Constraints on Circumgalactic Media from Sunyaev–Zel’dovich Effects and X-Ray Data

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Abstract

We use observational measurements of thermal and kinetic Sunyaev–Zel’dovich effects, as well as soft X-ray emission associated with galaxy groups, to constrain the gas density and temperature in the circumgalactic medium for dark matter halos with masses above $10^{12.5} M_\odot$. A number of generic models are used together with a Bayesian scheme to make model inferences. We find that gas with a single temperature component cannot provide a consistent model to match the observational data. A simple two-phase model assuming a hot component and an ionized warm component can accommodate all three observations. The total amount of the gas in individual halos is inferred to be comparable to the universal baryon fraction corresponding to the halo mass. The inferred temperature of the hot component is comparable to the halo virial temperature. The fraction of the hot component increases from (15–40)% for $10^{12.5} M_\odot$ halos to (40–60)% for $10^{14.5} M_\odot$ halos, where the ranges reflect uncertainties in the assumed gas density profile. Our results suggest that a significant fraction of the halo gas is in a nonthermalized component with the temperature much lower than the virial temperature.

1. Introduction

In the current paradigm of structure formation, galaxies are assumed to form and evolve in dark matter halos (see Mo et al. 2010 for a review). In this scenario, accretion and feedback together govern the growth of galaxies. The circumgalactic medium (hereafter CGM) is the repository for baryons, through which galaxies are connected to the intergalactic medium. Some of these baryons will be accreted by galaxies to form stars and central supermassive black holes, while most of them leave galaxies through outflows produced by supernova and quasars. Much of the ejected gas may be reaccreted, and so the gas may cycle through the CGM a number of times. Currently, the evidence for this paradigm is indirect, mainly from investigations of galaxy stellar masses, metallicities, and star formation rates over cosmic time. To study this paradigm directly, however, one needs to focus on the CGM, the ground zero for gas accretion and ejection.

The properties of the CGM have been studied in a number of ways. X-ray observations have been conducted to study the intracluster medium in galaxy clusters and groups (e.g., Wang et al. 2014; Anderson et al. 2015). The results demonstrate that a substantial amount of gas heating is actually by nongravitational sources, likely from the feedback of member galaxies (Cavaliere et al. 1998; Arnaud & Evrard 1999; Helsdon & Ponman 2000; Kravtsov & Yepes 2000; Babul et al. 2002; McCarthy et al. 2011; Kelly et al. 2020). A complementary way to study the CGM is through the Sunyaev–Zeldovich effect (hereafter SZE; Sunyaev & Zeldovich 1972) of free electrons on the spectrum of the cosmic microwave background (CMB) owing to inverse Compton scattering. The thermal SZE (hereafter tSZE) is proportional to the LOS integral of the electron pressure (or thermal energy density), while the kinetic SZE (kSZE) is proportional to the integral of the momentum density along a given LOS, thus providing two independent constraints on the properties of the ionized part of the CGM. Great efforts have been made to measure the SZE using CMB surveys, such as Planck, the Atacama Cosmology Telescope, and the South Pole Telescope. For example, using a sample of galaxy groups covering a large range of halo masses together with the Planck Compton parameter map (Planck Collaboration et al. 2014), Lim et al. (2018) found that the thermal content of the gas in low-mass halos is significantly lower than that expected from the simple self-similar model, where the halo gas is assumed to be at the virial temperature and to have a mass given by the universal baryon fraction. By stacking galaxy groups with known masses and peculiar velocities in Planck maps, Lim et al. (2020b) found that the total kSZE within halos implies a baryon to dark matter mass ratio that is comparable to the universal baryon fraction. The tSZE and kSZE results combined, therefore, indicate that not all the halo gas is at the virial temperature (Lim et al. 2020b).

Clearly, these observational results provide important information about the properties of the CGM. In this paper, we use the combination of SZE observations and soft X-ray data to constrain the density and temperature of the CGM. We use a set of generic models to show what we can learn from the observational data. The paper is organized as follows. We describe the observational data used in our analysis in Section 2, and models of halo gas in Section 3. Our analysis and results are presented in Section 4. Finally, we summarize and discuss our results in Section 5. Throughout the paper, we adopt a flat universe with matter density $\Omega_m = 0.308$ and the reduced Hubble constant $h = 0.678$, as given in Planck Collaboration et al. (2016a).

