Gas Contents of Galaxy Groups from Thermal Sunyaev–Zel’dovich Effects

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Abstract

A matched filter technique is applied to the \textit{Planck} all-sky Compton $y$-parameter map to measure the thermal Sunyaev–Zel’dovich (tSZ) effect produced by galaxy groups of different halo masses selected from large redshift surveys in the low-$z$ universe. Reliable halo mass estimates are available for all of the groups, which allows us to bin groups of similar halo masses to investigate how the tSZ effect depends on halo mass over a large mass range. Filters are simultaneously matched for all groups to minimize projection effects. We find that the integrated $y$-parameter and the hot gas content it implies are consistent with the predictions of the universal pressure profile model only for massive groups above $10^{14}\, M_{\odot}$, but much lower than the model prediction for low-mass groups. The halo mass dependence found is in good agreement with the predictions of a set of simulations that include strong active galactic nucleus feedback, but simulations including only supernova feedback significantly overpredict the hot gas contents in galaxy groups. Our results suggest that hot gas in galaxy groups is either effectively ejected or in phases much below the virial temperatures of the host halos.

Key words: galaxies: evolution \textendash{} galaxies: formation \textendash{} galaxies: halos \textendash{} methods: statistical

1. Introduction

In the current paradigm of galaxy formation, galaxies are thought to form and evolve within dark matter halos (see Mo et al. 2010 for a review). During the formation of dark matter halos, the cosmic gas component first moves along with the dark matter, then gets shock-heated as the halos collapse, and eventually forms hot gaseous halos. In an adiabatic case, the resulting distribution of the hot gas component follows roughly that of dark matter, and the amount of the hot gas per dark matter is roughly a constant, about the universal baryon fraction of the universe. In reality, however, a myriad of other physical processes, such as radiative cooling, star formation, feedback from supernovae (SNe) and active galactic nuclei (AGNs), etc., can change the hot gas content of the halos. Indeed, the hot gas fractions in low-mass halos are found to be lower than the constant baryon fraction both in observations (e.g., David et al. 2006; Gastaldello et al. 2007; Pratt et al. 2009; Sun et al. 2009) and in numerical simulations (e.g., McCarthy et al. 2010; Battaglia et al. 2013; Le Brun et al. 2014). Even in massive systems, such as rich clusters of galaxies where the total hot gas is found to be closer to the universal value, the distribution of the hot gas is found to be different from that of dark matter (e.g., Arnaud et al. 2010; Battaglia et al. 2012). However, current observational results are still uncertain, particularly for low-mass systems, and many competing theoretical models have been proposed to describe the formation and structure of gaseous halos. Clearly, an accurate determination of the hot gas content in dark matter halos is crucial for understanding galaxy formation and evolution in a way that is complimentary to the information provided by stars and cold gas.

