MEASURING AGN FEEDBACK WITH THE SUNYAEV-ZEL'DOVICH EFFECT

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ABSTRACT

One of the most important and poorly understood issues in structure formation is the role of outflows driven by active galactic nuclei (AGNs). Using large-scale cosmological simulations, we compute the impact of such outflows on the large-scale distribution of the cosmic microwave background (CMB). Like gravitationally heated structures, AGN outflows induce CMB distortions through both thermal motions and peculiar velocities, by processes known as the thermal and kinetic Sunyaev-Zel'dovich (SZ) effects, respectively. For AGN outflows the thermal SZ effect is dominant, doubling the angular power spectrum on arcminute scales. But the most distinct imprint of AGN feedback is a substantial increase in the thermal SZ distortions around elliptical galaxies, poststarburst elliptical galaxies, and quasars that is linearly proportional to the outflow energy. While point-source subtraction is difficult for quasars, we show that by appropriately stacking microwave measurements around early-type galaxies, the new generation of small-scale microwave telescopes will be able to directly measure AGN feedback at the level that is important for current theoretical models.

Subject headings: cosmic microwave background — galaxies: evolution — intergalactic medium — large-scale structure of universe — quasars: general

Online material: color figures

1. INTRODUCTION

Large-scale measurements of cosmic microwave background (CMB) anisotropies have played a central role in the development of the modern cosmological model. By giving us a picture of the universe during the epoch of linear fluctuations, they have provided us with a foundation upon which to interpret the subsequent growth of structure. Thus, from the spectacular initial detections made by the Cosmic Background Explorer (COBE) satellite (Smoot et al. 1992), to the detailed flatness constraints provided by balloon-borne missions (Hanany et al. 2000; Mauskopf et al. 2000), to the precision measurements of cosmological parameters derived from the Wilkinson Microwave Anisotropy Probe (WMAP) observations (Spergel et al. 2003, 2007), our understanding of structure formation has progressed hand in hand with improvements in large-scale CMB anisotropy measurements.

However, on angular scales below $\approx 10'$, the science potential of CMB measurements has yet to be realized. On these scales, Silk damping washes out the primary anisotropies, while a host of smaller scale secondary anisotropies are imprinted as the photons propagate across the universe. One of the most important sources of these effects is the scattering of CMB photons by hot electrons, a process that was first studied by Sunyaev & Zel'dovich (1970, 1972). This process can be divided into two contributions. The largest of these is the thermal Sunyaev-Zel'dovich (SZ) effect, in which inverse Compton scattering preferentially increases the energy of CMB photons passing through hot and dense regions, introducing anisotropies with a distinctive frequency dependence. A smaller contribution arises from the kinetic SZ effect, in which Doppler scattering in dense regions with significant peculiar motions induces fluctuations with the same frequency dependence as the CMB itself.

The most important source of such hot and dense regions is undoubtedly the gravitational collapse of gas into large dark matter halos, and numerous numerical simulations of the SZ effect from this process have been carried out by several groups (e.g., Scaramella et al. 1993; Hobson & Magueijo 1996; da Silva et al. 2000; Refregier et al. 2000; Seljak et al. 2001; Springel et al. 2001; Zhang et al. 2002; Roncarelli et al. 2007). Yet dark-matter–driven gravitational heating need not provide the dominant SZ contribution at all scales and in all environments. In fact, the gas that is responsible for the largest SZ distortions, the intracluster medium (ICM) in galaxy clusters, has been observed to have been substantially heated by nongravitational sources (Cavaliere et al. 1998; Kravtsov & Yepes 2000; Wu et al. 2000; Babul et al. 2002). In galaxy groups, such nongravitational effects are even more severe, causing groups with a large range of X-ray luminosities to all be heated to a similar value of $\approx 1$ keV per baryon (e.g., Arnaud & Evrard 1999; Helsdon & Ponman 2000).

But perhaps the most dramatic, yet most poorly understood manifestation of nongravitational heating is in establishing the observed “downsizing” (Cowie et al. 1996) trend in the evolution of star-forming galaxies and active galactic nuclei (AGNs). Here the issue is that since $z \approx 2$, the characteristic mass scale of star-forming galaxies and the typical luminosity of AGNs have dropped by over an order of magnitude (e.g., Arnouts et al. 2005; Treu et al. 2005; Pei 1995; Ueda et al. 2003; Barger et al. 2005). This “antihierarchical” trend is in direct conflict with the expectations of the long-standing model of structure formation, in which gas condensation and heating is driven purely by dark matter halos, which grow hierarchically by accretion and merging over time. In this picture, as gas falls into potential wells, it is shock-heated and must radiate this energy away before forming stars (Rees & Ostriker 1977; Silk 1977). The larger the structure,
the longer it takes to cool, and thus the formation history of galaxies is even more hierarchical than that of dark matter.

Although early modeling did not reproduce this downsizing behavior, the trend has been successfully reproduced in more recent theoretical models that include a large source of heating associated with outflows from AGNs (Scannapieco & Oh 2004; Binney 2004; Granato et al. 2004; Scannapieco et al. 2005; Di Matteo et al. 2005; Croton et al. 2006; Cattaneo et al. 2006; Thacker et al. 2006, hereafter TSC06; Di Matteo et al. 2008). In this picture, AGN outflows associated with broad absorption-line winds and/or radio jets heat the surrounding intergalactic medium (IGM) to sufficiently high temperatures to prevent it from cooling and forming further generations of stars and AGNs. This feedback requires an energetic outflow, driven by a large AGN, to be effective in the dense, high-redshift IGM, whereas in the more tenuous, low-redshift IGM, equivalently long cooling times can be achieved by less energetic winds. The lower the redshift, the smaller the galaxy that is able to exert efficient feedback, thus resulting in cosmic downsizing.

However, the details of AGN feedback remain extremely uncertain. Heating may be impulsive (e.g., TSC06), more gradual (e.g., Brüggen et al. 2005; Croton et al. 2006), or modulated primarily by the properties of the surrounding material (e.g., Dekel & Birnboim 2006). Furthermore, direct measurements of the kinetic energy input from AGNs are notoriously difficult and range from ~1% or less (de Kool et al. 2001) to ~60% of the AGN’s total bolometric energy (Chartas et al. 2007). Finally, several alternative ideas have been suggested to explain downsizing outside of the context of AGN feedback altogether (e.g., Kereš et al. 2005; Khochfar & Ostriker 2008; Birnboim et al. 2007).

