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Extragalactic source contributions to arcminute-scale Cosmic Microwave Background anisotropies

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Abstract. The possible contributions of the various classes of extragalactic sources (including, in addition to the canonical radio sources, GHz Peaked Spectrum sources, advection-dominated sources, starburst galaxies, high-redshift proto-spheroidal galaxies) to the arcminute scale fluctuations measured by the CBI, BIMA, and ACBAR experiments are discussed. At 30 GHz, fluctuations due to radio sources undetected by ancillary low-frequency surveys may be higher than estimated by the CBI and BIMA groups. High-redshift dusty galaxies, whose fluctuations may be strongly enhanced by the effect of clustering, could contribute to the BIMA excess signal, and dominate at 150 GHz (the ACBAR frequency). Moreover, in the present data situation, the dust emission of these high-redshift sources set an unavoidable limit to the detection of primordial CMB anisotropies at high multipoles, even at frequencies as low as $\simeq$30 GHz. It is concluded that the possibility that the excess power at high multipoles is dominated by unsubtracted extragalactic sources cannot be ruled out. On the other hand, there is room for a contribution from the Sunyaev-Zeldovich effect within clusters of galaxies, with a density fluctuation amplitude parameter σ_8 consistent with the values preferred by current data.

Key words. cosmic microwave background – galaxies: general – radio continuum: galaxies

1. Introduction

In the past few years different experiments (BIMA: Dawson et al. 2002; CBI: Mason et al. 2003; Readhead et al. 2004; and ACBAR: Kuo et al. 2004), aimed at measuring the anisotropies of the cosmic microwave background (CMB) on arcmin angular scales, have detected signals at multipoles $\ell > 2000$ in excess of the expected primordial CMB anisotropies. The origin of this excess signal, in the range $16 \lesssim \Delta T \lesssim 26\,\mu$K, is not well understood yet, although several possibilities have been discussed in the literature.

All experimental groups argue that it cannot be due to point-source contamination. If so, the most likely candidate is the thermal Sunyaev-Zeldovich (SZ) effect, which is expected to dominate CMB anisotropies on angular scales of a few arcminutes (Gnedin & Jaffe 2001). However, an interpretation on terms of SZ effects from clusters of galaxies (Bond et al. 2005; Komatsu & Seljak 2002) or to the inhomogeneous plasma distribution during the formation of large scale structure (Zhang et al. 2002) requires values of σ_8 (the rms density fluctuation on a scale of 8 h^{-1} Mpc) significantly higher than indicated by current data. SZ effects associated with the formation and the early evolutionary phases of massive spheroidal galaxies could account for the BIMA signal, although some parameters need to be stretched to their boundary values (De Zotti et al. 2004). Alternative interpretations advocate non-standard inflationary models (Cooray & Melchiorri 2002; Griffiths et al. 2003).

In this paper we revisit the contributions of extragalactic point sources to the power spectrum on arcminute scales at the relevant frequencies, including the possible role of faint sources, with flux densities too weak to be filtered out, and the effect of clustering. The outline of the paper is as follows. In Sect. 2 we describe the different source populations which give the dominant contributions to number counts at cm and mm wavelengths. In Sect. 3 we present our estimates of arcminute-scale CMB anisotropies due to extragalactic sources, while in Sect. 4 we summarize our main conclusions.

A flat ΛCDM cosmology with $\Omega_\Lambda = 0.7$ has been used throughout the paper.

2. Extragalactic sources at cm and mm wavelengths

The estimated contributions of the various populations of extragalactic sources to the counts at 30 GHz (the frequency of BIMA and CBI experiments) and at 150 GHz (ACBAR experiment), obtained from the model of De Zotti et al. (2005), which updates the model by Toffolatti et al. (1998), are shown in Fig. 1. In addition to the canonical flat- and steep-spectrum radio sources, the model takes into account star-forming galaxies with their complex spectra including both radio (synchrotron plus free-free) and dust emission, and the source populations characterized by spectra peaking at high radio frequencies, such as extreme GHz Peaked Spectrum (GPS) sources and accretion flows on almost inactive supermassive black-holes in early type galaxies (ADAF/ADIOS sources).