The thermal Sunyaev–Zel’dovich effect (tSZ hereafter; Sunyaev & Zeldovich 1972) provides a promising avenue to probe the hot gas in halos. As the CMB photons pass through galaxy systems, such as clusters and groups of galaxies (collectively referred to as groups of galaxies), they are scattered by the hot electrons by the inverse Compton process, producing a net energy gain in the photon gas and changing the CMB temperatures in the directions to the groups. Thus, studying the cross-correlation of the imprints of the tSZ effect on the CMB with galaxy groups allows one to probe the hot gas components in halos associated with galaxy systems. Compared to X-ray observations, the tSZ effect is less sensitive to the hot gas density, thus making it possible to explore the hot gas in the outskirts of halos and also in low-mass halos where the gas density is expected to be low. However, extracting the tSZ signal reliably from CMB observations is not easy. First, the signal to be detected is usually comparable to or lower than the primary CMB, and there are also contaminations, such as Galactic emissions, dust, and point sources. As a result, individual detection and analysis of the tSZ effect are currently only possible for rich clusters of galaxies (e.g., Planck Collaboration et al. 2013a). For low-mass groups, stacking of many systems is required to increase the signal-to-noise. Second, the beam sizes of current instruments are usually insufficient to resolve low-mass systems, so that assumptions about the spatial distribution of the hot gas are required. Finally, the signal from low-mass systems can be contaminated by the projections of larger halos along the same line-of-sights, and such contamination is not straightforward to eliminate.
Recently, Planck Collaboration et al. (2013b) used the all-sky Planck multi-frequency temperature maps and a sample of locally brightest galaxies as tracers of dark matter halos to investigate the tSZ effects produced by galaxy systems with halo masses down to $\sim 4 \times 10^{12} M_\odot$. Remarkably, their results show that the universal pressure profile (UPP) model, in which the hot gas fraction relative to halo mass is independent of halo mass, matches their data well. This finding is in conflict with the results obtained from X-ray observations and hydrodynamic simulations, where a much lower fraction is found for hot gas in low-mass systems. Using a hydrodynamic simulation, Le Brun et al. (2015) found that the UPP of Arnaud et al. (2010) adopted by Planck Collaboration et al. (2013b) in their matched filter method may lead to overestimations of the integrated tSZ signal within $R_{500}$ for low-mass systems; though, they found that the flux within $5R_{500}$ is robust to the change in the adopted profile. However, Greco et al. (2015) showed that adopting another popular pressure profile of Battaglia et al. (2012), instead of that of Arnaud et al. (2010), leads to differences that are well within the observational uncertainties, and so the high gas fraction found by Planck Collaboration et al. (2013b) cannot be explained by the adopted profile. Ma et al. (2015) cross-correlated the Planck tSZ map with the gravitational lensing map from CFHTLenS survey and found that the prediction of the UPP model is 20% higher than the data. Vikram et al. (2017) cross-correlated the Planck tSZ map with the group catalog of Yang et al. (2007) and found that the two-halo terms dominate the tSZ signal for systems of $M_{500} \lesssim 10^{13} h^{-1} M_\odot$, indicating that the projection effect is an important issue.

In this paper, we extract the tSZ signal from the Planck all-sky Compton parameter map for galaxy systems of different halo masses, using the group catalog of Lim et al. (2017a). The catalog is constructed for four large redshift surveys with the use of the halo-based group finder of Yang et al. (2005, 2007). This provides the largest sample of galaxy groups in the low-$z$ universe to study the tSZ effects over a large range of galaxy systems. In particular, reliable halo mass estimates are provided for all groups, so that we can bin groups of similar masses to investigate how the tSZ effect depends on halo mass. We employ the matched filter technique (Haehnelt & Tegmark 1996; Herranz et al. 2002; Melin et al. 2005, 2006) to extract the tSZ signal from the Planck map. In particular, we simultaneously match the filters to all galaxy systems in the catalog, so that projection effects produced by halos along the lines of sight are properly taken care of.

The outline of this paper is as follows. We describe the observational data used in our analysis in Section 2 and our method to extract the tSZ signal in Section 3. We present our main results as well as comparisons with results from earlier studies and from numerical simulations in Section 4. Finally, we summarize and conclude in Section 5.

We adopt the cosmological parameters from the Planck observation (Planck Collaboration et al. 2016a), $\{\Omega_m, \Omega_\Lambda, h, \sigma_8\} = \{0.308, 0.692, 0.678, 0.831\}$ throughout this paper unless specified otherwise.

2. Observational Data

2.1. The Planck y-map

Planck (Tauber et al. 2010; Planck Collaboration et al. 2011), a space mission to measure the CMB anisotropy, is an all-sky observation in nine frequency bands ranging from 30 to 857 GHz, with angular resolutions from 31′ to 5′. For our analysis of the tSZ effects, we use the Planck NILC (Needlet Independent Linear Combination; Remazeilles et al. 2011) all-sky tSZ Compton parameter map (Planck Collaboration et al. 2016b), also referred to as the NILC y-map, which is part of the publicly released Planck 2015 data. The map is constructed from the full mission data set, using a combination of different frequency maps to remove the primary CMB fluctuations and to minimize contamination from foreground sources. For more details of the y-map construction, the readers are referred to the original paper cited above. To limit the Galactic foreground contamination, which is mainly due to thermal dust emissions, we mask the brightest 40% of the sky by applying the corresponding mask provided in the Planck 2015 data release. For contamination from extragalactic sources, such as radio and infrared galaxies, we apply the mask provided in the same data release for point sources.

