Extragalactic Radio Sources and CMB Anisotropies

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Abstract. Confusion noise due to extragalactic sources is a fundamental astrophysical limitation for experiments aimed at accurately determining the power spectrum of the Cosmic Microwave Background (CMB) down to arcmin angular scales and with a sensitivity $\Delta T/T \approx 10^{-6}$. At frequencies $\lesssim 200–300$ GHz, the most relevant extragalactic foreground hampering the detection of intrinsic CMB anisotropies is constituted by radio loud Active Galactic Nuclei (AGN), including “flat–spectrum” radio galaxies, quasars, BL-LACs and blazars. We review our present understanding of astrophysical properties, spectra, and number counts of the above classes of sources. We also study the angular power spectrum of fluctuations due both to Poisson distributed and clustered radio sources and give preliminary predictions on the power spectrum of their polarized components. Furthermore, we discuss the capabilities of future space missions (NASA’s MAP, Bennett et al. 1995; ESA’s Planck Surveyor, Bersanelli et al. 1996) in studying bright radio sources over an almost unexplored frequency interval where spectral signatures, essential for the understanding of the physical processes, show up.

1. Introduction

In the last fifteen years, deep VLA surveys have allowed to extend direct determinations of radio source counts down to $\mu$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 areal densities of several sources arcmin$^{-2}$.

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At bright fluxes, the radio source population is dominated by classical, strongly evolving, powerful radio galaxies (Fanaroff-Riley classes I and II) and quasars, whose counts begin to converge below \( \sim 100 \) mJy. The VLA surveys, however, have revealed a flattening in differential source counts (normalized to Euclidean ones) below a few mJy at 1.41 GHz (Condon & Mitchell 1984), at 4.86 GHz (Donnelly et al. 1987; Fomalont et al. 1991), and, most recently, also at 8.44 GHz (Windhorst et al. 1993, 1995; Partridge et al. 1997; Kellermann et al. 1999; Richards et al. 1998).

Several scenarios have been developed to interpret this “excess” in the number counts of faint radio sources: a non-evolving population of local \((z < 0.1)\) low-luminosity galaxies (Wall et al. 1986); strongly evolving normal spirals (Condon 1984, 1989); and actively star-forming galaxies (Windhorst et al. 1985, 1987; Danese et al. 1987; Rowan–Robinson et al. 1993).

Thus, the currently available deep source counts are more than sensitive enough to include any radio source of the familiar steep and “flat”-spectrum classes contributing to fluctuations detectable by any of the forthcoming space borne CMB anisotropy experiments (see Toffolatti et al., 1998; De Zotti & Toffolatti, 1998). Extrapolations in flux density are not required: the real issue is the spectral behaviour of sources, since existing surveys extend only up to 8.4 GHz and hence a substantial extrapolation in frequency is necessary to reach the frequency bands of the MAP and Planck Surveyor missions. The point has to be carefully discussed, since important spectral features, carrying information on physical conditions of sources, are expected at cm to mm wavelengths. These include the transition from optically thick to thin synchrotron emission for “flat”-spectrum sources, the steepening of the synchrotron spectrum due to radiation energy losses by the relativistic electrons, and the mm-wave excesses due to cold dust emission.

On the other hand, future space missions will also provide complete samples of the extremely interesting classes of extragalactic radio sources characterized by inverted spectra (i.e. flux density increasing with frequency), which are very difficult to detect in radio frequency surveys. Strongly inverted spectra up to tens of GHz can be produced in very compact, high electron density regions, by synchrotron or free-free absorption. This is the case for GHz peaked spectrum radio sources (GPS), which are currently receiving an increasing amount of interest. Also of great interest are advection dominated sources (ADS), which turn out to have a particularly hard radio emission spectrum.

In §2 we briefly discuss the spectral properties, at mm and sub-mm wavelengths, of the different classes of sources mentioned above. In §3 we deal with number counts while, in §4, we present estimates of the angular power spectrum of intensity and polarization fluctuations due to discrete extragalactic sources and discuss the effect of clustering. In §5 we summarize our main conclusions.

2. Radio sources at mm and sub-mm wavelengths

2.1. Compact, “flat”-spectrum radio sources

The observed spectral energy distributions (SEDs) of “flat”-spectrum radio sources (compact radio galaxies, radio loud QSOs, BL Lacs) generally have a gap at mm/sub-mm wavelengths (see Figure 1). Those sources which have data
in this interval frequently show a dip in the mm region, indicative of a cross-over of two components.