Because of their inverted low-frequency spectra, GPS and ADAF/ADIOS sources are potentially worrisome. However, GPS sources are rare and the analysis made by De Zotti et al. (2000) implies that they likely have very flat counts and therefore are minor contributors to small scale fluctuations. Furthermore, the repeated multifrequency measurements by Tinti et al. (2005) have demonstrated that most GPS candidates identified with quasars in the sample of Dallacasa et al. (2000) are in fact flaring blazars, so that the surface densities of bona-fide GPS sources is probably substantially lower than estimated by De Zotti et al. (2000), a conclusion further supported by an examination, carried out by De Zotti et al. (2005), of GPS candidates in the WMAP sample (Bennett et al. 2003).

ADAF/ADIOS sources are far more numerous, but have a low radio power. The estimate by De Zotti et al. (2005) of their counts is well below that by Perna & Di Matteo (2000), whose results are probably affected by a numerical error, and implies that also these sources do not contribute significantly to the fluctuations measured by the BIMA and CBI experiments. On the other hand, Pierpaoli & Perna (2004; model A) pointed out that if the standard ADAF model (Narayan & Yi 1994) is used, these sources could make up to 40–50% of the BIMA and CBI excesses. We note, however, that the standard ADAF scenario faces a number of serious difficulties, some of which are summarized in Sect. 4.3 of De Zotti et al. (2005), suggesting that the radio emission is suppressed by massive outflows. It is therefore likely that the results of model A by Pierpaoli & Perna (2004) should be regarded as, probably generous, upper limits.

As for starburst galaxies, the slope of their differential counts can exceed 3, if these objects have to account for the very steep ISOCAM 15 μm counts below a few mJy, as implied by recent analyses (Gruppioni et al. 2003; Franceschini et al. 2003; Pozzi et al. 2004; Silva et al. 2005). In this case, their main contribution to small scale fluctuations comes from weak sources, at μJy levels, far fainter than those removed from CBI and BIMA maps. On the other hand, the counts of such sources are tightly constrained by μJy counts at 1.4 GHz (Richards 2000), 5 GHz (Fomalont et al. 1991), and 8.4 GHz (Fomalont et al. 2002). Taking such constraints into account and applying an average spectral index $\alpha = 0.8$, appropriate for this class of sources, we find that they can only provide a minor contribution to the excess power detected by BIMA and CBI: $\sim 4.3\,\mu$K at $\ell \simeq 6880$, by using the nominal 6σ detection limit, $S_{\rm d} = 150\,\mu$Jy, for BIMA and $\sim 5.0\,\mu$K at $\ell \simeq 2500$ ($S_{\rm d} = 3.4$ mJy) for CBI, respectively. Their contribution is negligible at the ACBAR frequency.

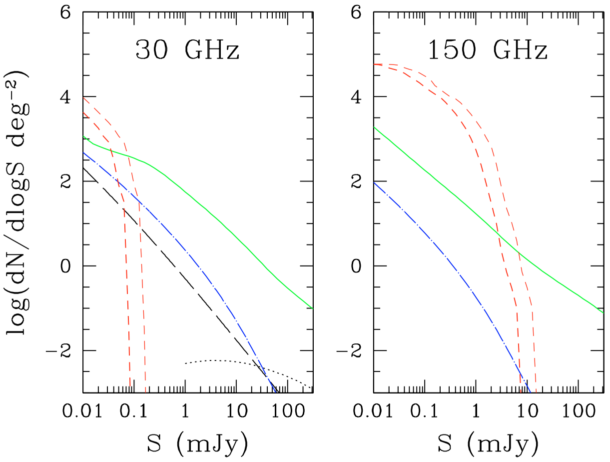

Fig. 1. Differential counts, $dN/d\log S$, of different source populations at 30 and 150 GHz, based on the De Zotti et al. (2005) evolution model. Solid lines: canonical flat– plus steep-spectrum sources; dot-dashed lines: starburst galaxies; short-dashed lines: dusty proto-spheroidal galaxies with (upper curve) and without the mm excess (see text). In the left-hand panel only the estimated counts of GPS sources (dotted line) and of ADAF/ADIOS sources (long-dashed line) are also shown.