2.2. Galaxy Groups

In order to determine the tSZ signals from halos associated with different galaxy systems, we need a well-defined group catalog that provides reliable information for both the positions and halo masses of the galaxy systems in the universe. Furthermore, since the tSZ signals are typically weak for individual groups, and since it is necessary to stack many systems to increase the signal-to-noise ratio, a well-defined group catalog is also needed to interpret the stacking results. In this paper, we use the group catalogs given in Lim et al. (2017a), which uses four redshift catalogs of galaxies (2MRS, 6dF, SDSS, and 2dF) to achieve an almost all-sky (91%) coverage and the best depth reachable by these galaxy catalogs in each region of the sky. Groups are identified with the adaptive halo-based group finder of Yang et al. (2005, 2007) with some modifications (see Lim et al. 2017a for details). Tests with realistic mock galaxy catalogs show that the halo masses assigned by the group finder match well the true masses, with a typical scatter of 0.2–0.3 dex. The catalogs provide two different halo mass estimates based either on the luminosities and stellar masses of member galaxies, and we use the masses based on the stellar masses. We combine 2MRS, 6dF, and SDSS to construct our sample of groups with $\log M_{500}/M_\odot \geq 12$ for the tSZ analysis. For sky regions covered by more than one catalog, the preference is given in the order of SDSS, 6dF, and 2MRS. The sample contains a total of 471,696 galaxy systems (groups), of which 3851 have $\log M_{500}/M_\odot \geq 14$, 112,494 have $13 \leq \log M_{500}/M_\odot \leq 14$, and 240,747 have $12 \leq \log M_{500}/M_\odot \leq 13$. Following conventions in previous SZ effect analyses, we define a halo by a radius $R_{500}$, within which the mean density is 500 times the critical density at the redshift in question. The mass, $M_{500}$, used above is the halo mass within $R_{500}$. The halo masses and radii provided in the group catalogs are $M_{200}$ and $R_{200}$, respectively. To convert these quantities to the corresponding $M_{500}$ and $R_{500}$, we assume NFW profiles (Navarro et al. 1997) and concentration parameters as given by Neto et al. (2007).

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3. Method and Analysis

3.1. The Matched Filter Technique

Detecting the SZ signals physically related with a galaxy system is not trivial, as other effects, such as the primary CMB anisotropies, Galactic foreground, and other sources, can all contaminate the signals we want to obtain (see Section 4). Using a simple aperture photometry to extract the signals may thus lead to large uncertainties in the extracted signals (see, e.g., Melin et al. 2006). To limit source confusions and background contamination, we employ the matched filter (MF) technique, first proposed for SZ analyses by Haehnelt & Tegmark (1996), which is designed to maximize the signal-to-noise for an SZ source by imposing prior knowledge of the signals given the noise power spectra. For the case considered here, this means to optimally extract the tSZ signals from groups of galaxies, under the constraint of the power spectrum of the noise of the Planck maps. In practice, we closely follow Melin et al. (2005, 2006), who presented an extended and general formalism to extract signals from SZ surveys using the multi-filtering technique of Herranz et al. (2002). Such an MF technique has been applied in many recent analyses of the SZ effects in different surveys (e.g., Planck Collaboration et al. 2013a, 2013b, 2017; Li et al. 2014; Le Brun et al. 2015).

In the MF approach, the Fourier transform of the filter that maximizes the signal-to-noise is given by

\[
\hat{F}(k) = \left[ \frac{1}{P(k)} \int \frac{d^2k'}{(2\pi)^2} \hat{\tau}(k')\hat{B}(k') \right]^{-1} \hat{\tau}(k)\hat{B}(k) P(k),
\]

where \(\hat{\tau}(k)\) is the Fourier transform of the assumed spatial profile of groups, \(\hat{B}(k)\) is the Fourier transform of a Gaussian beam function that mimics the convolution in the Planck observation with the FWHM of 5', and \(P(k)\) is the noise power spectra. As the NILC y-map used here is already cleaned of the primary CMB anisotropies, \(P(k) = P_{\text{noise}}\), where \(P_{\text{noise}}\) is the power spectrum of the noise map for the Planck y-map, as provided in the data release. The choice of the spatial filter function is not straightforward, and it can affect the integrated signals extracted. Indeed, using hydrodynamic simulations, Le Brun et al. (2015) found that the extracted tSZ signals can change significantly depending on the filter shape adopted. In our analysis, we adopt the UPP given in Arnaud et al. (2010, hereafter A10), the form of which can be written as

\[
P(r) = A [E(z)z^{6/3}P(r/R_{500}, M_{500})],
\]

where \(E(z) \equiv H(z)/H_0\), \(P\) specifies the shape of the profile, and \(A\) is an overall amplitude (see A10 for details). This profile was derived from a combination of X-ray observations of XMM-Newton REXCESS cluster sample (Bohringer et al. 2007) at \(r \leq R_{500}\) and hydrodynamic simulations at larger radii. As a test, we have also used the spatial filter adopted in Le Brun et al. (2015) but did not find any significant changes in our results.