Here we show that the definitive measurement resolving this issue may again come from the microwave background, through observations of SZ distortions. Since they directly probe the spatial distribution of heated gas, SZ detections are able to place constraints on the primary theoretical uncertainty in AGN feedback models: namely, the nature and degree of nongravitational gas heating. Fortunately, the rise in importance of this issue for theory has been paralleled by recent advances in observation. Motivated primarily by deriving cosmological constraints through the detection of galaxy clusters (e.g., Holder et al. 2000; Majumdar & Mohr 2003; Battye & Weller 2003; Schulz & White 2003), a large number of blank-field small-scale CMB surveys are now under way, using telescopes that will push into the interesting regime for AGN feedback. These include surveys with the Atacama Cosmology Telescope (Kosowsky et al. 2006), the South Pole Telescope (Ruhl et al. 2004), the Atacama Pathfinder Experiment (Dobbs et al. 2006), and the Sunyaev-Zel’dovich Array (Loh et al. 2005), many of which will be coordinated to overlap with optical surveys. These advances are particularly important as less sensitive small-scale CMB surveys have already hinted at an excess of SZ distortions (Mason et al. 2003; Bond et al. 2005; Dawson et al. 2006; Kuo et al. 2007).

In this work we make use of the first large-scale cosmological hydrodynamical simulation to explicitly include AGN feedback (TSC06), to construct detailed maps of its imprint on the CMB. By analyzing these maps and comparing them with other observables, we are able to determine the most promising approaches to using these ongoing surveys to constrain AGN feedback. Previous studies of nongravitational heating on the SZ background focused on the impact of starburst winds at high redshifts (Majumdar et al. 2001; White et al. 2002) and signatures from Population III stars (Oh et al. 2003). Natarajan & Sigurdsson (1999), Yamada et al. (1999), Yamada & Fujita (2001), Lapi et al. (2003), Platania et al. (2002), and recently, Chatterjee & Kosowsky (2007) have made analytic estimates of the impact of quasar winds on the CMB power spectrum and the cross-correlation of the SZ effect with galaxy clusters and optical sources. While this manuscript was in press, Bhattacharya et al. (2007) used cosmological simulations to study the impact of AGN feedback on galaxy groups. Here we show directly from simulations that although basic quantifiers such as the power spectrum are difficult to interpret, approaches based on the cross-correlation of SZ distortions with optical observations will soon provide a clean and direct probe of AGN feedback.

The structure of this work is as follows. In §2 we describe our numerical simulations and the methods used to construct maps of the CMB distortions from the kinetic and thermal SZ effects. In §3 we compute the contribution of AGN outflows to the CMB power spectrum, calculate their impact on the regions surrounding individual galaxies and AGNs, and quantify the sensitivity of CMB-galaxy cross-correlations to AGN feedback. Our conclusions are summarized in §4.

2. METHOD

2.1. Simulations

In order to disentangle the signature of AGN feedback from SZ distortions that are due purely to gravitational heating, we made use of two simulations: the large AGN feedback simulation first presented in TSC06 (using 2 × 640³ particles), and a new smaller scale comparison simulation (using 2 × 320³ particles) in which structure formation, gas cooling, and star formation were tracked exactly as in the fiducial run, but no outflows were added. In both cases, on the basis of a wide range of cosmological constraints (e.g., Spergel et al. 2003; Vianna & Liddle 1996; Riess et al. 1998; Perlmutter et al. 1999), we adopted a cold dark matter cosmological model with the parameters ₘ = 0.7, ₐ = 0.3, ₐₐ = 0.7, ₗ = 0.046, ₚ = 0.9, and ₛ = 1, where ₘ is the Hubble constant in units of 100 km s⁻¹ Mpc⁻¹; ₐ, ₐₐ, and ₗ are the total matter, vacuum, and baryonic densities, in units of the critical density; ₚ is the variance of linear fluctuations on the 8 h⁻¹ Mpc scale; and ₛ is the “tilt” of the primordial power spectrum. Note that these parameters are slightly different than those preferred by the more recent WMAP data (Spergel et al. 2007), which were released after our large AGN feedback run had already been completed. Initial conditions were computed using the Eisenstein & Hu (1999) transfer function.

In both runs, as in our previous work (e.g., Scannapieco et al. 2001), simulations were conducted with a parallel OpenMP-based implementation of the HYDRA code (Thacker & Couchman 2006), which uses the adaptive particle-particle, particle-mesh algorithm to calculate gravitational forces (Couchman 1991) and the smooth particle hydrodynamic (SPH) method to calculate gas forces (Lucy 1977; Gingold & Monaghan 1977). As the details of this code and our outflow implementation are described in detail elsewhere (Scannapieco et al. 2001; TSC06), here we only summarize the aspects most relevant to the SZ effect.

As our study is targeted to relatively large and late-forming structures, for both runs we have kept the metallicity constant at Z = 0.05, in order to mimic a moderate level of enrichment. Similarly, because the epoch of reionization is poorly known and because reionization has little impact on mass scales greater than 10⁹ M⊙ (Barkana & Loeb 1999), we did not include a photoionization background in either simulation. In our AGN feedback run, which was designed to cover a large range in the
AGN luminosity function, we used a simulation box of size 146 \, h^{-1} \, \text{comoving Mpc} on a side that was filled with $2 \times 640^3$ particles, which corresponded to a dark matter particle mass of $1.9 \times 10^8 \, M_\odot$ and a gas particle mass of $2.7 \times 10^7 \, M_\odot$. Our comparison simulation, which was carried out purely for the purposes of the current study, used $320^3$ particles in a box measuring $73 \, h^{-1} \, \text{comoving Mpc}$ on a side, corresponding to the same particle masses as in the AGN run. Both runs were terminated at $z = 1.2$, at which point integration became expensive and impractical in a shared-queue environment, due to the single-stepping nature of HYDRA. This means that our results do not contain the SZ contribution from lower redshifts, during which most galaxy clusters are formed. However, as $z = 1.2$ is well past the peak epoch of AGN activity (e.g., Ueda et al. 2003; Barger et al. 2005), our results do well at quantifying the AGN contribution to the SZ effect, which is our main focus here.

