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 to the arcminute scale fluctuations measured by the CBI, BIMA, and ACBAR experiments are discussed. It is concluded that unsubtracted sources can easily account for the excess power at high multipoles detected by CBI and BIMA observations. Anisotropies due to dusty proto-spheroidal galaxies can contribute significantly to the signal measured by ACBAR in the highest multipole bins.

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 \( \Delta T \lesssim 26 \mu K \), 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 effect (SZE), which is expected to dominate CMB anisotropies on angular scales of a few arcminutes (Gnedin & Jaffe 2001). However, an interpretation on terms of SZEs from clusters of galaxies (Bond et al. 2002; Komatsu & Seljak 2002) or to the inhomogeneous plasma distribution during the formation of large scale structure (Zhang et al. 2002) requires values of \( \sigma_8 \) (the rms density fluctuation on a scale of 8 \( h^{-1} \) Mpc) significantly higher than indicated by current data (see, e.g., Cooray & Melchiorri 2002; Pierpaoli et al. 2003). SZEs 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 Section 2 we describe the different source populations which give the dominant contributions to number counts at cm and mm wavelengths. In Section 3 we present our estimates of arcminute-scale CMB anisotropies due to extragalactic sources, while in Section 4 we summarize our main conclusions.

A flat \( \Lambda \)CDM 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) are shown in Fig. 1. The counts of canonical steep- and flat-spectrum radio sources, and of active star-forming galaxies (primarily starburst galaxies) come from the model of Toffolatti et al. (1998) which successfully reproduces the low-frequency counts down to sub-mJy levels. It is worth mentioning that the more recent data at 8.4 GHz (Fomalont et al. 2002) on deep counts down to $\simeq 10 \, \mu$Jy are still in very good agreement with the model predictions, thus confirming that the choices on the source populations and on their cosmological evolution were basically correct. The quoted model is also consistent with the recent high-frequency survey data at $\nu \leq 30$ GHz, with a maximum offset of a factor of $\simeq 0.7$ at the brightest fluxes (see, e.g., Bennett et al. 2003; Argüeso et al. 2003). The Toffolatti et al. (1998) model does not include radio-source populations with spectra raising with frequency, such as GHz-Peaked Spectrum (GPS) sources and Advection Dominated Accretion Flows (ADAFs). However such sources have much lower surface densities than canonical radio sources even at high frequencies, and therefore their contribution to small scale fluctuations is negligible. This is shown by the detailed analysis by De Zotti et al. (2000) for GPS sources. As for ADAFs, we note that Perna & Di Matteo (2000) have strongly overestimated their counts, probably due to a numerical error. Their estimates are ruled out by the current results of the Ryle telescope, ATCA and WMAP surveys.

The slope of the differential counts of starburst galaxies can exceed 3, if these objects have to account for the very steep ISOCAM $15 \mu$m 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. 2004). In this case, their main contribution to small scale fluctuations comes from weak sources, at $\mu$Jy levels, far fainter than those removed from CBI and BIMA maps. On the other hand, the counts of such sources are tightly constrained by $\mu$Jy 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, we find that they can only provide a minor contribution to the excess power detected by BIMA and CBI: $\simeq 3.1 - 4.8 \mu$K at $\ell \simeq 6880$, by using two different detection limits, $S_d = 150$ and $400 \, \mu$Jy, for BIMA and $\simeq 3.7 \mu$K at $\ell \simeq 2500$ ($S_d = 3.4$ mJy) for CBI, respectively. Their contribution is negligible at the ACBAR frequency.

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 $\mu$m and 1.2mm 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 ($S_\nu \propto \nu^\alpha$), takes over. Since these sources are at typical redshifts $\gtrsim 2$ (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 (thick) 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 $\lambda \gtrsim 1$ mm was however detected in several Galactic clouds, combining Archeops with WMAP and DIRBE data (Bernard et al. 2003; Dupac et al. 2003a), and in NGC1569 (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. 2003b). 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 40m 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 $S_{31\text{GHz}} > 21$ 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.

On the other hand, 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 $S_{30\text{GHz}} \approx 400$ mJy, not removed by the constraint matrix) and of variability. While our discussion in §2 indicates that inverted-spectrum sources should not be a big problem in the present framework, flat-spectrum sources are highly variable on timescales of years, and the variability amplitude increases with frequency (Impey & Neugebauer 1988; Ciaramella et al. 2004) 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 18 GHz flux densities of extragalactic sources detected by the ATCA pilot survey (Ricci et al. 2004) and the SUMSS flux densities at 0.84 GHz (i.e. at a frequency not far from that of the NVSS survey).

Flat-spectrum sources dominate the point-source contribution to CBI fluctuations. Based on the above argument, it can be expected that they are effectively subtracted only down to $S_{30\text{GHz}} \simeq 3-4$ mJy. If so, the residual Poisson fluctuations due to them can account for the excess power reported by Readhead et al. (2004), $\Delta T^2 = 355^{+137}_{-122} \mu K^2$ (see Fig. 3, left-hand panel).

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. (2004). 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 $S_{30\text{GHz}} < 3.4$ 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. The differential counts of detected sources sink down below $\simeq 400 \mu$Jy (see Fig. 2) suggesting the onset of incompleteness, since Fomalont et al. (1991) find, at the same frequency, that the counts are consistent with keeping a constant slope in the flux density range from 1 mJy to 16 $\mu$Jy. The counts by Fomalont et
al. (1991), \( N(S) = (23.2 \pm 2.8) \times S^{-1.18 \pm 0.19} \text{arcmin}^{-2} \) for 16 \( \mu \text{Jy} \leq S \leq 1 \text{mJy} \), are, again, in agreement with predictions of the Toffolatti et al. (1998) model. For example, the model yields \( N(S) \approx 0.025 \) and \( 0.093 \text{arcmin}^{-2} \) for \( S = 400 \) and 100 \( \mu \text{Jy} \), respectively, to be compared with the observed values of \( \approx 0.020 \) and \( 0.101 \text{arcmin}^{-2} \).