Figure 1 shows an example of the constructed filters, which assumes a group with \(\log(M_{500}/M_\odot) = 14\) and an angular radius \(\theta_{500} \sim 6.2\), and the universal pressure profile given above.

![Figure 1. Example of the matched filter constructed for the tSZ analysis. Here a universal profile of Arnaud et al. (2010) is adopted as a spatial filter for a group of \(M_{500}/M_\odot = 14\) and an angular radius \(\theta_{500} \sim 6.2\).](image)

3.2. Extracting the tSZ Signal

Theoretically, the tSZ signal is characterized by a Compton y-parameter,

\[
y = \frac{\sigma_T}{m_e c^2} \int P_e \, dz,
\]

where \(\sigma_T\) is the Thompson cross-section, \(m_e\) is the rest-mass of electron, \(c\) is the speed of light, \(P_e\) is the electron pressure, and the integration is over the line of sight to the observer.

The filters described above are then placed at the group centers and “matched” to the y-map to yield an estimate of the tSZ flux within \(R_{500}\), \(Y_{500}\) defined by

\[
d_A(z)^2 Y_{500} = \frac{\sigma_T}{m_e c^2} \int_{R_{500}} P_e \, dV,
\]

where \(d_A(z)\) is the angular diameter distance to a group at redshift \(z\). Since \(Y_{500}\) depends mainly on halo mass at a given \(z\) and evolves with \(z\) as \(E(z)^{2/3}\), at a fixed halo mass, it is useful to define a new quantity,

\[
\tilde{Y}_{500} = Y_{500}E^{-2/3}(z) \left( \frac{d_A(z)}{500 \text{ Mpc}} \right)^2,
\]

which is expected to be a function of only halo mass scaled to \(z = 0\), if the intrinsic tSZ flux is indeed only a function of mass.

To extract the SZ signals associated with galaxy groups from the observed y-map, a matched filter is put at each of all the groups in our group sample according to its halo mass and redshift. We then simultaneously tune the amplitudes of the filters for individual \(M_{500}\) bins as listed in Table 1, assuming the amplitudes for all the groups in a given \(M_{500}\) bin to be the same. The overall best match between the matched filters and the observed y-map is sought on the basis of the sum of the \(\chi^2\) over all the pixels covered by the filters. The simultaneous matching of individual groups allows us to take into account
eliminate such effects. We thus carry out a number of further tests to examine any possible residuals due to projection effects. In our first test, we remove all pixels covered by the groups at $z < 0.03$, and the results are shown by stars in Figure 2(b). As one can see, the signals for low-mass systems are changed relative to the fiducial case, suggesting that our results for low-mass groups may still be affected by projection effects. In the second test, the filters for groups below a halo mass limit are shifted by a given amount with respect to the group centers. Thus, if the signals extracted for these groups were not associated with them but produced by diffuse electrons associated with larger structures, such a shift would not change the signals obtained for these groups. As an example, the diamonds in Figure 2(b) show the result in which filters for groups with $\log M_{500}/M_\odot < 13.4$ are shifted randomly by $3\Delta R_{500}$, while the filters for more massive groups are still located at the group centers. As one can see, while no significant change is seen for groups with $\log M_{500}/M_\odot > 13.4$, the signals for the lower mass groups are reduced. This suggests that the signals detected in the matched filters are associated with these low-mass groups. Finally, we make another test by adding to each group an artificial $y$-parameter profile, which is given by the observed mean profile corresponding to its mass and redshift. The artificial $y$-parameter profile has the same shape as that given by the adopted pressure profile, and its amplitude is determined from a broken power-law fit to the observed mean amplitude as a function of halo mass. The test is intended to examine the robustness of the results against a change in the signal-to-noise. As the artificial signals added are the mean values at given masses, the test changes the signal-to-noise of the composite $y$-map in each pixel compared to that of the original map, which changes the weights given to individual pixels when matching filters. The matched filter technique is then applied to the sum of this artificial map with the original map. The original signals are well recovered by the differences between the results obtained from the coadded map and the added component, as shown by the crosses in Figure 2(b), demonstrating that our method can reliably extract the signals we put in.

