THE CONTRIBUTION OF THE KINEMATIC SUNYAEV–ZEL’DOVICH EFFECT FROM THE WARM-HOT INTERGALACTIC MEDIUM TO THE FIVE-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE DATA

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ABSTRACT

We study the contribution of the kinematic Sunyaev–Zel’dovich (kSZ) effect, generated by the warm-hot intergalactic medium, to the cosmic microwave background temperature anisotropies in the five-year Wilkinson Microwave Anisotropy Probe (WMAP) data. We explore the concordance ΛCDM cosmological model, with and without this kSZ contribution, using a Markov chain Monte Carlo algorithm. Our model requires a single extra parameter to describe this new component. Our results show that the inclusion of the kSZ signal improves the fit to the data without significantly altering the best-fit cosmological parameters except Ω_b h^2. The improvement is localized at the ℓ ≳ 500 multipoles. For the best-fit model, this extra component peaks at ℓ ∼ 450 with an amplitude of 129 µK^2, and represents 3.1% of the total power measured by WMAP. Nevertheless, at the 2σ level a null kSZ contribution is still compatible with the data. Part of the detected signal could arise from unmasked point sources and/or Poissonianly distributed foreground residuals. A statistically more significant detection requires the wider frequency coverage and angular resolution of the forthcoming Planck mission.

Key words: cosmic microwave background – cosmology: observations – cosmology: theory

1. INTRODUCTION

Baryons represent a small fraction of the total mass-energy budget of the universe and do not play a predominant role in its evolution. They are the only matter component that has been identified directly. The baryon fraction of the universe has been determined at different redshifts through a variety of methods: Ω_b h^2 = 0.020 ± 0.002 (Burles et al. 2001) from big bang nucleosynthesis (BBN), Ω_b h^2 > 0.021 (Rauch et al. 1997) from the Lyα forest, and Ω_b h^2 = 0.02273 ± 0.00062 (Dunkley et al. 2009) from the cosmic microwave background (CMB) primary anisotropies. The baryon fraction measured from the well observed components at z = 0 is Ω_b h^2 = 0.010 ± 0.003 (Fukugita et al. 1998), indicating that half of the baryons in the local universe are still undetected.

Cosmological simulations of large-scale structure formation (Petitjean et al. 1995; Zhang et al. 1995; Hernquist et al. 1996; Katz et al. 1996; Theuns et al. 1998; Davé et al. 1999) have shown that the intergalactic gas has evolved from the initial density perturbations into a complex network of mildly nonlinear filaments in the redshift interval 0 < z < 6. With cosmic evolution, a significant fraction of the gas collapses into bound objects; baryons in the intergalactic medium (IGM) are in filaments containing Lyα systems with low H i column densities and, at low redshifts, shock-confined gas with temperatures T_e ∼ 0.01–1 keV and overdensities δ_h ∼ 10–50 (Davé et al. 2001; Cen & Ostriker 2006). An important fraction of the missing baryons could be located in this web of shock-heated filaments, called “warm-hot intergalactic medium” (WHIM). Observational efforts to detect this “missing baryon” component range from looking at its emission in the soft X-ray bands (Zappacosta et al. 2005), ultraviolet absorption lines in the spectra of more distant sources (Nicastro et al. 2005), or Sunyaev–Zel’dovich (SZ) contributions in the direction of superclusters of galaxies (Génova-Santos et al. 2008; see Prochaska & Tumlinson 2008 for a review). Indirect searches of the WHIM using the SZ effect have been inconclusive. The SZ imprint due to galaxy clusters in the Wilkinson Microwave Anisotropy Probe (WMAP) data is well measured (Atrio-Barandela et al. 2008a), but when this component is removed no signal associated with the WHIM remains (Hernández-Monteagudo et al. 2004).