1. Introduction

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2. Observational Data

2.1. Thermal SZE

The tSZE is produced by the inverse Compton scattering of CMB photons as they encounter high-energy thermal electrons in hot gas (Sunyaev & Zeldovich 1972; Rephaeli et al. 2005). The tSZE presents itself as a distortion in the CMB spectrum, and its strength is characterized by the Compton $y$-parameter:

$$ y \equiv \frac{\sigma_T}{m_e c^2} \int P_e dl, $$

where $\sigma_T$ is the Thompson cross section, $m_e$ is the electron mass, $P_e = k_B n_e T_e$ is the electron pressure with $k_B$ being the Boltzmann constant, $n_e$ the electron number density, and $T_e$ the electron temperature. The integration is along the line of sight (LOS). For the galaxy groups/halos concerned, the total tSZE flux within a radius $R$ of an object is described by a quantity $Y_R$, defined as

$$ Y_R = \frac{\sigma_T}{m_e c^2} \int_{V_R} P_e dV, $$

where $d_A$ is the angular diameter distance of the object, and $V_R$ is the volume within $R$. The intrinsic tSZE flux can then be expressed in terms of a normalized quantity,

$$ Y_R \equiv E^{-2/3}(z) Y_R \left( \frac{d_A(z)}{500 \text{ Mpc}} \right)^2, $$

where

$$ E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_m (1+z)^3 + \Omega_{\Lambda}} $$

is included to make $Y_R$ independent of the redshift for a given halo mass. The intrinsic tSZE, therefore, provides a measure of the thermal energy of electrons.

In our analysis, we use the results obtained by Lim et al. (2018), who used a spatial filter to extract tSZE signals associated with galaxy groups of various halo masses from the Planck NILC all sky tSZ Compton parameter map (Remazeilles et al. 2011; Planck Collaboration et al. 2016b). Lim et al. (2018) assumed that the spatial pressure profile follows the universal pressure profile (UPP) model of Arnaud et al. (2010). They divided galaxy groups into a number of subsamples according to halo mass and obtained the average tSZE amplitude, $Y_{200}$, for galaxy groups contained in the same halo mass bin. The quantity $Y_{200}$ is the same as $Y_{R200}$, where $R_{200}$ is the radius within which the mean density of the halo is 200 times the critical density of the universe. We define the halo mass $M_{200}$ as the mass of a halo within $R_{200}$. Since the Planck observation does not resolve the flux distribution for all individual halos, the values of $Y_{200}$ they obtained should be used in combination with the adopted UPP to get the total tSZE flux of the halo. For our analysis, we convert the observational quantity to

$$ P_{200} \equiv \int_{V_{200}} P_e dV. $$

The black data points in the left panel of Figure 1 show $P_{200}$ as a function of $M_{200}$, while the shaded region represents the error of the measurement. Here $M_{200}$ is the halo mass defined by the dark matter mass enclosed by $R_{200}$. The error in the original data was obtained using the variance among different independent samples. There may be covariance among different halo mass bins. However, the correlation coefficients were found to be much smaller than one, and we thus ignore the covariance in our analysis.

2.2. Kinetic SZE

The kSZE is produced by the Doppler effect on CMB photons as they are scattered by electrons associated with galaxy systems that have bulk motion (Sunyaev & Zeldovich 1970):

$$ k \equiv \left( \frac{\Delta T}{T_{\text{CMB}}} \right)_k \propto \frac{\sigma_T}{c} \int n_e (\mathbf{v} \cdot \hat{r}) dl, $$

where $\mathbf{v}$ represents the bulk motion peculiar velocity of the gas, $\hat{r}$ is the unit vector along the LOS in question, and the integration is along the LOS. For halos with known peculiar velocities, one can estimate the following quantity from the kSZE signal:

$$ K_{200} \equiv \frac{1}{d_A(z)^2} \sigma_T \int_{V_{200}} n_e dV. $$

From this, one can obtain the intrinsic kSZE flux,

$$ \mathcal{K}_{200} \equiv K_{200} \left( \frac{d_A(z)}{500 \text{ Mpc}} \right)^2. $$

We use the data of $K_{200}$ obtained by Lim et al. (2020b) for our analysis. They applied spatial filters to the Planck 100, 143, and 217 GHz channel maps to extract kSZE signals of galaxy groups of different masses simultaneously, assuming that $n_e$ follows the profile described in Plagge et al. (2010).

