THE THERMAL SUNYAev-ZEL'DOVICH SIGNATURE OF BARYONS IN THE LOCAL UNIVERSE

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Draft version March 20, 2022

ABSTRACT

Using cosmological hydrodynamical simulations, we investigate the prospects of the thermal Sunyaev-Zeldovich (tSZ) effect to detect the missing baryons in the local universe. We find that at least 80% of the tSZ luminosity is generated in collapsed structures, and that ~70% of the remaining diffuse tSZ luminosity (i.e., ~15% of the total) comes from overdense regions with $\delta_{\text{gas}} > 10$, such as filaments and superclusters. The gas present in slightly overdense and underdense regions with $\delta_{\text{gas}} < 10$, despite making up only 50% of the total baryon budget, leaves very little tSZ signature: it gives rise to only ~5% of the total tSZ luminosity. Thus, future Cosmic Microwave Background (CMB) observations will be sensitive to, at best, one half of the missing baryons, improving the current observational status, but still leaving one half unobserved. Since most of the tSZ is generated in haloes, we find a tight correlation between gas pressure and galaxy number density. This allows us to predict the CMB Comptonization from existing galaxy surveys and to forecast the tSZ effect from the local structures probed by the Two Micron All Sky Survey (2MASS) galaxy catalog.

Subject headings: cosmology: cosmic microwave background, observations - methods: numerical - galaxies: clusters: general

1. INTRODUCTION

Recent cosmological observations like galaxy surveys (e.g., 2dFGRS, Cole et al. 2001; SDSS, Tegmark et al. 2004), Supernovae (e.g., SNLS, Astier et al. 2006) or Cosmic Microwave Background (CMB) (e.g., WMAP, Spergel et al. 2003, 2006) give strong support to the Cosmic Microwave Background (CMB) observations will be sensitive to, at best, one half of the missing baryons, improving the current observational status, but still leaving one half unobserved. Since most of the tSZ is generated in haloes, we find a tight correlation between gas pressure and galaxy number density. This allows us to predict the CMB Comptonization from existing galaxy surveys and to forecast the tSZ effect from the local structures probed by the Two Micron All Sky Survey (2MASS) galaxy catalog.

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Using cosmological hydrodynamical simulations, we investigate the prospects of the thermal Sunyaev-Zeldovich (tSZ) effect to detect the missing baryons in the local universe. We find that at least 80% of the tSZ luminosity is generated in collapsed structures, and that ~70% of the remaining diffuse tSZ luminosity (i.e., ~15% of the total) comes from overdense regions with $\delta_{\text{gas}} > 10$, such as filaments and superclusters. The gas present in slightly overdense and underdense regions with $\delta_{\text{gas}} < 10$, despite making up only 50% of the total baryon budget, leaves very little tSZ signature: it gives rise to only ~5% of the total tSZ luminosity. Thus, future Cosmic Microwave Background (CMB) observations will be sensitive to, at best, one half of the missing baryons, improving the current observational status, but still leaving one half unobserved. Since most of the tSZ is generated in haloes, we find a tight correlation between gas pressure and galaxy number density. This allows us to predict the CMB Comptonization from existing galaxy surveys and to forecast the tSZ effect from the local structures probed by the Two Micron All Sky Survey (2MASS) galaxy catalog.

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With the advent of high resolution and high sensi-

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Draft version March 20, 2022

Preprint typeset using LATEX style emulateapj v. 6/22/04
less than 5% of all baryons, (Fukugita & Peebles 2004).

Because in overdense regions most of the tSZ is generated in haloes, we find a tight correlation between the gas pressure giving rise to the tSZ and the number galaxy density field, \( p_e \propto n_{gal}^{2.2} \). This allows us to build tSZ templates and to make predictions for the tSZ signal from existing galaxy surveys.