As in TSC06, bright quasar-phase AGNs are associated with galaxy mergers, which are tracked by labeling gas particles and identifying new groups in which at least 30% of the accreted mass does not come from a single massive progenitor. Once a merger has been identified, we compute the mass of the associated supermassive black hole, $M_{\text{BH}}$, from the circular velocity of the remnant, $v_c$, using the observed $M_{\text{BH}}$-$v_c$ relation (Merrit & Ferrarese 2001; Tremaine et al. 2002; Ferrarese 2002), which gives

$$M_{\text{BH}} = 2.8 \times 10^8 \left( \frac{v_c}{300 \, \text{km} \, \text{s}^{-1}} \right)^5. \quad (1)$$

Here $v_c$ is estimated as

$$v_c = \left[ \frac{4\pi}{3} G \rho_v(z) r_v \right]^{1/2}, \quad (2)$$

where $G$ is the gravitational constant, $\rho_v(z)$ is the virial density as a function of redshift, and $r_v$ is the implied virial radius for a group of $N$ gas particles with mass $m_g$:

$$r_v = \left[ \frac{Nm_g \Omega_0 / \Omega_b}{(4/3) \pi \rho_v(z)} \right]^{1/3}. \quad (3)$$

Following Wyithe & Loeb (2002) and Scannapieco & Oh (2004), we assume that for each merger the accreting black hole shines at its Eddington luminosity ($1.2 \times 10^{38} \, \text{ergs} \, s^{-1} \, M_\odot^{-1}$) for a time that is taken to be a fixed fraction, 0.055, of the dynamical time of the system, $t_{\text{AGN}} = 0.055 r_v/v_c = 5.8 \times 10^{-3} \Omega(z)^{-1/2} H(z)^{-1}$. In TSC06 it was demonstrated that, apart from a discrepancy for the very luminous end, this simple model does extremely well at reproducing the observed AGN luminosity function, as well as the large- and small-scale clustering of AGNs over the full range of simulated redshifts. Furthermore, the discrepancy at the very luminous end for the simulation as compared to the semianalytic model could be attributed to the relative efficiency of shock heating on substructure (e.g., see Agertz et al. [2007] for a discussion of numerical "stripping" issues). Note that our approach does not distinguish between AGNs formed in gas-rich "wet" mergers and in gas-poor "dry" mergers, nor can we do so, given our simple burst model for star formation, which becomes progressively less accurate at lower redshifts, at which point the quiescent mode of star formation dominates. Unlike at $z = 0$, however (e.g., Bell et al. 2006), dry mergers are likely to be relatively unimportant at the $z \geq 1.2$ redshifts that we are studying.

For example, the semianalytic estimates in Figure 5 of Hopkins et al. (2008) show that the ratio of gas-rich to gas-poor $4 \times 10^{12} \, M_\odot$ mergers ranges from $10:1$ at $z = 2$ to $2:1$ at $z = 1$, indicating that gas-poor mergers are relatively unimportant above our final redshift of $z = 1.2$.

In our fiducial run, we assume that a fixed fraction $\epsilon_k = 0.05$ of the bolometric energy of each AGN is channeled into a kinetic outflow, and the remainder is emitted as light. This value is consistent with other estimates from the literature (e.g., Furlanetto & Loeb 2001; Nath & Roychowdhury 2002), as well as observations (Chartas et al. 2007). Energy input from stars can be estimated in galaxy clusters from the total metallicity, which provides a rough count of the total number of massive stars formed. Even if one assumes that all the kinetic energy from supernovae and stellar winds is deposited directly into the ICM with no radiative losses, it is still difficult to match the energy that is necessary for cluster preheating. For more realistic models, the energy falls short of cluster preheating by roughly an order of magnitude (e.g., Kravtsov & Yepes 2000; Tozzi et al. 2000; Brighenti & Mathews 2001; Babul et al. 2002; Tornatore et al. 2004) and is likely to be greatly exceeded by AGN feedback from large, forming bulges.

Each of our AGN outflows is launched with an energy input of

$$E_k = 6 \times 10^{56} \frac{M_{\text{BH}} t_{\text{AGN}}}{M_\odot} \, \text{ergs}. \quad (4)$$

Given the uncertainties surrounding AGN outflows, we simply model each expanding outflow as a spherical shell at a radius of $2r_v$, which is constructed by rearranging all the gas that is within this radius, but outside $r_v$, and below a density threshold of 2.5$\rho_\odot$. Finally, the radial velocity $v_r$ and the postshock temperature $T_s$ of the shell are determined by fixing $T_s = (13.6 \, K)(v_r/(1 \, \text{km} \, \text{s}^{-1}))^2$, and choosing $v_r$ such that the sum of the thermal and kinetic energies of the shell equals $E_k$ minus the energy used to move particles from their initial positions into the shell. As shown in TSC06, this prescription results in a level of preheating in galaxy clusters and groups that is in good agreement with observations.

In Figure 1, we show the mass-averaged gas temperature in our AGN feedback (solid line) and comparison (dashed line) runs. [See the electronic edition of the Journal for a color version of this figure.]
2.2. Construction of SZ Maps

As the thermal and kinetic SZ effects have different frequency distributions, we calculate each of them separately from our simulations. In the (nonrelativistic) thermal SZ case, the change in the temperature of the CMB as a function of frequency is given by

\[
\frac{\Delta T}{T} = y\left(\frac{e^x + 1}{e^x - 1} - 4\right),
\]

where \(x = h\nu/kT_{\text{CMB}}\) is the dimensionless frequency and the Compton \(y\) parameter is defined as

\[
y \equiv \sigma_T \int dl \, n_e \frac{k(T_e - T_{\text{CMB}})}{m_e c^2},
\]

where \(\sigma_T\) is the Thompson cross section, \(m_e\) is the electron mass, \(n_e\) is the density of the electrons, \(T_e\) is the electron temperature, \(T_{\text{CMB}}\) is again the temperature of the CMB, and the integral is performed over the proper distance along the line of sight. Note that \(y\) is simply a rescaled version of the line-of-sight integral of the pressure. Note also that in the Rayleigh-Jeans limit, in which \(x \ll 1\), equation (5) reduces to \(-2y\), and we focus on this limit throughout our discussion below.

