Extragalactic Source Counts and Contributions to the Anisotropies of the Cosmic Microwave Background. Predictions for the Planck Surveyor mission.

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Accepted 1998 January 15. Received 1997 December 19; in original form 1997 September 29

ABSTRACT

We present predictions for the counts of extragalactic sources, the contributions to fluctuations and their angular power spectrum in each channel foreseen for the Planck Surveyor (formerly COBRAS/SAMBA) mission. The contribution to fluctuations due to clustering of both radio and far–IR sources is found to be generally small in comparison with the Poisson term; however the relative importance of the clustering contribution increases and may eventually become dominant if sources are identified and subtracted down to faint flux limits. The central Planck frequency bands are expected to be “clean”: at high galactic latitude (|b| > 20°), where the reduced galactic noise does not prevent the detection of the extragalactic signal, only a tiny fraction of pixels is found to be contaminated by discrete extragalactic sources. Moreover, the “flat” angular power spectrum of fluctuations due to extragalactic sources substantially differs from that of primordial fluctuations; therefore, the removal of contaminating signals is eased even at frequencies where point sources give a sizeable contribution to the foreground noise.

Key words: cosmic microwave background: anisotropies, foregrounds – radio and far–IR sources: counts, spatial distribution – galaxies: evolution.

1 INTRODUCTION

The long-sought COBE/DMR discovery (Smoot et al. 1992) of anisotropies of the Cosmic Microwave Background (CMB) has stimulated an outburst of activity in the field. Many new experiments have been undertaken and detections of CMB fluctuations have been reported on several angular scales (see White, Scott & Silk 1994; Smoot 1997 for reviews).

An unavoidable fundamental limitation to these measurements is set by astrophysical foregrounds. Due to the large beam size, the COBE/DMR data are, to some extent, contaminated by the galactic emission (see, e.g., Kogut et al. 1996a,b) whereas they are basically unaffected by extragalactic foreground sources (Banday et al. 1996; Kogut et al. 1994). On the other hand, extragalactic foregrounds are a major problem for high resolution experiments reaching the sensitivity of \( \Delta T/T \simeq 10^{-6} \), as the recently selected ESA’s COBRAS/SAMBA – now Planck Surveyor – and NASA’s MAP satellite missions, as well as some balloon–borne experiments, do.

This paper presents a thorough analysis of the extragalactic foreground contribution to small scale fluctuations, over the full wavelength range from \( \sim 1 \) cm down to \( \sim 300 \) \( \mu \)m covered by the Planck mission. The ten channels currently foreseen for the experiment as well as some relevant details on the payload characteristics are given in Table 1.

Estimates of temperature fluctuations due to a Poisson distribution of extragalactic sources have been worked out by Franceschini et al. (1989, 1991), Wang (1991), Blain & Longair (1993), Toffolatti et al. (1995), Danese et al. (1996), Tegmark & Efstathiou (1996), and Gawiser & Smoot (1997).

In the frequency range of interest here, there are im-
portant contributions both from the high frequency tail of the spectrum of radio sources and from the long wavelength portion of the dust emission in galaxies. The present work improves on previous analyses for both populations.

We adopt updated models for the evolution of galaxies which account for the faint number counts at 60 µm, recently reassessed by Bertin, Dennefeld & Moshir (1997) as well as for the preliminary estimates of deep counts at 6.7 and 15 µm (Oliver et al. 1997) obtained from long exposures with the camera of the Infrared Space Observatory (ISO) and at 170 µm with the ISO long-wavelength photometer (Kawara et al. 1997), as discussed by Franceschini et al. (1997). Our models deal in a self-consistent way with the evolution of the spectral energy distribution of galaxies from UV to far-IR wavelengths (Mazzei, Xu & De Zotti 1992; Mazzei, De Zotti & Xu 1994), so that we can take advantage of surveys in a broad wavelength range to test them. Also, they naturally predict a relationship between the dust temperature and the spectral energy distribution of galaxies from UV to far-IR wavelengths (Mazzei, Xu & De Zotti 1992; Mazzei, De Zotti & Xu 1994), consistent with the observed warmer dust emission spectra, consistent with the observed and the bolometric luminosity of IRAS selected galaxies (cf. e.g. Sanders & Mirabel 1996).

Moreover, we have explored various possibilities for the shape of the high frequency spectra of radio selected sources to take into account that the situation is likely rather complex: on one side, the non thermal emission spectrum of compact sources is expected to steepen or even to break at mm wavelengths; on the other hand, substantial contributions at these wavelengths probably due to dust emission have been reported for several objects.

We also give a quantitative estimate of the additional contributions to fluctuations due to clustering.

The outline of the paper is as follows. In Section 2 we briefly review the basic formalism. In Section 3 we deal with source counts and their extrapolation to the Planck bands. Our results are presented and discussed in Section 4. Finally, in Section 5, we summarize our main conclusions.

Throughout this paper we will adopt an Einstein-de Sitter (Ω = 1) cosmology with a Hubble parameter of $H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$.

# 2 BASIC FORMALISM

All the estimates presented in this paper are based on the assumption of “point-like” sources. As shown by Rowan–Robinson & Fabian (1974), this is a good approximation as far as the angular sizes of sources do not exceed the beam width. This is generally the case for the Planck mission (FWHM ≥ 10′ at ν ≤ 140 GHz and FWHM ≥ 4.4 for the high frequency channels; see Table 1); the pixels contaminated by the few bright very extended sources will be anyway removed.

