ENTROPY AT THE OUTSKIRTS OF GALAXY CLUSTERS AS IMPLICATIONS FOR COSMOLOGICAL COSMIC-RAY ACCELERATION

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ABSTRACT

Recently, gas entropy at the outskirts of galaxy clusters has attracted much attention. We propose that the entropy profiles could be used to study cosmic-ray (CR) acceleration around the clusters. If the CRs are effectively accelerated at the formation of clusters, the kinetic energy of infalling gas is consumed by the acceleration and the gas entropy should decrease. As a result, the entropy profiles become flat at the outskirts. If the acceleration is not efficient, the entropy should continue to increase outward. By comparing model predictions with X-ray observations with Suzaku, which show flat entropy profiles, we find that the CRs have carried $\lesssim 7\%$ of the kinetic energy of the gas away from the clusters. Moreover, the CR pressure at the outskirts can be $\lesssim 40\%$ of the total pressure. On the other hand, if the entropy profiles are not flat at the outskirts, as indicated by combined Plank and ROSAT observations, the carried energy and the CR pressure should be much smaller than the above estimations.

Key words: cosmic rays – galaxies: clusters: general – galaxies: clusters: intracluster medium – large-scale structure of universe

Online-only material: color figure

1. INTRODUCTION

The existence of cosmic rays (CRs) in clusters of galaxies is clearly indicated by radio synchrotron emission (Feretti et al. 2012). The CRs may be accelerated at shocks or turbulence in the X-ray hot gas (e.g., Fujita & Sarazin 2001; Brunetti et al. 2001; Fujita et al. 2003; Kang & Jones 2005; PFrommer et al. 2007), and they may play important roles in the evolution of clusters. For example, they may heat the cores of clusters (Fujita & Ohira 2011, 2012, 2013). Since the background gas is hot, their acceleration efficiency in clusters could be very different from that of objects in the Galaxy (e.g., supernova remnants (SNRs)). However, the lack of firm observational evidence of CRs with the exception of radio observations prevents us from understanding their acceleration. Thus, other observational approaches that can clarify CR acceleration in clusters are strongly desired.

X-ray observations with Suzaku have revealed the entropy of the hot gas of clusters at their outskirts. Here, the entropy is defined as $K \equiv k_B T / n \rho/\gamma$, where $k_B$ is the Boltzmann constant, $\gamma = 5/3$ is the adiabatic index, and $T$ and $n$ are the gas temperature and the number density, respectively. Numerical simulations, in which non-gravitational heating (e.g., energy ejection from galaxies) and radiative cooling are not included, predicted that the entropy should increase with $r$ as $r^{-1.0}$, while $r$ is the distance from the cluster center (Voit et al. 2005; Burns et al. 2010). On the other hand, the Suzaku observations have shown that the entropy profiles flatten at $r \gtrsim 0.5r_{200}$ (Bautz et al. 2009; Kawaharada et al. 2010; Hoshino et al. 2010; Akamatsu et al. 2011; Simionescu et al. 2011; Sato et al. 2012; Walker et al. 2012a; Ichikawa et al. 2013; see Figure 13 of Sato et al. 2012), where $r_{200}$ ($\sim 2$ Mpc) is the radius within which the mean mass density is 200 times the critical density for a flat universe and is often considered to be the typical radius of clusters.

Several ideas have been proposed to solve this discrepancy. Gas clumping could lead to the overestimation of the gas density, which in turn could lead to the underestimate of entropy (Nagai & Lau 2011). However, gas clumping is effective mainly at $r \gtrsim r_{200}$, because the clumps tend to be destroyed within the cluster. Non-equilibrium between ions and electrons may also decrease entropy. This is because heavier ions have most of the kinetic energy of gas and they are first thermally heated at shocks. If it takes a long time for the kinetic energy of the ions to be transferred to lighter electrons, the observed temperature of the electrons could be low. This may decrease the observed entropy of gas (Hoshino et al. 2010; Akamatsu et al. 2011). However, numerical simulations have shown that the degree of non-equilibrium is small (Wong & Sarazin 2009), although it may depend on the dynamical state of clusters (Akhori & Yoshikawa 2008; Rudd & Nagai 2009). Moreover, from observations of the Sunyaev–Zel’dovich effect, Planck has shown that the gas pressure at the outskirts of clusters does not significantly drop. This suggests that the ions and electrons are in equilibrium (Planck Collaboration et al. 2013). For some clusters, accretion of matter toward them may decrease at low redshifts. Although this makes the entropy profiles flatten at their outskirts, it does not seem to be effective enough to be consistent with the observed systematic flattening (Cavaliere et al. 2011).

