POINT SOURCES IN THE CONTEXT OF FUTURE SZ SURVEYS

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ABSTRACT

We look at the impact of infrared (IR) and radio point sources on upcoming large-yield Sunyaev-Zel’dovich (SZ) cluster surveys such as those to be undertaken by the Atacama Pathfinder Experiment (APEX), the South Pole Telescope (SPT), and the Atacama Cosmology Telescope (ACT). The IR and radio point-source counts are based on observations by the Submillimeter Common-User Bolometric Array (SCUBA) and the Wilkinson Microwave Anisotropy Probe (WMAP) instruments, respectively. We show that the contributions from IR-source counts, when extrapolated from the SCUBA frequency of 350 GHz to the operating frequencies of these surveys (~100–300 GHz), can be a significant source of additional noise, which needs to be accounted for in order to extract the optimal science from these surveys. These surveys give us an opportunity to study IR sources, their numbers and clustering properties, opening a new window to the high-redshift universe. For the radio point sources, the contribution depends on a more uncertain extrapolation from 40 GHz, but is comparable to the IR near 200 GHz. However, the radio signal may be correlated with clusters of galaxies and have a disproportionately larger effect.

Subject headings: cosmic microwave background — cosmology: theory — galaxies: clusters: general

1. INTRODUCTION

The study of anisotropies in the cosmic microwave background (CMB) has proven to be a gold mine for cosmology. The primary anisotropies on scales larger than 10\(^{-3}\) have now been probed with high fidelity by the Wilkinson Microwave Anisotropy Probe (WMAP) (Bennett et al. 2003) over the whole sky, leading to strong constraints on our cosmological model. Within the next few years, this activity will be complemented by high angular resolution, high-sensitivity observations of secondary anisotropies by the Sunyaev-Zel’dovich (SZ) effect (Sunyaev & Zel’dovich 1972, 1980), the Atacama Pathfinder Experiment Sunyaev-Zel’dovich (APEX) SZ survey,\(^4\) the South Pole Telescope (SPT)\(^5\), and the Atacama Cosmology Telescope (ACT)\(^6\), which are aiming to make arcminute-resolution maps with 10 \(\mu\)K sensitivity (or better) at millimeter wavelengths.

The dominant secondary anisotropy is expected to be the Compton scattering of cold CMB photons from hot gas along the line of sight, known as the thermal Sunyaev-Zel’dovich (SZ) effect (Sunyaev & Zel’dovich 1972, 1980; for recent reviews see Rephaeli 1995 and Birkinshaw 1999), although other signals can be present at lower amplitudes. In principle, a measurement of such anisotropies would constrain cosmological parameters (Weller, Battye, & Kniessl 2001; Levin, Schulz, & White 2002; Majumdar & Mohr 2003; Hu 2003), probe the thermal history of the intracluster medium (Majumdar 2001; Zhang, Pen, & Wang 2002), put useful constraints on reionization models through the kinetic SZ effect (Zhang, Pen, & Trac 2003), and allow us to map the dark matter back to the surface of last scattering (Seljak & Zaldarriaga 1999; Zaldarriaga & Seljak 1999; Hu 2001; Hirata & Seljak 2003; Okamoto & Hu 2003).

However, like the primary anisotropies the secondary signals must be disentangled from other astrophysical emissions at the observed frequencies. One of the major sources of contamination on small scales are point sources (by which we mean throughout sources unresolved at arcminute resolution). The purpose of this paper is to outline how point sources impact high resolution CMB experiments and the associated “confusion noise,” describe how one can make small extrapolations of existing data to estimate the amplitude of this noise, and finally discuss the science that can come from studies of this source population. We make use of new observational constraints on the number of sources at frequencies and flux levels relevant to APEX SZ, SPT, and ACT.