Atrio-Barandela & Mücket (2006) developed a formalism to account for the contribution of the IGM/WHIM to the CMB anisotropies via the thermal SZ (tSZ; Sunyaev & Zeldovich 1972) effect. The main assumption was that missing baryons were distributed as a diffuse gas phase outside bound objects. Its filamentary structure was assumed to be described by a log-normal distribution function, which accurately models a mildly nonlinear density field when the velocity field remains in the linear regime (Coles & Jones 1991). The predicted power spectrum of the tSZ effect peaks at ℓ ∼ 2000–4000, with an amplitude similar to the tSZ from galaxy clusters. More recently, in Atrio-Barandela et al. (2008b) we studied the contribution of the kinematic SZ (kSZ; Sunyaev & Zeldovich 1980) effect. We found that the kSZ power spectrum had a maximum peak at ℓ ∼ 400–600. In this paper, we search for a possible kSZ contribution in the five-year WMAP data. We use a Markov chain Monte Carlo (MCMC) method to sample the parameter space of the concordance ΛCDM model with and without a kSZ component to determine if there is a statistically significant contribution. Briefly, in Sections 2 and 3 we describe the model and the numerical implementation of the MCMC, and in Section 4 we present our results and summarize our main conclusions.

2. THE THERMAL AND KINEMATIC SZ EFFECT FROM THE IGM/WHIM

The tSZ effect is the weighted average of the electron pressure along the line of sight; the kSZ is proportional to the column density of the free electrons along the line of sight n, weighted
by the radial component of their peculiar velocities:

\[
\left( \frac{\Delta T}{T_0} \right)_{\text{tSZ}} (\hat{n}) = G(\nu) \frac{k_B \sigma_T}{m_e c^2} \int dl \, n_e T_e \, ,
\]

\[
\left( \frac{\Delta T}{T_0} \right)_{\text{kSZ}} (\hat{n}) = \frac{\sigma_T}{c} \int dl \, n_e (\vec{v} \cdot \hat{n}) .
\]  

(1)

In these expressions, \( T_e, n_e, \) and \( v_e \) are the electron temperature, density, and peculiar velocity, respectively, \( k_B \) is the Boltzmann constant, \( \sigma_T \) is the Thompson cross section, \( m_e c^2 \) is the electron annihilation energy, \( c \) is the speed of light, and \( G(\nu) \) is the frequency dependence of the tSZ effect. In the Rayleigh–Jeans regime, \( G(\nu) \approx -2 \) with less than 20% variation at WMAP frequencies.

For an isothermal cluster, the tSZ to kSZ ratio is dominated by the spatial variations of the electron density fluctuations on spheres of \( 8 \) \( \times \) 1000 multipoles. On these angular scales, the kSZ contribution is negligible. The final tSZ power spectrum depends on cosmological and physical parameters: the cutoff scale \( \delta_{\max} \), the amplitude of the matter density fluctuations on spheres of \( 8 \) \( h^{-1} \) Mpc, \( \sigma_8 \), the mean gas temperature \( T_0 \), the gas polytropic index \( \gamma \), and the mean gas temperature at reionization, \( T_m \). The kSZ contribution depends on the Jeans length \( \ell_0 \), \( \sigma_8 \), and \( f_b \). Since the product \( \gamma T_m \) fixes \( \ell_0 \), the kSZ contribution requires less parameters than the tSZ.

In Figure 1(a), we compare CMB power spectrum of the concordance \( \Lambda \)CDM model with the kSZ and tSZ WHIM contributions. The parameters of the concordance model are those of the best-fit five-year WMAP data. The SZ contributions are calculated using \( \sigma_8 = 0.77, \gamma = 1.3, \gamma T_m \approx 1.3 \times 10^4 \) K, and \( f_b = 0.5 \). First, the relative amplitude of the thermal and kinematic contributions depends on model parameters; the kSZ effect could be larger than the tSZ effect since the average temperature of the IGM is rather low. Second, since the IGM is not isothermal, the tSZ contribution is dominated by the mildly overdense regions, which subtend smaller angles than the filaments themselves, so its power is shifted to higher \( \ell \). In Figures 1(b) and (c), we show the contribution of different redshift intervals to the total power for each of the WHIM contributions. In both cases, the main contribution comes from \( z = 0 \) to 0.4. Contributions from higher redshifts decrease rapidly.