For the kinetic SZ effect, on the other hand, the magnitude of the CMB distortions is frequency-independent, and \(\Delta T/T = -b\). In this case, \(b\) is given by

\[
b \equiv \sigma_T \int dl \, n_e \frac{v_r c}{\rho_i},
\]

where \(v_r\) is the radial peculiar velocity of the gas, and the integral is again performed along the line of sight. In the very largest clusters there are relatively minor corrections to equations (6) and (7) due to relativistic effects, which can safely be ignored for our purposes here (e.g., Rephaeli 1995; Itoh et al. 1998; Nozawa et al. 2006).

To construct maps of these distortions from our simulations, we followed a method similar to those of da Silva et al. (2000) and Springel et al. (2001). For each simulation output, we smoothed the density, temperature, and velocity fields onto a cubic grid. The smoothing procedure used the standard SPH smoothing methodology, in which cells at a distance \(|r_{\text{cell}} - r_i|\) from a particle \(i\) are incremented by

\[
A_{\text{cell}} \equiv \frac{1}{w_{n_i}} \frac{A_i}{\rho_i} m_i W(|r_{\text{cell}} - r_i|, h_i),
\]

where \(A_i\) is the scalar field value for particle \(i\), \(\rho_i\) is the density of particle \(i\), \(W\) is the B2-spline kernel, and \(w_{n_i}\) is a normalization factor. The smoothing process generalizes in the natural fashion for vector fields. The normalization factor is required to ensure that the weighting of the assigned kernel is correct when summed across a finite number of cells (the standard kernel definition normalizes to unity over a continuous spherical volume of radius \(2h_i\)). If a particle is smoothed over \(n_{\text{cell}}\) cells within a spherical volume specified by the radius \(2h_i\), then \(w_{n_i}\) is given by

\[
w_{n_i} = \sum_{k=1}^{n_{\text{cell}}} W(|r_{\text{cell}_k} - r_i|, h_i),
\]

where we have used \(k\) to indicate that the summation is over cells, rather than over particles.

![Fig. 2.—Top: Evolution of the average Compton \(y\) parameter as a function of redshift for the AGN feedback run (solid line) and the comparison run (dashed line). In this panel, and in all panels in this figure, we show the total signal integrated down from \(z = 10\) to the \(z\)-value displayed on the \(x\)-axis. Middle: Total rms value of \(\Delta T/T - \langle\Delta T/T\rangle\) from the thermal SZ effect, integrated down from \(z = 10\) to the \(z\)-value on the \(x\)-axis. This is calculated by subtracting the overall mean value of \(\Delta T/T\) from the map and computing the rms pixel scatter of the remainder. The thick lines are as in the top panel, and the thin solid (AGN feedback) and dashed (comparison run) lines correspond to grouping pixels into \(16 \times 16\) 1′ × 1′ bins before computing the variance. Bottom: Total rms value of \(\Delta T/T\) from the kinetic SZ effect as a function of redshift, with lines as in the middle panel. [See the electronic edition of the Journal for a color version of this figure.]

Once the smoothed grid had been constructed, it was projected in the \(x\), \(y\), and \(z\)-directions. Since projection amounts to a summation along each axis direction, the smoothing process could potentially have been performed in two dimensions alone. However, we projected the three-dimensional grid to ensure that the integration in the projection axis accounted for the quantization effects associated with smoothing onto a fixed number of cells. Next we constructed two grids spanning a square patch of sky, measuring 1.1° on a side and made up of 1024² rays in the fiducial run and 0.55° on a side and made up of 512² rays in the comparison run, such that in both cases the full simulation subtended an angle equal to the field at our highest redshift output of \(z = 10\). Finally, we projected along each of our sight lines, choosing a random translation and orientation at every redshift, and weighting the slices according to equations (6) and (7).

3. RESULTS

3.1. Overall Properties

In Figure 2, we study which redshifts contribute most to the SZ effect by integrating the total signal from \(z = 10\) (our assumed redshift of reionization) down to various redshifts. From equation (6), the change in the average Compton \(y\) distortion per unit \(dl\) is proportional to the mass-averaged temperature. Thus, as is consistent with the temperature evolution shown in Figure 1, \(\langle y\rangle\) is roughly 50% higher in the AGN feedback run at all redshifts.

Yet the average SZ distortion is not the most easily detectable quantity. Rather, the majority of CMB measurements are differential in nature and are sensitive to small changes on top of an overall background that is much less well measured. To quantify these differences, we plot the rms pixel scatter in \(\Delta T/T - \langle\Delta T/T\rangle\)
due to the thermal SZ effect in the middle panel of Figure 2, and that due to the kinetic SZ (kSZ) effect in the bottom panel of this figure. Here $\langle \Delta T / T \rangle$ is the average overall CMB spectral distortion, which is nonzero only in the thermal SZ case. For both the thermal SZ and kSZ effects, the changes in the amplitude of $\Delta T / T - \langle \Delta T / T \rangle$ indicate that AGNs have a minor impact on the overall variance of the temperature and velocity. Note also that the rms scatter from the thermal SZ effect, which is dominated by adding sources on top of an otherwise smooth background, is still significantly increasing in strength down to $z = 1.2$ and is likely to continue increasing down to $z = 0$. In fact, Roncarelli et al. (2007), in their Figure 6, show that about 40% of the value of $\Delta T / T$ from the thermal SZ effect is accumulated below $z = 1.2$. On the other hand, the value of $\Delta T / T$ in the kSZ case grows very slowly at low redshift, and it would not be not likely to change much if we were able to integrate down to $z = 0$.

