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POINT SOURCES IN THE CONTEXT OF FUTURE SZ SURVEYS

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ABSTRACT

We look at the impact of Infra-Red (IR) and radio point sources on upcoming large yield Sunyaev-Zel'dovich (SZ) cluster surveys such as APEX, SPT and ACT. The IR and radio point source counts are based on observations by the the SCUBA and 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 ($\sim 100-300$ 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. Alternatively, 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 — galaxies: clusters — cosmology: theory

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 $10'$ have now been probed with high fidelity by 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 SZA[1], APEX-SZ experiment[2], the South Pole Telescope (SPT[3]) and the Atacama Cosmology Telescope (ACT[4]) which are aiming to make arcminute resolution maps with 10μK 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)) though other signals can be present at lower amplitudes. In principle, a measurement of such anisotropies would constrain cosmological parameters (Weller et al. (2001), Levin et al. (2002), Majumdar & Mohr (2003), Hu (2003)), probe the thermal history of the intra-cluster medium (Majumdar (2001), Zhang & Pen (2002)), put useful constraints on re-ionization models through the kinetic SZ effect (Zhang et al. (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 source of contamination on small scales are point sources (by which we shall 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 which can come from studies of this source population. We make use of new observational constraints on the number of sources at frequencies and flux level relevant to APEX-SZ, SPT and ACT.

[1] http://astro.uchicago.edu/sza/
[2] http://bolo.berkeley.edu/apexsz/
[3] http://astro.uchicago.edu/spt/
[4] http://www.hep.upenn.edu/~angelica/act/act.html

2. POINT SOURCES AS NOISE

We will see that point sources will be particular troublesome for high resolution surveys, and we will 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 modelling). 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))

$$C_\ell(\nu) = \int_0^{S_{\rm cut}} S_\nu^2 \frac{{\rm d}N}{{\rm d}S_\nu}\, dS_\nu + w_\ell\,(I_\nu)^2, \qquad (1)$$

assuming that all sources with $S>S_{\rm cut}$ are removed. Here, $I_\nu = \int S\,{\rm d}N/{\rm d}S\;dS$ is the background contributed by sources below $S_{\rm cut}$. 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 $w(\theta)$:

$$C(\theta) = \frac{1}{4\pi}\sum_\ell (2\ell+1) C_\ell P_\ell(\cos\theta) \qquad (2)$$

$$w(\theta) = \frac{1}{4\pi}\sum_\ell (2\ell+1) w_\ell P_\ell(\cos\theta), \qquad (3)$$

with $P_\ell(\cos\theta)$ the Legendre polynomial of order ℓ. The first term in equation (1) is the usual Poisson shot-noise term (see Peebles (1980) §46, or Tegmark & Efstathiou (1996)), the second is due to clustering, assuming that the clustering is independent of flux. All reasonable dN/dS give a C_ℓ which 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 will recast our results in 'temperature' units. This is easily done by applying the conversion factor between flux and temperature which is given by

$$\begin{aligned}\frac{\partial B_\nu}{\partial T} &= \frac{2k}{c^2}\left(\frac{kT_{\rm CMB}}{h}\right)^2 \frac{x^4 {\rm e}^x}{({\rm e}^x-1)^2} \\ &= \left(\frac{99.27\,{\rm Jy\ sr}^{-1}}{\mu{\rm K}}\right)\frac{x^4{\rm e}^x}{({\rm e}^x-1)^2}, \qquad (4)\end{aligned}$$

where B_ν is the Planck function, k is Boltzmann's constant, $x \equiv h\nu/k_B T_{\rm CMB} = \nu/56.84\,{\rm GHz}$ is the 'dimensionless frequency' and $1\,{\rm Jy} = 10^{-26}\,{\rm W\,m^{-2}Hz^{-1}}$. Conveniently a $10\,\mu$K CMB fluctuation in a $1'$ FWHM pixel gives a flux close to 1mJy viz:

$$S_\nu = 0.3\,{\rm mJy}\left(\frac{\sigma}{10\mu{\rm K}}\right)\left(\frac{\theta}{1'}\right)^2 \qquad @150{\rm GHz} \qquad (5)$$

$$S_\nu = 0.4\,{\rm mJy}\left(\frac{\sigma}{10\mu{\rm K}}\right)\left(\frac{\theta}{1'}\right)^2 \qquad @220{\rm GHz} \qquad (6)$$

$$S_\nu = 0.3\,{\rm mJy}\left(\frac{\sigma}{10\mu{\rm K}}\right)\left(\frac{\theta}{1'}\right)^2 \qquad @350{\rm GHz} \qquad (7)$$