## 2.1 Sky fluctuations from randomly distributed sources

The problem has been extensively discussed in the literature (Scheuer 1957, 1974; Condon 1974; Franceschini et al. 1989); we recall here only the basic points. A useful estimate of the fluctuation level generated by randomly distributed sources is provided by the second moment, $\sigma$, of the distribution of the mean number, $R(x)$, of responses $x = Sf(\psi)$ to sources of flux $S$ located at an angular distance $\theta$ from the beam axis, $f(\psi)$ being the angular power pattern of the detector, for which we adopt a gaussian shape with FWHM $\theta_0$:

$$\sigma^2 = \int_0^{\infty} x^2 R(x) dx = \pi \theta_0^2 I(x_c),$$

with

$$I(x_c) = \int_{-\infty}^{\infty} dx^2 \int_0^{\infty} d\psi \psi N \left( \frac{x}{f(\psi)} \right) \exp(4\psi \ln 2),$$

where $\psi = (\theta/\theta_0)^2$, $N(S)$ are the differential source counts per steradian at a given frequency $\nu$ and $x_c$ is the limit above which a source is considered to be individually detected. Following Condon (1974), we set $x_c = 3\sigma$; $g$ is usually taken in the range 3–5. We adopt $x_c = 5\sigma$ throughout this paper. The confusion standard deviation $\sigma$ is related to the rms brightness temperature fluctuations $(\Delta T/T)_{\text{rms}} \equiv (\langle (\Delta T/T)^2 \rangle)^{1/2}$, at the wavelength $\lambda$ by:

$$\left( \frac{\Delta T}{T} \right)_{\text{rms}} = \frac{\lambda^2 \sigma}{2kT\omega_{\text{eff},1}} \left[ \exp \left( \frac{h\nu}{kT} \right) - 1 \right]^2 \times \exp \left( -\frac{h\nu}{kT} \right) / \left( \frac{kT}{h\nu} \right)^2,$$

where $\omega_{\text{eff},1} = \int d\omega f(\psi)$

is the effective beam area, $d\omega$ being the solid angle differential element (De Zotti et al., 1996a). In terms of the angular distance $\theta$ from the beam axis equation (4) reads $\omega_{\text{eff},1} = \pi f d\theta^2 f(\theta)$ (Franceschini et al., 1989). $T = 2.726 K$ (Mathers et al. 1994) is the brightness temperature of the CMB. In terms of intensity fluctuations we have:

$$\left( \frac{\Delta I}{I} \right)_{\text{rms}} = \frac{\sigma}{I_{\text{eff},1}}.$$

In the Rayleigh Jeans region $\Delta I/\nu \simeq \Delta T/T$ while at the peak of the intensity of the CMB, $\langle \lambda \simeq 1 \text{ mm} \rangle$, $\Delta I_\nu/\nu \simeq 3\Delta T/T$.

## 2.2 Fluctuations due to clustered sources

Clustering decreases the effective number of objects in randomly distributed cells and, consequently, enhances the cell-to-cell fluctuations (Peebles 1980; Barcons & Fabian 1988). The analysis of a complete sample of nearby ($z < 0.1$) radiogalaxies selected at 1.4 GHz (Peacock & Nicholson 1991) has shown that, at least in a particular range of radio power, sources are strongly clustered (correlation length $r_0 \simeq 22(H_0/50)^{-1}$ Mpc). Evidences of a strong angular correlation were found by Kooiman, Burns & Klypin (1995) in the Green Bank 4.85 GHz catalog. More recently, Loan, Wall & Lahav (1997) estimated the angular two–point correlation function of sources selected at 4.85 GHz, by combining the Green Bank and Parkes–MIT–NRAO surveys. For an evolution index of the correlation function (Peebles 1980) in the range $-1.2 < \epsilon < 0$ they found 26 Mpc < ($H_0/50)r_0$ < 36 Mpc.
The contribution of clustering to intensity fluctuations is straightforwardly obtained from the angular correlation function \( C(\theta_s) \), as a function of the angular separation \( \theta_s \), setting \( \theta_s = 0 \) (see, e.g., De Zotti et al. 1996a). If the clustering scale is much smaller than the Hubble radius, we have:

\[
\left( \frac{\delta T}{T} \right)_{cl} = \Gamma(\theta_s \to 0) = \sqrt{\frac{C(\theta_s \to 0)}{(I)^2}}
\]

where \( (I) \) is the mean background intensity and

\[
C(\theta_s) = \left( \frac{c}{4\pi H_0} \right)^2 \int d\omega f(\theta, \varphi) \int d\omega f(\theta', \varphi') \times \int_{\Delta(z_{\max})}^{\Delta(z_{\min})} dz \frac{\delta_{i\Delta}(z)}{(1+z)^5(1+\Omega z)^{\beta}} \times \int_{\Delta(r_{\max})}^{\Delta(r_{\min})} d(\delta z)\xi(r, z).
\]

Here \( \xi(r, z) = h(z)\xi_0(r) \) is the two-point spatial correlation function, with \( \xi_0(r) = (r_0/r)^{\beta} \). For the clustering evolution function we adopt the usual simple expression \( h(z) = (1 + z)^{-3+\beta} \). \( \Delta(r_{\max}) \) is the value of \( \delta z \) corresponding to the maximum scale of clustering, \( S_t \) is the adopted flux limit and

\[
\text{effective volume emissivity, } n_e(L, z) \text{ being the comoving number density of sources and } K(L, z) \text{ the K-correction factor. The pairs of angles } (\theta, \varphi) \text{ and } (\theta', \varphi') \text{ define two directions separated by an angle } \theta_s. \text{ It is worth stressing that, while for differential source counts } [N(S) \propto S^{-\beta}] \text{ with slope } \beta < 3 \text{ the Poisson noise is dominated by the sources just below the detection threshold, } S_t, \text{ the main contribution due to clustering always comes from the faintest sources which do actually cluster on the given angular scale. Therefore, lowering } S_t \text{ results in an increase of the relative importance of the clustering term in comparison with the Poisson one.}