The purpose of this paper is to search for a tSZ contribution in the five-year WMAP data, which are sensitive to \( \ell \lesssim 1000 \) multipoles. On these angular scales, the kSZ contribution is largest while the tSZ is larger at \( \ell \approx 3000 \). Friedman et al. (2009) see no evidence of a tSZ component at \( 2000 < \ell < 3000 \) and Sharp et al. (2009) constrain the tSZ power spectrum at \( \ell \approx 4000 \) to be \( \lesssim 149 \mu \text{K}^2 \) at 95% confidence.
cases using $\sigma$ power spectrum depends only on three parameters: component. This restriction simplifies our study since the $kSZ$ is then negligible. For this reason, we shall consider only a $kSZ$ contributions for $z$ scaling relation:

Each of these three parameters permits us to write the following of the maximum amplitude of the $kSZ$ power spectrum with $f$ but not the shape or position of the maximum, variations on 

\[ \Delta T_{kSZ} \approx 2 \mu K \left( \frac{\delta_b}{50} \right) \left( \frac{f_b}{0.5} \right) \left( \frac{L}{30 \text{ Mpc}} \right) \left( \frac{V_B}{600 \text{ km s}^{-1}} \right), \]

(7) where $\delta_b$ is the overdensity of a typical filament and $L$ is the coherence scale of a motion with amplitude $V_B$. As explained in Atrio-Barandela et al. (2008b), the distribution of the effect is rather skewed and 9% of all lines of sight will produce an effect 1.8–6 times larger than the estimate from Equation (7). In the concordance model, bulk flow velocities of $\sim 200$ km s$^{-1}$ are typical for volumes of $R \sim 100$ Mpc $h^{-1}$ radius. Kashlinsky et al. (2008, 2009) reported a bulk flow of amplitude 600–1000 km s$^{-1}$ on a scale of 300 Mpc $h^{-1}$ that could give a much larger contribution. A significant fraction of the temperature decrement of $-230 \mu K$ detected in the intercluster medium of the Corona Borealis Supercluster by Génova-Santos et al. (2005) could be due to thermal and kinematic SZ contributions. However, that decrement is in a direction almost perpendicular to the bulk flow cited above and, because of its orientation with respect to the line of sight, this flow would not induce a significant kSZ contribution in Corona Borealis. Only a smaller kSZ contribution could exist due to peculiar motions on the scale of the supercluster itself.

3. MARKOV CHAIN MONTE CARLO PARAMETER ESTIMATION

To explore the parameter space of $\Lambda$CDM models with and without a kSZ contribution, we used the April 2008 version of the cosmomc package (Lewis & Bridle 2002).
This software implements a MCMC method that performs parameter estimation using a Bayesian approach. When the kSZ contribution is included, precomputed $C^kSZ_{\ell}$ are added at each step of the chain to the theoretical power spectrum, computed with camb (Lewis et al. 2000) for each set of the cosmological parameters. The model is compared with the data using the likelihood code supplied by the WMAP team (Dunkley et al. 2009).

We considered the concordance ΛCDM model, defined by a spatially flat universe with cold dark matter (CDM), baryons, and a cosmological constant Λ. The relative contributions of these components are given in units of the critical density: $\Omega_{\Lambda,0}$, $\Omega_{\text{cdm},0}$, and $\Omega_b,0 = 1 - \Omega_{\Lambda,0}$, where $\Omega_m = \Omega_{\text{cdm},0} + \Omega_b,0$ is the total matter density. The specific parameters used in the analysis were the physical densities $\Omega_b h^2$ and $\Omega_{\text{cdm},0} h^2$, where $h = H_0/100$ km s$^{-1}$ Mpc$^{-1}$ is the normalized Hubble constant. To minimize degeneracies, instead of $h$ we used the angular size of the first acoustic peak $\theta$, i.e., the ratio of the sound horizon to the angular diameter distance to last scattering (Kosowsky et al. 2002). We considered adiabatic initial conditions and assumed an instantaneous reionization parameterized by its optical depth $\tau$.