Finally, in Figure 2 we also show the rms scatter in $\Delta T / T - \langle \Delta T / T \rangle$ in the case in which we bin our pixels into $16 \times 16$ groups of roughly $1''$ on a side, which corresponds more closely to the resolution of the upcoming generation of microwave telescopes. This smoothing has the largest impact on the kSZ effect, especially in the comparison run, indicating that much of the scatter in this case comes from the very smallest scales, as will be discussed in more detail in §3.2.

In Figure 3 we directly compare maps of the thermal SZ distortions from both runs, integrated down to our final simulation redshift of $z = 1.2$. The maps clearly indicate a lack of small hot regions in the AGN feedback run relative to the comparison run. To help bring out the structure in these maps, we also plot the same data on a logarithmic scale in Figure 4. Here we see that the AGN feedback run has a higher average level of distortions, consistent with the $\langle y \rangle$ evolution in Figure 2. Furthermore, although it is difficult to ascertain the overall level of the variance between the maps, it is clear that the scale of the structures is quite different. In particular, although the AGN feedback simulation has fewer small pockets of hot gas, these are compensated by a number of larger and more diffuse heated regions. On the other hand, the kinetic SZ maps from the two simulations were indistinguishable by eye and are suitable only for analysis with a more detailed, quantitative approach.

3.2. Power Spectrum

3.2.1. Results from Simulated Maps

The most common measure of CMB fluctuations is the angular power spectrum, which is obtained by decomposing the temperature distribution on the sky into spherical harmonics, $\Delta T / T (\mathbf{\hat{n}}) = \sum_{l,m} a_{l,m} Y_{l,m}(\mathbf{\hat{n}})$, and carrying out an average over the coefficients, $C_\ell = (2\ell + 1)^{-1} \sum_{m=-\ell}^{\ell} a_{l,m} a_{l,-m}^\ast$, where the asterisk denotes a complex conjugate. For a small field of view, as is the case for our constructed map, this is equivalent to performing a Fourier transform to obtain

$$\frac{\Delta T}{T}(\kappa) = \int d^2\theta \exp(-i\kappa \cdot \theta) \frac{\Delta T}{T}(\theta),$$

(10)

where $\theta$ and $\kappa$ are two-dimensional vectors in the plane of the sky, and then carrying out an azimuthal average to obtain

$$C_\ell = P_{\text{ang}}(\kappa = \ell) = \frac{1}{2\pi} \int d\phi \frac{\Delta T}{T}(\kappa, \phi) \frac{\Delta T}{T}(\kappa, \phi),$$

(11)

where $\kappa = (\kappa \cos \phi, \kappa \sin \phi)$. Finally, as an additional check, one can use the fact that the mean squared temperature variance is equal to $\sum_{\ell}(2\ell + 1)C_\ell/(4\pi)$.

In Figure 5 we plot the angular power spectrum from our AGN feedback and comparison simulations, averaging over 16 realizations of the maps: $4.4'' \times 4.4''$ in the AGN feedback case.
Fig. 5—Top: Power spectrum of the thermal SZ distortions in the AGN feedback run (thick solid line) and the comparison run (thick dashed line), integrated down to \( z = 1.2 \). The band surrounding the AGN feedback results quantifies the sample variance by comparing quadrants, as discussed in the text. The open squares represent measurements by the CBI experiment (Bond et al. 2005), the filled circles represent measurements by the ACBAR experiment (Kuo et al. 2007), and the stars represent measurements from the BIMA CMB Anisotropy Survey (Dawson et al. 2006). These are plotted around the primary anisotropy signal (dotted line). The dot-dashed lines show the level of anisotropies detectable by an experiment spanning a 20' × 20' area with a \( \theta_{\text{FWHM}} = 2' \) beam with a noise level of (10 \( \mu K \))^2 per arcmin^2 (upper line), and with a \( \theta_{\text{FWHM}} = 1' \) with a noise level of (2 \( \mu K \))^2 per arcmin^2 (lower line). Bottom: Power spectrum from the kinetic SZ distortions in the AGN feedback run (thick solid line) and the comparison run (thick dashed line), integrated down to \( z = 1.2 \). Again, the band surrounding the solid line gives the variance between quadrants. The symbols and dot-dashed lines are as in the top panel. [See the electronic edition of the Journal for a color version of this figure.]

and 2.2' × 2.2' in the comparison case. As we expected from a visual inspection of Figures 3 and 4, AGN feedback has a clear impact on the thermal SZ signal, smoothing the structures at the smallest scales (\( \ell \geq 10^4 \)), while at the same time adding large heated regions that increase the overall fluctuations at larger scales (\( \ell \leq 10^3 \)). On the other hand, AGN feedback has only a weak impact on the kinetic SZ effect, slightly smoothing the smallest structures, without having a noticeable impact on larger scales. To some extent, the lack of this large-scale signal may be due to our choice of initially spherical outflows, which should not significantly add to the total integrated column of material moving toward or away from the observer along any line of sight. If outflows were extremely asymmetric, however, according to equations (6) and (7), the ratio of the distortions in the kinetic to the thermal SZ effects would go as

\[
\frac{b}{y} \approx \frac{v/c}{kT/m_{\text{e}}^2} \approx \frac{m_\gamma}{m_\nu (v/c)}. \tag{12}
\]

For a typical outflow velocity of \( v \approx 1000 \text{ km s}^{-1} \), this gives a value of \( b/y \approx 1/6 \), such that even in this extreme case, the increase in \( C_\ell \) due to the kinetic SZ effect would be at least 30 times smaller than the thermal signal.

As our comparison simulation spans a smaller volume than the fiducial AGN-feedback simulation, we also include in this figure a simple estimate of sample variance. We have divided our 16 QSO-feedback realizations into quadrants, each of which is the size of the maps that we generated from the comparison simulation. We then calculated the \( C_\ell \)-values from the thermal SZ and kSZ effects for each quadrant separately, yielding a range of values that surrounds the solid lines. In the case of the thermal SZ effect, the sample variance caused the values of \( C_\ell \) to change by roughly \( \pm 25\% \), which is much less than the differences between the feedback and comparison models. In the kSZ case, which is dominated by smaller scales and hence better sampled, the differences were less than \( \pm 10\% \).