In this Letter, we propose that the entropy profiles may reflect CR acceleration in clusters and could be used as a tool to study it. We focus on the acceleration at “accretion shocks” around the clusters. These shocks are generated through gas infall toward the clusters as they grow by accreting dark matter and gas from the outside (e.g., Evrard et al. 1996; Ryu et al. 2003; Skillman et al. 2008). If the CR acceleration at the shocks is effective, the CRs should consume much of the kinetic energy of the gas and should affect the entropy of the gas (Bykov 2005). Thus, the flattened entropy profiles may be the result of the past CR acceleration around the clusters.

2. MODELS

It is widely believed that if CRs are effectively accelerated at a shock, their pressure changes the structure of the shock (Drury & Voelk 1981; Drury 1983; Malkov & O’C Drury 2001). Before we investigate the entropy profiles of clusters, we consider the jump conditions at the shock. We treat gas and CRs as two fluids hereafter. We define three distinct regions with a shock: (0) the
far upstream region where the influence of accelerated CRs can be ignored, (1) a region just upstream of the shock where the presence of the CRs affects the shock structure, and (2) a region downstream from the shock. We indicate each region by lower indices. For example, the gas density and velocity in the far upstream region are $\rho_0$ and $v_0$, respectively. The spatial scale of region (1) is much smaller than the size of a cluster, and it cannot be resolved by current X-ray telescopes. The gas density and temperature could, respectively, change from $\rho_2$ and $T_2$ far downstream of the shock as the cluster grows.

The CR acceleration consumes gas energy. We discuss the accompanied entropy change at a shock based on the model of Vink et al. (2010). We represent the energy flux that is carried away by CRs diffusing away far upstream by $F_{cr}$. The flux is normalized to the kinetic energy flux of the shock:

$$
\epsilon_{esc} \equiv \frac{F_{cr}}{(1/2)\rho_0 v_0^2} .
$$

The fraction of the downstream CR pressure is

$$
w \equiv \frac{P_{2, cr}}{P_2} = \frac{P_{2, cr}}{P_{th} + P_{2, cr}} ,
$$

where “cr” and “th” represent the CR and the thermal components, respectively. The Mach number of the shock defined at the region far upstream is

$$M_0 \equiv \sqrt{\frac{1}{\gamma g} \frac{\rho_0 v_0^2}{P_0}} .
$$

The compression ratios across the different regions are

$$\chi_1 \equiv \frac{\rho_1}{\rho_0} , \quad \chi_2 \equiv \frac{\rho_2}{\rho_1} , \quad \chi_{12} \equiv \frac{\chi_1 \chi_2}{\chi_2} = \frac{\rho_2}{\rho_0} .
$$

Assuming that the thermal component evolves adiabatically in region (1), the pressure is given by $P_{1, th} = P_0 \chi_1^{\gamma g}$. Thus, the total compression ratio is given by

$$\chi_{12} = \frac{(\gamma g + 1)M_0^2 \chi_1^{\gamma g}}{(\gamma g - 1)M_0^2 \chi_1^{\gamma g} + 2} .
$$

The CR pressure fraction is given by

$$w = \frac{1 - \chi_{12}^{\gamma g} + \gamma g M_0^2 (1 - 1/\chi_1) + 1}{\gamma g M_0^2 (1 - 1/\chi_{12})} ,
$$

and the escaping energy flux is given by

$$\epsilon_{esc} = 1 + \frac{2G_0}{\gamma g M_0^2} - 2G_2 \frac{\chi_2}{\chi_{12}} \frac{\gamma g}{\gamma g - 1} ,
$$

where

$$G_0 \equiv \frac{\gamma g}{\gamma g - 1} , \quad G_2 \equiv \frac{\gamma g}{\gamma g - 1} + (1 - w) \frac{\gamma g}{\gamma g - 1} ,
$$

and $\gamma g$ is the adiabatic index for the CR component. Equations (5)–(8) show that $\epsilon_{esc}$ and $w$ are represented by $\chi_1$ for a given $M_0$. The entropy difference across the shock is written as

$$\Delta S = \frac{3}{2} k_B \ln \left( \frac{K_2}{K_0} \right) .
$$

In this equation,

$$\frac{K_2}{K_0} = (1 - w) \frac{1}{\chi_{12}^{1/\chi_2}} \left[ 1 + \gamma g M_0^2 \left( \frac{1 - 1}{\chi_2} \right) \right] ,
$$

which means that $\Delta S$ is also the function of $M_0$ and $\chi_1$ (Vink et al. 2010).