2. NUMERICAL SIMULATIONS

We ran a cosmological simulation of a LCDM cosmology (\( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7, \Omega_b = 0.045, h = 0.7, \sigma_8 = 0.9, n = 1 \)) with a box of 200 Mpc/h side, 1024\(^3\) hydro grid cells, and 512\(^3\) dark matter particles using the TVD+PM code of Trac & Pen (2004). The comoving grid spacing is 195 kpc/h and the dark matter particle mass resolution is \( 5 \times 10^6 \, h^{-1} M_\odot / h \). The Eulerian hydro algorithm computes the spatial and temporal changes in the conserved mass, momentum, and total energy. The thermal energy is calculated by subtracting the kinetic energy from the total energy, while the pressure and temperature are related to the thermal energy by the standard equation of state. The simulation is adiabatic. We recall the definition of the the Comptonization parameter \( (y \equiv \int dr \sigma_T n_e (k_B T_e)/n_e c^2, \) with \( \sigma_T \) the Thomson cross-section, \( k_B \) the Boltzmann constant and \( m_e, n_e, T_e \) the electron mass, density and temperature, respectively), in order to introduce the derivative \( dy/dr \) as a proxy for electron pressure, \( (dy/dr \propto p_e \propto n_e T_e) \). Likewise, we define \( Y \equiv \int d\rho \, dy/d\rho \), as a proxy for tSZ luminosity, since both quantities are also proportional. Bound dark matter particles classified as haloes are identified using an ellipsoidal overdensity threshold of 200 times the average density. This defines the halo boundaries which are used to distinguish between tSZ generated in collapsed structures and in the diffuse phase.

3. WHERE IS THE TSZ PRODUCED?

We distinguish tSZ luminosity being generated in cells belonging to clusters of galaxies \((M_{cl} \geq 5 \times 10^{13} \, h^{-1} M_\odot)\), to small haloes (also referred to as galaxy groups, and defined as all haloes resolved in the simulation with masses below \( 5 \times 10^{13} \, h^{-1} M_\odot \)), and to a diffuse gaseous phase (defined as all gas cells not belonging to any halo). Given the dark mass particle resolution in our simulation, we choose our mass threshold for the halo definition to be \( \sim 10^{12} \, h^{-1} M_\odot \): all haloes below this limit are regarded as diffuse gas, and hence our estimates for the diffuse tSZ contribution should be regarded as optimistic.

Figure (1a) shows the cumulative distribution of the pressure in the box versus gas density contrast. Collapsed structures show a halo-mass-weighted average gas overdensity of \( \sim 93 \), (marked by the vertical solid line). When integrating -i.e., volume weighting- the tSZ luminosity in the three cell subsets defined above (galaxy clusters, small haloes and diffuse gas), we find that \( \sim 70\% \) of total tSZ luminosity is generated in galaxy clusters, and, out of the \( \sim 30\% \) remaining, around one third of it (i.e., \( \sim 10\% \) of the total) is generated in small haloes. This leaves the diffuse phase a \( \sim 20\% \) contribution, even though it hosts \( \sim 70\% \) of the total baryonic mass. Further, one fourth of this diffuse gas is located in underdense regions, whose tSZ luminosity is negligible (< 1\%).

This suggests that the detection, via the tSZ effect, of the diffuse gas will be hampered by the presence of small (and plausibly unresolved) haloes: this is shown in Figure (1b), where the ratio of the gas pressure generated in small haloes over the sum of the contributions from the diffuse gas and small haloes is plotted versus the total gas pressure, (in all cases the pressure is computed in cells of 12 h\(^{-1}\)Mpc side). The vertical line marks the total pressure corresponding to the average galaxy number density. We see that, in slightly overdense regions hosting large pressure (right of the vertical line), the tSZ luminosity outside galaxy clusters is preferentially generated in smaller haloes rather than in diffuse gas, i.e., when searching for the tSZ signature of diffuse gas in overdense regions one must carefully subtract the...
contribution from small haloes. Projection effects in future CMB maps will further enhance this contamination. Only when considering the very overdense regions of the universe (far right end of this plot), the relative weight of the diffuse phase takes over, since in such environments there are no small haloes (all haloes are clusters). Note however that the mass threshold for our cluster definition (5 × 10^{13} h^{-1} M_{\odot}) corresponds to abundant and not-so-tSZ-bright objects, and that these sources may still be responsible for a significant amount of confusion noise.

4. THE PRESSURE - HALO CORRELATION

Since more than 80% of the tSZ luminosity is generated in collapsed structures, there must be a correlation between the gas pressure and the number density of haloes, or the gas pressure and the galaxy number density.

To investigate this correlation, we populate the haloes in the simulation using two different algorithms: the first one (Scoccimarro et al. (2001), hereafter SSHJ) characterizes the halo galaxy population by a binomial distribution, whereas the second (Kravtsov et al. (2004), hereafter K04) uses a Poissonian distribution. As in Smith et al. (2006), both algorithms are normalized to give the same average galaxy number density, \langle n_g \rangle \simeq 3 \times 10^{-2} h^3 Mpc^{-3}, and this requires slightly different choices for the halo minimum mass hosting a galaxy. As shown in Figure (2a), the correlation found between dy/dr and galaxy number density (computed in cells of 12h^{-1}Mpc side) is very similar in both cases, and well fitted by a power law of index \gamma \approx 2.1 - 2.3 for the SSHJ and K04 methods (filled circles and filled triangles, solid and dashed lines, respectively). The slope obtained in both cases is close to the prediction that a polytropic gas model (p \propto \rho^\gamma) provides for a self-gravitating system, \gamma = 2.