At each step in the chain, a set of initial values for the cosmological parameters and for $\gamma T_m$ is randomly drawn from a Gaussian distribution with a standard deviation equal to the value listed in Table 1 multiplied by 2.4. Since we found that $\gamma T_m$ was strongly correlated with $\Omega_b h^2$ and $\ln(10^{10} A_s)$, we reran the chains using the eigenvalues of the covariance matrix of the parameters (computed with the getdist package) as distribution widths. We ran nine independent chains, with a total number of 150,000 independent samples, when no kSZ is included. With kSZ, we fixed the baryon fraction in WHIM at five different values $f_b = 0.3, 0.4, 0.5, 0.6, 0.7$ (we also tried to constrain a model with $f_b$ as a free parameter, but the degeneracies did not allow us to obtain reliable results). In each case, we ran eight independent chains of similar sizes with a total number of samples $\geq 225,000$. We used the $R$ statistic (Gelman & Rubin 1992) as a convergence criterion. All our parameters have $R$ well below 1.2: $R \approx 1.008$ for $\log(\gamma T_m)$ and $\approx 1.002$ for the other parameters.

### 4. RESULTS AND DISCUSSION

In Figures 3(a)–(c), we plot the mean one-dimensional likelihoods for $\gamma T_m$, $\sigma_8$, and the more informative rms temperature fluctuation introduced by the kSZ signal defined as

$$\langle \Delta T_{\text{kSZ}} \rangle^{1/2} = \left[ \frac{1}{4\pi} \sum_{\ell=2}^{1000} (2\ell + 1) C^kSZ_{\ell} \right]^{1/2}. \quad (9)$$

The different lines correspond to different baryon fractions. Since the kSZ parameters affect the amplitude of the spectrum most significantly (see Figure 2), for each $f_b$ the maximum one-dimensional likelihood of $\gamma T_m$ shifts but the kSZ signal remains roughly constant (see Figure 3(c)). This high degeneracy indicates that five-year WMAP data are insensitive to the fraction of baryons in the WHIM, and hereafter we will quote results for $f_b = 0.5$.

In Figures 3(d)–(f), we show the mean two-dimensional likelihoods for pairs of parameters. The solid lines represent $1\sigma$ and $2\sigma$ contours, whereas the white dots indicate the positions of the maximum likelihood in the full parameter space. Not unexpectedly, their positions are slightly shifted with respect to the two-dimensional likelihood maxima. In fact, Markov chains estimate confidence intervals more precisely than locate the maximum of the likelihood, the bias being larger the greater the model dimensionality (Liddle 2004). Figure 3(d) shows a noticeable degeneracy between $\sigma_8$ and $\log(\gamma T_m)$. Within the $1\sigma$ confidence region $\Delta_A$ varies between $\approx 20 \mu K^2$ and $\approx 300 \mu K^2$. Regions with high values of $\sigma_8$ and low values