It would be natural to assume that CRs are accelerated at the accretion shocks (Fujita & Sarazin 2001; Kang & Jones 2005; Pfrommer et al. 2007), although clear evidence has not been discovered. The CRs would carry the gas energy away and lower the entropy. We compare the entropy profiles predicted by numerical simulations that do not include CR acceleration with those obtained through X-ray observations. Contrary to density and temperature, entropy is conserved if there is no heating and cooling, which is an advantage of discussing entropy. The entropy profile predicted by the numerical simulations is

$$K_{sim}(r) = 1.32 K_{200}(r/r_{200})^{1.1} ,
$$

where $K_{200} \approx 362 \text{ keV cm}^2 (T_X / \text{keV})$ and $T_X$ is the gas temperature (Voit et al. 2005). If we adopt the entropy profiles obtained with Suzaku, they can be fitted as

$$K_{obs}(r) \propto (r/r_{200})^{1.1} e^{-r/r_{200}}
$$

(Walker et al. 2012b). At $r \sim 0.3 r_{200}$, the entropy profiles do not become flat and they are not much affected by the activities of central active galactic nuclei (AGNs). Thus, we assume that

$$K_{obs}(0,3 r_{200}) = K_{sim}(0,3 r_{200}) ,
$$

which gives the normalization of Equation (12). Although there is debate about an appropriate position of the normalization ($r \sim 0.3 r_{200}$; Eckert et al. 2013), it would not affect the following results when the observed entropy profiles significantly deviate from those predicted by the theoretical simulations. Figure 1 shows $K_{sim}(r)$ and $K_{obs}(r)$ for $T_X = 8$ and 4 keV. Although $K_{obs}$ slightly decreases at $r \gtrsim 0.7 r_{200}$, the curve should be regarded as “flat” for $r \gtrsim 0.5 r_{200}$ considering the errors of the observations. We note that while non-thermal pressure owing to turbulence in gas may affect the entropy profile (Lau et al. 2009), it should be included in $K_{sim}$ obtained by high-resolution...
numerical simulations that can follow turbulence. Thus, the difference between $K_{\text{sim}}$ and $K_{\text{obs}}$ is caused by something other than the non-thermal pressure.

We assume that a cluster gradually grows from the outside as it accretes matter from the outside. The entropy of the gas that falls into the cluster may not be zero because it could have been heated through activities of galaxies and AGNs in the field (Kaiser 1991; Cavaliere et al. 1997; Ponman et al. 1999). In fact, widely distributed metals outside clusters may indicate such activities (Fujita et al. 2008). The entropy of the gas before passing accretion shocks is estimated to be $K_{\text{out}} \sim 100–400 \text{ keV cm}^2$ (Voit et al. 2003), and we adopt $K_{\text{out}} = K_0 = 200 \text{ keV cm}^2$.

We ignore heating and cooling of the gas except for the heating at accretion shocks around the cluster ($r \gtrsim r_{200}$). The motion of the gas is fundamentally controlled by the gravity from dark matter, and thus the infall velocity of the gas toward the cluster and the Mach number of the accretion shocks ($M_0$) do not significantly depend on the presence or absence of CR acceleration at the shocks, while the postshock gas (region 2) is significantly affected by it. Therefore, the Mach number of the shock $M_0 = M(r)$, through which the gas located at the radius $r$ at present had passed, can be estimated using $K_{\text{sim}}(r)$ and $K_{\text{out}}$. Since $K_{\text{sim}}(r)$ is the entropy when the CR acceleration is ignored, the relation among $M$, $K_{\text{sim}}$ and $K_{\text{out}}$ should be described by the Rankine–Hugoniot relation that does not include the effects of CRs ($\chi_1 = 1$):

$$\frac{K_{\text{sim}}(r)}{K_{\text{out}}} = \frac{2\gamma_g M(r)^2 - (\gamma_g - 1)}{\gamma_g + 1} \left[ \frac{(\gamma_g - 1)M(r)^2 + 2}{(\gamma_g + 1)M(r)^2} \right]^{\gamma_g/\gamma_g - 1}. \quad (14)$$

Figure 2 shows the profiles of the Mach number $M(r)$ derived from Equation (14). The Mach number is the increasing function of $r$ and reaches $M \sim 10$ at $r \sim r_{200}$. We emphasize that entropy is conserved for a given gas element, and that the gas observed at $r$ at present was not necessarily there when it passed a shock. Therefore, the radius of the shock could be larger than $r_{200}$ at the time when the gas passed the shock. In other words, the position of the shock is not specified in our model.

Assuming that CR acceleration makes $K_{\text{obs}}$ smaller than $K_{\text{sim}}$ at the outskirts of clusters, the entropy difference at the shocks for the observed clusters is obtained by using Equations (9) and (10) with $M_0 = M(r)$:

$$\Delta S[M(r), \chi_1(r)] = \frac{3}{2} k_B \ln \left[ \frac{K_{\text{obs}}(r)}{K_{\text{out}}} \right]. \quad (15)$$

Since we already know $K_{\text{obs}}(r)$ (Equations (12) and (13)) and $M(r)$ (Figure 2), we can derive $\chi_1(r)$ from Equation (15).