### 2.3 Angular power spectrum analysis of the intensity fluctuations

We consider, as usual, the spherical harmonic expansion of the sky temperature fluctuations:

\[
\frac{\delta T}{T} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^i Y_{\ell m}^i(\theta, \varphi).
\]

If the fluctuations are a stationary process, the angular power spectrum is independent of \( m \) (see Peebles 1993, p. 517), so that

\[
C_\ell(\nu) = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}^i|^2 \rangle = \langle |a_{\ell 0}^i|^2 \rangle.
\]

with

\[
a_{\ell 0}^i = \int \frac{\delta T}{T}(\theta, \varphi) Y_{\ell 0}^i(\theta, \varphi) d\Omega,
\]

or, in terms of Legendre polynomials,

\[
a_{\ell 0}^i = \int_0^{2\pi} \int_0^{\pi} \frac{\delta T}{T}(\theta, \varphi) \sqrt{\frac{2\ell+1}{4\pi}} P_{\ell}(\cos \theta) \sin \theta d\theta d\varphi.
\]

The estimate of \( C_\ell(\nu) \) is obtained by dividing the sky in \([N \times N]\) “equal area” cells (the cell dimension being \( 1.5 \times 1.5 \text{ arcmin}^2 \)) \([\delta \varphi_{-1, 1} \times \delta \varphi_{1, 1}] \) so that in every cell the fluctuation \( \delta T/T_0 \) can be considered constant. Then

\[
a_{\ell 0}^i = \frac{N_i}{N} \sum_{i=1}^{N} \sum_{j=1}^{N} \left( \frac{\delta T}{T} \right)_{i, j} \sqrt{\frac{2\ell+1}{4\pi}} \frac{2\pi}{N} A_{\ell i}(\nu). \quad (13)
\]
where

\[ \frac{A_{\ell(i)}}{2\ell + 1} = \int_{\cos \vartheta} \vartheta d\vartheta = \frac{1}{2\ell + 1} \left[ P_{\ell-1} (\cos \vartheta_i) - P_{\ell+1} (\cos \vartheta_{i-1}) \right]. \]

The temperature fluctuations \( \langle \delta T_i/T \rangle, j \rangle \) in every cell were calculated from simulations of the all-sky distribution of extragalactic point-like sources, based on our estimates of the source counts for each frequency channel of the Planck mission, rather than from the formulae derived by Tegmark & Efstathiou (1996). This approach allows to calculate the angular power spectrum under more general conditions (in particular allowing for the effect of clustering) since it only requires that the overall source distribution be statistically isotropic. We have checked that, assuming a Poisson distribution and using the source counts estimated by Tegmark & Efstathiou (1996), our method reproduces their results. Following Tegmark & Efstathiou (1996) we then computed the quantities

\[ \delta T_\ell (\nu) = [\ell (\ell + 1) C_\ell (\nu)/2\pi]^{1/2}. \]

3 SOURCE COUNTS AND THEIR EXTRAPOLATION TO MILLIMETER AND SUB-MM WAVELENGTHS

3.1 Counts of radio sources

Deep VLA surveys have allowed to extend direct determinations of radio source counts down to \( \mu\text{Jy} \) levels at 1.41, 4.86 and 8.44 GHz. At these frequencies counts now cover about 7 orders of magnitude in flux and reach an areal density of several sources arcmin\(^{-2}\). Therefore, at these frequencies, fluctuations can be determined directly from the counts down to angular scales much smaller than those of interest here.

As shown by Figure 1, the model by Danese et al. (1987) provides a good fit to the available data, at least for \( S > 100 \mu\text{Jy} \). Particularly encouraging is the good agreement with the deep counts at 8.44 GHz (Windhorst et al. 1993; Partridge et al. 1997), which were produced several years after the model, indicating that the adopted distribution of spectral indices of sources was appropriate.

Counts below 100 \( \mu\text{Jy} \) affect fluctuations due to radio sources on scales much smaller than those reachable by the Planck mission.

The assumptions about source spectra are obviously the most critical ingredient for the purposes extrapolation of the observed counts to much higher frequencies.

Radio loud AGNs, including "flat"-spectrum radio-galaxies, quasars, BL-Lacs, mostly at substantial \( z \), are expected to dominate the counts in the Planck low frequency channels for \( S \gtrsim 1 \text{mJy} \) and, correspondingly, the contribution of extragalactic sources to fluctuations on the angular scales of interest here.

The analysis of Impey & Neugebauer (1988), giving the spectral indices of 162 blazars, and the quasi-simultaneous observations of 176 bright compact sources done by Edelson (1987), have shown that compact sources have "flat" spectra \( S(\nu) \propto \nu^{-\alpha} \), with \( \alpha \approx 0 \), although with some scatter) at least up to \( \sim 100 \text{GHz} \). This conclusion agrees with previous analyses (Owen, Spangler & Cotton 1980), which showed that the spectral indices of most strong flat-spectrum radio sources keep flat \((\alpha < 0.3)\) in the range 1 to 100 GHz.