An additional contribution is expected from dusty proto-spheroidal galaxies, which may account for galaxies selected by SCUBA and MAMBO surveys (Granato et al. 2001, 2004), whose counts at 850 μm and 1.2 mm appear to fall down very rapidly at flux densities above several mJy (Scott et al. 2002; Borys et al. 2003; Greve et al. 2004). The spectral energy distribution of nearby dusty galaxies is dominated by synchrotron plus free-free emission at $\lambda > 2$–3 mm (Bressan et al. 2002), while at shorter wavelengths dust emission, rapidly raising with frequency ($S_\nu \propto \nu^4$), takes over. Since these sources are at typical redshifts >2 (Chapman et al. 2003), dust emission can significantly contribute to the counts even at 30 GHz. When dust emission comes in, the counts, already steep because of the effect of the strong cosmological evolution, are boosted by the large negative K-correction.

The poor knowledge of the millimeter emission of these sources, however, makes estimates of their contributions to the 30 GHz counts quite uncertain. The two short-dashed lines in Fig. 1 show the counts we obtain using the physical evolutionary model by Granato et al. (2004) but with two choices for the spectral energy distribution (SED). The lower (thicker) line refers to the SED produced by the code GRASIL (originally described by Silva et al. 1998). An excess emission by a factor $\simeq 2$ at $\lambda \geq 1$ mm was however detected in several Galactic clouds, combining Archeops with WMAP and DIRBE data (Bernard et al. 2003; Dupac et al. 2003), and in NGC 1569 (Galliano et al. 2003). The origin of the excess is still not understood. Possibilities discussed in the literature are that the grain sizes or composition change in dense environments or that there is an intrinsic dependence of the dust emissivity index on temperature (Dupac et al. 2004). If the excess is due to very cold grains (Reach et al. 1995; Galliano et al. 2003) it cannot be present in the high-z proto-spheroids. But if it is a general property of the SED of dusty galaxies, the predicted counts of dusty proto-spheroids are given by the upper (thin) short-dashed curve.

3. Contributions of extragalactic sources to arcminute scale anisotropies

3.1. Observations with the Cosmic Background Imager (CBI)

The strategy of the CBI group (Mason et al. 2003; Readhead et al. 2004) to remove the point source contamination comprises pointed 31 GHz observations with the OVRO 40 m telescope of all NVSS sources with 1.4 GHz flux density ≥6 mJy, and direct counts at 31 GHz using the CBI deep and mosaic maps. Although the 4σ threshold of OVRO observations is 6 mJy, the survey is 99% complete only at $S_{31\ \rm GHz} > 21$ mJy. The limiting flux density ranges from 6 to 12 mJy in the deep CBI maps, and from 18 to 25 mJy in the mosaic maps. Subtraction of OVRO detected sources removes two-thirds of the observed power level.

Furthermore, they have adopted the constraint matrix approach to remove from their dataset all NVSS sources with flux densities greater than 3.4 mJy at 1.4 GHz (Readhead et al. 2004), and have estimated the contribution to fluctuations due to sources below the NVSS cutoff using the observed OVRO-NVSS distribution of spectral indices and adopting a rather shallow power-law slope for the counts ($N(>S) \propto S^{-0.875}$); for comparison, Richards (2000) finds $N(>S) \propto S^{-1.4\pm0.1}$ for $40\ \mu$Jy $< S_{1.4} < 1$ mJy (see also Windhorst et al. 1993).