## 3. RESULTS AND DISCUSSION

From $M_0 = M(r)$ and $\chi_1(r)$, we obtain $\epsilon_{\text{esc}}(r) = \epsilon_{\text{esc}}[M(r), \chi_1(r)]$ and $w(r) = w[M(r), \chi_1(r)]$ using Equations (5)–(8), which are shown in Figure 3. In the calculations, we assumed that $\gamma_{\text{esc}} = 4/3$. Figure 3 shows that $\epsilon_{\text{esc}}$ and $w$ increase outward and reach $\epsilon_{\text{esc}} \sim 0.07$ and $w \sim 0.4$ at $r \sim r_{200}$. These values are often estimated for the Galactic SNRs (Vink et al. 2010), although their Mach numbers are typically an order of magnitude larger than those of the cluster shocks considered in this study. Nevertheless it is interesting that clusters have similar values of $\epsilon_{\text{esc}}$ and $w$. Since other factors such as clumping of the gas (Nagai & Lau 2011) or a decrease of matter accretion toward the clusters (Cavaliere et al. 2011) may partially contribute to the decrease of the entropy, the actual values of $\epsilon_{\text{esc}}$ and $w$ could be somewhat smaller than the above values.

We implicitly assumed that the accretion shock is a single shock. However, the accreted gas may have passed multiple shocks. In that case, the Mach number of the inner shocks may be smaller than $M$ in Figure 2 because of the heating at the outer shocks. Thus, our model could not be applied to dynamically active clusters that have complicated shock structures. However, the CRs may be reaccelerated at multiple shocks and the acceleration efficiency may be large in spite of the low Mach numbers (Kang & Ryu 2011). Therefore, CR acceleration at multiple shocks with small Mach numbers may be qualitatively similar to that at a shock with a large Mach number. At least we can say that the difference between $K_{\text{obs}}$ and $K_{\text{sim}}$ indicates that a significant fraction of the gas energy must have been converted to CRs even in the case of multiple shocks.

Some cosmological numerical simulations do not show the drastic temperature decrease or density increase at cluster outskirts in spite of CR acceleration (e.g., Pfrommer et al. 2007; Vazza et al. 2012). Although we could not identify the cause, it may be because their assumed acceleration efficiency is smaller than those we obtained. In fact, if a constant high efficiency of
50% is adopted, the temperature significantly drops (Figure 3 of Pfrommer et al. 2007). Moreover, the efficiency in the central region of a cluster may need to be much lower than that at the outskirt in order to reproduce the flat entropy profile. In our model, the CR acceleration is prohibited in the central region because of the low Mach number attributed to the preheated model, the CR acceleration is prohibited in the central region outskirt in order to reproduce the flat entropy profile. In our region of a cluster may need to be much lower than that at the Pfrommer et al. 2007). Moreover, the efficiency in the central region. This may be favorable for the non-detection of gamma rays from the central regions of clusters (Ackermann et al. 2010) because gamma rays are produced through proton–proton interaction.

Our model predicts that entropy decreases in the region where CR acceleration is effective. The CR pressure is $w \gtrsim 0.1$, which is the typical value for the Galactic SNRs (Vink et al. 2010), at $0.5 r_{200} \lesssim r \lesssim r_{200}$ (Figure 3(b)). In this region, synchrotron emission from electrons (“radio relics”) has often been discovered (Feretti et al. 2012). Although the electrons seem to be accelerated at shocks created during cluster mergers, the Mach numbers are relatively small ($\mathcal{M} \sim 2–4$) (van Weeren et al. 2011; Akamatsu & Kawahara 2013). At these small Mach numbers, CR acceleration may be difficult. However, if there is a pre-existing CR population, CR reacceleration at the shocks could increase their energy high enough to emit the synchrotron radiation (Kang & Ryu 2011). The entropy decrease at cluster outskirts may indicate the existence of a pre-existing CR population. Moreover, the CRs may amplify magnetic fields (Lucek & Bell 2000; Bell 2004; Fujita et al. 2010, 2011). Thus, magnetic fields amplified by the CRs may be found at the cluster outskirts in the future. The CRs accelerated at the accretion shocks may contain ultra-high-energy ones (Inoue et al. 2005).

Note that the flat entropy profiles have not been confirmed in the combined analysis of the pressure profiles obtained with Planck and the density profiles obtained with ROSAT (Eckert et al. 2013). In that study, the entropy continues to increase outward. If this is the case, our model indicates that the CR acceleration efficiency is much smaller than those estimated above. This could constrain the aforementioned reacceleration model for the radio relics. This also shows that the future confirmation of the entropy profiles is important in terms of CR acceleration in clusters. At present, the model and observational uncertainties suggest that the estimated values of $\varepsilon_{\text{acc}} \sim 0.07$ and $w \sim 0.4$ at $r \sim r_{200}$ at the beginning of this section should be regarded as upper limits.

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