Based on the test results presented above, we conclude that the results for groups with masses above $10^{13.5}M_\odot$ are stable. For groups of lower masses, however, significant variations are still present from sample to sample. We have also applied the same methods to different maps, such as the Planck MILCA (Modified Internal Linear Combination Algorithm; Hurier et al. 2013) all-sky tSZ Compton parameter map (Planck Collaboration et al. 2016b), which is known to have a different degree of dust contamination, and Planck multi-frequency temperature maps at 100 and 143 GHz, in which dust effects are expected to be smaller than in other bands. We found that the results do not change significantly, especially for groups above $10^{13.5}M_\odot$, indicating that our results are robust against residual dust emissions from galaxies.

Assuming virial temperatures, we estimate the hot gas contents of galaxy groups within $R_{200}$ from the integrated fluxes of $\tilde{Y}_{500}$. Here the NFW profile and the hot gas profile of A10 are used to convert quantities to the corresponding ones within $R_{200}$, and the virial temperature is defined as

$$T_{\text{vir}} = \frac{\mu m_p GM_{200}}{2k_B R_{200}},$$

where $\mu$ is the mean molecular weight, $m_p$ is the proton mass, and $k_B$ is the Boltzmann constant. The results obtained from the

| $\log M_{500}/M_\odot$ | $\tilde{Y}_{500}$ $(10^{-6} \text{arcmin}^2)$ | Variance $(10^{-6} \text{arcmin}^2)$ | No. of Systems |
|-----------------|-----------------|-----------------|----------------|
| 12.3            | $-0.0600$       | 0.360           | 40,689         |
| 12.5            | $-0.0480$       | 0.174           | 41,848         |
| 12.7            | 0.0564          | 0.231           | 40,521         |
| 12.9            | 0.0675          | 0.330           | 37,344         |
| 13.1            | 0.144           | 0.450           | 32,063         |
| 13.3            | 0.735           | 0.600           | 25,744         |
| 13.5            | 2.85            | 1.17            | 19,020         |
| 13.7            | 6.60            | 1.77            | 12,500         |
| 13.9            | 30.3            | 3.00            | 6203           |
| 14.1            | 59.7            | 7.50            | 2163           |
| 14.3            | 273             | 22.8            | 484            |
| 14.5            | 756             | 45.3            | 195            |
| 14.7            | 1520            | 83.7            | 71             |

Notes.

* These data are presented in Figure 2 by triangles.

$^a$ These are the $1\sigma$ dispersion among individual systems in each mass bin.
fiducial sample and the three subsamples are shown in Figure 3. Here we see that the inferred hot gas contents of low-mass groups within $R_{200}$ are lower than the universal baryon fraction, shown by the horizontal line, by a factor of $\sim 10$. Even for groups with $M_{200} \sim 10^{14} M_\odot$, the hot gas fraction is only about one-half; only in the most massive groups (clusters) is the fraction close to unity. Of course, the gas fraction could be much higher if the gas temperature is much lower than the virial temperature, and measurements of the tSZ effect alone cannot break the density–temperature degeneracy. In any case, the implied low density and/or temperature of the halo gas in low-mass groups have important implications for theories of galaxy formation, as to be discussed in the following.

4.2. Comparisons with Earlier Results and Theoretical Models

Planck Collaboration et al. (2013b; PCXI hereafter) used the same Planck data and a similar matched filter approach to extract the tSZ signals around the locally brightest galaxies (LBGs) selected from the SDSS survey. An isolation criterion is adopted so that each LBG is the dominating one (in terms of luminosity) in its neighborhood, probably representing the central galaxy of a halo. Based on the mean relation between the stellar masses of central galaxies and the halo masses obtained from the semi-analytic galaxy formation model of Guo et al. (2013), a halo mass is assigned to each of the LBGs. The $\tilde{Y}_{500}$--$M_{500}$ relation obtained by PCXI is plotted in Figure 2(a) as circles, and matches the expectation of the UPP model of A10, shown by the dashed line. As one can see,
our results are in good agreement with that of PCXI only for massive groups with \( M_{500} > 10^{14} M_\odot \), but the amplitudes we obtain for groups of lower masses are much lower. Indeed, our \( \bar{Y}_{500} - \bar{Y}_{500} \) relation is very different from that given by the UPP model. We suspect that there are two factors that may cause the difference between our and PCXI’s results.

