; Nath & Majumdar 2011; Chaudhuri & Majumdar 2011; Chaudhuri et al. 2012) such that

$$\frac{d\Delta}{dM_{\Delta}} = \frac{1}{4\pi r^2 P_{\Delta}(r)} = \frac{1}{4\pi r^2} \left( \frac{\sigma_{\Delta}}{P_{\Delta}(r)} \right)^{1/v}$$

$$\frac{dP_{\Delta}}{dM_{\Delta}} = \frac{GM_{\Delta}(< r)}{4\pi r^4}.$$  \hspace{1cm} (21)

where $\sigma_{\Delta} = P_{\Delta}^{1/v}(r)$ (or $K_{\Delta} = \mu_g m_p^{5/3} n^{1/3}(r)$) is the entropy index and $M_{\Delta}$ is the gas mass enclosed up to the radius $r$. The ICM properties are calculated by solving Eq. (21) in time steps of $\Delta t$ after incorporating heating, radiative cooling and conduction. The entropy index at a given radius changes by amount

$$\Delta \sigma_{\Delta}(r) = \frac{2}{3} \frac{\sigma_{\Delta}(r)}{P_{\Delta}(r)} [\epsilon_{\text{heat}}(r) - \epsilon_{\text{cool}}(r) - \epsilon_{\text{cond}}(r)] \Delta t.$$  \hspace{1cm} (22)

In order to consider the redistribution of gas on account of heating and cooling, one much update the entropy index in the each time step with respect to the same gas mass shells as

$$\sigma_{\Delta}(M_{\Delta}) \rightarrow \sigma_{\Delta}(M_{\Delta}) + \Delta \sigma_{\Delta}(M_{\Delta}).$$  \hspace{1cm} (23)

The boundary condition for Eq. (21) is updated such that pressure at the gas mass shell initially at virial radius, is always equal to its initial pressure. Since we heat the ICM up to the maximum radius of 0.3$r_{500}$, we see that the boundary condition has no effect on the derived pressure profile in the inner regions where the impact of feedback is significant. The second boundary condition assumes $M_{\Delta} \approx 0$ at $r \approx 0$.

For the numerical stability, the conduction term is integrated using time steps that satisfy the Courant condition (Ruszkowski & Begelman 2002)

$$\Delta t_{\text{cond}} \leq \frac{0.5 (\Delta r)^2 k_b}{\xi_c (\gamma - 1)}.$$  \hspace{1cm} (24)

Using the above time-steps, we need to evolve the cluster profiles for the age of the cluster. We define the cluster formation epoch as the time when the cluster has a mass greater than $\frac{1}{3} M_{\text{vir}}$ for the first time. This assumption is motivated by the results of the numerical simulations which show that gravitational potential does not change much after the cluster assembles its $\frac{1}{3}$ of its total mass Navarro et al. (1997). Using this definition for the epoch of cluster formation Nath (2004) found a convenient fit for the cluster age ($t_{\text{age}}$), for a cluster, observed at a redshift of $z$

$$t_{\text{age}} = 2.5 \times 10^9 \text{yrs} (1 + z)^{1.6} \left( \frac{M_{\text{vir}}}{10^{14} M_{\odot}} \right)^{-0.09}.$$  \hspace{1cm} (25)

We consider the AGN duty cycle, which is defined as the fraction of time the AGN heating is active (or ICM possesses radio bubbles), to be 50%. This value is the lower limit of the duty cycle as found by Dunn & Fabian (2006); Birzan et al. (2012). The cooling and conduction terms, on the other hand, are kept always on throughout the cluster age.

For our analysis, we will assume $\xi_s = \xi_c = 0.1$ as our fiducial conductivity and viscosity fractions. In the next section, we will see the importance of conduction in distributing the heating of the ICM. In contrast, the viscosity fraction, $\xi_c$, has a negligible impact on the heating profile since the dissipation length is highly dependent on $\xi_c$ through Eq. (12).