The spectral shape carries a good deal of extremely interesting information on the physical properties of sources. For example, in flow models of compact radio sources the spectrum steepens at the frequency at which the radiative cooling time equals the outflow time (cf. Begelman et al. 1984); for “hot spots”, this typically lies in the millimeter or far-IR part of the spectrum, while, in cocoons or extended regions of lower surface brightness, the break moves down to lower frequencies.

According to the basic model of Blandford & Rees (1974) and Scheuer (1974), which is supported by a large body of observational evidence, the spectral break frequency, \( \nu_b \), at which the synchrotron spectrum steepens, is related to the magnetic field \( B \) and to the “synchrotron age” \( t_s \) (in Myr) by \( \nu_b \approx 96(30 \mu G/B)^3 t_s^{-2} \text{GHz}. \) Thus, the systematic multifrequency study at the Planck and MAP frequencies will provide a statistical estimate of the radio source ages and of the evolution of the spectrum with cosmic time: both are pieces of information of great physical importance. Various evolutionary models of the radio emission spectrum have been proposed based on different assumptions (“one-shot” or continuous injection of relativistic electrons, complete or no isotropization of the pitch-angle distribution; see Myers & Spangler 1985 for a summary). These models strongly differ in the form of the falloff above \( \nu_b \); hence measurements at mm and sub-mm wavelengths will provide crucial information on the physical effects operating in radio sources.

Also, many compact “flat”-spectrum sources are observed to become optically thin at high radio frequencies. Correspondingly, their spectral index steepens to values (\( \alpha \approx 0.75 \)) typical of extended, optically thin sources.

In the case of blazars (Brown et al. 1989) the component dominating at cm wavelengths is rather “quiescent” (variations normally occur on timescales of years) and has a spectral turnover at \( \sim 2–5 \text{ cm} \), where the transition between optically thick and optically thin synchrotron emission occurs. At higher frequencies the emission is dominated by a violently variable “flaring” component, which rises and decays on timescales of days to weeks, and has a spectral turnover at mm/sub-mm wavelengths. The “quiescent” emission may be identified with emission from the bulk of a relativistic jet aligned close to the line of sight, while the flaring component may arise in smaller regions of enhanced emission within the jet, where emitting electrons are injected or reaccelerated. The study of the flaring component is clearly central to understanding the mechanisms responsible for variability in radio loud active nuclei; the mm/sub-mm region is crucial in this respect, since it is in this region that the flare spectra become self absorbed.

It is known from VLBI studies that the apparently smooth “flat” spectra of compact radio sources are in fact the combination of emissions from a number of components with varying synchrotron self absorption turnover frequencies which are higher for the denser knots. It may be argued (Lawrence 1997) that the mm/sub-mm region measures sub-parsec scale, unresolved regions, including the radio core.

Excess far-IR/sub-mm emission, possibly due to dust, is often observed from radio galaxies (Knapp & Patten 1991). Planck data will allow to assess whether this is a general property of these sources; this would have interesting
Figure 1. Continuum energy distributions for radio-loud and radio-quiet quasars, adapted from Elvis et al. (1994). The central panel shows the mean spectral energy distribution for radio loud (dashed line) and radio quiet (solid line) quasars, normalized at 1.25 µm. Also shown are the energy distributions of 4C 34.47 (upper panel) and Mkn 586 (lower panel), representative of the radio-loud and radio-quiet class, respectively.
implications for the presence of interstellar matter in the host galaxies, generally identified with giant ellipticals, which are usually thought to be devoid of interstellar matter. 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.

2.2. GHz Peaked Spectrum radio sources

Current predictions on number counts do not explicitly include sources with strongly inverted spectra, peaking at mm wavelengths, that would be either missing from, or strongly underrepresented in low frequency surveys and may be difficult to distinguish spectrally from fluctuations in the CMB (Crawford et al. 1996).

The recent study of GHz Peaked Spectrum radio sources (GPS) by O’Dea and Baum (1997) has revealed a fairly flat distribution of peak frequencies extending out to 15 GHz in the rest frame, suggesting the existence of an hitherto unknown population of sources peaking at high frequency (see also Lasenby 1996). The host galaxies appear to be a homogeneous class of giant ellipticals with old stellar populations whereas GPS quasars present a different redshift distribution and have radio morphologies quite unlike those of GPS galaxies (Snellen et al. 1998a,b,c).