As current all sky maps of the local galaxy distribution do not have distance information, we want to investigate the correlation between projected galaxy density and y. We extend our simulated volume to a box of 600 h^{-1}Mpc side, exploiting the fact that the simulation box has periodic boundary conditions. We then place an observer in the center and project on a HEALPix (Górski et al. 2005) map of resolution parameter N_{side} = 512 a sphere of 300 h^{-1}Mpc radius. We produce maps of y and galaxies, smooth them with a Gaussian beam of FWHM = 12.6 arcmins, and sort the pixels in increasing projected number of galaxies. After binning them in groups of 32 pixels (for display purposes), we obtain a correlation between y and the projected galaxy overdensity \langle n_g \hat{n} / \langle n_g \rangle, \hat{n} denoting a direction on the sky), shown in Figure (2b).

We find that for slight galaxy overdensities (few times the background density), there is a tight correlation between galaxy number density and the Comptonization parameter y. This suggests using existing galaxy catalogs to predict the degree of Comptonization of the CMB sky. The volume used in our projection is close to that sampled by the Two Micron All Sky Survey (hereafter 2MASS, Jarrett et al. 2003). We thus use a map of projected galaxies from this survey (constructed as in Hernández-Monteagudo et al. (2004)) to make a prediction of the y sky. When comparing the galaxy maps from 2MASS and our simulation we find that they both show similar galaxy densities and clustering properties. We approximate the correlation given in Figure (2b) by five power laws (given by the solid lines), and invert the 2MASS-based galaxy catalog into a y map.

The overall y normalization is set by imposing that the 256 highest density pixels have a tSZ decrement of -73 \pm 17 \mu K, as found at 94 GHz by Hernández-Monteagudo et al. (2004) (all maps have been convolved by the same Gaussian beam). The power spectrum of the resulting y map (in units of \mu K^2 at Rayleigh-Jeans frequencies) is shown in Figure (2c) by filled circles: its amplitude and shape is very close, at high multipoles, to the power spectrum of the y map produced from our simulation (solid line). They only differ clearly at large scales (\ell < 10), for which the y power spectrum estimated from 2MASS is higher. This prediction for the local tSZ power spectrum is remark-

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**Fig. 2.**

(a) Pressure – galaxy number density correlation, according to SSHJ (filled circles and solid line) and K04 (filled triangles, dashed line) prescription to populate haloes with galaxies. (b) Correlation between Comptonization parameter y and projected galaxy overdensity (K04 prescription) obtained after projecting a simulated sphere of 300 h^{-1} Mpc radius. (c) Rayleigh-Jeans (RJ) expectation for our prediction of the local tSZ power spectrum computed from 2MASS galaxy catalog and the y–galaxy correlation (filled circles). The tSZ power spectrum (RJ) from our simulated volume is given by the solid line, and decomposed into the halo (dashed line) and diffuse (dot-dashed line) contributions.
ably close both in shape and amplitude to those obtained by Hansen et al. (2005), Dolag et al. (2005) via an independent approach. Our computation should be a valid prediction for the tSZ power at low \( \ell \)s, but at high \( \ell \)s the neglected high-redshift cluster population will dominate.

5. PROSPECTS FOR DIFFUSE TSZ DETECTION

Since we have separated in our simulation the gas belonging to collapsed haloes from the gas in a diffuse phase, it is possible to compute maps and power spectra of the halo and the diffuse components separately. The dot-dashed line at the bottom of Figure (2c) provides the power spectrum of the diffuse gas in our simulation, whereas the dashed line corresponds to the tSZ power spectrum generated by gas located in haloes (note its proximity to the total contribution [solid line]). A map of diffuse tSZ is given in Figure (3a), and comparing to the total tSZ contribution (Figure 3b). We conclude that most of the diffuse tSZ signal visible on the CMB sky (and more than 90% of the total tSZ luminosity) is generated in overdense regions traced by the clusters and superclusters, (i.e., the diffuse warm gaseous component present in voids leaves negligible tSZ signature). The amplitude of the diffuse phase is at best ten times (a hundred times in \( C_\ell \)'s) smaller than the tSZ signal generated in haloes, even at large angular scales. In particular since galaxies trace superclusters and filaments (corresponding to \( \delta_{\text{gas}} > 10 \)), the diffuse gas in these regions could be targeted by tSZ observations with specifications similar to those of e.g. ACT (http://www.hep.upenn.edu/act/). These regions contain 50% of the baryons: thus tSZ observations may decrease the ratio of unseen baryons in the local universe from \( \sim 9 \) to \( \sim 2 \). In practice, the limiting factor in detecting this signal will be confusion noise from unresolved haloes. Note that the ratio of tSZ luminosities of the collapsed and diffuse baryon components does not equal the ratio of the corresponding tSZ-induced angular power spectra, since the latter quantities depend on the contrast of tSZ sources against the CMB background. This makes the search for the (diffuse) missing baryons even more challenging. The detection of part of the diffuse tSZ may be feasible in nearby superclusters after masking out all compact sources and well characterized nearby galaxy clusters. However, we must conclude that the tSZ, despite of providing a new tool to unveil the presence of unseen warm and hot gas, will still miss a significant fraction of the baryons in the local Universe.