At still higher frequencies, a steepening or even a spectral break of the synchrotron emission is expected. On the other hand, the presence of excess mm emission over extrapolations from cm wavelengths has been established by Knapp & Patten (1991) for a sample of nearby radio galaxies. Observations of large mm fluxes attributed to dust emissions have been reported for several distant radio galaxies (see Mazzei & De Zotti, 1996 and references therein). The inferred dust masses are 1–2 orders of magnitude higher than found for nearby radio galaxies. The two components (synchrotron and dust emission) may well have different evolution properties.

In view of the uncertainties on the spectra mentioned above, our estimates of counts and fluctuations due to radio selected sources have been calculated as it follows. We adopt the Danese et al. (1987) simple luminosity evolution model and three different choices for the average spectral index of "flat-spectrum" compact sources: a) \( \alpha = -0.3 \), b) \( \alpha = 0.0 \), and c) \( \alpha = 0.3 \) at \( 30 < \nu < 200 \text{GHz} \), with a steepening to \( \alpha = 0.7 \) at higher frequencies; below 20 GHz we have set \( \alpha = 0 \). As for "steep"-spectrum sources (elliptical, S0 and starburst galaxies), whose contribution to source counts is actually minor in the whole frequency range of interest here, the radio power–spectral index relation determined by Peacock and Gull (1981) has been adopted. The maximum and minimum number of expected radio sources in each Planck channel, given in Table 2, correspond to the two extreme values of \( \alpha \) for compact sources.

Holdaway et al. (1994) carried out sensitive 90 GHz observations of a sample selected at 5 GHz and observed at 8.47 GHz. They derived a distribution of spectral indices between 8.4 GHz and 90 GHz which allowed them to extrapolate to 90 GHz the 5 GHz source counts. They estimate that, over the entire sky, there are 178 sources with \( S_{90\text{GHz}} > 1 \text{Jy} \), almost a factor of 2 less than predicted by our model. However, as discussed by these authors, their estimate is somewhat below the number of known sources with \( S_{90\text{GHz}} > 1 \text{Jy} \), so that it should be viewed as a lower limit.

On the other hand, our estimate may miss a population of sources with strongly inverted radio spectra. However, the analysis by Condon et al. (1995) of a large sample of extragalactic sources detected by IRAS at \( \lambda = 60 \mu\text{m} \) and identified with VLA radio source catalogues at 4.85 GHz, found no evidence of a significant population of sources with spectra rising steeply from centimeter to millimeter wavelengths.

3.2 Counts of far–IR sources

Both in the case of normal and of many active galaxies (as far as we can tell, based on the very limited information currently available), at wavelengths shorter than a few mm (in the rest frame), dust emission rapidly overwhelms the radio emission. Due to the very steep increase with frequency of the dust emission spectrum at mm and sub-mm wavelengths \((\alpha \sim -3.5)\) the wavelength at which dust emission takes over does not change much between radio quiet and radio loud sources, in spite of the fact that the ratio of radio to far-IR

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emission for the former class is orders of magnitude lower than for the latter.

As in the case of radio sources, estimates of the counts of far-IR sources in the frequency region covered by the Planck instruments are difficult because of the wide gap with the nearest wavelength (60 $\mu$m) where the most extensive (yet relatively shallow) surveys exist. There is a considerable spread in the distribution of dust temperatures, so that the observed 1.3 mm/60 $\mu$m flux ratios of galaxies span about a factor of 10 (Chini et al. 1995; Franceschini & Andreani 1995; see also De Zotti et al. 1996b). A tentative estimate of the luminosity function of galaxies at mm wavelengths based on a 1.25 mm/60 $\mu$m bivariate luminosity distribution has been presented by Franceschini, Andreani & Danese (1997).

Furthermore, the observational constraints on evolution properties of far-IR sources are very poor. They come essentially from IRAS 60 $\mu$m counts, which cover a limited range in flux and are rather uncertain at the faint end (Hacking & Houck 1987; Gregorich et al. 1995; Ashby et al. 1996; Bertin, Dennefeld & Moshir 1997).

From a theoretical point of view, there is a great deal of uncertainty on the physical processes governing galaxy formation and evolution. Some models assume that the comoving density of galaxies remained essentially constant after their formation, while they evolved in luminosity due to the ageing of stellar populations and the birth of new generations of stars (pure luminosity evolution; see, i.e., Franceschini et al., 1994 for a most complete discussion on the subject). On the other hand, according to the hierarchical galaxy formation paradigm, big galaxies are formed by coalescence of large numbers of smaller objects (see, e.g. White 1996 and references therein).

Furthermore, evolution depends on an impressive number of unknown or poorly known parameters: merging rate, star formation rate, initial mass function, galactic winds, infall, interactions, dust properties, etc.

Although the evolutionary history is highly uncertain, strong evolution is expected in the far-IR/mm region particularly for early type galaxies since during their early phases they must have possessed a substantial metal enriched interstellar medium. This expectation is supported by evidences of large amounts of dust at high redshifts (cf. in particular the case of high-$z$ radiogalaxies: Mazzei & De Zotti, 1996) and by the intensity of the isotropic sub-mm component reported by Puget et al. (1996) from an analysis of COBE/FIRAS data (see Burigana et al. 1997).

Moreover, the K-correction due to the steep increase with frequency of the dust emission spectrum below the peak, generally located at $\lambda \sim 60-150$ $\mu$m, strongly amplifies the evolutionary effects, that may thus be appreciable in the relatively shallow Planck surveys, at least in the highest frequency bands.