At the flux-density levels relevant for the CBI experiment, apart from SZ effects (see Sect. 1), the dominant contribution to fluctuations due to extragalactic sources is expected to come from the classical steep- and flat–spectrum radio sources. However, an accurate determination of the 30 GHz fluctuations due to sources with $S_{1.4} \leq 3.4$ mJy is very difficult because of the effect of sources with inverted spectra (in fact, Readhead et al. 2004 report the detection of a source, NGC 1068, with $S_{30\ \rm GHz} \simeq 400$ mJy, not removed by the constraint matrix), and of variability. The difficulty is illustrated by the results of high-frequency surveys. Ricci et al. (2004) found that the 18 GHz flux densities of extragalactic sources detected by the ATCA pilot survey are not significantly correlated with the SUMSS flux densities at 0.84 GHz (i.e. at a frequency not far from that of the NVSS survey). Waldram et al. (2003) also reported a large spread (about a factor of 10) of the 15 to 1.4 GHz flux density ratios of sources detected in their 9C survey at 15 GHz, although the flux densities at the two frequencies are correlated. They also noted that pointed 15 GHz observations of the NVSS sources with $S_{1.4} \geq 25$ mJy in the area covered by their survey would have detected 434 sources above the 9C survey limit of 25 mJy but would have missed 31 sources having $S_{15} \geq 25$ mJy but $S_{1.4} < 25$ mJy. The distribution of spectral indices has a systematic drift towards flatter values with decreasing low-frequency flux density down to $S_{1.4} \simeq 1$ mJy (Windhorst et al. 1993), so that the fraction of sources with inverted spectra is expected to be higher at the fainter flux density levels of interest here.

High frequency surveys emphasize flat-spectrum sources. The dominant flat-spectrum population are blazars, that are highly variable on timescales of years and whose variability amplitude increases with frequency (Impey & Neugebauer 1988; Ciaramella et al. 2004). The monitoring campaigns at 22, 37 and 87 GHz by the Metsähovi group (Teräsranta et al. 1998) have shown that intensity variations by factors of several are common at these frequencies, so that a substantial fraction of such sources may have had, at the moment of the CBI observations, 30 GHz fluxes higher than 3.4 mJy, even by a considerable factor. Variability can indeed account, to a large extent, for the lack of a correlation between the ATCA 18 GHz and the SUMSS 0.84 GHz flux densities (Ricci et al. 2004) and for the large spread of the 15 to 1.4 GHz flux density ratios (Waldram et al. 2003).

To appraise residual fluctuations at 30 GHz due to unsubtracted sources we have adopted the analytical description of the counts below a few mJy by Richards (2000; $\mathrm{d}N/\mathrm{d}S_{1.4} = AS_{1.4}^{-\gamma}$ with $A = 8.3 \pm 0.4$ and $\gamma = 2.4 \pm 0.1$) and computed the Poisson fluctuations at 30 GHz of those sources with $S_{1.4} < 3.4$ mJy, assuming a Gaussian distribution of spectral indices with mean $\bar{\alpha} = 0.4$ (Fomalont et al. 1991; Windhorst et al. 1993) and two values of the dispersion ($\sigma = 0.3$ or 0.4), based on the width of the distribution of $\alpha_{1.4}^{15.2}$ of Waldram et al. (2003, their Fig. 9). A comparison with the 30 GHz counts yielded by the De Zotti et al. (2005) model, which takes into account the available information from high-frequency surveys, shows that, in the 30 GHz flux density range relevant to estimate fluctuations, the counts extrapolated using the upper values of A and γ are somewhat too high if $\sigma = 0.4$; more consistent counts (only slightly above the model predictions) are obtained with the central values $A = 8.3$, $\gamma = 2.4$. To bound the plausible range of residual fluctuations we have therefore considered the cases $A = 8.3$, $\gamma = 2.4$, $\sigma = 0.4$ (upper dotted line in the left-hand panel of Fig. 2) and $A = 7.9$, $\gamma = 2.3$, $\sigma = 0.3$ (lower dotted line).