| Basic Parameter | Parameter | Starting Limits | Starting Points | Distribution Width |
|-----------------|-----------|-----------------|-----------------|-------------------|
| $\Omega_b h^2$  | 0.005, 0.1 | 0.0223          | 0.001           |                    |
| $\Omega_{\text{cdm},0} h^2$ | 0.01, 0.99 | 0.105           | 0.01            |                    |
| $\Omega_{\Lambda,0}$ | 0.5, 10   | 1.04            | 0.002           |                    |
| $\ln(10^{10} A_s)$ | 2.7, 4.0 | 3.0             | 0.01            |                    |
| $n_s$           | 0.5, 1.5  | 0.95            | 0.01            |                    |
| $\tau$          | 0.01, 0.8 | 0.09            | 0.03            |                    |
| $\log(\gamma T_m)$ | 3.778, 4.740 | 4.096          | 0.006           |                    |
The parameters that maximize the likelihood are given in Table 2. The 1σ confidence intervals have been computed from the one-dimensional mean likelihood distributions. The values for the concordance model agree well with those given by the WMAP team (Dunkley et al. 2009), indicating that we are correctly exploring the parameter space. The model with kSZ has larger error bars, as we are fitting the same data with an extra degree of freedom. The best-fit model has a kSZ power spectrum with a maximum amplitude of $A_{\text{kSZ}} = 129^{+138}_{-52} \mu K^2$ centered at $\ell \approx 438$, corresponding to $y_{\text{T}} = 1.3^{+0.4}_{-0.2} \times 10^4$ K.

The rms temperature fluctuation is $\langle T_{\text{CMB}}^2 \rangle^{1/2} = 19^{+7}_{-5} \mu K$, very significant compared with the contribution from the primordial CMB. $\langle T_{\text{CMB}}^2 \rangle^{1/2} = 110 \mu K$. None of the parameters except $\Omega_b h^2$ differ by more than 1σ from those of the concordance model. The model with kSZ gives a higher value for $\Omega_b h^2$. This reinforces the slight discrepancy between the values obtained from CMB temperature anisotropies and from BBN. As indicated above, adding kSZ boosts the value of $\Omega_b h^2$ since of log($y_{\text{T}}$) are strongly ruled out since they overpredict the kSZ contribution. At the 2σ level, the absence of a kSZ contribution is compatible with the data. This is also seen in Figure 3(e). Models with kSZ prefer a lower value of $\sigma_8$ (see Figure 3(b)), since adding kSZ requires less primordial CMB power. Figures 3(e) and (f) respectively show that $\Omega_b h^2$ is proportional to $<T_{\text{kSZ}}^2>^{1/2}$, and inversely proportional to $\log(y_{\text{T}})$. Physically, kSZ adds power mainly at $\ell \approx 400$–600 and the amplitude of the second acoustic peak gets reduced to fit the data. As a result, the best-fit value for $\Omega_b h^2$ increases.

Table 2

| Parameter | CMB Alone | CMB and kSZ |
|-----------|-----------|-------------|
| $\Omega_b h^2$ | 0.0223^{+0.0007}_{-0.0006} | 0.0234^{+0.0020}_{-0.0008} |
| $\Omega_{\text{dm}} h^2$ | 0.1086^{+0.0081}_{-0.0060} | 0.1096^{+0.0068}_{-0.0085} |
| $\Omega_k$ | 1.040^{+0.004}_{-0.003} | 1.042^{+0.005}_{-0.004} |
| $\ln(10^{10} A_s)$ | 3.06 ± 0.05 | 3.02 ± 0.08 |
| $n_s$ | 0.96 ± 0.02 | 0.95 ± 0.02 |
| $\tau$ | 0.088^{+0.020}_{-0.019} | 0.087^{+0.023}_{-0.017} |
| $y_{\text{T}} (10^4 \text{K})$ | 1.31^{+0.41}_{-0.23} | |
| $\chi^2$ | 2661.05 | 2657.83 |

Notes. These results correspond to a fraction of baryons in the form of WHIM of $f_b = 0.5$. The upper and lower (below the line) sets correspond to independent and derived parameters, respectively. The central values have been derived from the sample with the minimum $\chi^2$ in the chains (also shown in the table), whereas the 1σ confidence limits were derived from the 0.159 and 0.841 points of the cumulative probability distribution given by the one-dimensional mean likelihoods.

it reduces the height of the second acoustic peak. The difference in $\sigma_8$ is also notable even if the confidence regions overlap at the 1σ level. Our estimate is closer to the values obtained...
from the number density of galaxy clusters and the optical or X-ray cluster mass functions. For example, Voevodkin & Vikhlinin (2004) found $\sigma = 0.72 \pm 0.04$ from the baryon mass fraction of a sample of 63 X-ray clusters. After compiling cluster determinations since 2001, Hetterscheidt et al. (2007) obtained $\sigma = 0.728 \pm 0.035$, whereas from another compilation of the weak lens cosmic shear they found $\sigma = 0.847 \pm 0.029$.