The degree and extent of heating of ICM in the effervescent model are effectively controlled by two parameters $r_{\text{inj}}^{\text{ff}}$ and $r_{\text{cutoff}}^{\text{ff}}$, while the corresponding two parameters for the acoustic model are: $L_{\text{Ac}}^{\text{inj}}$ and $f_{\text{cutoff}}$. In both the cases, the $r_{\text{inj}}^{\text{ff}}$ or the $L_{\text{Ac}}^{\text{inj}}$ controls the amplitude, i.e., the overall heating, and should be linked to the energy spewed out by the central super-massive black hole. Indeed, as we show later, the injected energy has a simple scaling relation with the mass of the black hole (related together by the underlying $M_{\text{BH}} = M_{\text{halo}}$ relation. The parameters $r_{\text{cutoff}}$ and $f_{\text{cutoff}}$ control the overall shape of the heating profiles, i.e. it controls the radii beyond which heating exponentially/sharply falls. For the effervescent model, it is natural to assume heating cutoff parameter $r_{\text{cutoff}}$ to be also 0.1$r_{500}$ and 0.3$r_{500}$ since both observations (Iqbal et al. 2017b) and simulations (Gaspari et al. 2014) shows no significant non-gravitational heating beyond (0.1–0.3)$r_{500}$. Similarly, for the acoustic model, the radial range of the feedback can be suitably controlled by limiting the frequency spectrum. Since the perturbation by the sound wave depends on the wavelength, which is inversely proportional to
the frequency, one can choose a minimum frequency such that the length scale matches 0.1r_{500} and 0.3r_{500} beyond which there should not be excess heating. In practice, the maximum wavelength needs to be less than 0.1r_{500} or 0.3r_{500} since conduction helps in propagating the heat further. We fix frequency range to be f_6 = 0.05 - 0.50 and f_\delta = 0.01 - 0.50 such that the extent of feedback is only up to 0.1r_{500} and 0.3r_{500} respectively. The choice of increasing the upper cutoff in frequency leading to wavelengths less than the injection length-scale has a negligible effect on the results. Once, t_{\text{cutoff}} or f_6 is fixed to achieve the ra-
dial dependence, one has to find a suitable overall amplitude $L_{\text{inj}}^{\text{eff}}$ ($L_{\text{inj}}^{0,\text{Ac}}$) such that there is excess energy (entropy) up to a given radius. Finally, we note that heating due to a single frequency of $f_{-6} = 0.01$ or less is not favored by X-ray observations. Such frequencies correspond to density perturbations on length scales of $\geq 100$ kpc, for sound speed of $1000$ km s$^{-1}$ (Fabian et al. 2016), which would have been easily observed by Chandra or XMM-Newton if present. However, if the acoustic heating is produced by the waves with a frequency spectrum, it would be difficult to separate out different perturbation modes through current X-ray observations.

4. Results

4.1. Initial heating and cooling profiles

We start by comparing the initial heating and cooling profiles in the absence of any evolution of the ICM. Since the injected initial luminosity depends on the central black hole physics, and hence independent of the same mechanical luminosity for a given cluster mass in both of the heating models. This is shown in Fig. 1, where the left-hand panel shows the cooling rate versus heating rate in the ICM for the effervescent model using initial Planelles et al. (2017) profile for three cluster masses: $2 \times 10^{14} M_\odot$ (upper panel), $6 \times 10^{14} M_\odot$ (middle panel) and $2 \times 10^{15} M_\odot$ (bottom panel) at redshift $z = 0$. The parameters of the heating model are roughly chosen such that heating not only balances the cooling but also produces excess energy in the cluster cores. One can see that the heating rate with $r_{\text{cutoff}} = 0.3 r_{500}$ (blue line) and $r_{\text{cutoff}} = 0.1 r_{500}$ (red line) produces excess energy in the cluster cores for all the three cluster masses. Increasing $L_{\text{inj}}^{\text{eff}}$ further will only increase the normalization of the heating profiles. As expected, a higher amount of energy feedback is required for massive clusters.