The additional contribution to CMB fluctuations given by correlated positions in the sky of canonical steep- and flat-spectrum radio sources has been recently analyzed by González-Nuevo et al. (2005). Their outcomes indicate that the extra power due to the clustering of radio sources cannot, by itself, explain the excess signal detected by CBI and BIMA. Using the $w(\theta)$ estimated by Blake & Wall (2002) from sources in the NVSS survey down to $S \simeq 10$ mJy – which can represent a realistic approximation to the clustering properties of faint undetected sources in the CBI fields – they found that clustered radio sources at $S_{30\ \rm GHz} < 3.4$ mJy can give an extra power $\Delta T \simeq 3$–$4\ \mu$K, which has to be summed up – in quadrature – to the Poisson term, $\Delta T \simeq 20$–$22\ \mu$K. The dominance of Poisson over clustering fluctuations even at faint fluxes is due to the strong dilution of the clustering signal of extragalactic radio sources by the broadness of their luminosity function and of their redshift distribution (Dunlop & Peacock 1990; Toffolatti et al. 1998; Negrello et al. 2004).

3.2. Observations with the Berkeley-Illinois-Maryland Association Array (BIMA)

To remove the point source contamination, the BIMA group (Dawson et al. 2002) have carried out a VLA survey at 4.8 GHz of their fields. These observations reached a rms flux

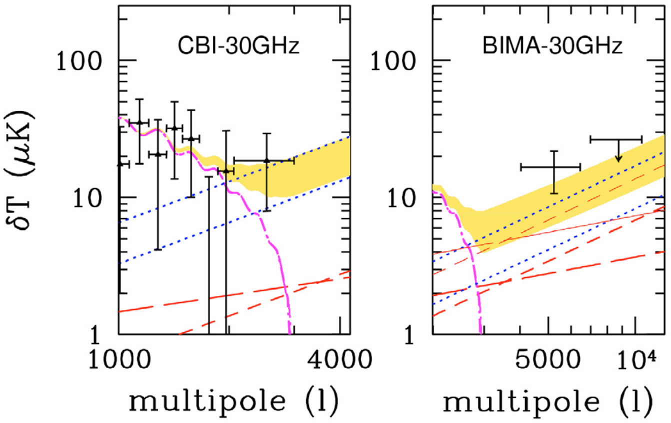

Fig. 2. Angular power spectrum ($\delta T = \sqrt{\ell(\ell+1)C_\ell/2\pi}$) measured at 30 GHz by CBI (*left-hand panel*; data points from Readhead et al. 2004) and by BIMA *(right-hand panel*; data points from Dawson et al. 2002). In each panel, we have plotted the primordial CMB angular power spectrum (dot-dashed-line), the estimated range of contributions of unsubtracted canonical radio sources (dotted lines; see text), and of Poisson distributed (short-dashed line) and clustered (long-dashed line) proto-spheroidal galaxies. In the BIMA case, the upper pair of long- and short-dashed lines refers to proto-spheroidal galaxies with the submillimeter excess mentioned in Sect. 2 (not shown in the other panel). The contributions of the latter sources are insensitive to the adopted flux limit because of the very steep counts. The shaded areas show the ranges spanned by the quadratic sum of the different contributions.

of ≃25 μJy beam^{-1} for a 9′ FWHM region with center coinciding with the center of the corresponding BIMA field. Sources with flux density > $6\sigma_{\rm VLA}$ within 8′ of the pointing center were projected out. On the other hand, point sources with flux densities $S_{4.8} > 150$ μJy, lying at an angular distance θ from the BIMA field center, cannot be detected (and removed) by VLA observations if $S_{4.8} < S_{\rm lim}(\theta) = 6\sigma/f(\theta)$, where $f(\theta)$ is the VLA response function, assumed Gaussian.

Therefore, we have estimated the fluctuations in the BIMA fields due to sources fainter than $150\,\mu{\rm Jy}/f(\theta)$, where θ is the angular distance from the pointing direction, by adopting the number counts at 4.8 GHz of Fomalont et al. (1991), $N(>S) = (23.2 \pm 2.8) S_{4.8,\mu{\rm Jy}}^{-1.18\pm0.19}$ arcmin^{-2}, extrapolated to 30 GHz with a mean spectral index $\alpha = 0.4$ ($S_\nu \propto \nu^{-\alpha}$), appropriate for the relevant flux-density range (Fomalont et al. 1991; Windhorst et al. 1993). The corresponding power spectrum is shown in Fig. 2 (right-hand panel), where the shaded area reflects the range of values corresponding to the uncertainties in the counts of Fomalont et al. (1991) and in the dust emission spectrum of high redshift proto-spheroidal galaxies (see below).