2. POINT SOURCES AS NOISE

We will see that point sources will be particularly troublesome for high-resolution surveys, and we attempt to quantify their effect in terms of an equivalent noise. Such a quantification can only be approximate; however, it is a useful metric by which to judge the relative importance of different components and to plan survey strategies. Physically, the IR point sources are thought to be dusty, high-redshift galaxies, and so we do not expect them to be correlated with any particular place on the sky or any particular low-redshift source (such as a cluster of galaxies). We note, however, that the counts are sufficiently steep that lensing by the larger clusters can non-trivially increase the number of sources observed above a given flux cut, and this should be taken into account in interpreting our results (see, e.g., Perrotta et al. 2003 for recent theoretical modeling). The radio sources are more problematic (Holder 2002), as they are likely to be correlated with the SZ signal from clusters of galaxies to some extent. Since this correlation is difficult to quantify at present, we will simply provide noise estimates for them as well.
To proceed, we calculate the angular power spectrum for a population of point sources described by a flux distribution and a clustering amplitude. If we assume that the number of sources of a given flux is independent of the number at a different flux, and if the angular two-point function of the point sources is $w(\theta)$, then the angular power spectrum, $C_l$, contributed by these sources is (Scott & White 1999)

$$C_l(\nu) = \int_0^{S_{\text{cut}}} \frac{dN}{dS_{\nu}} dS_{\nu} + w_l(L_s)^2,$$

assuming that all sources with $S > S_{\text{cut}}$ are removed. Here, $L_s = \int S dN/dS dS$ is the background contributed by sources below $S_{\text{cut}}$. Following the conventional notation, $C_l$ is the Legendre transform of the correlation function $C(\theta)$ produced by the sources, and $w_l$ is the Legendre transform of $w(\theta)$, thus

$$C(\theta) = \frac{1}{4\pi} \sum_{l} (2l+1) C_l P_l(\cos \theta)$$

and

$$w(\theta) = \frac{1}{4\pi} \sum_{l} (2l+1) w_l P_l(\cos \theta),$$

where $P_l(\cos \theta)$ is the Legendre polynomial of order $l$. The first term in equation (1) is the usual Poisson shot-noise term (see § 46 in Peebles 1980; or Tegmark & Efstathiou 1996), and the second is due to clustering, assuming that the clustering is independent of flux. All reasonable $dN/dS$ values give a $C_l$ that converges at the faint end and is very insensitive to the upper flux-density cut.

Because these sources are contributing a foreground to CMB anisotropy experiments, we recast our results in units of $\text{FWHM}$, $\theta_{\text{FWHM}}$, using

$$C_l = (\theta_{\text{FWHM}} \sigma_{\text{pix}})^2,$$

and express $\sigma_{\text{pix}}$ in $\mu\text{K}$ for a fiducial 1' pixel. This value can be rescaled to any desired resolution using equation (8). This $\sigma_{\text{pix}}$ noise is closely related to the standard “confusion noise” often quoted by radio astronomers. To make the connection more explicit, let us write

$$\frac{dN}{dS} = \frac{N_0}{S_0} g\left(\frac{S}{S_0}\right),$$

which defines $g(x)$. Then the noise induced by the sources is

$$\sigma_{\text{conf}} = S_0 (N_{\text{pix}})^{1/2} \mathcal{I}(x),$$

with $x = S_{\text{cut}}/S_0$, $N_{\text{pix}} = N_0 \theta_{\text{pix}}^2$ and

$$\mathcal{I}^2(x) = \int_0^x ds s^2 g(s).$$

If we assume we can subtract sources brighter than $n\sigma$, this simplifies to

$$\sigma_{\text{conf}} = S_0 \left(\frac{x}{n}\right) \text{ where } \frac{x}{\mathcal{I}(x)} = n\sqrt{N_{\text{pix}}}.\quad (11)$$

Upon converting between flux and temperature units and accounting for the flux cut, this expression is the same as equation (8). We mention finally one additional complication that we can include. If the sources have a frequency spectral index distribution $F(\beta)$, and we assume different subpopulations are independent, then we can generalize the above to

$$\sigma_{\text{conf}}^2 = N_{\text{pix}} \int d\beta F(\beta) S_0^2(\beta) \mathcal{I}^2(\beta) \langle x(\beta) \rangle,$$

where $S_0(\beta)$ indicates the value of $S_0$ obtained by extrapolating the fiducial $S_0$ to the required frequency using $S_0 \propto \nu^\beta$. This tends to be a relatively small effect. Even a 30% Gaussian uncertainty in $\beta$ with $\langle \beta \rangle = 0$ (see § 3 below) increases the confusion noise at 5 mJy by only 10% over the $\beta = 0$ value. For this reason, we work with uniform, constant $\beta$ from now on.