The amplitude of the profile for each group is assumed to depend on its halo mass. Together with the peculiar velocities of individual groups given by Wang et al. (2012), Lim et al. (2020b) obtained the amplitude of the ionized gas profile as a function of halo mass by matching the model maps with the observational ones. We use their result of $K_{200}$ as a function of halo mass, $M_{200}$, which is shown as the black data points in the middle panel of Figure 1. The shaded region is the error of the measurement. The error in the original data was estimated using independent samples and methods that accounts for systematic effects. The correlation coefficients between different halo mass bins were found to be much smaller than one and are ignored in our analysis. There might also be covariance between the kSZE and tSZE measurements. Unfortunately such covariance is not quantified.

Turbulent motions of the gas within individual groups/clusters may contribute to the kSZE signal, thereby affecting the interpretation of the observation. Unfortunately, our knowledge about such motions is still poor. Using gas simulations, Ruan et al. (2013) found that the impact of the turbulence is less than 10% compared with the peculiar velocity in the kSZE signal even for clusters that have undergone a recent merger. This uncertainty is much smaller than that represented by the error bars of the data. In addition, the results used here are the averages over many groups/clusters of similar masses. We thus expect that the effects generated by turbulent motions within individual systems are further reduced in the results.
2.3. X-Ray Luminosity

X-ray emissions from galaxy groups/clusters are produced by the hot intracluster/group gas generated by bremsstrahlung. The X-ray luminosity depends on the temperature, density, and metallicity of the gas and can be written as:

\[
L(\nu_1, \nu_2) = \int_{\nu_1}^{\nu_2} \int \nu_1 \nu_2 n_H(r) \epsilon_x(T, \nu, Z) dV d\nu, \tag{9}
\]

where \(\nu_1\) and \(\nu_2\) specify the frequency range, \(n_H\) is the total hydrogen number density, and \(\epsilon_x(T, \nu, Z)\) is the emissivity at the temperature \(T\), frequency \(\nu\), and metallicity \(Z\). We use the Astrophysical Plasma Emission Code\(^7\) to calculate the emissivity. The code includes physical processes such as bremsstrahlung, radiative recombination, and two-photon radiation. The exact assumption of the metallicity does not have a significant impact on our results and we use \(Z = 0.05Z_\odot\) here. For our analysis, we use the X-ray measurements from Anderson et al. (2015), who obtained the X-ray luminosity for halos of different masses by using the ROSAT All-Sky Survey. They extracted an average X-ray luminosity for locally brightest galaxies (LBGs) of a given stellar mass by stacking the X-ray images around them, using the LBG sample of Planck Collaboration et al. (2013). The same stacking procedure was applied to groups/clusters in numerical simulations to validate their method and error estimates. Their using of LBGs ensures the systems selected are well isolated, so that the covariance in the X-ray luminosity between them is expected to be small.

For high-mass galaxies, they converted the galaxy stellar mass into a halo mass using the simulation calibrations presented in Planck Collaboration et al. (2013). For low-mass systems, they used an abundance matching method to estimate \(M_{500}\) from the stellar mass. Their final results are summarized as the X-ray luminosity, \(L_{X,500}\), in the energy range between 0.5 and 2 keV within the radius of \(R_{500}\). Here \(R_{500}\) is the halo radius within which the mean density is 500 times the critical density of the universe, and \(M_{500}\) is the dark mass enclosed by \(R_{500}\). Their results for the \(L_{X,500} - M_{500}\) relation are shown as the black data points in the right panel of Figure 1. Here we convert \(M_{500}\) into \(M_{200}\) assuming a Navarro–Frenk–White profile. We note that the \(L_{X,500}\) as a function of halo mass obtained by Anderson et al. (2015) is very similar to that obtained by Wang et al. (2014). As one can see, the X-ray luminosity depends both on gas density and temperature. The dependence on gas density is strong, \(\sim n^2\), while the temperature dependence is relatively weak, \(\sim T^{1/2}\). The \(n^2\) dependence implies that the X-ray luminosity depends not only on the mean gas density but also the density profile and clumpiness of the gas distribution. The kSZ and tSZ measurements described above provide two additional constraints on these two quantities; the kSZ constrains the average gas density without depending on gas temperature and profile, while the tSZ constrains the average of \(nT\) within individual halos. Thus the three measurements can be used to constrain three independent properties of the halo gas. In addition to the average gas density and mean temperature with halos, we will use the data to constrain the gas fraction in the hot component assuming a two-phase medium, and to constrain the gas density profile.