The fluctuations due to forming spheroidal galaxies, not represented in the 4.8 GHz counts, get comparable contributions from both the Poisson and the clustering term, while the latter term turns out to be small, compared to the former, for the other classes of sources relevant here. Adopting the standard expression for the two-point correlation function, $\xi(r) = (r/r_0)^{-1.8}$ with a constant comoving clustering length $r_0 = 8.3\ h^{-1}$ Mpc, h being the Hubble constant in units of 100 km s^{-1} Mpc^{-1} (see Negrello et al. 2004), we find, at $\ell_{\rm eff} = 6864$, a Poisson contribution of ≃5 μK and a clustering contribution of ≃3 μK. Clearly these contributions, to be summed in quadrature to the contribution discussed above, have a minor effect. If, however, these sources show the mm excess mentioned in Sect. 2, their contribution to fluctuations would be approximately doubled (see Fig. 2; right-hand panel), and, summed in quadrature to the above estimate of the contribution of radio sources, could account for the reported excess signal.

3.3. Observations with the Arcminute Cosmology Bolometer Array Receiver (ACBAR)

The ACBAR measurements in the 150 GHz band reported by Kuo et al. (2004) up to multipoles $\ell = 3000$ are consistent with the primordial CMB power spectrum predicted by standard cosmological models. On the other hand, the measured power in the highest multipole bin is also consistent with the excess detected by the CBI experiment. Fluctuations due to extragalactic radio sources in the ACBAR band are quite small (of a few μK at $\ell_{\rm eff} = 2507$). Quoting results by Blain et al. (1998), Kuo et al. (2004) conclude that dusty proto-galaxies are also not expected to contribute significantly to the observed signal. However, the Blain et al. (1998) estimate actually refers to Poisson fluctuations only, while it has been pointed out by several authors (Scott & White 1999; Haiman & Knox 2000; Magliocchetti et al. 2001; Perrotta et al. 2003; Negrello et al. 2004) that the strong positional correlation of SCUBA galaxies, indicated by observational data and theoretical arguments, implies that the main contribution on ACBAR scales comes from source clustering. On the other hand, the rest-frame mm-wave emission of these sources is poorly known. If dusty proto-spheroidal galaxies have the excess emission (compared to model expectations) discussed in Sect. 3.2 (Fig. 3, right-hand panel), the power measured in the highest multipole bin is easily explained in terms of fluctuations due to undetected high-z galaxies. Anyway, dusty proto-spheroids are always giving a relevant contribution to the measured power, even without excess emission (Fig. 3, left-hand panel).

4. Conclusions

Contamination from extragalactic point sources appears to be a likely candidate to account for a large fraction, perhaps for most of the excess power on arcminute scales detected by the CBI and BIMA experiments. The fluctuations due to radio sources undetected by the ancillary low-frequency surveys may in fact be higher than estimated by the CBI and BIMA groups. On the other hand, we argue that extreme GHz Peaked Spectrum sources and advection dominated sources, potentially worrisome because of their spectra peaking at high microwave/mm-wave wavelengths, should provide only a minor contribution to the CBI and BIMA signals.