First, we simultaneously match all groups in our sample, which takes into account the projection effects by larger halos along the lines of sight of low-mass groups, while PCXI matches individual filters separately. In a test where we first subtracted the local flat backgrounds averaged over annulus between \([2R_{200}, 3R_{200}]\) around each group, and then matched individual filters and stacked the signals for groups of similar masses, we found that we can roughly recover the results of PCXI for low-mass halos, despite of the differences in other details between our method and theirs. This indicates that the contamination by other groups is not flat, and that it is important to match the filters to all groups simultaneously in order to correct for such projection effects. In principle, there could be residual projection effects from halos not included in the catalogs either because they are located outside the redshift ranges of the catalogs or because they are too faint to be included in the group catalogs. The contribution from halos beyond the redshift range is expected to be uncorrelated with the groups at lower \( z \), and so it increases the noise level but does not bias the average signals obtained for these groups. Groups that are located within the sample volume but missing because they fall below the observational limits have halo masses \( M_{500} < 10^{13} M_\odot \). Our tests by matching filters only to groups with higher masses showed that the signals obtained for groups above \( 10^{13} M_\odot \) are not affected significantly by excluding lower mass groups in the filter matching. This demonstrates that the projection effects produced by halos below the mass completeness limit do not have a significant impact on our results.

Second, PCXI uses the mean relation between the central galaxy mass and halo mass to estimate halo mass, while our halo masses are estimated from our halo-based group finder. Given that the central galaxy mass increases only slowly with halo mass at \( M_{200} > 10^{13} M_\odot \) (Yang et al. 2003), and the relation has significant amounts of scatter (e.g., Yang et al. 2008), binning based on central galaxy mass may mix halos of very different masses.

Greco et al. (2015) used an LBG sample similar to that used by PCXI, together with the Planck temperature aperture photometry, instead of the matched filter, to extract tSZ signals associated with the LBGs. They found that their results are consistent with the UPP model within the uncertainties of the data. It is unclear if the difference between their results and ours is produced by the different mass proxies used to bin the data or by the different methods used to extract the tSZ signals. In a forthcoming paper, we will address this issue by examining how different methods adopted in the literature affect the extracted SZ signals. Vikram et al. (2017) examined the cross-correlation between groups in the catalog of Yang et al. (2007) and the Planck y-map, and found that two-halo terms dominate the signals around halos of \( M_{200} \lesssim 10^{13–13.5} h^{-1} M_\odot \). This is in qualitative agreement with our finding that the stacked signals for low-mass groups are dominated by projection effects. Taking account of the projection effects based on Vikram et al. (2017), Hill et al. (2017) found some evidence for a broken power-law relation between \( M_{500} \) and \( \bar{Y}_{500} \), which is in qualitative agreement with our results.

We also compare our results with those from two hydrodynamic simulations. The first is that presented in Le Brun et al. (2015), who used the cosmo-OWLS suite of cosmological simulations (Le Brun et al. 2014), an extension of the OverWhelmingly Large Simulations (OWLS; Schaye et al. 2010), to model the tSZ effects. The simulation has a box size of \( 400 h^{-1} \) Mpc on a side, and assumes cosmological parameters either from the WMAP7 or the Planck. Their fiducial runs include both stellar and AGN feedback. In Figures 2(a) and 3, the predictions of two of their models are plotted as the two solid curves. The upper curves correspond to their AGN feedback model AGN8.0, which assumes that accreting black holes heat their surrounding gas to a temperature \( \Delta T_{\text{heat}} = 10^8 \) K, while the lower curves are for their AGN8.5, which assumes \( \Delta T_{\text{heat}} = 3 \times 10^8 \) K. Clearly, our results are in good agreement with their results, particularly from that of the AGN8.5 run.