3. Models of Halo Gas

In this section, we describe our methods to model the density and temperature of gas in halos. We use the electron number density, \(n_e\), to represent the density of the gas. We also assume that the gas temperature is the same as the electron temperature, \(T_e\). We examine a number of different cases with different assumptions of the gas density and temperature.

3.1. Single-phase Models

As our fiducial assumption for the gas density, we use the following profile:

\[
n_e(M_{200}, r) = n_0(M_{200})[1 + (r/r_c)^2]^{-3/2}, \tag{10}
\]

where \(r_c = R_{200}/c\), with \(c\) being the concentration of the halo, and \(\beta = 0.86\). The amplitude of the profile, \(n_0\), is assumed to depend on \(M_{200}\), and we use the \(c-M_{200}\) relation given by Bullock et al. (2001) to compute \(r_c\). This profile is adopted from Plagge et al. (2010) and is the same as that used in Lim et al. (2018). The first set of models we consider assume that all the halo gas is in a single phase with a given temperature profile, \(T_{\text{vir}}\). This set of models is denoted by \(M1\).

The simplest assumption in modeling the hot gas temperature in galaxy groups/clusters is that the gas is at the virial temperature,

\[
T_{\text{vir}} = \frac{\mu G M_{\text{vir}} m_p}{2 k_B r_{\text{vir}}}, \tag{11}
\]

where \(M_{\text{vir}}\) and \(r_{\text{vir}}\) are the virial mass and radius of the halo, respectively, \(m_p\) is the proton mass, \(\mu\) is the mean molecular density, and \(k_B\) is the Boltzmann constant.
weight, and $G$ is the gravitational constant. In our analysis we take $M_{\text{vir}} = M_{200}$ and $r_{\text{vir}} = R_{200}$.

We therefore consider a model, $M_1 - T_{\text{vir}}$, where the hot gas temperature is assumed to be uniform within halos and is equal to $T_{\text{vir}}$, and the gas density is given by Equation (10) with $n_0(M_{200})$ constrained by the observational data.

More generally, we follow Loken et al. (2002) and consider models in which the gas temperature profile is given by

$$\log_{10}(T) = \mu + \sigma \log_{10}\left(\frac{M_{200}}{\frac{3 \times 10^{14} M_\odot}}\right),$$

(13)

for the component at different temperatures. To allow variance in the relations, we use the distribution $N(\mu, \sigma)$, which is a normal distribution with mean $\mu$ and variance $\sigma$. We find that the observational data can be described by the following simple assumptions:

$$\mu_{n} = \mu_{n0} + \alpha_{n} \log_{10}\left(\frac{M_{200}}{\frac{3 \times 10^{14} M_\odot}}\right),$$

and

$$\sigma_{n} = \sigma_{n0} + \beta_{n} \log_{10}\left(\frac{M_{200}}{\frac{3 \times 10^{14} M_\odot}}\right),$$

(15)

where $\mu_{n0}$, $\alpha_{n}$, $\sigma_{n0}$, and $\beta_{n}$ are model parameters to be determined by the observational data. Similarly, for the gas temperature, we assume

$$\log_{10}(T_{0}) = N(\mu_{T}, \sigma_{T}),$$

(16)

with

$$\mu_{T} = \mu_{T0} + \alpha_{T} \log_{10}\left(\frac{M_{200}}{\frac{3 \times 10^{14} M_\odot}}\right),$$

and

$$\sigma_{T} = \sigma_{T0} + \beta_{T} \log_{10}\left(\frac{M_{200}}{\frac{3 \times 10^{14} M_\odot}}\right).$$

The model parameters, $\mu_{T0}$, $\alpha_{T}$, $\sigma_{T0}$, and $\beta_{T}$ are again to be constrained by observational data. We assume that the variances in the density and temperature are independent, so that they can affect the predicted mean only for $L_X$, but the predicted dispersion for all three observational quantities may be affected. Based on these assumptions on gas density and temperature, we consider models in which variances are allowed in $n_0$ or $T_0$, or in both, as listed in Table 1.