For the acoustic case, the right-hand panel in Fig. 1 shows the heating profiles for the same three cluster masses by considering spectrum having $\zeta = 1.8$ in the frequency ranges $f_{-6} = 0.01 - 0.1$ (solid blue line) and $f_{-6} = 0.05 - 0.50$ (solid red line), and with $\xi_s = \xi_c = 0.1$. For comparison, we also show the heating profiles for two single frequencies, $f_{-6} = 0.01$ (dashed blue line) and $f_{-6} = 0.05$ (dashed red line). We find that for a spectrum of frequencies, the heating rate is dominated by the lowest frequency (i.e $f_{-6} = 0.01$ or $f_{-6} = 0.05$). We note that the effective radial range of heating can be reduced not only by increasing the frequency but also by increasing the conductivity fraction $\xi_c$. As in the effervescent case, changing the magnitude of acoustic luminosity only changes the normalization of the heating profiles. As can be seen in the figure, the heating profiles having the frequency spectrum of $\zeta = 1.8$ with frequencies $f_{-6} = 0.01 - 0.50$ or $f_{-6} = 0.05 - 0.50$ produces more realistically decreasing heating profiles, unlike in single frequency case, say, with $f_{-6} = 0.01$ where the heating profile is flatter to a higher radius and then suddenly drops. This is easy to understand since a range of frequencies affect a range of length scales with an average contribution to all the scales till it reaches the lowest frequency (or highest wavelength) after which the heating falls off; on the other hand, a single frequency only has one dissipation length and the heating drastically falls beyond that radius. Therefore, we will only consider the acoustic model having a frequency spectrum in the rest of our calculations. Next, we turn our attention to the evolution of thermodynamical profiles as a response to heating, cooling, and conduction.

4.2. Evolution of the ICM with effervescent heating

Fig. 2 shows the evolution of pressure (top) and entropy (middle) and temperature (bottom) for the $6 \times 10^{14} M_\odot$ cluster by considering effervescent model with $L_{\text{inj}}^{\text{eff}} = 2.5 \times 10^{45}$ ergs s$^{-1}$ and $r_{\text{cutoff}} = 0.3 r_{500}$ (left panel) and $L_{\text{inj}}^{\text{eff}} = 4.5 \times 10^{44}$ ergs s$^{-1}$ and $r_{\text{cutoff}} = 0.1 r_{500}$ (right panel) for the ‘entire’ cluster radial range, i.e (0.02 – 3) $r_{500}$. The evolution also include the cooling and conduction ($\xi_c = 0.1$). The values of $L_{\text{inj}}^{\text{eff}}$ are chosen so as to produce excess energy up to $0.3 r_{500}$ (left panel) and $0.1 r_{500}$ (right panel). The profiles are evolved for the time period of $t_{\text{age}} = 2.2 \times 10^9$ yrs with the AGN heating switched off at half the time interval. Cooling and conduction, on the other hand, are always present throughout the age of the cluster. The time steps used to evolve the ICM is taken to be $10^4 - 10^5$ years. However, in the figure, the profiles are plotted after each $\approx 1.3 \times 10^8$ years (thin dashed lines). The initial profiles prior to heating are represented by thick solid blue lines in all the sub panels. Similarly, the final profiles at the end of $t_{\text{age}}$ are shown by thick solid black lines. As the heating is turned on, the pressure profiles start to decrease until the heating is stopped (at $0.5 t_{\text{age}}$), after which profiles start to rise back slowly. This is due to the fact that the gas is pushed out due to the central heating, which later falls back. We see that the pressure profiles during the evolution are always within the Planck Collaboration V (2013) observed dispersion. The entropy and temperature profiles, as expected, show a reverse trend. They initially increase and then decrease after the heating is switched off. The fractional difference between the initial and final profiles are also shown in Fig. 2. One can see that the fractional difference can be more 50% near the center and has a very strong central radial dependence. We can also see that the fractional difference profiles becomes zero at $\sim 0.1 r_{500}$ and $\sim 0.3 r_{500}$, as expected.