In view of the above, we adopt here two different descriptions of the cosmological evolutions of far-IR sources.

i) Our reference model is an updated version of model C of Franceschini et al. (1994; opaque model), which provides a good fit (see Fig. 2) to the 60 $\mu$m IRAS counts, as recently reassessed by Bertin et al. (1997) and to the far-IR extragalactic background spectrum estimated by Puget et al. (1996), as shown by Burigana et al. (1997). The model also predicts counts at 170 $\mu$m and at 850 $\mu$m which are in agreement, respectively, with the preliminary estimates by Kawara et al. (1997) using the ISO long-wavelength photometer and by Smail, Ivison & Blain (1997) using the new bolometer array, SCUBA, on the JCMT (see Fig. 3).

Moreover, we find agreement with the recent estimate of the “source” confusion noise by Bertin et al. (1997; their Section 4.1), from the analysis of the IRAS Very Faint Source Sample (VFSS). Their estimated value is $\sigma_{\text{conf}} \sim 20$ mJy, about 2/3 of the total noise of 30.2 ± 1.2 mJy (instrumental noise plus source confusion added up in quadrature). By comparison, our reference model gives a confusion standard deviation of $\sigma_{\text{conf}} \sim 18-20$ mJy, with a gaussian beam pattern of FWHM=3 arcmin and integrating up to a source detection limit $x_c \sim 100$ mJy.

The updated opaque model adds a density evolution up to $z = 2$ of late type galaxies (spirals, irregulars, starburst) only, proportional $\exp(2\tau(z))$, with $\tau(z) = 1 - t(z)/t_0$, $t(z)$ being the age of the universe at redshift $z$ and $t_0$ its present age. The estimated $\Delta T/T_{\text{rms}}$ levels as well as the spatial power spectra of fluctuations due to far-IR extragalactic sources have all been computed exploiting this model (see Section 4).

On the other hand, the signal detected by Puget et al. (1996) may be contaminated by cold dust emission from an extended Galactic halo (Fixsen et al. 1996). In that case our reference model would provide an upper limit to the evolution of extragalactic sources in the far-IR.

ii) A lower evolution rate in the far-IR is implied by the moderate extinction model by Franceschini et al. (1994). This second model predicts source counts which are still compatible with the IRAS 60 $\mu$m counts and with the quoted estimated counts at 170 $\mu$m by Kawara et al. (1997). On the other hand, they slightly underestimate the number of sources quoted by Smail, Ivison & Blain (1997).

The estimated number counts, $N(>S_{\text{lim}})_{\text{FIR}}$, of far-IR sources in the HFI frequency channels are a factor $\sim 1.2-1.8$ lower than the counts plotted in Fig. 4 (our reference model) if $S_{\text{lim}} \sim 1$ Jy (the lower value, 1.2, applies to the number counts ratio at 857 GHz whereas the value 1.8 is found for the same ratio at 143 GHz). If we adopt the fainter flux limit of $S_{\text{lim}} \sim 10^{-2}$ Jy then the model predicts counts $\sim 1.4-2.2$ times lower than the updated model C. The increasing difference between the estimated number counts, if one moves shortward in frequency from 857 GHz down to 143 GHz, is determined by the steep rise with increasing frequency of the dust emission spectrum in the sub-mm domain which entails more important contributions to the counts from high redshift galaxies.

The $\Delta T/T_{\text{rms}}$ levels are only $\sim 20-40\%$ lower than those predicted by the reference model at the angular resolution limit of the HFI instrument. At larger angular scales the difference is negligible since the two models predict a very similar number of bright sources (see before). The maximum and minimum number of expected individually detected far-IR sources in the Planck surveys at $|b| > 20^\circ$ given in Table 2 correspond to the predictions of the updated model C and of the moderate extinction model.

The contribution of dust-rich galaxies to the radio counts (see Table 2) has been estimated assuming a linear relationship between the far-IR flux at 60 $\mu$m (dominated by the starburst component) and the radio centimetric flux. The ratio of the 60 $\mu$m to the radio flux at 1.4 GHz was assumed to be $S_{60\mu m}/S_{1.4\,\text{GHz}} \simeq 140$ (see Helou et al., 1985).
The contributions of AGNs to the counts in the high frequency channels (where, however, star-forming galaxies should be the dominant population) are even more uncertain, since they depend on the evolution of both the non-thermal component and the dust emission, which in turn depend on several unknown or poorly known factors, such as the evolution of the nuclear energy source, the effect of possible circumnuclear starbursts, the abundance, properties and distribution of dust, and so on. The IRAS survey data do not help much, since the detection rate of quasars was extremely low.

Taking only into account the evolution of the non-thermal component, assumed to parallel that observed in X-rays, and adopting the spectral energy distributions used by Granato et al. (1997) for type 1 and type 2 AGNs, we expect a detection rate of radio quiet AGNs increasing with increasing frequency: only a few of them are expected at 1.4 mm, but their number should increase up to a few hundreds at the highest frequencies. In any case, the number of radio quiet AGNs is negligible compared with the number of far-IR galaxies.

### 3.3 Total counts

Our estimates (see Table 2 and Figure 4) indicate that Planck counts are dominated by radiosources for frequencies up to about 200 GHz. Note that the large differences in the estimated numbers of radio selected sources is determined by the variation of the adopted values for the average spectral index of compact sources (see Section 3.1). It is interesting that significant numbers of radio galaxies should be detectable in all frequency channels, so that the Planck mission will allow to explore their poorly known high frequency spectra.