In Figure 4(a), we compare the accuracy of the fitting of the two models to the five-year WMAP data. We plot the best-fit power spectra for the models with and without kSZ after subtracting the WMAP experimental band powers. The kSZ model achieves a better fit to the experimental data points in the multipole range $\ell \sim 300$–700. The same conclusion can be obtained from Figure 4(b), where we plot the ratio of the binned $\chi^2$ per $\ell$-band for the model without and with kSZ (note that these values were calculated, just for illustrative purposes, by applying the $\chi^2$ statistics to the binned best-fit theoretical power spectra, and not by the WMAP likelihood code). This ratio is overall $>1$ in the range $\ell \sim 300$–700, even though within this interval there are some particular bins where the concordance model produces a slightly better fit.

Introducing the kSZ component, the $\chi^2$ reduces by $\Delta \chi^2 = -3.3$, from 2661.05 to 2657.83. Evaluating the statistical significance of this result requires taking into account the number of degrees of freedom, given by the difference between the number of independent data points $N$ and the number of model parameters $k$. The WMAP likelihood is computed as a sum of different temperature and polarization terms (Dunkley et al. 2009). In this computation, 968 points correspond to the TT power spectrum at $\ell = 33$–1000 and 427 to the TE cross-correlation at $\ell = 24$–450. For low ($\ell \leq 23$) multipoles, the likelihood associated with the TT, TE, EE, and EB correlations is evaluated directly from 1170 pixels of the temperature and polarization maps. In total $N = 2565$. Adding the kSZ contribution raises the number of parameters from $k = 6$ to $k = 7$. Note that the $\chi^2$ per degree of freedom also decreases when the kSZ component is included, from $\chi^2_{\text{det}} = 1.0399$ to 1.0390. Increased number of model parameters always improves the fit to a particular data set but the model loses predictive power. In Bayesian statistics, information criteria can be used to decide whether the introduction of a new parameter is favored by the data. Examples are the Akaike information criterion (Akaïke 1974) defined as $\text{AIC} = 2k + \chi^2$ or the more conservative Bayesian information criterion (Schwarz 1978) $\text{BIC} = \chi^2 + k \ln N$. Since we are adding a single parameter, we obtain $\Delta \text{AIC} = -1.2$, which is marginal evidence in favor of introducing this new parameter, while $\Delta \text{BIC} = 4.1$ is evidence against it, reflecting the fact that no kSZ component is compatible with the data at the $2\sigma$ level. Even if at present model selection does not clearly favors the kSZ contribution, it is a model well motivated physically and, as remarked by Linder & Miquel (2008), model selection needs to involve physical insight. A statistically more significant measurement would require a wider frequency coverage and angular resolution, as will be provided by the forthcoming Planck mission.