It is very hard to guess how common such sources may be. Snellen (1997) exploited the sample of de Vries et al. (1997) to estimate a count of 22 ± 10 Jy$^{-3/2}$sr$^{-1}$ for sources having peak frequencies between 1 and 8 GHz and peak flux densities between 2 and 6 Jy. He also found that counts of GPS sources are only slowly decreasing with increasing peak frequency in that range. If indeed the distribution of peak frequencies extends up to several tens GHz keeping relatively flat, it is conceivable that from several tens to hundreds of GPS sources will be detected by Planck, whereas MAP could detect only a few of them.

Therefore, although these rare source will not be a threat for studies of CMB anisotropies, we may expect that Planck surveys will provide crucial information about their properties. GPS sources are important because they may be the younger stages of radio source evolution (Fanti et al. 1995; Readhead et al. 1996) and may thus provide insight into the genesis and evolution of radio sources; alternatively, they may be sources which are kept very compact by unusual conditions (high density and/or turbulence) in the interstellar medium of the host galaxy (van Breugel et al. 1984).

2.3. Advection-dominated sources

Another very interesting class of inverted spectrum radio sources, is that characterized by advection-dominated emission (Narayan & Yi 1995; Fabian & Rees 1995; Di Matteo & Fabian 1997). Convincing observational evidence for the presence of super-massive black-holes (BH) in many nearby galaxies have been accumulating in recent years (Kormendy & Richstone 1995; Magorrian et al. 1998; Ho 1999). These data seem to imply that an important, possibly dominant, fraction of all massive galaxies with appreciable spheroidal component (hence
the E/S0 galaxies in particular, but also early-type spirals) host a black-hole
with a mass roughly proportional to that of the hosting spheroid. Franceschini
et al. (1998) have found a tight relationship between the BH mass and both the
nuclear and total radio flux at centimetric wavelengths. The radio flux turns
out to be proportional to $M_{\text{BH}}^{2.5-3}$. This is consistent with the radio centimetric
flux being contributed by cyclo-synchrotron emission in an advection-dominated
accretion flow. The latter should correspond to a situation in which the accre-
tion rate is low, as typically expected for the low-density ISM in local early type
galaxies.

A property that distinguishes this emission is an inverted spectrum with
spectral index $\alpha = 0.4$ up to a frequency of 100–200 GHz, followed by fast
convergence (far-IR and optical emission is expected to be very weak). Based
on the analysis by Franceschini et al. (1998), we would expect that some sources
of this kind may detected by Planck at 70 and 100 GHz. This assumes that the
advection flows evolves in redshift $\propto (1 + z)^3$, as suggested by analyses of faint
radio-optical samples of E/S0’s. In spite of the limited statistics, this would be
a way to test for the presence of massive BH’s and of the evolution of the ISM
in galaxies up to moderate redshifts.

2.4. Free-free self absorption cutoffs in AGN
High frequency free-free cutoffs may be present in AGN spectra. Ionized gas in
the nuclear region absorbs radio photons up to a frequency:

$$\nu_{\text{ff}} \simeq 50 \frac{g}{5} \frac{n_e}{10^5 \text{cm}^{-3}} \left( \frac{T}{10^4 \text{K}} \right)^{-3/4} \text{GHz} .$$

(1)

Free-free absorption cutoffs at frequencies $> 10$ GHz may indeed be expected,
in the framework of the standard torus scenario for type 1 and type 2 AGN, for
radio cores seen edge on, and may have been observed in some cases (Barvainis &
Lonsdale, 1998). They provide constraints on physical conditions in the parsec
scale accretion disk or infall region for the nearest sources of this kind.

3. Counts of radio sources at cm to mm wavelengths

Source counts are presently available only at cm wavelengths. In carrying out
extrapolations to mm wavelengths, several effects need to be taken into account.
On one side, the majority of sources with flat or inverted spectra at 5 GHz
have spectral turnovers below 90 GHz (Kellermann & Pauliny-Toth 1971; Owen
& Mufson 1977). This is not surprising since, as noted above, astrophysical
processes work to steepen the high frequency source spectra.

On the other side, high frequency surveys preferentially select sources with
harder spectra. For power law differential source counts, $n(S, \nu_0) = k_0 S^{-\gamma}$, and
a Gaussian spectral index distribution with mean $< \alpha >_0$ and dispersion $\sigma$, the
counts at a frequency $\nu$ are given by $n(S, \nu) = n(S, \nu_0)(\nu/\nu_0)^{\alpha_{\text{eff}}}$ with (Kellermann
1964; Condon 1984): $\alpha_{\text{eff}} = < \alpha >_0 + \ln(\nu/\nu_0)\sigma^2(1 - \gamma)^2/2$. Estimates
neglecting the dispersion of spectral indices underestimate the counts by a factor
$\exp[\ln^2(\nu/\nu_0)\sigma^2(1 - \gamma)^2/2]$. The spectral index distribution between 5 and 90
GHz determined by Holdaway et al. (1994) has $\sigma = 0.34$; for Euclidean counts, $\gamma = 2.5$, the correction then amounts to about a factor of 3.