We thank R.E. Smith and R. Sheth for useful discussions. We acknowledge the use of HEALPix package, and the Two Micron All Sky Survey. CHM is supported by NASA grants ADP03-0092 and ADP04-0093 and NSF grant PIRE-0507765. RJ is partially supported by NSF grant PIRE-0507765 and by NASA grant NNG05GG01G. LV is supported by NASA grants ADP03-0092 and ADP04-0093.

REFERENCES

Astier, P., et al. 2006, A&A, 447, 31
Atrio-Barandela, F., & Mücke, J. P. 2006, ApJ, 643, 1
Battistelli, E. S., et al. 2006, ArXiv Astrophysics e-prints,
Böhringer, H., et al. 2000, ApJS, 129, 425
Cen, R., & Ostriker, J. P. 2005, ArXiv Astrophysics e-prints,
Croft, R. A. C., Weinberg, D. H., Katz, N., & Hernquist, L. 1998, ApJ, 495, 44
Dolag, K., Hansen, F. K., Roncarelli, M., & Moscardini, L. 2005, MNRAS, 363, 29
Fukugita, M., & Peebles, P. J. E. 2004, ApJ, 616, 643
Genova-Santos, R., et al. 2005, MNRAS, 363, 79
Görgöki, K.M., E. Hivon, A.J. Banday, B.D. Wandelt, F.K. Hansen, M. Reinecke, & M. Bartelmann, 2005 ApJ, 622, 759
Hansen, F. K., Branchini, E., Mazzotta, P., Cabella, P., & Dolag, K. 2005, MNRAS, 361, 783
Hernández-Monteagudo, C., Genova-Santos, R., & Atrio-Barandela, F. 2004, ApJL, 613, L89
Jarrett, T. H., Chester, T., Cutri, R., Schneider, S. E., & Huchra, J. P. 2003, AJ, 125, 525
Kravtsov, A. V., Berlind, A. A., Wechsler, R. H., Klypin, A. A., Gottlöber, S., Allgood, B., & Primack, J. R. 2004, ApJ, 609, 35
Kull, A., Böhringer, H. 1999, A&A, 341, 23
McDonald, P., et al. 2005, ApJ, 635, 761
Motl, P. M., Hallman, E. J., Burns, J. O., & Norman, M. L. 2005, ApJ, 623, L63
Nicastro, F., et al. 2005, ApJ, 629, 700
Nicastro, F., et al. 2005, Nature, 433, 495
Scoccimarro, R., Sheth, R. K., Hui, L., & Jain, B. 2001, ApJ, 546, 20
Sheth, R. K., & Tormen, G. 1999, Mon. Not. Roy. Astron. Soc., 308, 119

Fig. 3.— (a) All-sky diffuse tSZ contribution in our simulated volume, as opposed to the total tSZ contribution, (panel (b)).
Smith, R. E., Watts, P. I. R., & Sheth, R. K. 2006, MNRAS, 365, 214
Spergel, D. N., et al. 2003, ApJS, 148, 175
Spergel, D. N., et al. 2006, ArXiv Astrophysics e-prints, [arXiv:astro-ph/0603449]
Sunyaev, R. A., & Zeldovich, Y. B. 1980, ARA&A, 18, 537
Tegmark, M., et al. 2004, ApJ, 606, 702

Zappacosta, L., Mannucci, F., Maiolino, R., Gilli, R., Ferrara, A., Finoguenov, A., Nagar, N. M., & Axon, D. J. 2002, A&A, 394, 7
Trac, H., & Pen, U.-L. 2004, New Astronomy, 9, 443