The kSZ contribution represents 3.1% of the power measured in five-year WMAP data. This contribution is larger than expected; typical filaments would give rise to $\Delta T_{\text{kSZ}} \sim 2$–5 $\mu$K (Equation (7)). We would need a more accurate (numerical) model to establish which would be the physical conditions that give rise to the quoted kSZ signal. Numerical simulations over large cosmological volumes are computationally very expensive because they require high resolution over most of the volume. In fact, spatial resolution is usually an important limitation. Adaptive mesh refinement (AMR) techniques are efficient at describing the dynamics of gas in the high dense regions but their resolution falls sharply in less dense environments (Refregier & Teyssier 2002), while smooth particle hydrodynamics (SPH) codes do not yet resolve scales as small as the Jeans length (Bond et al. 2005), that effectively dominate the WHIM SZ contribution (Atrio-Barandela & Mücke 2006). Hallman et al. (2007) used the AMR Enzo code (O’Shea et al. 2005) to simulate a $(512$ $\text{Mpc}$ $h^{-1})^3$ volume including unbound gas, and found that one-third of the SZ flux in a 100 $\text{square degree}$ region comes from objects with masses below $5.0 \times 10^{13} \text{M}_\odot$ and filamentary structures made up of WHIM gas, a conclusion similar to that reached by Hernández-Monteagudo et al. (2006). Hallman et al. (2009) focused in the low-density WHIM gas by restricting their analysis of the same AMR simulation to regions with temperatures in the range $10^5$–$10^7$ K and overdensities $\delta < 50$, even though their low-mass halos were not yet resolved gravitationally. They computed the radiation power spectrum from that simulation and found a similar shape to that of Figure 1, although with a much smaller amplitude. The high amplitude we found could be an indirect confirmation of large-scale peculiar motions reported in Kashlinsky et al. (2008, 2009). If bulk flows of this amplitude are very common, filaments at higher redshift could also contribute significantly, thereby increasing the total signal. Also, we must take into account a possible foreground contamination: power spectra with a single maximum are also good models for Poissonian distributed foreground residuals or unresolved point sources. Since the WMAP window function exponentially damps power at $\ell \gtrsim 600$, the convolution of a $C_\ell = \text{const.}$ spectrum with this window function peaks at $\ell < 600$ and has a shape similar...
to that of the spectrum described above. Foreground subtraction
can differ in the range 3–5 μK depending on the method (Ghosh
et al. 2009) and some residuals could be present on the data
at that level. To distinguish the WHIM kSZ and foreground
signals, we will have to include the frequency dependence,
admittance, and location of the maximum for each component.
In the simplest model with kSZ and one foreground, we would
need four parameters to model both contributions so an analysis
of all components is unfeasible with WMAP 3 frequency bands
(Q, V, and W).

To conclude, we have explored the parameter space of the concordance
model to show that the WHIM kSZ contribution
could be at least as high as 3% the total power of five-year WMAP
data. This large amplitude is difficult to account for in the con-
cordance ΛCDM model, where filaments are expected to have
≤ 5 μK contributions. It could be an indication that large-scale
flows are rather common. We cannot rule out that part of this
contribution could be due to unmasked point sources and/or
foreground residuals. The Planck satellite, with its wider fre-
cquency coverage, lower noise, and different scanning strategy,
is well suited for detecting the IGM/WHIM thermal and kine-
matic contributions with much higher statistical significance
and to distinguishing this signal from other foreground contribu-
tions.