The surface density of sources brighter than \( S_{48} \approx 400 \mu \text{Jy} \) in the BIMA fields (total area \( \approx 0.1 \text{deg}^2 \)) is \( 6.9 \times 10^{-2} \text{arcmin}^{-2} \), corresponding to the highest normalization factor (26) and the flattest slope (-0.99) of the Fomalont et al. (1991) formula. The dotted line in Fig. 2 corresponds to these values of the slope and of the normalization. Taking into account that below \( S_{48} \approx 400 \mu \text{Jy} \) the fraction of flat-spectrum sources is approximately constant and \( \approx 60\% \) (cf. Table 9 of Fomalont et al. 1991), neglecting the contribution of steep-spectrum sources and adopting a spectral index \( \alpha = -0.2 \) \( (S_\nu \propto \nu^\alpha) \) for the flat-spectrum sources, the power at the average BIMA multipole \( \ell_{\text{eff}} = 6864 \) due to sources below the completeness limit is \( \Delta T \approx 23 \mu \text{K} \), at the upper end of the range found by Dawson et al. (2002). This estimate has been decreased by 20\%, down to \( \Delta T \approx 19 \mu \text{K} \), to take into account the removed sources below the completeness limit (Fig. 3; right-hand panel).

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 \( r_0 = 8.3 h^{-1} \text{Mpc} \), being the Hubble constant in units of 100 \( \text{km s}^{-1} \text{Mpc}^{-1} \), (see Negrello et al. 2004) we find, at \( \ell_{\text{eff}} = 6864 \), a Poisson contribution of \( \approx 5 \mu \text{K} \) and a clustering contribution of \( \approx 3 \mu \text{K} \). Clearly these contributions, to be summed in quadrature to the contribution discussed above, have a minor effect. On the other hand, if these sources show the mm excess mentioned in Sect. 2, their contribution to fluctuations would be approximately doubled (see Fig. 3), and, when summed in quadrature to the above estimate of the contribution of flat-spectrum sources, would imply a signal only marginally consistent with, or in excess of, the BIMA data. Thus the BIMA fluctuation level is providing interesting constraints on the mm spectrum of these sources.

### 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 \( \mu \text{K} \) at \( \ell_{\text{eff}} = 2507 \)).

**Fig. 3.** 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 plot: the primordial CMB angular power spectrum (dot-dashed line); the estimated contribution of undetected Poisson distributed flat– and steep–spectrum radio sources (dotted line); the contribution of undetected Poisson distributed (short-dashed line) and of clustered (long-dashed line) proto-spheroidal galaxies; the thick solid line shows the sum of the different contributions. In the CBI case we have plotted the contributions of radio sources with \( S_{30\text{GHz}} \leq 3.4 \text{mJy} \), based on the Toffolatti et al. (1998) model. In the BIMA case we have used the counts shown by the dotted line in Fig. 2 extrapolated as described in the text, with a flux limit of \( S_{1.4\text{GHz}} \leq 400 \mu \text{Jy} \); the resulting fluctuation amplitude was decreased by 20\% to allow for the partial subtraction of sources below the adopted flux limit. The contributions of proto-spheroidal galaxies are insensitive to the adopted flux limit because of the very steep counts. In the right-hand panel we also show (upper short- and long-dashed thin lines) the contribution of proto-spheroidal galaxies with excess mm-wave emission (see text).
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. 4, left-hand panel).

4. Conclusions

Contamination from extragalactic point sources appears to be a likely candidate to account for the excess power on arcminute scales detected by the CBI and BIMA experiments. We have shown that the population of undetected classical flat– and steep–spectrum radio sources is the dominant contributor to arcminute-scale fluctuations at 30 GHz.

Galaxies whose radio emission is associated with very active star-formation (starburst and proto-spheroidal galaxies) are expected to provide a relatively small, but not negligible, contribution. In the case of active star-forming galaxies at high-redshifts, such as those detected by SCUBA and MAMBO surveys, the 30 GHz flux may be due to red-shifted dust emission at rest-frame mm wavelengths. Using the model by Granato et al. (2004), we find that these sources yield fluctuations of a few to several $\mu$K on arc-min scales. Their rest-frame spectral energy distribution at mm wavelengths, however, is largely unknown, and may well be higher than implied by the models we adopted. In any case, it is important to keep in mind that, because the dust emission spectrum rises very steeply with frequency, lower frequency surveys cannot be used to remove their effect from 30 GHz maps. 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 $\sim 30$ GHz.

The strong clustering of dusty proto-spheroidal galaxies indicated by observational data (see Negrello et al. 2004, and references therein) gives rise to a signal which is comparable to or higher than the Poisson term at $\ell \leq 2500$–3000, given that the clustering-to-Poisson ratio increases with the angular scale, i.e. with decreasing multipole number (De Zotti et al. 1996). As discussed in Sect 3.3, this signal is contributing significantly to the excess power measured by ACBAR in the highest multipole bin.

New interesting constraints on the CMB angular power spectrum up to $\ell \sim 2500$ at 34 GHz should be provided in the next future by the VSA experiment. The reduced noise level of the new configuration and an effective cleaning of deep fields down to $\sim 5$ 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 $S_{34} \sim 1$ 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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