4.3. Evolution of the ICM with acoustic heating

Similarly, the evolution of thermal profiles with acoustic heating, cooling, and conduction is shown in Fig. 3. We assume a frequency spectrum with $\zeta = 1.8$ and $\xi_s = \xi_c = 0.1$. We choose the same values of mechanical luminosity as that in the effervescent heating. We see that an acoustic luminosity of $L_{\text{inj}}^{\text{Ac}} = 2.5 \times 10^{45}$ ergs s$^{-1}$ in the frequency range of $f_{-6} = 0.01 - 0.50$ and an acoustic luminosity of $L_{\text{inj}}^{0,\text{Ac}} = 4.5 \times 10^{44}$ ergs s$^{-1}$ in the frequency range of $f_{-6} = 0.05 - 0.50$ could produces excess energy up to $0.3 r_{500}$ and $0.1 r_{500}$, respectively. Our results show that the optimal frequency range should be smaller than then frequency range of $f_{-6} = 0.2 - 1$ as predicted by Fabian et al. (2005) so as to produce the feedback up to $0.1 r_{500}$ or $0.3 r_{500}$. Similar to the effervescent case, here also, the pressure (entropy) profile is pushed up (down) in the inner regions as the ICM is heated and then rise (fall) after heating is shut off. Moreover, pressure profiles during the evolution too lie within the observed Planck Collaboration V (2013) dispersion. Similarly, the fractional change (also shown in Fig. 3) can be more 50% near the center in the acoustic heating. One finds that in the case of acoustic heating, one gets sharp discontinuities around $0.04 r_{500} - 0.05 r_{500}$ in the entropy and temperature profiles as soon as the cluster is heated which then moves forward with time evolution. However, as soon as heating is turned off, due to conduction, one gets smooth profiles at the end of evolution. It is also likely that acoustic heating due to frequencies $f_{-6} < 0.01$ and $f_{-6} > 0.50$ are likely to be suppressed - the former range of frequencies would require a relatively large value of injected luminosity to balance.
the cooling while the later range of frequencies would inject energy only into the very central region (producing very high entropy/temperature.)