3. NOISE ESTIMATES

The remaining step in computing the effective noise contributed by point sources is the production of a model for the counts. While it is theoretically quite difficult to predict these functions, we are fortunate to have observations at close to the

$$\frac{\partial B_{v}}{\partial T} = \frac{2k}{c^2} \left(\frac{kT_{\text{CMB}}}{h}\right)^2 \frac{x^4 e^x}{(e^x - 1)^2} \quad (4)$$

$$S_v = 0.3 \text{ mJy} \left(\frac{\sigma}{10 \mu\text{K}}\right)^2 \text{ at } 150 \text{ GHz} \quad (5)$$

$$S_v = 0.4 \text{ mJy} \left(\frac{\sigma}{10 \mu\text{K}}\right)^2 \text{ at } 220 \text{ GHz} \quad (6)$$

$$S_v = 0.3 \text{ mJy} \left(\frac{\sigma}{10 \mu\text{K}}\right)^2 \text{ at } 350 \text{ GHz}, \quad (7)$$

indicating that these upcoming surveys will be probing the source population at the mJy level.

Since the clustering of the sources is highly uncertain at present, we set $w_l = 0$, although we return to this issue in § 5. For now, this is a conservative assumption, as we expect the sources to be nontrivially clustered if they are associated with rare, highly biased tracers of the density field at high $z$, but we also expect those correlations to be most important at low $l$. In the Poisson limit, the $C_l$ are independent of $l$, i.e., they have the same shape as Poisson/white noise. We therefore express our results in terms of an “effective” point-source noise, $\sigma_{\text{pix}}$, per pixel of FWHM, $\theta_{\text{FWHM}}$, using

$$\sigma_{\text{pix}} = \frac{\sqrt{\mathcal{I}^2(x)}}{\sqrt{N_{\text{pix}}}}.$$
relevant frequencies and flux levels. It is thus a more robust method to extrapolate from the observations than to start from an ab initio theoretical model.

### 3.1. Radio Sources

For the radio point sources, a fit to the $Q$-band data from WMAP (Bennett et al. 2003) can be written as

$$\frac{dN}{dS_\nu} = \frac{N_0}{S_0} \left( \frac{S_\nu}{S_0} \right)^{-2.7},$$

where $N_0 = 1200\; \text{deg}^{-2} = 4 \times 10^6\; \text{sr}^{-1}$ with an uncertainty of around 30% and $S_0 \sim 1\; \text{mJy}$. In obtaining these numbers we need to extrapolate from very high flux levels to mJy levels, and this extrapolation is sensitive to the slope of the distribution. There is evidence that the slope flattens from $-2.7$ to $-2.2$ at lower fluxes. We shall choose $-2.3$ as a compromise, since $S_\nu^{2.2}dN/dS$ is roughly flat in Figure 13 of Bennett et al. (2003). For $S_0 = 1\; \text{mJy}$, this lowers $N_0$ to $80\; \text{deg}^{-2}$. The extrapolation to higher frequency is also somewhat uncertain. The primary emission mechanism in these sources is synchrotron emission, which for a power-law electron spectrum would give a power law $S_\nu$. However, synchrotron “aging” and optical depth effects can give departures from a power-law spectrum, allowing a wide range of spectral shapes including spectra that peak at or above 100 GHz. Advection-dominated accretion onto a supersmassive black hole is also characterized by a strongly inverted spectrum peaking at millimeter wavelengths, as are radio afterglows of gamma-ray bursts. In addition, many of the sources with significant flux at high frequency are thought to be young, compact sources, which are likely to be highly time variable.