### 3.2. Two-phase Models

Because of processes like radiative cooling, feedback, and thermodynamic and hydrodynamic instabilities, halo gas is expected to be a multiphase medium consisting of gas components at different temperatures (Mo et al. 2010, e.g., see chapter 8). Unfortunately, the details of such multiphase media are poorly understood. Here we consider a simple case in which the halo gas is a two-phase medium, with a hot component at temperature $T_h$ and a warm component with temperature $T_w$, both assumed to be fully ionized. These two components are assumed to be in pressure equilibrium, so that at any given location

$$n_h T_h = n_w T_w,$$

(19)

where $n_h$ and $n_w$ are the local densities of the hot and warm components, respectively. We model the mass fraction in the hot component as

$$f_h = \frac{M_h}{M_h + M_w} = f_{h0} \left(\frac{M_{200}}{M_{200}}\right)^{\phi_h},$$

(20)

where $M_h$ and $M_w$ are the total masses in the two components, respectively. The volume filling factors of the two components, $\phi_h$ and $\phi_w$, are defined as

$$\phi_h = \frac{V_h}{V_h + V_w} = 1 - \phi_w,$$

so that

$$\phi_h = \frac{M_h}{n_w \phi_w} = \frac{f_h}{1 - f_h}. $$

(21)

(22)

It can then be shown that

$$\phi_h = \frac{T_h f_h}{T_h f_h + T_w (1 - f_h)}.$$  

(23)

Finally, the total gas density and pressure can be written as

$$n_e = n_h \phi_h + n_w \phi_w = n_h \phi_h + \frac{T_h}{T_w} \phi_w,$$

(24)

and

$$P_e = \frac{n_e T_h}{\phi_h + \phi_w T_h/T_w}. $$

(25)

As one can see, once models are adopted for $n_e$, $T_h$, $T_w$, and $f_h$, one can make model predictions for the kSZ through $n_e$ and for the tSZ through $P_e$. For the X-ray luminosity, we assume that the warm component contributes little, so that it can be obtained through $n_h$ and $T_h$ in the volume occupied by the hot component specified by $\phi_h$.

For all the two-phase models, listed as M2 in Table 1, we assume that $T_w = 10^5$ K at the halo center and follows the

| Models of Halo Gas |
|-------------------|
| Model | Gas Phase | Variance in $T_0$ | Variance in $n_0$ |
| M1 - $T_{\text{vir}}$ | 1-phase | No; $T = T_{\text{vir}}$ | No |
| M1 - no scatter | 1-phase | No | No |
| M2 - $T_{\text{vir}}$ | 2-phase | No; $T = T_{\text{vir}}$ | Yes |
| M2 - no scatter | 2-phase | No | No |
| M2 - $T_{\text{vir}}$ | 2-phase | Yes | No |
| M2 - no scatter | 2-phase | Yes | Yes |

| Models of Halo Gas |
|-------------------|
| Model | Gas Phase | Variance in $T_0$ | Variance in $n_0$ |
| M1 - $T_{\text{vir}}$ | 1-phase | No; $T = T_{\text{vir}}$ | No |
| M1 - no scatter | 1-phase | No | No |
| M2 - $T_{\text{vir}}$ | 2-phase | No; $T = T_{\text{vir}}$ | Yes |
| M2 - no scatter | 2-phase | No | No |
| M2 - $T_{\text{vir}}$ | 2-phase | Yes | No |
| M2 - no scatter | 2-phase | Yes | Yes |
same profile as $T_h$. Since the volume occupied by the warm phase is in general much smaller than that occupied by the hot phase, the exact value assumed for $T_w$ is not important, provided that it is much smaller than $T_h$ and sufficiently high to ensure the ionization fraction is close to one. We also assume that $f_0$ is described by Equation (20), $n_0$ by Equation (10), and $T_h$ is either equal to $T_{vir}$ (Model M2−$T_{vir}$) or described by Equation (12), with $T_0$ being the temperature at halo center. Similar to the single-phase models, variances in $n_0$ and $T_0$ are included in some of the two-phase models, as described in Table 1. We adopt the $\beta$-model of Equation (10) for the $n_e$ profile, with the concentration parameter $c$ describing the core radius. A higher $c$ leads to more concentrated distribution of the gas. As mentioned earlier, we use the model of Bullock et al. (2001) for $c$ as a function of halo mass. To examine the impact of the assumed gas profile on our results, we also consider a new model, M2$^*$−$T_{0}$, which is the same as M2−$T_{0}$ except that the concentration parameter is reduced by a factor of two.