4.4. Importance of conductivity

Incorporating conductivity is crucial for ICM thermodynamics. In Figure 4, we show the final pressure and entropy profiles for a $6 \times 10^{14} M_\odot$ cluster when conductivity is neglected (i.e., $\xi_c = 0$)
Fig. 3. ICM thermodynamics for the Acoustic model. Evolution of pressure (top), entropy (middle) and temperature (bottom) profiles as a function of radius in acoustic heating for a cluster of mass $6 \times 10^{14} M_\odot$ at $z = 0$ with spectrum $\zeta = 1.8$ and $f_{\delta} = 0.01 - 0.50$ (left panel) and $f_{\delta} = 0.05 - 0.50$ (right panel). The evolution also includes cooling and conduction with $\xi_\kappa = 0.1$ and $\xi_\nu = 0.1$. The evolution of the profiles are shown at intervals of $13 \times 10^8$ years with thin red dashed lines. The pressure (entropy) is seen to fall (rise) as the gas is heated and then rise (fall) after heating is switched off. Initial and final states correspond to thick solid blue and black lines respectively. The blue and red shaded regions are the dispersion of the stacked XMM-Newton and Planck pressure profiles of 62 clusters form Planck Collaboration V (2013) (their figure 4). For each panel, we also show the fractional change between the initial and final profiles ($P_{\text{fin}}$, $K_{\text{fin}}$, $T_{\text{fin}}$). As can be seen, ignoring conduction results in the unphysical negative gradient in entropy profiles near the cluster center even for small values of luminosities, and becomes worse for higher values of the luminosities. The high values of central entropy correspond to the unreasonable central temperature ($> 25$ keV); however, pressure remains less affected. Moreover, we see that heating becomes more centrally peaked in the acoustic model compared to the effervescent heat-
ing and it becomes difficult to have feedback reach up to 0.3r500. In general, the impact of conduction lies in the fact that it tries to make the ICM isothermal by transporting the large amount of energy injected near the center to the outer region which results in the entropy/temperature flattening. This can be seen in Fig. (2) (effervescent model) and Fig. (3) (acoustic model) where the final temperature profiles becomes more or less flat in the inner regions with \( \xi_e = 1 \). In the case of effervescent heating, for a given \( L_{\text{inj}} \), higher values of the conductivity fraction \( \kappa \) will try to make the gas temperature uniform more efficiently without changing the final profiles significantly. In particular, with conduction, we can have energy feedback reach 0.3r500 even with a lower \( f_{\text{conoff}} = 0.1r500 \) and end up with similar final profiles as those obtained with \( L_{\text{inj}} = 2.5 \times 10^{45} \) and \( f_{\text{conoff}} = 0.3r500 \). Its impact is more complex in the acoustic model where the heating also depends on the value of \( \xi_e \). One finds that ignoring conductivity in the acoustic model, decreases the overall amplitude of the heating profiles; however, the effective heating profile extends to a larger radius, and one requires a relatively larger value of \( L_{\text{inj}} \) to balance the cooling near the center. For a given \( L_{\text{inj}} \), as we increase the \( \xi_e \) from our fiducial value of 0.1, the heating rate becomes more centrally peaked but so does the heat conductance from the central region to the outer region. This makes the final temperature profile more or less isothermal in the inner region. However, note that due to the very high central heating arising with frequency ranges \( f_{\phi} > 0.01 \), it is not possible to have reasonable feedback profiles up to 0.3r500 (especially for the high mass clusters) even though final profiles are isothermal in the inner region. This is an important difference between effervescent and acoustic energy transport models.

### 4.5. Comparison with the observations

Given that we can calculate the AGN feedback needed to balance cooling up to a certain radius for both scenarios of heating, we can estimate the mass dependence of the central injected energy. Here, we study the evolution of ICM properties of the galaxy clusters in the range \( 2 \times 10^{14} - 2 \times 10^{15} M_\odot \). Fig. 5 shows the derived scaling relation between the injected effervescent (acoustic) luminosity with the total mass of the cluster such that one gets excess energy up to 0.1r500 or 0.3r500. For the effervescent heating and assuming \( \xi_e = 0.1 \) we get

\[
\log \left( \frac{L_{\text{inj}}}{10^{45} \text{ergs sec}^{-1}} \right) = -0.96 + 1.73 \log \left( \frac{M_{\text{vir}}}{10^{14} M_\odot} \right) \quad \text{for } f_{\text{conoff}} = 0.3r500
\]

\[
\log \left( \frac{L_{\text{Aco}}}{10^{45} \text{ergs sec}^{-1}} \right) = -1.58 + 1.52 \log \left( \frac{M_{\text{vir}}}{10^{14} M_\odot} \right) \quad \text{for } f_{\text{conoff}} = 0.1r500
\]

Similarly for the acoustic heating and assuming \( \xi_e = 0.1 \) we get

\[
\log \left( \frac{L_{\text{Aco}}}{10^{45} \text{ergs sec}^{-1}} \right) = -0.81 + 1.59 \log \left( \frac{M_{\text{vir}}}{10^{14} M_\odot} \right) \quad \text{for } f_{\phi} = 0.01 - 0.50
\]

\[
\log \left( \frac{L_{\text{Aco}}}{10^{45} \text{ergs sec}^{-1}} \right) = -1.64 + 1.49 \log \left( \frac{M_{\text{vir}}}{10^{14} M_\odot} \right) \quad \text{for } f_{\phi} = 0.05 - 0.50
\]