Thus, while the differences between the two simulations are statistically significant, the increase in the large-scale angular power spectrum is not dramatic, even in the thermal case. For comparison, in Figure 5 we have also plotted the primary CMB signal, as well as a summary of recent measurements from the CBI and ACBAR experiments. From these points it is clear that the secondary anisotropies seen in current experiments are not likely to have been imprinted by SZ distortions at \( z \geq 1.2 \), nor does the possible excess of small-scale power seen in the CBI experiment (see, however, Kuo et al. 2007) appear to be related to AGN feedback.

3.2.2. Required Sensitivity and Resolution to Detect AGN Distortions

In the near future, however, the increase in the angular power spectrum that is due to AGN feedback will be well within the range of experiments. To calculate these sensitivities, we make use of the simple estimate from Jungman et al. (1996), which gives the rms noise at a multipole \( \ell \) as

\[
\sigma_\ell = \left[ \frac{2}{(2\ell + 1)f_{\text{sky}}} \right]^{1/2} \left[ C_\ell + (w_{\text{sky}})^{-1} \ell^2 \sigma_\ell^2 \right], \tag{13}
\]

where \( w \equiv (\sigma_{\text{pix}}\theta_{\text{FWHM}})^2 \) is the weight per solid angle, a pixel-size-independent measure of the noise that is calculated from the full width at half-maximum of the Gaussian beam, \( \theta_{\text{FWHM}} \), and the noise variance per \( \theta_{\text{FWHM}} \times \theta_{\text{FWHM}} \) pixel, \( \sigma_{\text{pix}}^2 \). Finally, \( \sigma_{\ell} = (7.42 \times 10^{-3})\theta_{\text{FWHM}} \) is a measure of the beam size and \( f_{\text{sky}} \) is the fraction of the sky covered.

Comparing these measurements with the \( C_\ell \)-values from our simulations, we see that the excess due to AGN feedback is easily measurable by an experiment with a typical full width at half-maximum beam size of \( \theta_{\text{FWHM}} = 1' \) and a noise level of about (2 \( \mu K \))^2 per arcmin^2, scanning over a 20' × 20' patch of the sky. However, the most convincing constraints on AGN feedback are not likely to come from statistical constraints derived purely from the microwave background.

3.3. Cross-Correlations

Unlike the primary microwave background signal, the SZ distortions are not well described by Gaussian random fields. Rather, they contain a wealth of information beyond the angular power spectrum. In fact, as is particularly clear from Figures 3 and 4, the thermal SZ distribution is much more reminiscent of lower redshift galaxy surveys than \( z \approx 1000 \) measurements. Furthermore, the structures seen in these maps are in fact imprinted by galaxy activity, meaning that they are strongly correlated with the positions of sources in large-field optical and infrared surveys. With this in mind, we considered the cross-correlation of our maps with three types of optical sources:

1. Quasars, which are identified as newly formed black holes that shine for \( t_d = 0.055r/v_c \) of the dynamical time of the system (as in § 2.1).
2. Poststarburst elliptical (E+A) galaxies, which are identified as mergers observed within 200 Myr of coalescence.
3. *Elliptical galaxies*, which are identified as mergers observed at any time after coalescence.

In Figure 6 we show the results of co-adding the thermal SZ distortions around each of these objects as selected in a $2.2\,\text{arcmin} \times 2.2\,\text{arcmin}$ region, made up of 4 maps in the AGN feedback run and 16 maps in the comparison run. The most obvious feature in this plot is the overall higher level of the SZ background in the AGN feedback run, a feature that is difficult to observe directly, as is discussed in § 2.1. Beyond this overall offset, however, these images also uncover a substantial "halo" of SZ distortions, which is much higher in amplitude and more spatially extended in the AGN feedback case. While this excess is somewhat lost in the noise for the quasars, which are the rarest sources, it is clearly and dramatically present in the co-added maps of the much more numerous E+A and elliptical galaxies. As we expected from our discussion above, constructing similar co-added images of the kSZ effect yielded differences that were at least an order of magnitude smaller.

To further study the detectability of the much more promising thermal signal, we processed each of the images in Figure 6 in a manner similar to the way in which one might work with real data sets in the near future. First, we shifted each of them by the offset between the AGN feedback and comparison cases. Next, for the impact of AGN outflows is well above the noise for all sources, even if $\theta_{\text{FWHM}} = 2'$ and $\sigma_{\text{pix}}^2 = (10 \, \mu\text{K})^2$ per arcmin$^2$ (cross-hatched regions) and as $(2 \, \mu\text{K})^2$ per arcmin$^2$ (filled regions).

The impact of AGN outflows is well above the noise for all sources, even if $\theta_{\text{FWHM}} = 2'$ and $\sigma_{\text{pix}}^2 = (10 \, \mu\text{K})^2$ per arcmin$^2$. However, in most cases, the profile of the SZ signal above the noise is indistinguishable from that of a point source (which would appear on this plot as an inverted parabola that drops by a factor of 2 at a distance of $\theta_{\text{FWHM}}/2$). At the same time, quasars themselves are often significant microwave point sources. To estimate this intrinsic contribution, we convert the flux per unit frequency, $F_\nu$, to CMB temperature units as

$$
\Delta T = \left(\frac{dB_\nu}{dT}\right)^{-1} \frac{F_\nu}{\theta_{\text{FWHM}}} = \frac{1 \, \mu\text{K}}{0.0084 \, \text{mJy}} \left(\frac{1}{\theta_{\text{FWHM}}}\right)^2 F_\nu \frac{(e^x - 1)^2}{x^2e^x},
$$

where $\theta_{\text{FWHM}} = 2'$ and $\sigma_{\text{pix}}^2 = (10 \, \mu\text{K})^2$ per arcmin$^2$. However, in most cases, the profile of the SZ signal above the noise is indistinguishable from that of a point source (which would appear on this plot as an inverted parabola that drops by a factor of 2 at a distance of $\theta_{\text{FWHM}}/2$). At the same time, quasars themselves are often significant microwave point sources. To estimate this intrinsic contribution, we convert the flux per unit frequency, $F_\nu$, to CMB temperature units as