### 4. Analysis and Results

To constrain a model with observational data, we generate a set of $n_e$ and $T_h$ for a given set of model parameters. We then compute the corresponding $K_{200}$, $P_{200}$, and $L_{500}$, and compare them with the observational data. For X-rays, we integrate the X-ray flux within $R_{500}$ to compare with observation. The comparison between model predictions and observational data is through the likelihood function,

$$L = \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} \exp \left[-\frac{(M_i(\Theta) - D_i)^2}{2\sigma_i^2}\right],$$

where $M_i(\Theta)$ is the prediction of the model specified by the parameter set $\Theta$ for the $i$th data point, $D_i$ is the corresponding observational data, and $\sigma_i$ is its error. The posterior distribution of model parameters is sampled with the PyMultinest, a Python module of the MultiNest sampling engine for both parameter estimation and model selection (Buchner et al. 2014). We assume a flat prior for each parameter, with its range chosen sufficiently broad (see Table 2). For reference, the posterior model parameters for M2−$T_{0}$, $n_0$ are also shown in Table 2; those for other models are given in the Appendix.

To examine how different models can accommodate the observational data, we compute the Bayesian evidence,

$$E(\mathcal{M}) = \int P(D|\mathcal{M}, \Theta) P(\Theta|\mathcal{M}) d\Theta,$$

(27)

where $P(D|\mathcal{M}, \Theta)$ is the probability of the data given the model $\mathcal{M}$ with a given set of model parameters, $\Theta$, and $P(\Theta|\mathcal{M})$ is the prior distribution of model parameters. As defined, the Bayesian evidence is the probability of the observational data in a model family $\mathcal{M}$, and thus can be used to compare different model families in their abilities to accommodate the observational data. Figure 2 shows the logarithms (to natural base) of the Bayesian evidence ratio, $\ln(E(\mathcal{M})/E(\mathcal{M}_0))$, of a given model $\mathcal{M}$ relative to the reference model, $\mathcal{M}_0$, which is chosen to be M1−$T_{vir}$. As one can see, all the two-phase models give a similar evidence ratio, about 60 in logarithmic scales, while all the single-phase models have a ratio about 30. Typically, a Bayesian evidence ratio of more than 20 in a logarithmic scale indicates a significant preference between the two models in comparison. It is thus clear that the combination of the sSZE, kSZE, and $L_X$ data has a significant preference to the two-phase hypothesis (M2), while a single-phase model with gas at the virial temperature is the least favored.

To see more clearly how the models fit observational data, we use the posterior distribution of each individual model to predict the observations. As examples, the predictions of M1−$T_{0}$ and M2−$T_{0}$ are shown in Figure 1. Clearly, M1−$T_{0}$ cannot accommodate the three sets of observational data simultaneously: it significantly underpredicts kSZE but overpredicts $L_X$. In contrast, M2−$T_0$ matches all the three observations well. We find that the results of these two models represent those of the two model sets, M1 and M2, well, indicating that the key to matching the observational data is the assumption of a two-phase medium, while other details, such as the inclusion of scatter in model parameters, only play a minor role. We find that model M2−$T_{vir}$ matches the observational data only slightly worse than the other M2 models, suggesting that the average hot gas temperature needed to fit the data is not very different from $T_{vir}$. Model M2$^*$−$T_{0}$ has Bayesian evidence similar to M2−$T_{0}$, and their posterior predictions for the three sets of observations are also very similar, indicating that these observations do not provide a strong constraint on the gas density profile. However, as we will show below, the change of gas density profile can affect the model inferences significantly.