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

Since the clustering of the sources is highly uncertain[5] at present, we will set $w_\ell = 0$, though we shall return to this issue in §5. For now this is a conservative assumption as we expect the sources to be non-trivially 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 $\sigma_{\rm pix}$ per pixel of FWHM $\theta_{\rm pix}$ using

$$C_\ell = \left(\theta_{\rm pix}\sigma_{\rm pix}\right)^2 , \qquad (8)$$

[5] Though we expect this to improve soon with the release of data from the SHADES survey, http://www.roe.ac.uk/ifa/shades/, and of course APEX-SZ, SPT and ACT.

and express $\sigma_{\rm pix}$ in μK for a fiducial $1'$ pixel. This value can be rescaled to any desired resolution using Eq. 8. This $\sigma_{\rm pix}$ is closely related to the standard 'confusion noise' often quoted by radio astronomers. To make the connection more explicit let us write

$$\frac{dN}{dS} \equiv \frac{N_0}{S_0}\, g\left(\frac{S}{S_0}\right) \qquad (9)$$

which defines $g(x)$. Then the 'noise' induced by the sources is $\sigma_{\rm conf} = S_0\sqrt{N_{\rm pix}}\,\mathcal{I}(x)$ with $x = S_{\rm cut}/S_0$, $N_{\rm pix} = N_0\theta_{\rm pix}^2$ and

$$\mathcal{I}^2(x) = \int_0^x ds\, s^2 g(s) \qquad . \qquad (10)$$

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

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

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

$$\sigma_{\rm conf}^2 = N_{\rm pix}\int d\beta\ \mathcal{F}(\beta) S_0^2(\beta)\mathcal{I}^2\left(x(\beta)\right) \qquad (12)$$

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

3. NOISE ESTIMATES

The remaining step in computing the effective noise contributed by point sources is thus 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 relevant frequencies and flux levels. It is thus more robust to extrapolate 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

$$\frac{dN}{dS_\nu} = \frac{N_0}{S_0}\left(\frac{S_\nu}{S_0}\right)^{-2.7} \qquad (13)$$

where $N_0 = 1200\,{\rm deg}^{-2} = 4\times10^6\,{\rm sr}^{-1}$ with an uncertainty of around 30% and $S_0 \simeq 1\,{\rm mJy}$. 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 $S^{5/2}dN/dS$ is roughly flat in Fig. 13 of Bennett et al. ((2003)). For $S_0 = 1\,{\rm mJy}$ this lowers N_0 to $80\,{\rm deg}^{-2}$. 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_ν. However synchrotron 'aging' and optical depth effects can give departures from a power-law spectrum, allowing a wide range of spectral shapes including spectra which peak at or above 100 GHz. Advection dominated accretion onto a super-massive 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 will 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 $\beta = -0.3$ (Tegmark & Efstathiou (1996)) and $\beta = 0$ (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 et al. (1997)) from which we can extract source counts. In particular we shall use the recent work of Borys et al. (2003) who give a phenomenological fit to the counts at 350 GHz:

$$\frac{dN}{dS_\nu} = \frac{N_0}{S_0}\left[\left(\frac{S_\nu}{S_0}\right) + \left(\frac{S_\nu}{S_0}\right)^{3.3}\right]^{-1} \qquad (14)$$

with $N_0 = 1.5 \times 10^4\,\mathrm{deg}^{-2} = 4.9 \times 10^7\,\mathrm{sr}^{-1}$ and $S_0 \simeq 1.8\,\mathrm{mJy}$. This model provides a reasonable fit to the existing data near 1 mJy that does not over-produce the far-infrared background (FIB) light (Puget et al. (1996)).