A good fraction of the observed spread of spectral indices is due to variability whose rms amplitude, in the case of blazars, increases with frequency, reaching a factor of about 1.5 at a few hundred GHz (Impey & Neugebauer 1988). In some cases, variations by a factor of 2 to 3, or more, have been observed (e.g. 3C345: Stevens et al. 1996; PKS0528 + 134: Zhang et al. 1994; 0738 + 545 and 3C279: Reich et al. 1998). The highest frequency outbursts are expected to be associated to the earliest phases of the flare evolution. Since the rise of the flare is often rather abrupt (timescale of weeks), they were probably frequently missed.

In view of the uncertainties on the spectra of radio selected AGNs, and the poor knowledge on number counts and spectral properties of inverted spectrum sources discussed in §2, an accurate modelling of radio source counts at $\nu \sim 100$ GHz is currently impossible. However, the simple model adopted by Toffolatti et al. (1998) appears to be remarkably successful.

These authors adopted the luminosity evolution scheme of Danese et al. (1987), who considered three classes of sources: powerful radio galaxies and radio loud quasars (distinguishing between extended, steep spectrum, and compact, “flat” spectrum sources), and evolving starburst/interacting galaxies. The average spectral index, $\alpha (S \propto \nu^{-\alpha})$, of “flat-spectrum” sources was taken to be $\alpha = 0.0$ for $\nu \leq 200$ GHz, with a steepening to $\alpha = 0.75$ at higher frequencies. 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 in connection with the MAP and Planck missions, the radio power–spectral index relation determined by Peacock and Gull (1981) was adopted. This simple recipe has allowed to reproduce, without any adjustment of the parameters, the deep counts at 8.44 GHz (Windhorst et al. 1993; Partridge et al. 1997), which were produced several years after the model (see Figure 2).

This scenario, implying a substantial contribution of active star-forming galaxies to sub-mJy counts at cm wavelengths, is consistent with the results by Kron et al. (1985) and Thuan & Condon (1987) indicating that the optical counterparts of sub-mJy sources are mainly faint blue galaxies, often showing peculiar optical morphologies indicative of high star formation activity and of interaction and merging phenomena. Moreover, the spectra are similar to those of the star–forming galaxies detected by IRAS (Franceschini et al. 1988; Benn et al. 1993). On the other hand, a recent work by Gruppioni, Mignoli & Zamorani (1999), reaching a fainter magnitude limit in the spectroscopic identifications of sources selected at 1.4 GHz with a flux limit of 0.2 mJy, finds that the majority of their radio sources are likely to be early type galaxies.

Optical identifications of sources at $\mu$Jy flux levels (Hammer et al. 1995; Windhorst et al., 1995; Richards et al., 1998) show that they are made mainly of star-forming galaxies, with a smaller fraction of ellipticals, late-type galaxies with nuclear activity and local spiral galaxies.

It may be noted that the counts predicted by Toffolatti et al. (1998) at frequencies above 100 GHz may be somewhat depressed by the assumption of a spectral break at 200 GHz for all “flat”–spectrum sources while examples are known of sources with a flat or inverted spectrum up to 1000 GHz. In view of
Figure 2. 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), adapted from Toffolatti et al. (1998). The contributions of the most relevant classes of radio sources according to the model of Danese et al. (1987) are shown. For references on the data points see Danese et al. (1987); additional data are from Donnelly et al. (1987), Fomalont et al. (1991), Windhorst et al. (1993), Partridge et al. (1997).
this, we updated the baseline model of Toffolatti et al. by assuming that the steepening of the spectral indices to $\alpha = 0.75$ occurs at $\nu = 1000$ GHz.

### 3.1. Comparison with other estimates of source counts

Sokasian et al. (1999) have produced skymaps of bright radio sources at frequencies up to 300 GHz by means of detailed individual fits of the spectra of a large number of sources compiled from several catalogs, including the all sky sample of sources with $S_{5\text{GHz}} \geq 1$ Jy (Kühr et al. 1981). Their estimated number of sources brighter than $S_{90\text{GHz}} = 0.4$ Jy is about a factor of two below that predicted by Toffolatti et al. (1998). A very similar result was obtained by Holdaway et al. (1994) based on the observed distribution of 8.4–90 GHz spectral indices. On the other hand, these empirical estimates yield, strictly speaking, lower limits, since sources with inverted spectra may be under-represented in the primary sample. Furthermore, in the presence of substantial variability, estimates using mean fluxes underpredict actual counts of bright sources.