Although the very steep 15 μm counts of starburst galaxies below a few mJy imply a very strong cosmological evolution, the radio surveys down to μJy levels constrain the contribution of their *radio* emission to fluctuations at 30 GHz to be relatively small. On the other hand, the *dust* emission at rest-frame mm wavelengths from star-forming galaxies at high-redshifts,

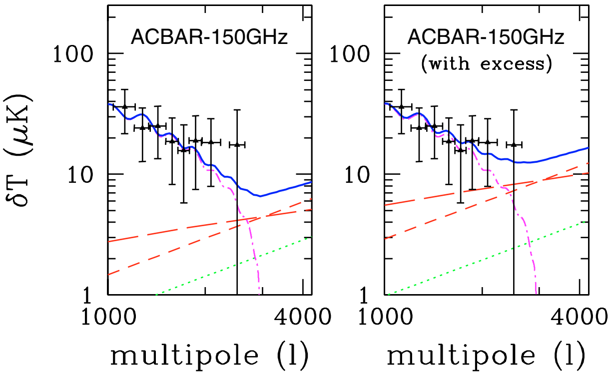

Fig. 3. Angular power spectrum ($\delta T = \sqrt{\ell(\ell+1)C_\ell/2\pi}$) measured by ACBAR at 150 GHz (data points are from Kuo et al. 2004). The dotted, long- and short-dashed, and dot-dashed curves have the same meaning as in Fig. 2; the solid lines are the quadratic sum of all the contributions. The contribution given by undetected Poisson distributed and clustered proto-spheroidal galaxies has been calculated without (*left-hand panel*) and with (*right-hand panel*) the excess mm-wave emission discussed in the text. In this case we adopted $S_{\rm lim} \simeq 24$ mJy (*left-hand panel*) and $S_{\rm lim} \simeq 43$ mJy (*right-hand panel*) for source detection. These limits correspond to the 5σ source detection threshold estimated as in Negrello et al. (2004) for a $5'$ *FWHM*.

such as those detected by SCUBA and MAMBO surveys, can be redshifted down to 30 GHz. Using the spectral energy distributions given by the Granato et al. (2004) model, we find that these sources yield fluctuations of a few to several μK on arcminute scales. Their rest-frame spectral energy distribution at mm wavelengths, however, is poorly known, and may well be higher than implied by the adopted model.

Moreover, observational indications and the theoretical arguments converge in suggesting that they are highly clustered (see Negrello et al. 2004, and references therein), so that their fluctuations may be strongly super-Poissonian for multipoles $\ell \lesssim 3000$ (remember that the clustering-to-Poisson ratio increases with the angular scale, i.e. with decreasing multipole number, De Zotti et al. 1996). Clustering fluctuations of the high-z galaxies detected by (sub)-mm SCUBA and MAMBO surveys may indeed dominate the contamination by extragalactic sources of the signal measured by the ACBAR experiment at 150 GHz.

Because the dust emission spectrum rises very steeply with frequency, lower frequency surveys cannot be used to remove their effect from 30 GHz maps. In the present data situation, they therefore set an *unavoidable* limit to the determination of the primordial CMB angular power spectrum at high multipoles, even at frequencies as low as ~30 GHz.

We stress that the present results are fully compatible with the estimated contributions of Sunyaev-Zeldovich effects in clusters of galaxies to the arcminute scale anisotropies. In fact, while an interpretation of the full CBI and BIMA signals in terms of SZ fluctuations would require a density fluctuation amplitude (measured by the parameter σ_8) at or above the limit allowed by current data (Bond et al. 2005), our analysis leaves room for an SZ contribution corresponding to the σ_8 values favoured by analyses of CMB, cosmic shear, and large scale structure data (Spergel et al. 2003; Pierpaoli et al. 2003; Van Waerbecke et al. 2005).

New interesting constraints on the CMB angular power spectrum up to $\ell \sim 2500$ at 34 GHz should be provided in the near future by the VSA experiment (see, e.g., Rebolo et al. 2004). The reduced noise level of the new configuration and an effective cleaning of deep fields down to ~5 mJy – by dedicated observations with the Ryle Telescope at 15 GHz – will shed new light on the nature of the excess at high multipole and on the point source populations mainly contributing to the number counts at $S_{34} \sim$ a few mJy. Moreover, *Planck* HFI data as well as the forthcoming surveys by the *Herschel* telescope – at frequencies where the emission due to cold dust grains is the dominant one – shall be unique in determining much better the cosmological evolution, the emission and the clustering properties of high-redshift dusty galaxies.

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