We can use the posterior model distributions to make predictions for the gas mass and temperature as functions of halo mass. Here again we use M2−$T_{0}$ and M2$^*$−$T_{0}$ as demonstrations. We estimate the baryon mass in halos of a given mass by integrating the corresponding gas density profile within $R_{200}$, assuming a fully ionized primordial gas with a hydrogen mass fraction of $Y_H = 0.76$. In the top panel of Figure 3 we show the total and hot gas masses, both normalized by halo mass, versus the halo mass. Red and blue lines are for M2−$T_{0}$ and M2$^*$−$T_{0}$, respectively, while the solid and dashed lines are for the total and hot gas, respectively. For all cases, the error bars represent the 90th percentile of the posterior predictions. For comparison we also show the universal baryon

| Name | Prior | Posterior | Relevant Equation |
|------|-------|-----------|-------------------|
| $\alpha_f$ | $[0.5, 1.8]$ | $0.79 \pm 0.07$ | Equation (17) |
| $\beta_f$ | $[5.5, 8.5]$ | $7.89 \pm 0.07$ | Equation (17) |
| $\sigma_{n_e}$ | $[0, 0.2]$ | $0.08 \pm 0.06$ | Equation (16) |
| $\sigma_t$ | $[-1, 0]$ | $-0.20 \pm 0.16$ | Equation (15) |
| $\sigma_{\beta}$ | $[-0.4, 0.4]$ | $0.17 \pm 0.07$ | Equation (17) |
| $\mu_{n_e}$ | $[2.5, 4.5]$ | $3.36 \pm 0.05$ | Equation (14) |
| $\sigma_{f_0}$ | $[0, 0.2]$ | $0.06 \pm 0.04$ | Equation (15) |
| $\beta_f$ | $[0, 0.6]$ | $0.20 \pm 0.06$ | Equation (20) |
| $f_{10}$ | $[0.3, 0.9]$ | $0.32 \pm 0.07$ | Equation (20) |

Note. Posteriors for the M2−$T_{0}$, $n_0$ model are listed as an example. Details of the models can be found in Section 3.
The posterior predictions of the central temperature of the hot halo gas. The $\beta$-model of Equation (10) is motivated by observations of massive clusters (e.g., McDonald et al. 2017), and is roughly consistent with the hot gas profiles of clusters in gas simulations (Lim et al. 2020a). For halos of lower masses, the hot gas profile is not well known from observation. In numerical simulations, the gas profiles of these lower-mass halos can be significantly affected by feedback. Using data from EAGLE (Schaye et al. 2015) and Illustris TNG (Marinacci et al. 2018; Nelson et al. 2018, 2019; Naiman et al. 2018; Pillepich et al. 2018; Springel et al. 2018), Lim et al. (2020a) found that the $\beta$-model is a rough approximation to the halo gas in low-mass halos, provided that the core radius $r_c$ is increased by a factor of two. Thus, the results of models $M2-T_0$ and $M2^*-T_0$ may represent the range expected from the uncertainties in the hot gas profile. However, if the core radius $r_c$ in Equation (10) were comparable to the virial radius for low-mass halos, so that the profile is approximately flat, the inferred mass in the hot component would approach the universal fraction, leaving no room for the presence of the warm component. In this case, the gas temperature would be about 10 times lower than the corresponding virial temperature, as shown in Lim et al. (2020b).

5. Summary and Discussion

In this work, we combine observational data of kSZE, tSZE, and $L_X$ to constrain the density and temperature of diffuse gas
in halos. We use a number of generic models and a Bayesian scheme to explore the constraints provided by the observational data. Our main results can be summarized as follows.

1. Single-phase models, in which all the halo gas is assumed to have a similar temperature, cannot accommodate the observational data, suggesting that halo gas is not completely thermalized to a single phase. The tension may be alleviated if the gas density profile is much shallower than that seen in numerical simulations. A nearly flat profile is needed to explain the observational data with a single-phase model.

2. Simple two-phase models, which assume a hot gas component and an ionized warm component in pressure equilibrium, can match the observational data well without depending on model details.

3. The predicted total (hot plus warm) gas mass fraction in individual halos is comparable to the universal baryon fraction, suggesting that most halos can retain most of the baryons in their possession.

4. The hot gas component in a halo has a temperature that is comparable to the virial temperature of the halo.

5. The fraction of the hot component is found to increase from (15–40)% for $10^{12.5}M_\odot$ halos to (40–60)% for $10^{14.5}M_\odot$ halos, where the lower and upper bounds cover uncertainties in the assumed density profiles.