A comparison of the log $N$–log $S$ of radio sources with the predicted ones for dusty galaxies (even allowing for very different evolutionary scenarios: De Zotti et al. 1999, their Figure 1) shows an abrupt change in the populations of bright sources observed in channels above and below $\sim 1$ mm: radio sources dominate at the longer wavelengths and dusty galaxies at the shorter ones. This is due to the steep increase with frequency of the dust emission spectrum in the mm/sub-mm region (typically $S_\nu \propto \nu^{3.5}$), which makes the crossover between radio and dust emission components only weakly dependent on their relative intensities; moreover, dust temperatures tend to be higher for distant high luminosity sources, partially compensating for the effect of redshift.

At, say, $\nu \geq 200$–300 GHz dusty galaxies dominate the number counts of extragalactic sources. We only briefly remind the point in the next subsection and defer to the comprehensive reviews of Guiderdoni et al. (1999) and of Mann et al. (1999) for a thorough discussion.

### 3.2. Counts of dusty galaxies

Although the situation is rapidly improving, thanks to the deep ISO counts at $175\mu m$ (Kawara et al. 1997; Puget et al. 1999), to the preliminary counts at $850\mu m$ with SCUBA on JCMT (see Mann et al. 1999, for a review on the subject) and to the important constraints from measurements of the far-IR to mm extragalactic background (Schlegel et al. 1998; Hauser et al. 1998; Fixsen et al. 1998), first detected by Puget et al. (1996), current estimates are affected by bigger uncertainties than in the case of radio sources.

In fact, predicted counts have a higher responsiveness to the poorly known evolutionary properties, because of the boosting effect of the strongly negative K corrections. The most extensive surveys, carried out by IRAS at $60\mu m$, cover a limited range in flux and are rather uncertain at the faint end (Hacking & Houck 1987; Gregorich et al. 1995; Bertin et al. 1997). It is then not surprising that predictions of recent models differ by substantial factors.

Again, substantial extrapolations in frequency are required, and have to deal with the poor knowledge of the spectrum of galaxies in the mm/sub-mm region; the 1.3 mm/$60\mu m$ flux ratios of galaxies are observed to span about a factor of 10 (Chini et al. 1995; Franceschini & Andreani 1995).
4. Angular power spectrum of source fluctuations

The effect of radio sources as a limiting factor for the detection of primordial CMB anisotropies has been extensively analyzed by many authors (see, e.g., Franceschini et al. 1989; Blain & Longair 1993; Danese et al. 1996; Gawiser & Smoot 1997). More recently, detailed analyses of the problem have been worked out by Toffolatti et al. (1998) for the Planck Surveyor mission, and by Refregier, Spergel & Herbig (1999) for the MAP mission.

The relevant formalism is readily available in the literature (see, e.g., De Zotti et al. 1996; Tegmark & Efstathiou 1996; Toffolatti et al. 1998; Scott & White 1999) and we skip it here. A Poisson distribution of extragalactic point sources produces a simple white-noise power spectrum, with the same power in all multipoles, so that their contribution to fluctuations in a unit logarithmic multipole interval increases with \(\ell\) as \(\ell(\ell + 1)C_\ell \propto \ell^2\) (for large values of \(\ell\)), while, at least for the standard inflationary models, which are consistent with the available anisotropy detections, the function \(\ell(\ell + 1)C_\ell\) yielded by primordial CMB fluctuations is approximately constant for \(\ell \lesssim 100\), then oscillates and finally decreases quasi exponentially for \(\ell \gtrsim 1000 (\theta \gtrsim 10')\). Hence confusion noise due to discrete sources will dominate at small enough angular scales.

Figure 3 shows the expected angular power spectra of the extragalactic foregrounds components at 30, 100 and 217 GHz, corresponding to the central frequencies of three Planck channels; also, MAP has channels centered at 30 and 94 GHz. The two lines for each population (radio sources and far-IR sources) are obtained assuming that sources can be identified and removed down to fluxes of 1 or 0.1 Jy.

Radio sources give the most relevant contribution to CMB fluctuations up to, say, \(\sim 200\) GHz, whereas dusty galaxies dominate at higher frequencies. At 217 GHz, the Poisson fluctuation level due to far-IR selected sources predicted by the model of Guiderdoni et al. (1998) is higher than that of radio selected sources, whereas it falls below the radio component if we adopt the Toffolatti et al. model. As discussed by De Zotti et al. (1999), the latter model falls somewhat short of the best current estimate of the far-IR to mm extragalactic background (Fixsen et al. 1998), while model E by Guiderdoni et al. tends to exceed it.