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$$

where $\theta_{\text{FWHM}}$ is the 1.17/1024 = 0.0644 arcmin$^2$ pixel size of our maps, $N_{\text{src}}$ is the number of sources that would be found in a $20' \times 20'$ region of the sky, and the pixel noise level, $\sigma_{\text{pix}}$, is again estimated as $(10 \, \mu\text{K})^2$ per arcmin$^2$ (cross-hatched regions) and as $(2 \, \mu\text{K})^2$ per arcmin$^2$ (filled regions).
where $B_\nu$ is the Planck function and, as in equation (5), $x \equiv h\nu/kT_{\text{CMB}}$ (Scott & White 1999). The ratio of $\nu L_\nu$ at microwave wavelengths to the quasar’s bolometric luminosity is $\approx 1000$ for “radio-loud” objects, which make up about 10% of the population, and several orders of magnitude less for radio-quiet objects (Elvis et al. 1994). If we estimate a typical comoving distance to a quasar as $\approx 3000$ Mpc $h^{-1}$ and consider a typical observing frequency of 100 GHz, this gives

$$\Delta T \approx \frac{M_{\text{BH}}}{10^6 M_\odot} \left( \frac{1'}{\theta_{\text{FWHM}}} \right)^2 \mu K,$$

which is much larger than the thermal SZ signal.

While this value can be reduced substantially by selecting radio-quiet quasars, a better approach is to work with objects that were observed at later times after the merger. In Figure 8 we show the azimuthally averaged excess thermal SZ contribution around poststarburst galaxies, identified as mergers observed after the quasar phase, but within 200 Myr after coalescence. Here we have converted each black hole mass to its corresponding bulge dynamical mass using a factor of $400$, as obtained from the analysis in Marconi & Hunt (2003). Working with these sources has two main advantages. First, as they are much more common, one can consider slightly larger bulges and hence larger and more spatially extended SZ distortions, while at the same time improving the number of sources that can be co-added in a fixed region of the sky. Furthermore, as the nuclear luminosities are typically more than 100 times lower during this phase (e.g., Hopkins et al. 2008), point-source subtraction is much easier, although some exclusion of radio-loud sources may still be necessary.

In Figure 9 we show the SZ contribution obtained by co-adding all bulges observed at any time after the initial quasar phase. Again we have converted black hole mass into bulge dynamical mass, as well as into overall $B$-band luminosity, following observed relations (Marconi & Hunt 2003). Extending our analysis in this way has only a weak impact on the SZ profile, while at the same time improving the statistics even further. In this case the complete spatial profiles of the sources are observable.
with more than 10σ precision out to very large radii, clearly tracing out the impact of AGN feedback. Note that these sources are relatively easy to detect, as even given a typical luminosity distance of 10^4 Mpc, they are readily observed by a photometric survey with an overall magnitude limit of m_B \sim 22.

Background contributions from dust emission in elliptical galaxies are also expected to fall below the levels necessary to affect these measurements. In a far-infrared (FIR) Spitzer survey of nearby elliptical galaxies, Temi et al. (2007) quantified such emission from warm diffuse dust at 70 and 160 μm in a large sample of elliptical galaxies with distances of \sim 100 Mpc and masses up to \sim 10^{12} M_\odot. In all cases, L_{160 μm} was less than 10^{42} ergs s\(^{-1}\), and colors were consistent with the peak of the dust emission being shortward of 160 μm. Again, if we take a typical comoving distance of 3000 Mpc h\(^{-1}\) for the elliptical galaxies from our simulation, this gives a value of 0.024 mJy at 160 μm. Finally, if we interpolate down to 100 GHz in the Rayleigh-Jeans limit, this is \sim 6 \times 10^{-5} mJy, or 0.003 μK. This is roughly 2 orders of magnitude smaller than the SZ signal that is expected for 10^{12} M_\odot bulges, and it should appear as a increment rather than as an SZ decrement. Thus, dust contamination is unlikely to be a problem, but it is nevertheless important enough to be kept in mind. Any conclusive measurement should examine the spectral signature of distortions around bulges, and ideally it should include FIR follow-up measurements if possible.

Finally, the level of thermal y distortions observed by co-adding around bulges is a precise and linear measure of the most important quantity for modeling the impact of AGN outflows on galaxy formation. Integrating equation (6) over a patch of sky around a source, we have

\[ \int dθ_y(θ) = \frac{σ_τ}{m_e c^2} \frac{1}{l_{\text{ang}}^2} \int dV n_e(V) k[T_e(V) - T_{\text{CMB}}], \]  

(17)

where l_{\text{ang}} is the angular diameter distance to the source, θ is a vector in the plane of the sky in units of radians, and the volume integral is performed over the heated region around the source. But this integral is simply \((2/3)E_{\text{Brem}}(1 + A)/(2 + A)\), where A = 0.08 is the cosmological number abundance of helium. The line-of-sight integral of the pressure has thus been transformed into a

![Diagram of average excess thermal SZ distortions around poststarburst (E+A) galaxies in our simulations, observed within 200 Myr of a merger. As there are many more of these galaxies than there are quasars, we select slightly larger objects in this figure than in Fig. 7. Thus, from top to bottom, the panels correspond to black hole masses of 1 × 10^10, 3 × 10^9, and 1 × 10^8 M_\odot (marked on the left panels), or equivalent bulge dynamical masses of 4 × 10^{12}, 1 × 10^{12}, and 4 × 10^{11} M_\odot (marked on the right panels). Otherwise the panels, lines, and shaded regions are the same as in Fig. 7. Thus, the left panels show distortions as observed with a θ_{FWHM} = 1' beam; the thick solid (AGN feedback) and dashed (comparison) lines show the average value of the SZ distortions averaged over all sources in a 2.2' × 2.2' region of the sky, bracketed by the maximum and minimum signal in 1.1' × 1.1' quadrants; and the shaded regions show the noise levels attainable by averaging over 20' × 20', with instrument noise as specified in Fig. 7. [See the electronic edition of the Journal for a color version of this figure.]
volume integral of the pressure. This means that by integrating the Compton distortions over the sky, we can directly measure the thermal energy added to the IGM for each object. If we re-write equation (17) in terms of angles in units of arcminutes and the low-frequency microwave background distortions in units of $\mu K$, this becomes

$$E_{\text{thrm}} = -4.8 \times 10^{60} \text{ergs} \frac{\Delta T(\theta)}{\mu K \text{arcmin}^2},$$  

(18)

where $\Delta T(\theta)$ is the angular distance in units of 3000 Mpc and $E_{\text{thrm}}$ is the total excess thermal energy associated with the source, which is the thermal energy gained from the initial collapse of the baryons, plus the contribution from the AGN, minus the losses due to cooling and the $PdV$ work done during expansion.