Also, the number of galaxies that should be detected in the high frequency channels is large enough to allow statistical investigations of their properties in this particularly interesting range and the definition of reliable local luminosity functions.

### 4 RESULTS AND DISCUSSION

Our estimates of the rms temperature fluctuations \((\langle \Delta T/T \rangle)_{\text{rms}} \equiv \langle (\Delta T/T)^2 \rangle^{1/2}\) as a function of the angular scale, and of the angular power spectra \([\delta T^2, \text{eq. (15)}]\) of fluctuations due to extragalactic point sources are shown in Figures 5–6 and 7–8 respectively.

#### 4.1 Poisson fluctuations

In Figures 5 and 6 the thick solid line corresponds to the case of “flat”-spectrum radio sources with average spectral index \(\alpha = 0\) above 20 GHz and far-IR sources evolving according to the updated model C by Franceschini et al. (1994). Sources brighter than 1 Jy are assumed to be individually identified and removed (a rather conservative assumption: cf. Table 2). The effect of subtracting fainter sources, identified by means of independent, deeper surveys is also shown.

Although we expect that the individually detected sources in the high galactic latitude Planck surveys at frequencies up to about 200 GHz (see Table 2) will be mostly radio sources, a significant contribution to fluctuations may come from far-IR sources well below the detection limit.

In fact, the steepness of the counts of far-IR sources in the flux density interval where evolution sets in (and its effect is boosted by the steep K-correction) implies that their dominant contribution to fluctuations may not come, as usual, from flux densities corresponding to one source per beam (where radiosources probably dominate) but, in some cases, from the fainter fluxes where the slope \(\beta\) of differential counts becomes \(> 3\).

On an angular scale \(\theta_0 \simeq 10^\circ\) far-IR sources do not contribute more than a few \(\%\) of the confusion fluctuations for \(\nu \lesssim 100\) GHz; at 150–200 GHz the contributions of radio and far-IR sources are comparable, while at higher frequencies, far-IR sources dominate.

The amplitude of confusion fluctuations, after subtraction of only those sources which are individually detected by the Planck instruments themselves, decreases from \(\Delta T/T \simeq 5 \times 10^{-6}\) at 30 GHz to \(\simeq 10^{-6}\) at \(\sim 100–150\) GHz, well below the expected rms primordial fluctuations.

It may be noted that up to \(\simeq 100\) GHz the rms fluctuations due to discrete sources, as a function of the angular scale, show a broad maximum at \(\theta_0 \simeq 10^\circ\), while they increase with decreasing \(\theta_0\) at higher frequencies, due to the contribution of evolving far-IR sources which becomes more and more important with increasing angular resolution of the survey.

As previously pointed out, the estimates of fluctuations due to far-IR sources are particularly uncertain since the available information on both their spectra and their evolutionary properties is poor. However, the deep IRAS 60 \(\mu\)m counts on one side and the upper limits on the far-IR background intensity on the other, strongly constrain the amplitude of fluctuations at the angular resolution of the high frequency channels of the Planck mission. Phenomenological pure luminosity evolution models without changes in the source spectra with cosmic time (Franceschini et al., 1988; 1991) consistent with the high 60 \(\mu\)m counts by Gregorich et al. (1995), which may be overestimated at the faint end because of source confusion, and barely consistent with the conservative upper limit on the extragalactic far-IR background derived by Shafer et al. (1997), entail fluctuations very close to those implied by the updated model C on scales above the angular resolution of the Planck mission; only below \(\sim 1.5\) arcmin the fluctuation level increases by a factor of 1.5–2.

Note that the effect of source variability is already included, in a statistical sense, in the above estimates. In fact, variability affects source counts in a manner similar to the Eddington effect: the observed counts are made systematically higher at brighter fluxes, since sources are preferentially detected in their brighter phases. Since fluctuations are estimated from observed counts, the effect is automatically taken into account. On the other hand, variability seriously hinders subtractions of sources based on observations at different frequencies or non-simultaneous.

#### 4.2 The effect of clustering

In the case of radio sources, based on the results by Loan et al. (1997), we have adopted an angular two-point correla-
Table 2. Instrumental and confusion noise estimates for the Planck mission and expected numbers of individually detectable sources at $|b| > 20^\circ$.

| $\nu_{\text{eff}}$ (GHz) | $\lambda_{\text{eff}}$ (mm) | beam (arcmin) | $\sigma_{\text{noise}}$ (mJy) | $\sigma_{\text{Gal}}$ (mJy) | $\sigma_{\text{conf}}$ (mJy) | $S_{\text{lim}}^{(1)}$ (mJy) | $S_{\text{lim}}^{(2)}$ (mJy) | $N(> S_{\text{lim}})_{\text{radio}}$ (8 sr) | $N(> S_{\text{lim}})_{\text{FIR}}$ (8 sr) |
|--------------------------|--------------------------|---------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 30                       | 10.0                     | 33            | 13             | 100            | 37             | 78             | 650             | 300-800         | 0-2             |
| 44                       | 6.8                      | 23            | 19             | 45             | 17             | 80             | 480             | 450-1600        | 3-10            |
| 70                       | 4.3                      | 14            | 25             | 15             | 8              | 68             | 330             | 600-2500        | 6-18            |
| 100                      | 3.0                      | 10.2          | 27             | 7              | 6              | 64             | 350             | 500-2800        | 4-12            |
| 100                      | 3.0                      | 10.6          | 13             | 7              | 6              | 64             | 330             | 500-2800        | 4-12            |
| 143                      | 2.1                      | 7.4           | 12             | 6              | 4              | 56             | 290             | 330-3600        | 5-15            |
| 217                      | 1.38                     | 4.9           | 14             | 5              | 4              | 31             | 180             | 350-4000        | 120-200         |
| 353                      | 0.85                     | 4.5           | 24             | 18             | 18             | 16             | 200             | 250-2000        | 2000-3500       |
| 545                      | 0.55                     | 4.5           | 44             | 62             | 45             | 3              | 450             | 40-250          | 6000-10000      |
| 857                      | 0.35                     | 4.5           | 36             | 120            | 70             | -              | 700             | 10-50           | 17000-25000     |