Figure 3 also indicates that source removal is much more effective in reducing the Poisson fluctuation level at \(\lambda \gtrsim 1\) mm. In fact, in this wavelength range fluctuations are dominated by the brightest sources below the detection limit, while at shorter wavelengths the dominant population are evolving dusty galaxies whose counts are so steep that a major contribution to fluctuations comes from fainter fluxes.

Fluctuations in the Galactic emissions at \(|b| > 30^\circ\) are also plotted in Figure 3, for comparison. They are represented by long+short dashes (dust), dots+short dashes (free-free), and dots+long dashes [synchrotron: we have plotted both the power spectrum derived by Tegmark & Efstathiou (1996), \(C_\ell \propto \ell^{-3}\), and that observed in the Tenerife patch, \(C_\ell \propto \ell^{-2}\) (Lasenby 1996); the latter is significantly lower than the former in the range of scales where it has actually been measured, but has a flatter slope so that it may become relatively more important on small scales]. The heavy dashed line flattening at large \(\ell\) shows
Figure 3. Angular power spectra of the foreground components contributing to fluctuations at 30, 100 and 217 GHz. Following Tegmark & Efstathiou (1996), we have plotted, for each component, the quantity \( \delta T_\ell(\nu) = [\ell(2\ell+1)C_\ell(\nu)/4\pi]^{1/2} \). The upper heavy solid curve shows the power spectrum of CMB fluctuations predicted by the standard CDM model \( (\Omega = 1, H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_b = 0.05) \). The dotted lines show the unsmoothed noise contributions of the MAP (upper line) and Planck instruments; at 100 GHz both the HFI and LFI (lowest line) noise curves are plotted. The roughly diagonal thin lines show the contributions of extragalactic sources (radio sources: solid lines; far-IR sources: dashed lines). At 217 GHz the prediction of Guiderdoni et al. 1998 – their model E – is also plotted. We assume that sources brighter than 1 and 0.1 Jy can be identified and removed and we neglect the effect of clustering (see §4.1). The heavy dashed lines, flattening at large \( \ell \), refer to fluctuations due to the Sunyaev-Zeldovich effect. The angular power spectra of the galactic synchrotron, free-free and dust emission are also plotted. See text for more details.
the power spectrum of anisotropies due to the Sunyaev-Zeldovich effect computed by Atrio-Barandela & Mücke (1998) adopting a lower limit of $10^{14} \, M_\odot$ for cluster masses, a present ratio $r_{\text{virial}}/r_{\text{core}} = 10$, and $\epsilon = 0$.

For $\ell < 300$, corresponding to angular scales $> 30' \,[\ell \simeq 180^\circ/\theta(\text{deg})]$, diffuse Galactic emissions dominate total foreground fluctuations even at high Galactic latitudes. These are minimum at $\nu \simeq 70 \, \text{GHz}$ (Kogut 1996). For larger values of $\ell$ the dominant contribution is from extragalactic sources; their minimum contribution to the anisotropy signal occurs around 150-200 GHz. Therefore, the minimum in the global power spectrum of foreground fluctuations moves, at high galactic latitudes, from about 70 GHz for $\ell < 300$, to 150-200 GHz at higher values of $\ell$. The detailed spectral and evolutionary behaviour of sources determines the exact value of the frequency of the minimum foreground fluctuations; such frequency decreases with decreasing Galactic latitude (De Zotti et al. 1999).

On the other hand, in the frequency range 50–200 GHz, a higher contamination level due to source confusion could be produced by a still undetected population of sources whose emission peaks at $\sim 100 \, \text{GHz}$ (Gawiser, Jaffe & Silk, 1999). Anyway, the discussion in §1 and §2 indicates that unknown source populations are unlikely to give a fluctuation level much higher than the presently estimated one.

4.1. The effect of clustering

Toffolatti et al. (1998) found that clustering contribution to fluctuations due to extragalactic sources is generally small in comparison with the Poisson contribution. However, the latter, in the case of radio sources, comes mostly from the brightest sources below the detection limit, while the clustering term is dominated by fainter sources. Therefore, an efficient subtraction of radio sources decreases the Poisson term much more effectively than the clustering term, which therefore becomes relatively more and more important.