Our results have important implications for galaxy formation and evolution. Observations have shown that star formation in the universe is inefficient and that only a small fraction of the baryons are locked in stars (e.g., Li & White 2009). To prevent baryons from forming stars too quickly, feedback processes are invoked either to heat the star-forming gas or to eject it from galaxies. All numerical simulations of galaxy formation in the current paradigm need to incorporate some feedback processes to reproduce the stellar component observed in the universe. Most of the simulations seem to show the existence of hot gaseous halos with an average gas temperature comparable to the halo virial temperature and with mass significantly smaller than that implied by the universal baryon fraction (Lim et al. 2020a). These are consistent with our results for the hot gas component. However, in these simulations, a significant fraction of the baryons is ejected from halos by feedback effects, so that the warm phase implied by our results is insignificant. This indicates that the current cosmological simulations may not be able to resolve multiphase media or may have missed a significant nonthermalized gas component in gaseous halos. Indeed, using high-resolution zoomed-in simulations of clusters of galaxies, Nelson et al. (2014) found that a significant fraction of the gas pressure is nonthermal pressure produced by the bulk motion of cooler gas. This is consistent with the results that a substantial fraction of the gas in clusters is in a phase with temperature much lower than the virial temperature. For low-mass halos, the presence of a gas component at temperature lower than the virial temperature has been probed by QSO absorption line systems such as MgII and OVI (e.g., Werk et al. 2014; Zhu et al. 2014; Lan & Mo 2018). Unfortunately, the total amount of the gas implied by these systems are still uncertain (e.g., Tumlinson et al. 2017). Clearly, with data from large, high-resolution CMB surveys, such as CMB-S4, and all sky X-ray surveys, such as eROSITA, we hope to obtain much better constraints on the gaseous halos over a large mass range, so as to provide important insight about the processes by which gaseous halos and galaxies form and evolve.

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### Appendix

#### Posterior of Two-phase Models

In Table 3 we list the posterior model parameters for all the two-phase models except $M2-T_{\text{vir}}$ and $M2-T_0$. The details of $M2-T_0$ are listed in Table 2, while $M2-T_{\text{vir}}$ cannot accommodate the three sets of observational data.

| Parameter | $M2$–no scatter | $M2$–$T_0$ | $M2$–$n_0$ | $M2$–$T_0$, $n_0$ | Description |
|-----------|-----------------|----------|-----------|-----------------|-------------|
| $\alpha_T$ | $0.81 \pm 0.09$ | $0.96 \pm 0.07$ | $0.80 \pm 0.09$ | $0.91 \pm 0.12$ | Equation (17) |
| $\mu_{T0}$ | $7.93 \pm 0.07$ | $7.43 \pm 0.10$ | $7.96 \pm 0.08$ | $7.98 \pm 0.08$ | Equation (17) |
| $\sigma_{T0}$ | $0.09 \pm 0.01$ | $0.09 \pm 0.01$ | $0.10 \pm 0.04$ | $0.09 \pm 0.01$ | Equation (18) |
| $\beta_T$ | $-0.43 \pm 0.04$ | $-0.43 \pm 0.04$ | $-0.16 \pm 0.08$ | $-0.43 \pm 0.04$ | Equation (18) |
| $\alpha_N$ | $0.05 \pm 0.07$ | $-0.15 \pm 0.07$ | $0.06 \pm 0.07$ | $0.14 \pm 0.11$ | Equation (17) |
| $\mu_{n0}$ | $3.29 \pm 0.05$ | $3.42 \pm 0.07$ | $3.33 \pm 0.06$ | $3.26 \pm 0.06$ | Equation (14) |
| $\sigma_{n0}$ | $0.08 \pm 0.04$ | $0.08 \pm 0.04$ | $0.11 \pm 0.05$ | $0.08 \pm 0.04$ | Equation (15) |
| $\beta_n$ | $-0.07 \pm 0.04$ | $-0.07 \pm 0.04$ | $-0.10 \pm 0.07$ | $-0.07 \pm 0.04$ | Equation (15) |
| $\alpha_f$ | $0.15 \pm 0.07$ | $0.10 \pm 0.07$ | $0.14 \pm 0.07$ | $0.14 \pm 0.06$ | Equation (20) |
| $f_{SO}$ | $0.29 \pm 0.06$ | $0.46 \pm 0.11$ | $0.26 \pm 0.06$ | $0.27 \pm 0.06$ | Equation (20) |
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