Interestingly, as can be seen in the figure (and the above relations), both the heating models give a similar scaling for feedback. One finds the same slope, \( L_{\text{inj}} \) (or \( L_{\text{Aco}} \)) \( \propto M_{\text{vir}}^{1.5} \) when heating and cooling are balanced up to 0.1r500; however, the slope for the effervescent model scaling relation is slightly steeper than acoustic model when we consider energy balance up to a higher radius of 0.3r500. Also plotted in the same figure is the estimated mechanical jet power, \( L_{\text{jet}} \), using the BCG radio luminosity measurements at 1.4 GHz, \( L_{1.4} \), for the cluster sample used in Iqbal et al. (2018) 2 (their Tab. 1) by considering Godfrey & Shabala (2013) \( L_{\text{jet}} = L_{1.4} \) relation for FRII galaxies and using a spectral index of 0.6

\[
L_{\text{jet}} = 2.8 \times \left( \frac{L_{1.4}}{10^{31} \text{ergs s}^{-1} \text{Hz}^{-1}} \right)^{0.67} \times 10^{44} \text{ergs s}^{-1}.
\]

We see that the feedback up to 0.3r500 represents the upper limit of the observed mechanical luminosity and that most of the data center around 0.1r500. Note that there can be other fainter radio sources that have evaded detection but which still contribute to the heating of the ICM.

\[2 \] \( M_{\text{vir}} \) is assumed to be 1.25 \( \times M_{500} \)
Assuming that the scaling between the central black-hole mass and the virial mass of a galaxy, $M_{\text{BH}} \approx 10^{8}(M_{\text{vir}}/(10^{4}M_{\odot}))^{1/2}$, as given by Bandara et al. (2009) holds for cluster scales, one finds that that AGN mechanical luminosity can be approximated as $L_{\text{eff}} \approx 10^{43} \text{ergs s}^{-1} \frac{M_{\text{BH}}}{(10^{8}M_{\odot})}$. Comparing this with the Eddington luminosity of the central SMBH, $L_{\text{Edd}} \approx 10^{37.5} \text{ergs s}^{-1} \frac{M_{\text{BH}}}{(10^{8}M_{\odot})}$, one can see that the fraction of the total luminosity available as the AGN mechanical luminosity at 0.02$r_{500}$ is given by $\epsilon_{\text{Edd}} = \frac{L_{\text{Edd}}}{L_{\text{Edd}}}$ $\approx 10^{-3.5}$. This falls at the lower end of the range of values used in AGN feedback simulations for the super-Eddington accretion in order to explain the rapid assembly of $10^{10}M_{\odot}$ SMBHs in first billion years of the Universe (Massonneau et al. 2022).

5. DISCUSSION AND CONCLUSIONS

It is interesting to compare our results with the constraints on the total injected energy from the central AGN estimated for effervescent heating by Roychowdhury et al. (2005). It was seen that if the heating time, $t_{\text{heating}}$, lies between $5 \times 10^{5}$ to $5 \times 10^{9}$ years, the average jet luminosity, $L_{\text{jet}}$, would vary between $5 \times 10^{44}$ to $2 \times 10^{45}$ erg s$^{-1}$ for cluster masses ranging from $4 \times 10^{13}M_{\odot}$ to $10^{15}M_{\odot}$. This total heating time might include short multiple episodes of the central black hole, with bubbles consisting of relativistic plasma from earlier active phases, being spread out all through the cluster atmosphere. The authors concluded that it was possible to fit the excess entropy requirements for clusters of different masses with only one pair of $L_{\text{jet}}$ and $t_{\text{heating}}$. They also found the total energy injected into the ICM (and hence injected luminosity) to be proportional to $M_{\text{vir}}^{1.5}$ which agrees perfectly with our estimates. Moreover, they also found that this scaling is consistent with a scaling of the supermassive black hole mass in the central AGN and the cluster mass, $M_{\text{bh}} \sim 10^{-3}M_{\text{cl}}$, if the efficiency of conversion of energy by the accreting black hole is $\sim 0.25$. This scaling is reminiscent of the relation between black hole mass and galaxy mass (Bandara et al. 2009). Similar results were presented in Iqbal et al. (2018) who found BCG radio luminosity is proportional to cluster mass as $L_{\text{jet}} \propto M_{\text{vir}}^{1.29 \pm 0.19}$ for a sample of 38 galaxy clusters. Comparing these results with the current findings, it is worthwhile to point out that the robustness of these heating models rests upon the fact that the injected luminosity from the central AGN, be it effervescent or acoustic heating or a combination of both, lies in a similar range as demonstrated in this work. It is only natural to propose that both effervescent and acoustic heating are occurring in tandem with thermal conduction playing an important role in distributing the heat to the outer regions of the cluster atmosphere.