In the case of a power law angular correlation function ($w(\theta) \propto \theta^{1-\gamma}$), the power spectrum of intensity fluctuations is $C_\ell \propto \ell^{\gamma-3}$ (Peebles 1980; eq. 58.13). If this behaviour extends to large enough angular scales, i.e. to small enough values of $\ell$, the clustering signal, for a power law index not much steeper than the canonical value $\gamma \simeq 1.8$, will ultimately become larger than the Poisson anisotropy. On the other hand, for large values of $\theta$, $w(\theta)$ is expected to drop below the above power law approximation, and $C_\ell$ will correspondingly break down.

The preliminary estimates (Toffolatti et al., in preparation) reported in Figure 4 are based on the correlation functions of radio sources derived by Loan et al. (1997) and by Magliocchetti et al. (1999). The different slopes at large values of $\ell$ reflect different values of $\gamma$: the upper curve correspond to the larger value ($\gamma = 2.5$) obtained by Magliocchetti et al. (1999).

Scott & White (1999) have recently shown that if dusty galaxies cluster like the $z \sim 3$ Lyman break galaxies (Giavalisco et al. 1998), at frequencies $\geq 217 \, \text{GHz}$ the anisotropies due to clustering may exceed the Poisson ones on all scales accessible to Planck; in the 353 GHz (850 $\mu$m) channel the clustering signal may exceed the primordial CMB anisotropies on scales smaller than about 30'. It should be noted, however, that current models (Toffolatti et al. 1998;
Figure 4. Comparison of the Poisson component of the power spectra of radio and far-IR selected sources with the component due to clustering. The thick solid and the (thick and thin) dotted lines have the same meaning as in Figure 3. The roughly diagonal solid and dashed thin lines represent the Poisson component due to radio and far-IR selected sources, respectively (with the same limits for detection and removal in as Figure 3). The heavy dashed lines show the component due to clustering of radio sources estimated using the angular correlation functions derived by Loan et al. (1997; lower line) and by Magliocchetti et al. (1999). The heavy dot/dashed line represents the contribution due to clustering of far-IR sources estimated based on the angular correlation function of Lyman break galaxies.
Guiderdoni et al. 1998) strongly suggest a broad redshift distribution of sources contributing to the autocorrelation function of the intensity fluctuations, implying a strong dilution of the clustering signal. A further substantial overestimate of the effect of clustering may follow from the extrapolation to degree scales, with constant slope, of the angular correlation function determined on scales of up to a few arcmin. Our preliminary estimate shown in Figure 4, has been obtained by assuming that the angular correlation function of Lyman break galaxies substantially steepens at $\theta \simeq 6'$, consistent with the data of Giavalisco et al. (1998).

## 4.2. Polarization

The polarized spectra have not been studied as extensively as the intensity spectra. For a power law electron energy spectrum $dN/dE = N_0 E^{-p}$, the polarization level, $\Pi$, yielded by a uniform magnetic field is $\Pi = 3(p+1)/(3p+7)$ (LeRoux 1961). For a typical high frequency value of $p \sim 3$, $\Pi \sim 75\%$. Non-uniformities of the magnetic fields and differential Faraday rotation decrease the polarization level. However, the Faraday rotation optical depth is proportional to $\nu^{-2}$ so that Faraday depolarization is negligible at the high frequencies relevant for Planck and MAP.

Bouchet et al. (1998) have analyzed the possibility of extracting the power spectrum of CMB polarization fluctuations in the presence of polarized Galactic foregrounds using a multifrequency Wiener filtering of the data. They concluded that the power spectrum of E-mode polarization of the CMB can be extracted from Planck data with fractional errors $\lesssim 10-30\%$ for $50 \lesssim \ell \lesssim 1000$. The B-mode CMB polarization, whose detection would unambiguously establish the presence of tensor perturbations (primordial gravitational waves), can be detected by Planck with signal-to-noise $\simeq 2-4$ for $20 \leq \ell \leq 100$ by averaging over a 20% logarithmic range in multipoles.

Polarization of extragalactic radio sources, not considered by Bouchet et al. (1998), is an important issue as well. Flat spectrum radio sources are typically 4-7% polarized at cm and mm wavelengths (Nartallo et al. 1998; Aller et al. 1999). For random orientations of the magnetic fields of sources along the field of view, the rms polarization fluctuations are approximately equal to intensity fluctuations times the mean polarization degree (De Zotti et al., in preparation).

Our preliminary estimate of Figure 5 assumes a mean polarization of radio sources of 5%, close to the main peak of the percentage polarization distribution of the sample studied by Nartallo et al. (1998).