3.4. Measuring AGN Feedback

When we put these results together, a clear and direct way to constrain AGN feedback presents itself. This can be summarized as follows:

1. Obtain SZ data with 1' or 2' resolution at a noise level of a few $\mu K$ per arcmin$^2$ in a $\approx 400$ deg$^2$ patch of the sky in which near-infrared or optical photometry is available to a moderately deep magnitude limit (such as $m_B \approx 22$).

2. Select all quiescent early-type galaxies with photometric redshifts in the essential $z = 1$–3 redshift range for AGN feedback. Alternatively, if sufficiently good photometry is available, one can also study the subset of poststarburst ($E+A$) galaxies.

3. If possible, use radio and FIR observations to reject point sources and dust that may contaminate the thermal SZ signal.

4. Compute the excess thermal SZ signal summed within a $\approx 2'$ radius around each source, and use this to compute the total thermal energy as per equation (18). Carefully examine the spectral signature of these distortions as a further check of contamination.

5. Bin the results as a function of bulge mass, and average over each bin to compute the total average IGM thermal energy input associated with bulges as a function of mass.

The results of carrying out this procedure over $2.2'' \times 2.2''$ of the sky calculated from our simulations are shown in Figure 10. Here we have grouped all bulges in logarithmic bins of dynamical mass with widths of 0.25, again taking a fixed ration of 400 between $M_{\text{bulge}}$ and $M_{\text{BH}}$. To calculate the uncertainty in each bin, we have accounted for both Poisson noise and intrinsic scatter, taking $\sigma_{\text{bin}}(E_{\text{thrm}}) = \left[E_{\text{thrm,bin}} + \sigma_{\text{arc}}(E_{\text{thrm}})\right](N_{\text{bin}})^{-1/2},$

![Figure 9](image-url)
where \( E_{\text{thrm,bin}} \) is the average thermal energy in a given bin, \( \sigma_{\text{arc}}(E_{\text{thrm}}) \) is the rms scatter between sources in a given bin, and we computed \( N_{\text{bin}} \) conservatively as the number of sources in a given bin relative to a single realization of the map (1/4 of the 2.2' \times 2.2' region in the AGN feedback run and 1/16 of this region in the comparison run).

At both high and low redshifts the AGN feedback run shows a clear excess, which scales linearly with \( M_{\text{bulge}} \) as expected from equation (4). For comparison, we use this equation to plot the energy added to the IGM as a function of bulge dynamical mass. Since kinetic energy is converted into thermal energy as the outflows accrete material, and since radiative losses are small for these objects (e.g., Oh & Benson 2003; Scannapieco & Oh 2004), we expect that most of this energy should be observable as \( E_{\text{thrm}} \). In fact, Figure 10 shows that at both low and high redshifts, the thermal SZ excess closely traces this energy input as a function of bulge dynamical mass. Thus, AGN feedback is not only detectable by the SZ effect, but the level of this feedback as a function of mass can also be obtained directly from SZ measurements.

Finally, in Figure 11, we plot \( E_{\text{thrm}} \) for the poststarburst galaxies in our simulations. As there are fewer of these objects, this results in a higher overall scatter than in the case of all bulges, but the results are otherwise similar and consistent with the level of excess energy added to the AGN feedback run. While this is to be expected, given the instantaneous and impulsive nature of the outflows in our simulation, observations and comparisons of poststarburst galaxies with other elliptical galaxies may nevertheless help to distinguish this type of feedback from more gradual AGN heating, as is suggested, for example, in Croton et al. (2006).

4. CONCLUSIONS

Microwave background measurements have played a key role throughout the development of cosmology: establishing the modern inflationary model, constraining the initial conditions for structure formation, and providing precise measurements of cosmological parameters. Yet at smaller scales, the potential of CMB measurements is largely untapped.

At the same time, detailed observations at lower redshifts have uncovered the central importance of nongravitational heating, which is likely to be associated with outflows from AGNs. Although the details of this process remain uncertain, we have shown, using a suite of large numerical simulations, that the key observations that constrain this process may once again come from the microwave background. While AGN outflows impact the CMB both through their peculiar motions and through IGM heating, it is the thermal SZ signal that provides the most detailed measurements. By working purely with CMB observations, AGN feedback can be constrained both through a difficult-to-measure overall offset in the frequency spectrum and through a more easily detected shift in CMB anisotropies from \( \approx 0.1' \) to \( \approx 1' \) scales.

Although changes in the angular power spectrum from this shift will be marginally detectable with the upcoming generation of small-scale microwave telescopes, the true test of AGN feedback will come from the cross-correlation of these data with infrared and optical surveys. In particular, co-adding the CMB signal around quasars, poststarburst galaxies, and quiescent elliptical galaxies from our simulations shows a systematic “halo” of SZ distortions around each of these objects, which is much higher in amplitude and more spatially extended in the AGN feedback case. Also, although contamination from point-source emission makes quasars difficult to work with, the excess signal is clearly detectable for both E+A and older elliptical galaxies, which can be selected with only moderately deep \( m_B \approx 22 \) photometry.

Furthermore, as the thermal SZ effect is proportional to the line-of-sight integral of the pressure, summing up the excess distortion in a patch of sky around each type of source provides a sensitive and direct measure of the thermal energy associated...
with feedback. In fact, by carrying out this procedure on our simulation, we have shown that we can easily recover not only the overall level of AGN feedback, but also its dependence on galaxy mass, redshift, and galaxy type. Although it provides a popular and elegant solution to many outstanding problems, the impact of IGM heating by AGN outflows remains perhaps the most uncertain issue in galaxy formation. Together with large-field optical surveys, small-scale CMB experiments will soon be able to place strong constraints on this missing piece of our physical understanding of the history of the universe.

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