Given these large uncertainties, we attempt to bracket the reasonable range and extrapolate the fluxes to higher frequency assuming two different power-law spectral indices, $S_\nu \propto \nu^\beta$ with $\beta = -0.3 \text{}(\text{Tegmark \& Efstathiou 1996})$ and $\beta = 0 \text{}(\text{close to the mean of the distribution in Trushkin 2003}).$ At the mJy level we have close to one radio source per 50 beams if the point sources predominantly have a flat (or rising) spectrum.

### 3.2. IR Sources

For the IR sources, we can use observations at 350 GHz made with the Submillimeter Common-User Bolometer Array (SCUBA) (Holland et al. 1999) on the James Clerk Maxwell Telescope. SCUBA has been used to make several deep observations (Barger et al. 1998; Eales et al. 1998; Holland et al. 1998; Hughes et al. 1998; Smail, Ivison, & Blain 1997) from which we can extract source counts. In particular, we use the recent work of Borys et al. (2003), who give a phenomenological fit to the counts at 350 GHz

$$\frac{dN}{dS_\nu} = \frac{N_0}{S_0} \left[ \left( \frac{S_\nu}{S_0} \right) + \left( \frac{S_\nu}{S_0} \right)^{2} \right]^{-1},$$

with $N_0 = 1.5 \times 10^4\; \text{deg}^{-2} = 4.9 \times 10^7\; \text{sr}^{-1}$ and $S_0 \sim 1.8\; \text{mJy}.$ This model provides a reasonable fit to the existing data near 1 mJy that does not overproduce the far-infrared background (FIB) light (Puget et al. 1996). We estimate that the uncertainty in the normalization is roughly a factor of 2, due to the small sky area surveyed. We will extrapolate from 350 GHz to lower frequencies using $S_\nu \propto \nu^{3.2}$ with $\beta = 2.5$, close to the typical spectrum of a dusty starburst galaxy at high $z$. We also examine the effect of steepening the frequency dependence to a more conservative value $\beta = 3$.

In Figure 1, we have plotted the observed IR source counts of Borys, Chapman, & Scott (1999) and Smail et al. (1997) at 350 GHz along with our extrapolation to lower frequencies. Note that at 150 GHz there would be more than 100 IR point sources above 1 mJy deg$^{-2}$! This means there would be from tens to hundreds-of-thousands of IR sources (depending on the survey). These sources need to be carefully accounted for when considering secondary CMB science.

### 4. RESULTS

For 150 and 220 GHz, the point source contributions, assuming $1'$ pixels, are summarized in Tables 1 and 2. We do not include the effects of source clustering, which would increase these numbers, or gravitational lensing of the population by a foreground object such as a cluster. The corresponding power spectra are shown in Figures 2 (at 150 GHz) and 3 (at 220 GHz). We caution the reader that several of the processes on these figures are non-Gaussian, so the power spectra tell only some of the story. Nonetheless, we can see that point sources will make a large contribution to the signal at these frequencies, and will need to be properly accounted for in any analysis aimed at recovering the thermal SZ effect. Even more care will be required for processes with lower signal levels, or methods that assume that the underlying map is predominantly Gaussian in nature (as, for example, the primary CMB is), since residual emission needs to be carefully controlled.

There is one obvious strategy for controlling the effect of these point sources, and that is to use multiple observing frequencies and multiple instruments with matched sensitivities and resolutions.