Measurements of polarized thermal emission from dust are only available for interstellar clouds in our own Galaxy. The distribution of observed polarization degrees of dense clouds at 100 $\mu$m shows a peak at $\sim 2\%$ (Hildebrand 1996). We have adopted this value for mean polarization of dusty galaxies at mm/sub-mm wavelengths; this is likely to be an upper limit since the global percentage polarization from a galaxy is the average of contributions from regions with different polarizing efficiencies and different orientations of the magnetic field with respect to the plane of the sky; all this works to decrease the polarization level in comparison with the mean of individual clouds.

At 217 GHz the power spectrum obtained on the basis of the source counts of Guiderdoni et al. (model E) is also shown (upper thin dashed line). Note
Figure 5. Power spectrum of polarization fluctuations at 30, 100 and 217 GHz. The thick solid lines show the angular power spectrum of the CMB temperature anisotropies whereas the long dashes (three dots-dashed) lines show the power spectrum of polarized scalar (tensor) CMB fluctuations, respectively. A tilted CDM model with standard parameters and scalar to tensor quadrupole ratio $7(1 - n_s)$, $n_s = 0.9$, $n_t = 0.1$, has been adopted. The dotted lines show the instrumental noise power spectrum for polarization measurements. The thin solid (thin dashed) lines represent estimates of the angular power spectrum of extragalactic radio (far-IR) source fluctuations assuming that the emission of radio and far-IR sources is polarized, on average, at the 5% and 2% level, respectively. Estimates of the angular power spectra of the polarized synchrotron (thick dot-dashed line) and dust (thick dashes) emission of the Galaxy are also shown (see text).
that, since the emission of radio sources appears to be more polarized than that of dusty galaxies, radio sources give the dominant contribution to extragalactic polarization fluctuations up to 217 GHz. Anyway, Figure 5 shows that the main limitations to CMB polarization measurements come from Galactic emissions, not from extragalactic sources.

A brief summary on polarization fluctuations of Galactic emissions can be found in De Zotti et al. (1999). The power spectrum of the polarized component of Galactic synchrotron emission, shown in Fig. 5, has been obtained from the corresponding temperature fluctuation power spectrum (as estimated by Tegmark & Efstathiou 1996) assuming the signal to be 40% polarized. As for dust emission, we have taken up the estimates by Prunet et al. (1998) for the E-mode; the extrapolations to to 100 and 30 GHz are made adopting their dust emission spectrum. Free-free emission is not polarized. However, Thompson scattering by electrons in the HII regions where it is produced, may polarize it tangentially to the edges of the electron cloud (Keating et al. 1998). The polarization level is expected to be small, with an upper limit of approximately 10% for an optically thick cloud.

5. Conclusions

The very deep VLA surveys have allowed to extend radio source counts down to \( \mu \text{Jy} \) levels at \( \lambda \geq 3 \text{ cm} \); the bulk of radio sources in the Universe have probably been detected (Haarsma & Partridge 1998). On the other hand, estimates of the counts and of fluctuations due to extragalactic sources at mm/sub-mm wavelengths are made uncertain by the poor knowledge of their spectral properties in this spectral region as well as by the possibility that source populations with strongly inverted spectra may show up. However, as mentioned in §3, estimates based on very different approaches agree to within a factor of 2 up to \( \sim 100 \text{ GHz} \).

Conservative estimates indicate that, in the frequency range 50–200 GHz, extragalactic foreground fluctuations are well below the expected amplitude of CMB fluctuations on all angular scales covered by the Planck and MAP missions.

Current data on the angular correlation function of radio sources imply that fluctuations due to clustering are generally small in comparison with Poisson fluctuations; however, the relative importance of the former increases if sources are subtracted from the sky maps down to faint flux levels.

Fluctuations due to clustering may be more important at frequencies higher than \( \nu \sim 200 – 300 \text{ GHz} \), if high redshift dusty galaxies cluster like the Lyman break galaxies at \( z \sim 3 \).

The polarized emission of extragalactic sources will not be a threat for measurements of the polarized component of primordial CMB anisotropies; much stronger limitations come from Galactic synchrotron and dust emissions.

Moreover, future space mission like Planck (and, to a lesser extent, MAP) will not only provide all sky maps of the primordial CMB anisotropies but also unique information on the physics of compact radio sources and in particular on the physical conditions in the most compact components (transition from optically thick to optically thin synchrotron emission, ageing of relativistic electrons, high frequency flares) and on their relationship with emissions at higher energies (SSC versus EC models). They will also allow us to study the population
properties of inverted spectrum sources like GPS, sources with high frequency free-free self absorption, ADS, etc..

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