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REFERENCES

Akaie, H. 1974, IEEE Trans. Aut. Cont., 19, 716
Atrio-Barandela, F., Kashlinsky, A., Kocevski, D., & Ebeling, H. 2008a, ApJ, 675, L57
Atrio-Barandela, F., & Mückert, J. P. 1999, ApJ, 515, 465
Atrio-Barandela, F., & Mückert, J. P. 2006, ApJ, 643, 1
Atrio-Barandela, F., Mückert, J. P., & Génova-Santos, R. 2008b, ApJ, 674, L61
Bond, J. R., et al. 2005, ApJ, 626, 12
Burles, S., Nollett, K. M., & Turner, M. S. 2001, ApJ, 552, L1
Cen, R., & Ostriker, J. P. 2006, ApJ, 650, 560
Coles, P., & Jones, B. 1991, MNRAS, 248, 1
Davé, R., Hernquist, L., Katz, N., & Weinberg, D. H. 1999, ApJ, 511, 521
Davé, R., et al. 2001, ApJ, 552, 473
Dunkley, J., et al. 2009, ApJS, 180, 306
Friedman, R. B., et al. 2009, arXiv:0901.3134
Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518
Gelman, A., & Rubin, D. 1992, Stat. Sci., 7, 457
Génova-Santos, R., et al. 2005, MNRAS, 363, 79
Génova-Santos, R., et al. 2008, MNRAS, 391, 1127
Ghosh, T., Saha, R., Jain, P., & Souradeep, T. 2009, arXiv:0901.1641
Hallman, E. J., O’Shea, B. W., Burns, J. O., Norman, M. L., Harkness, R., & Wagner, R. 2007, ApJ, 671, 27
Hartman, E. J., O’Shea, B. W., Smith, B. D., Burns, J. O., & Norman, M. L. 2009, arXiv:0903.3239
Hernández-Monteagudo, C., Genova-Santos, R., & Atrio-Barandela, F. 2004, ApJ, 613, L89
Hernández-Monteagudo, C., Trac, H., Verde, L., & Jimenez, R. 2006, ApJ, 652, L51
Hutter, H., Schilke, P., Menten, K. M., & Menten, M. S. 2011, ApJ, 736, 16
Hutter, H., Schilke, P., Menten, K. M., & Menten, M. S. 2011, ApJ, 736, 16
Kashlinsky, A., Atrio-Barandela, F., Kocevski, D., & Ebeling, H. 2008, ApJ, 686, L49
Kashlinsky, A., Atrio-Barandela, F., Kocevski, D., & Ebeling, H. 2009, ApJ, 691, 1749
Katz, N., Weinberg, D. H., Hernquist, L., & Miralda-Escude, J. 1996, ApJ, 457, 57
Kosowsky, A., Milosavljevic, M., & Jimenez, R. 2002, Phys. Rev. D, 66, 063007
Lewis, A., & Bridle, S. 2002, Phys. Rev. D, 66, 103511
Lewis, A., Challinor, A., & Lasenby, A. 2000, ApJ, 538, 473
Liddle, A. R. 2004, MNRAS, 351, L49
Linder, E. V., & Miquel, R. 2008, Int. J. Mod. Phys. D, 17, 2315
Molnar, S. M., & Birkinshaw, M. 2000, ApJ, 537, 542
Nicastro, F., et al. 2005, Nature, 433, 495
O’Shea, B. W., Bryan, G., Bordner, J., Norman, M. L., Abel, T., Harkness, R., & Kritsuk, A. 2005, in Adaptive Mesh Refinement: Theory and Applications (Berlin: Springer), 341
Petitejean, P., Muecket, J. P., & Kates, R. E. 1995, A&A, 295, L9
Prochaska, J. X., & Tumlinson, J. 2008, in Astrophysics in the Next Decade: The James Webb Space Telescope and Concurrent Facilities, ed. H. A. Thronson, M. Stiavelli, & A. Tielens, arXiv:0805.4635
Rauch, M., et al. 1997, ApJ, 489, 7
Regier, A., & Teyssier, R. 2002, Phys. Rev. D, 66, 043002
Schwarz, G. 1978, Ann. Stat. 6(2), 461
Sharp, M. K., et al. 2009, arXiv:0901.4342
Sinyavev, R. A., & Zeldovich, Ya. B. 1972, Comment. Astrophys. Space Phys., 4, 173
Sinyavev, R. A., & Zeldovich, Ya. B. 1980, MNRAS, 190, 413
Theuns, T., Leonard, A., Efstathiou, G., Pearce, F. R., & Thomas, P. A. 1998, MNRAS, 301, 47
Voelvodkin, A., & Vikhlinin, A. 2004, ApJ, 601, 610
Zappacosta, L., Maiolino, R., Mannucci, F., Gilli, R., & Schuecker, P. 2005, MNRAS, 357, 929
Zhang, Y., Anninos, P., & Norman, M. L. 1995, ApJ, 453, 57