Finally, we make an estimate of the confusion noise as a function of beam size at these frequencies. For the radio sources $I(x) = [x^{3.2}/(3 - 2.3)^{1/2}]$, allowing us to estimate $\sigma_{\text{conf}}$ as a function of beam size. If we assume $\beta = 0$, the typical values for a $4\sigma$ cut at 150 GHz are $\sigma_{\text{conf}} = 2\; \text{mJy} at 5'$, $0.4\; \text{mJy} at 2'$, $0.1\; \text{mJy} at 1'$, and $0.05\; \text{mJy} at 0.5'$. For the
IR sources, $I(x)$ is a hypergeometric function. As $x \to 0$, $x/I(x) \to \sqrt{2}$, while $x/I(x) \propto x$ for $x \gg 1$. Assuming $\beta = 2.5$, the typical values for a 4 $\sigma$ cut at 150 GHz are $\sigma_{\text{conf}} = 3.8$ mJy at 5', 1.4 mJy at 2', 0.6 mJy at 1', and 0.3 mJy at 0.5'. In thermodynamic units this is, e.g., 20 $\mu$K at 1', in agreement with Table 2. We show the frequency dependence of the confusion noise in Figure 4.

5. DOING POINT-SOURCE STUDIES WITH APEX/SPT

The point sources described above represent an analysis challenge for studies of secondary CMB anisotropies such as the thermal and kinetic SZ effects or gravitational lensing. However, they also represent an increased science reach for the surveys in different fields of research.

At present, the SCUBA sources account for 40% of the 350 GHz submillimeter background (Borys et al. 2003), and thus go a long way toward resolving the high-z part of the cosmic far-infrared background (FIB). This suggests that APEX SZ, SPT, and ACT, with their high sensitivity and large areal coverage, could become ideal instruments for studying the FIB at the faint, but especially the bright, end of the source counts. As is evident from Figure 1, these future surveys would also be able to detect thousands of high-redshift sources.

These upcoming surveys would be able to probe the FIB correlations, which have been shown (Haiman & Knox 2000; Knox et al. 2001) to give an additional handle on early structure formation at $z > 1$. As we show in Figure 3, detailed observations of the FIB correlations are possible if we can accurately subtract the contribution from primary anisotropies and measure power on angular scales of a few degrees. Under assumptions similar to those in Knox et al. (2001), we expect that a 10$^2$ square degree survey to around 20 $\mu$K would make precision measurements (at the several percent level near $\ell \sim 10^3$) of the clustering of the FIB sources. Multiple frequency information will be crucial in separating the signal from other contaminants. In addition, since the FIB is composed of contributions from sources at different redshifts, the FIB sky maps at different frequencies are not perfectly correlated. The shape of the FIB power spectrum at different frequencies and the correlations between them can give information about the contributing sources (Knox et al. 2001). Studies of the FIB with these surveys would be complimentary to the high angular resolution optical and UV observation of the individual sources.

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**Table 1**

| $S_{\text{cut}}$ (mJy) | $\beta = 0$ | $\beta = -0.3$ |
|------------------------|-------------|-------------|
|                        | 150 GHz     | 220 GHz     | 150 GHz     | 220 GHz     |
| 1                      | 5           | 4           | 4           | 3           |
| 5                      | 9           | 8           | 7           | 5           |
| 10                     | 12          | 10          | 9           | 7           |
| 50                     | 20          | 17          | 16          | 12          |

Note.—Assuming a fiducial 1' pixel. We show extrapolations from 40 GHz assuming a spectral index of $\beta = 0$ and $-0.3$.

**Table 2**

| $S_{\text{cut}}$ (mJy) | $\beta = 2.5$ | $\beta = 3$ |
|------------------------|---------------|-------------|
|                        | 150 GHz       | 220 GHz     | 150 GHz     | 220 GHz     |
| 1                      | 15            | 23          | 11          | 20          |
| 5                      | 19            | 36          | 13          | 29          |
| 10                     | 20            | 39          | 13          | 32          |
| 50                     | 21            | 44          | 14          | 35          |

Note.—Assuming a fiducial 1' pixel. We show extrapolations from 350 GHz assuming a spectral index of $\beta = 2.5$ and 3. Any correlations in the sources will (likely) increase $\sigma_{\text{pix}}$.