(1) Flux density fluctuations of the cosmic microwave background corresponding to $\Delta T/T = 10^{-5}$

(2) Adopted detection limit for discrete sources, equal to $5 \times (\sigma^2_{\text{noise}} + \sigma^2_{\text{conf}} + \sigma^2_{\text{Galaxy}} + \sigma^2_{\text{CMB}})^{1/2}$. A rough estimate of anisotropies, $\sigma_{\text{Galaxy}}$, due to the galactic emission at high galactic latitudes ($|b| > 20^\circ$), has been obtained following Danese et al. (1996) and Bersanelli et al. (1996; Fig. 2.3, 2.4 and Appendix A.1) and taking into account the angular dependence of galactic dust fluctuations determined by Gautier et al. (1992). If we neglect this correction factor, the galactic dust fluctuations at 217, 353, 545 and 857 GHz turn out to be larger by a factor $\sim 2.2$.

4.3 Angular power spectra of fluctuations

Following Tegmark & Efstathiou (1996) we have computed, and plotted in Figures 7 and 8, the quantity $\delta T_\ell(\nu)=\langle(\ell+1)C_\ell(\nu)/2\pi\rangle^{1/2}$ which is roughly the average rms temperature fluctuation in the multipole range $\ell_0 \leq \ell \leq \ell_1$ with $\ln(\ell_1/\ell_0) = 1$.

The plotted power spectra are the mean of 50 simulations of the all sky distribution of sources. Fluctuations are dominated by radio sources at the lowest frequencies (30, 44, 65 and 100 GHz) and by the far-IR sources at the highest (353, 545 and 857 GHz); both classes of sources are important at the intermediate frequencies (143, and 217 GHz). For far-IR sources the updated model C has been adopted. As mentioned above, this model may overestimate the fluctuation level. A spectral index $\alpha = 0$ was adopted for “flat-spectrum” radiosources. The effect of clustering was neglected.

It is assumed that sources brighter than 1, 0.1 and 0.01 Jy are identified and removed from the maps (see caption). For the 217 GHz band we also show the effect of removing only the few brightest sources ($S > 10$ Jy). As shown by Table 2, we expect that it will be possible to directly detect, and subtract out, sources down to flux densities of a few to several hundred mJy.

It may be noted that lowering the flux limit for source subtraction decreases the amplitude of fluctuations more effectively at low than at high frequencies. This is because of the steepness of the counts of far-IR sources at sub-mm wavelengths, implying substantial contributions to fluctuations from very faint sources.

Our results for a flux density cutoff of 100 mJy are substantially below those obtained by Tegmark & Efstathiou (1996) adopting the same flux limit (see Fig. 7). This is due to their assumption of a spectral index $\alpha = 0$ for all sources selected at 1.5 GHz. This leads to a substantial overestimate of the expected counts, since most 1.5 GHz sources in the relevant flux density range are known to have a steep ($\alpha \simeq 0.7$) spectrum.
5 CONCLUSIONS

Although, as stressed above, the present estimates are rather uncertain, particularly in the high frequency bands, it can be safely concluded that at least the central frequency channels will allow a clean view of primordial anisotropies up to the maximum $\ell$–values accessible to the Planck mission. In fact, even under the most extreme assumptions compatible with the available information on high frequency spectra of radio sources and on the evolution properties of far-IR sources, the amplitude of fluctuations due to discrete sources in the 100–200 GHz range are well below the expected amplitude of primordial anisotropies.

The availability of multifrequency data allows an efficient identification of pixels contaminated by discrete sources. Table 2 shows that many sources not directly detectable in the central frequency channels can be identified at higher or lower frequencies. The corresponding pixels can be simply removed; thanks to the large area surveyed, the number of remaining clean pixels will be nevertheless very high. But a reliable subtraction of the contaminating flux may also be possible thanks to the fact that a significant number of sources of the various classes should be detectable in most or all frequency channels, allowing the definition of well defined template spectra.

Moreover, removal of contaminating signals is eased by the substantial difference between their power spectrum and that of primordial fluctuations (Tegmark & Efstathiou 1996).

On the other hand, the Planck mission will bridge the gap between radio surveys, carried out at $\nu \leq 8.4$ GHz ($\lambda \geq 3.6$ cm) and far-IR surveys (IRAS and ISO) at $\nu \geq 1500$–3000 GHz ($\lambda \leq 100$–200 $\mu$m), providing the first exploration of the whole sky in a spectral region where many interesting astrophysical phenomena are most easily investigated. A pot-pourri of issues for which these data will be extremely relevant include: bremsstrahlung emission as a tracer of evolution of stellar populations; high-frequency behaviour of the spectra of compact radio sources and implications for their physical properties; definition of unbiased samples of blazars; cold dust in galaxies and hints on its evolution; physical and evolutionary connections between nuclear activity and processes governing the abundance and the properties of the interstellar material; the relationships between different AGN classes and tests for unified models; energy source(s) of the huge far-IR emission from type 2 Seyferts and from some QSOs and radiogalaxies.