Currently, our approach does not account for the observed diversity between CC and NCC clusters. In particular, we find that our heating model is not able to reproduce high densities and low entropy in the inner regions as found in CC clusters. Therefore, it still remains to explain the wide variety of observed ICM properties, especially, the cool/non-cool core dichotomy observed in the population of galaxy clusters. Dubois et al. (2011) found that the interaction between an AGN jet and the ICM gas that regulates the growth of the AGN’s black hole, can naturally produce cool core clusters if the contribution of metals is neglected. However, as soon as metals are allowed to contribute to the radiative cooling, only the non cool core solution is produced. Similarly, it has also been argued that anisotropic thermal conductance (Barnes et al. 2019) or artificial conductance (Rasia et al. 2015) which enhance mixing of gas might naturally explain the formation of CC and NCC clusters. An immediate extension of the present work is to include cooling flows in the very central region since that would help us to produce cool cores if the mass accretion rate is high enough (Nath 2003). Additionally, the derived feedback profiles can be compared with precise multi-wavelength observations of galaxy clusters in the Cluster HEritage project (CHEX-MATE Collaboration 2021) which will allow us to probe the extent of AGN feedback in the galaxy clusters.

To conclude, the main focus of this work is to quantitatively compare effervescent and acoustic models of heating in the ICM. We study the evolution of ICM thermal profiles with these two models of AGN heating along with conduction and cooling in the clusters of mass range of $2 \times 10^{14}M_{\odot}$ to $2 \times 10^{15}M_{\odot}$ at redshift, $z = 0$ so as to produce excess energy up to 0.1$r_{500}$ or 0.3$r_{500}$. The heating can be controlled by tuning relevant parameters of the heating models. For effervescent heating, the relevant parameter is the outer radial cutoff of the heating, and for acoustic heating, it is the frequency of the plasma waves. We find that for acoustic heating to work in the range 0.1$r_{500}$ - 0.3$r_{500}$, the optimal frequencies should lie in the range of $f_{\text{ac}} = 0.01 - 0.5$. Our results show that, with current observational data, there is no preference for any of the heating mechanisms over the other. We find that one additionally requires conduction which significantly influences the properties of the ICM. As a result of the conduction, injected heat flows from the innermost regions of the cluster to the outer regions thus erasing strong temperature gradients. We also estimate the relation between the injected luminosity required to match the observations and the cluster mass. We find that both effervescent and acoustic produce the same scaling relations thus making it difficult to disentangle the heating models with the X-ray observations. We find injected luminosity scales with cluster mass as $M_{\text{vir}}^{1.5}$ for both effervescent and acoustic heating. Moreover, the inferred correlation is consistent with the observed mechanical jet power and radio luminosity relation, reinforcing the idea that AGNs provide the most dominant heating in the ICM.

It has been shown that the power spectrum of density/pressure fluctuations in the ICM can help us to probe the AGN feedback in galaxy clusters (Churazov et al. 2012; Gaspari...
et al. 2014b; Khatri & Gaspari. 2015; Zhuravleva et al. 2016). Effervescent heating is expected to be associated with density fluctuations (in the form of X-ray cavities caused by bubbles) whereas acoustic heating is mainly related to pressure fluctuations. Accurate measurements of small scale perturbations are expected from future X-ray satellites such as Athena. This will give us the ability to measure the fluctuations down to a few kpc allowing us to study the relatively contribution of AGN feedback models in heating the ICM.

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