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**Figure 2**—Angular power spectra of various sources at 150 GHz. The line labeled "primary" is the primary CMB anisotropy spectrum; the line labeled "tSZ" is the thermal SZ spectrum from White, Hernquist & Springel (2002), and is uncertain at the factor of 2 level. The dashed line labeled "noise" is the instrument noise assuming 10 $\mu$K per 1' pixel and a resolution of 1'. The two unlabeled lines rising rapidly to the top right of the plot are the Poisson contribution of the radio and IR sources for $S_{\text{cut}} = 5$ mJy, assuming $\beta = 0$ and 2.5 respectively.

**Figure 3**—Angular power spectra of various sources at 220 GHz. The thermal SZ "null." Lines are as in Fig. 2, except that a model of the correlations in the FIB from Knox et al. (2001) is also shown.
For the radio sources, these surveys operate at higher frequencies and are complementary to low-frequency compilations of radio point sources (Condon et al. 1998; White et al. 1997), giving us the opportunity to study the spectral dependence of known sources and to probe an entirely new population. Since, in general, radio point sources have non-trivial spectra (Herbig & Readhead 1992), the multifrequency detection of such sources would be invaluable to our understanding of the behavior of radio sources. Under reasonable assumptions associating different populations of radio sources (of a given lifetime) with halos (Haiman & Hui 2001; Martini & Weinberg 2001), one would be able to constrain cosmological models through a study of the clustering of radio sources. At 1 mJy we expect about 1 source per 50 arcmin$^2$, which would allow APEX SZ to constrain $1 + w(\theta)$ on arcminute scales at the several times 10$^{-3}$ level. Whether this is enough to perform a reliable measurement of $w(\theta)$ depends on the degree of bias and line-of-sight dilution of the clustering. At lower frequencies, the angular correlation function is $w(\theta) \propto \theta^{\gamma}$, with $\gamma \approx 1.8$. The amplitude, $A$, of $w(\theta)$ depends on the flux limit and flattens out for low flux limits. Extrapolating from the NRAO Very Large Array Sky Survey (NVSS) data, one would expect $A \approx 10^{-3}$ at 1 mJy (Overzier et al. 2003), which would be near or below the threshold for APEX SZ.

Clearly, to extract all of the excellent science that can be done with these instruments will require coordinated observations over a range of frequencies. In this regard, the submillimeter instruments intended for the APEX platform, or the planned SCUBA-2 with its higher angular resolution and frequency range, will be particularly valuable. For the radio sources, coordinated observations with the SZA or other lower frequency instruments would be useful.

6. DISCUSSION AND CONCLUSIONS

Advances in detector technology have brought us to the stage where sensitive, high angular resolution, wide-area surveys in the submillimeter waveband are practical. Several new instruments are funded and under construction that should map hundreds or thousands of square degrees of sky at arcminute resolution with sensitivities of around 10 $\mu$K. The stated aim of these surveys is to find clusters of galaxies using the Sunyaev-Zel’dovich effect.

At these sensitivities, foregrounds are of particular importance, and in this paper we have used new observational data on the IR and radio source counts to estimate their impact on upcoming surveys. The contribution from both radio and IR point sources are found to be nonnegligible. The IR point sources are of particular interest, because their number density is higher than was expected based on early theoretical modeling. Using a model of the source counts, we predict that surveys with 1$'$ resolution will be “confusion limited” before they reach 10 $\mu$K. Typical effective noise levels from unsubtracted point sources can be more than twice the nominal survey sensitivities at 150 GHz and 1$'$ resolution, and even higher at 220 GHz. The contamination by point sources has a strong impact on how such surveys will study the thermal SZ effect, and may provide the ultimate limitation to studies of the kinetic SZ effect and weak gravitational lensing. Such surveys need to make multifrequency observations or coordinate observations with other instruments to allow them to remove point sources to low flux levels.

Conversely, these instruments offer a golden opportunity to study the inverted-spectrum radio sources underrepresented in current surveys, map the FIB, and probe the high-$z$ universe. Not only will these upcoming surveys have the capability to detect thousands of high-redshift IR and radio sources to very low flux limits, they will also be able to look into the correlations of the FIB and the clustering of radio point sources.

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8 For more information on SCUBA-2, see: http://www.roe.ac.uk/atec/projects/scuba_two/.

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