van de Voort et al. (2016) used a suite of cosmological zoom-in simulations from the Feedback In Realistic Environments (FIRE; Hopkins et al. 2014; Faucher-Giguère et al. 2015; Feldmann et al. 2016) project, to study the tSZ effects around halos with \( M_{500} = 10^{10–13} M_\odot \). Sixteen and 36 zoom-in simulations were run to \( z = 0 \) and \( z \sim 2 \), respectively. In Figures 2(a) and 3, we use straight lines to roughly represent their low-\( z \) results. Here the universal profile of A10 is used to convert the predictions, which are integrated quantities within projected radius, to quantities within spheres needed in the comparison. It is seen that the predicted tSZ signals are much stronger than both our results and the simulations of Le Brun et al. (2015). We note, however, that the simulations used by van de Voort et al. (2016) do not include AGN feedback, which may be important for the halo mass range concerned here.

5. Summary and Conclusion

In this paper, we use the measurements of the tSZ effect from the Planck NILC all-sky Compton parameter map, together with the group catalogs of Lim et al. (2017a) to investigate the hot gas contents of galaxy groups. The catalogs contain a large number of uniformly selected groups with reliable halo mass estimates, which allows us to bin groups of similar halo masses to investigate the dependence of the tSZ effect on halo mass over a large mass range. We adopt the matched filter approach (Haehnelt & Tegmark 1996; Herranz et al. 2002; Melin et al. 2005, 2006), which optimizes the signal-to-noise ratio by imposing prior knowledge of the expected signals, to extract the tSZ signals produced by galaxy groups from the map. We jointly match the filters to all groups to minimize projection effects.

We test the robustness of our method by retaining or eliminating pixels covered by local galaxy systems, by truncating the matched filters at different radii, by shifting the filters for low-mass groups, and by adding artificial signals to the observational map. We find that our method performs well in these tests. We also found that the background fluctuations around low-mass systems are significantly affected by projections of massive halos. Such a projection effect can lead to the overestimation of the tSZ signals associated with low-mass groups if filters are not matched simultaneously to all groups.

We find that the integrated y-parameter and the hot gas content it implies are consistent with the predictions of the UPP
model only for massive groups with masses above $10^{14}\ M_\odot$, but much lower, by a factor of $\sim$10, than the model prediction for low-mass groups. Our results are in conflict with the findings from some previous studies (e.g., Planck Collaboration et al. 2013b; Greco et al. 2015), which reported that their data are in agreement with the predictions of the UPP model. The disagreement likely comes from the different treatments of projection effects and the different halo mass models used in these studies. The halo mass dependence we find is in good agreement with the predictions of a set of hydro simulations presented in Le Brun et al. (2015) that include strong AGN feedback, but the simulations of van de Voort et al. (2016), which include only supernova feedback, overpredict the hot gas contents in galaxy groups by a factor of 5–10.

Since the integrated $\gamma$-parameter is a measure of the thermal energy content of the hot halo gas, our results indicate that this energy content in low-mass groups is much lower than that expected from the universal baryon fraction in a hot halo at the virial temperature. This has important implications for galaxy formation and evolution. Since the total baryon fraction of stars and cold gas in galaxy groups and clusters is found to be well below the universal baryon fraction (e.g., Fukugita & Peebles 2004), it has been speculated that the missing baryons may be in hot defused halos. However, if the low energy content found here is due to a low gas content in the hot phase, then hot gas halos cannot account for the missing baryons. Alternatively, baryons originally associated with galaxy groups may be heated and ejected by some processes. The agreement of our results with the predictions of the simulation results of Le Brun et al. (2015) suggests that strong AGN feedback may be able to provide such a process and to accommodate the observational results. Yet another possibility is that a large fraction of baryons may be in phases with temperatures much lower than the virial temperatures of the groups. In this case, the low thermal energy content observed in low-mass halos is produced by the low gas temperature rather than by a reduced amount of gas. To distinguish the different possibilities, it is crucial to estimate the total mass in the warm-hot phase, so as to obtain a complete inventory of the baryons in low-mass halos. This can be done either through quasar absorption studies (e.g., Werk et al. 2014), or by investigating the kinetic SZ effect of galaxy groups (e.g., Hernández-Monteagudo et al. 2015; Hill et al. 2016; Planck Collaboration et al. 2016c; Schaan et al. 2016; Lim et al. 2017b), which depends on the electron density but not the temperature of the halo gas.

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