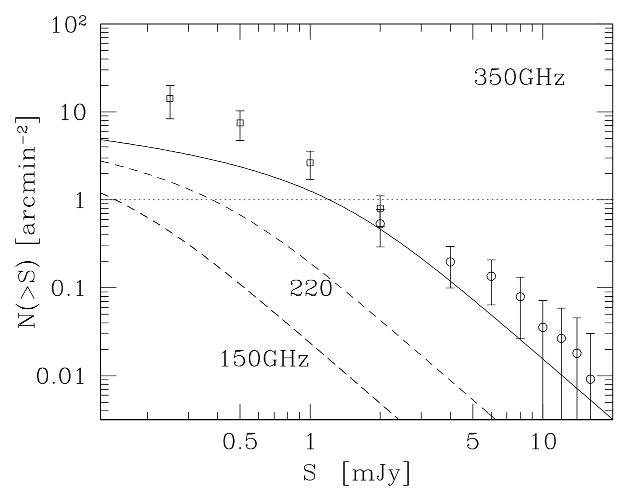

FIG. 1.— The cumulative SCUBA source counts at 350 GHz as a function of flux, S, from Smail et al. (1997) (squares) and Borys et al. (1999; 2003) (circles). The fit of Borys et al. (2003) is shown as the solid line, and the extrapolations to 220 GHz and 150 GHz assuming $S_\nu \propto \nu^{2.5}$ as dashed lines. Upcoming surveys will be sensitive to sources with $S \sim 1$ mJy.

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 frequency using $S_\nu \propto \nu^\beta$ with $\beta = 2.5$, close to the typical spectrum of a dusty star-bust galaxy at high-z. We will also examine the effect of steeping the frequency dependence to a more conservative value $\beta = 3$.

In figure 1, we have plotted the observed IR source counts of (Borys et al. (1999), 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 per deg^2! This means 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 Figs. 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 be a large contribution to the signal at these frequencies, which 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 which 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

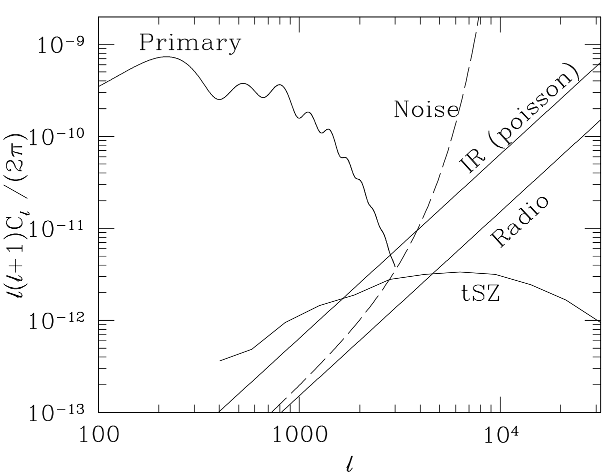

FIG. 2.— The angular power spectra of various sources at 150 GHz. The line labeled "primary" is the primary CMB anisotropy spectrum, the line labeled "tSZ" is the thermal SZ spectrum from White, Hernquist & Springel (2002) and is uncertain at the factor of 2 level. The (dashed) line labeled "noise" is 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 $S_{\rm cut} = 5$ mJy, assuming $\beta = 0$ and 2.5 respectively.

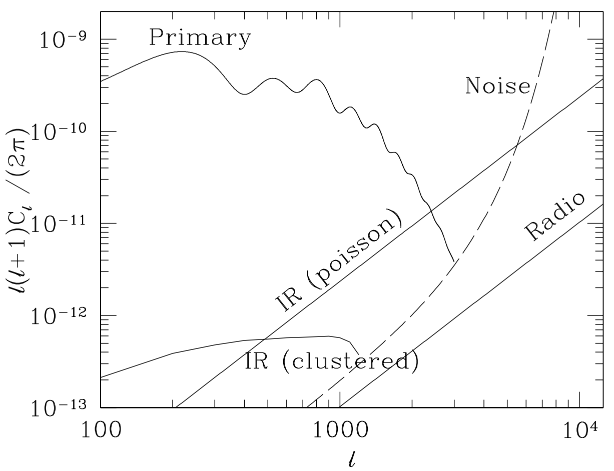

FIG. 3.— The angular power spectra of various sources at 220 GHz, the thermal SZ "null". Lines are as in Fig. 2 except that a model of the correlations in the FIB from Knox et al. (2001) is also shown.