6 ACKNOWLEDGMENTS

We wish to thank an anonymous referee for his comments and suggestions which helped us to improve the final presentation of this paper. We are grateful to M. Bersanelli and N. Mandolesi for providing us with updated information on the Low and High Frequency Instruments (LFI and HFI) foreseen for the Planck mission and to G. Smoot for useful comments on an early draft of this paper. This work has been partially supported by the Consiglio Nazionale delle Ricerche (CNR) and by the Agenzia Spaziale Italiana (ASI), contract 95–RS–116. LT and FAG would like to thank the Vicerrectorado de Investigación of the University of Oviedo (Spain) for continuous financial support during the years 1995 and 1996 (projects DF/95–213–1 and DF/94–213–6). LT and FAG acknowledge partial financial support from the Spanish “Dirección General de Enseñanza Superior” (DGES), under project PB95–1132–C02–02.

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FIGURE CAPTIONS

Figure 1. Comparison between predicted and observed differential source counts at 1.4, 5 and 8.44 GHz normalized to $150S^{-2.5}sr^{-1}Jy^{-1}$ (see top panel). The contributions of the most relevant classes of radio sources according to the model of Danese et al. (1987) are shown. For references for the data points see Danese et al. (1987); additional data are from Donnelly et al. (1987), Fomalont et al. (1991), Windhorst et al. (1993).

Figure 2. Differential 60µm galaxy counts normalized to $600S^{-2.5}sr^{-1}Jy^{-1}$. Data are from Hacking & Houck (1987), Rowan-Robinson et al. (1991), Gregorich et al. (1995), and Bertin et al. (1997). The solid line shows the predictions of model C by Franceschini et al. (1994), updated as described in the text. Also shown are the contributions to the counts from late type galaxies (spiral+irregular, short dashed line; starburst, dotted line), from early type galaxies (E and S0), assumed to go through a strongly dust absorbed phase during their early evolution (dot-dashed line), and from AGNs (long/short dashes).

Figure 3. Integral counts at 170 µm and at 850 µm. The meaning of the lines is the same as in Figure 2. The data points are the preliminary estimates by Kawara et al. (1997) at 170 µm and by Smail et al. (1997) at 850 µm. As stressed by the latter authors, their result might be, conservatively, taken as an upper limit; the plotted error bars for this point are 2σ.

Figure 4. Predicted integral counts in the Planck bands. The solid line shows the total counts. The dashed and dotted lines show, respectively, the contributions of radio and far-IR selected sources, as predicted by the models by Danese et al. (1987) and the Franceschini et al. (1994), updated as described in the text. We have adopted an average spectral index $\alpha = 0$ for “flat”-spectrum radio sources and the “opaque” model for the early evolution of early-type galaxies in the far-IR.

Figure 5. Temperature fluctuations due to discrete sources at $\nu=100$ GHz as a function of the angular scale. The solid, short-dashed, long-dashed, and dot-dashed lines covering the full range of angular scales correspond to the estimated Poisson contributions for different choices of the limiting flux above which sources are individually detected and subtracted out: 1 Jy, 0.1 Jy, 10 mJy, and 1 mJy, respectively. The lines plotted for scales larger than the Planck resolution at this frequency (10') show the contributions due to clustering of radiosources (clustering of far-IR sources has a negligible effect at this frequency); the upper curve assumes that sources are subtracted for $S > 1$ Jy, the lower one, for $S > 0.1$ Jy.

Figure 6. Temperature fluctuations due to discrete extragalactic sources at the frequencies indicated in each panel, as a function of the angular scale. As for the Poisson contribution, the lines have the same meaning as in Figure 5. Again, the contributions due to clustering are shown only for scales larger than the angular resolution of Planck instruments at each frequency: the dotted and dot-dashed lines
correspond to radiosources and to a flux limit of 1 and 0.1 Jy for source subtraction, respectively; the solid line corresponds to far-IR sources and a to $S_l=1$ Jy for source subtraction (lowering $S_l$ down to 0.1 Jy provides a negligible variation of the estimated contribution). At frequencies up to $\sim 100$ GHz the effect of clustering of far-IR sources is negligible and only the contribution of radiosources is shown; the opposite is true at $\nu \geq 353$ GHz. The contributions of both populations are given at 143 and 217 GHz; at the latter frequency they are very close to each other.

Figure 7. Angular power spectra of fluctuations due to a Poisson distribution of discrete sources at $\nu = 100$ GHz (see text for details). The solid, dot-dashed, and long/short dashed lines correspond to a flux limit for source removal of 1, 0.1, and 0.01 Jy, respectively. The dotted lines show the “unsmoothed” noise fields (defined as in Tegmark & Efstathiou 1996) foreseen for the Planck Surveyor detectors. The roughly horizontal thin dot–dashed line shows the dependence on multipole of temperature fluctuations predicted by the standard CDM model (scale-invariant scalar fluctuations in a $\Omega = 1$ universe with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, and baryon density $\Omega_b = 0.05$). The thin long–dashed line, labelled T&E96, shows the power spectrum estimated by Tegmark & Efstathiou (1996).

Figure 8. Same as in Figure 7, for the frequencies indicated in each panel. The dashed line in the 217 GHz panel refers to a removal of only the few brightest sources ($S > 10$ Jy). The short–dashed line in the upper left corner of the 30 GHz panel shows, for comparison, the “unsmoothed” noise field for COBE/DMR, calculated adopting the average pixel noise given by Bennett et al. (1994).