$S_{\rm cut}$ (mJy)	$\sigma_{\rm pix}(\mu{\rm K})$			
	$\beta=0$		$\beta=-0.3$	
	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

TABLE 1

THE EFFECTIVE NOISE FOR POISSON DISTRIBUTED RADIO SOURCES AT 150 AND 220 GHZ ASSUMING A FIDUCIAL $1'$ PIXEL. WE SHOW EXTRAPOLATIONS FROM 40 GHZ ASSUMING A SPECTRAL INDEX OF $\beta=0$ AND -0.3.

$S_{\rm cut}$ (mJy)	$\sigma_{\rm pix}(\mu{\rm K})$			
	$\beta=2.5$		$\beta=3$	
	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

TABLE 2

THE EFFECTIVE NOISE FOR POISSON DISTRIBUTED IR SOURCES AT 150 AND 220 GHZ 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 $\sigma_{\rm pix}$.

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 $\mathcal{I}(x)=\sqrt{x^{3-2.3}/(3-2.3)}$ allowing us to estimate $\sigma_{\rm conf}$ as a function of beam size. If we assume $\beta=0$ the typical values for a 4σ cut at 150 GHz are $\sigma_{\rm conf}=2\,$mJy at $5'$, 0.4 mJy at $2'$, 0.1 mJy at $1'$ and 0.05 mJy at $0.5'$. For the IR sources $\mathcal{I}(x)$ is a hypergeometric function. As $x\to 0$, $x/\mathcal{I}(x)\to\sqrt{2}$ while $x/\mathcal{I}(x)\propto x$ for $x\gg 1$. Assuming $\beta=2.5$ the typical values for a 4σ cut at 150 GHz are $\sigma_{\rm conf}=3.8\,$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 Fig. 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 increased science reach for the surveys in different fields of research.

At present, the SCUBA sources account for 40% of the 350 GHz sub-mm background (Borys et al. (2003)) and thus go a long way towards 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 has 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 Fig. 3, detailed observations of the FIB correlations are possible if we can accurately subtract the contribution from primary

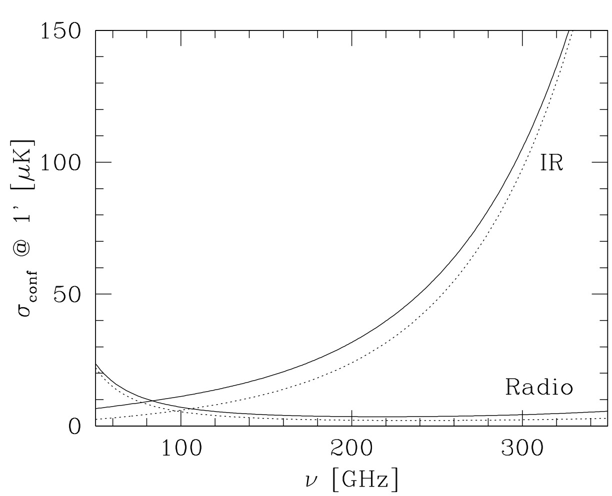

FIG. 4.— Confusion noise, in μK, for a $1'$ beam as a function of frequency. Contributions from Poisson distributed radio and IR sources are shown. The solid lines represent $\beta=0$ and 2.5 while the dotted lines represent $\beta=-0.3$ and 3 respectively.

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.

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 multi-frequency detection of such sources would be invaluable in 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 $w(\theta) \propto \theta^{1-\gamma}$ with $\gamma \simeq 1.8$. The amplitude, A, of $w(\theta)$ depends on the flux limit and flattens out for low flux limits. Extrapolating from the NVSS data one would expect $A \lesssim 10^{-3}$ 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 sub-mm instruments intended for the *APEX* platform or the planned SCUBA-2[6] 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 sub-mm are practical. Several new instruments are funded and under construction which 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 non-negligible. 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 multi-frequency observations or coordinate observations with other instruments to allow them to remove point sources to low flux levels.

Conversely these instruments will have 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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