Radio and Far-Infrared Extragalactic Sources at Planck Frequencies

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We discuss the main uncertainties affecting estimates of small scale fluctuations due to extragalactic sources in the Planck Surveyor frequency bands. Conservative estimates allow us to confidently conclude that, in the frequency range 100–200 GHz, the contaminating effect of extragalactic sources is well below the expected anisotropy level of the cosmic microwave background (CMB), down to angular scales of at least $\sim 10^\prime$. Hence, an accurate subtraction of foreground fluctuations is not critical for the determination of the CMB power spectrum up to multipoles $\ell \sim 1000$. In any case, Planck’s wide frequency coverage will allow to carefully control foreground contributions. On the other hand, the all sky surveys at 9 frequencies, spanning the range 30–900 GHz, will be unique in providing complete samples comprising from several hundreds to many thousands of extragalactic sources, selected in an essentially unexplored frequency interval. New classes of sources may be revealed in these data. Extremely compact radio sources, whose radio emission is relativistically boosted both in intensity and in frequency will be particularly prominent. Within this frequency region, very compact synchrotron components become optically thin; the corresponding break frequency is a key parameter in models of the energy distribution. Crucial information will be provided to understand the nature of radio sources with strongly inverted spectra. Scenarios for the cosmological evolution of galaxies will be tested.

1. INTRODUCTION

Astrophysical foregrounds constitute an unavoidable fundamental limitation to measurements of primordial anisotropies of the Cosmic Microwave Background (CMB). Due to the large beam size, the COBE/DMR data are, to some extent, contaminated by galactic emission (Kogut et al. 1996), whereas they are basically unaffected by extragalactic sources (Kogut et al. 1994; Banday et al. 1996). On the other hand, confusion noise due to discrete sources is likely to be the main limiting factor for experiments, like Planck, aimed at accurately determining the CMB power spectrum down to small angular scales (Tegmark & Efstathiou 1996; Toffolatti et al. 1998).

In §2 we review the main results of recent analyses of fluctuations due to extragalactic sources and discuss their uncertainties. In §3 we comment on the astrophysical information on such sources that will be provided by Planck surveys. In §4 we summarize our main conclusions.

2. FLUCTUATIONS DUE TO DISCRETE EXTRAGALACTIC SOURCES

The contributions of discrete extragalactic sources to small scale fluctuations have
been extensively discussed in the literature (Franceschini et al. 1989; Tegmark & Efstathiou 1996; Gawiser & Smoot 1997; Toffolatti et al. 1998; Guiderdoni et al. 1998; Blain et al. 1998). The main results can be summarized as follows.

The sharp rise of dust emission spectra with increasing frequency (typically $S_\nu \propto \nu^{3.5}$) determines a drastic change in the composition of the population of bright extragalactic sources above and below $\simeq 200$ GHz: radio sources (mostly “flat”-spectrum radiogalaxies, quasars, BL Lacs, blazars) dominate at lower frequencies, and evolving dusty galaxies at higher frequencies.

2.1 Fluctuations due to radio sources

Estimates of fluctuations due to radio sources are based on extrapolations of evolutionary models which fit the observed counts at several frequencies from 408 MHz to 8.44 GHz. As such counts reach much deeper flux levels than achievable by Planck, the critical ingredient for the extrapolation is not the evolution model but rather the spectral behaviour at high frequencies.

In carrying out extrapolations in frequency, 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 astrophysical processes work to steepen the high frequency source spectra. For a power law energy distribution of relativistic electrons $[N(E) \propto E^{-p}, \ p \simeq 2.5]$ the synchrotron self-absorption coefficient is proportional to $\nu^{-(p+4)/2}$ (Rybicki & Lightman 1979). Thus even the most compact synchrotron components become optically thin at high enough frequencies and the emission takes on a spectral index $\alpha \simeq (p-1)/2$ ($S_\nu \propto \nu^{-\alpha}$). A further steepening of the spectrum is produced by electron energy losses.

On the other side, high frequency surveys preferentially select sources with harder spectra. For power law differential source counts, $n(S, \nu_0) = k_0 S^{-\gamma}$, 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 have been observed at these frequencies (e.g. 3C345: Stevens et al. 1996; PKS0528 + 134: Zhang et al. 1994). 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.

If we adopt a lognormal model for the distribution of variable fluxes, such that the probability $p(S)$ that a source of average flux $\overline{S}$ is observed to have a flux $S$ is:

$$p(S) \ dS = \frac{1}{\sqrt{2 \pi \sigma_S}} \exp \left[-\frac{(\ln S - \ln \overline{S})^2}{2\sigma_S^2}\right] \frac{dS}{S},$$

and if the differential source counts in the absence of variability are described by
$n(S) = kS^{-\gamma}$, we get:

$$n(S) = kS^{-\gamma} \exp \left[ \frac{1}{2} (\gamma - 1)^2 \sigma_v^2 \right]$$

For $\sigma_v = \ln 1.5$ and $\gamma = 2.5$, counts are enhanced by a factor $\approx 1.2$. This enhancement factor is likely a lower limit, since, as mentioned above, high frequency outbursts are likely to have been undersampled.

An accurate modelling of all the above effects is impossible in the present data situation. However, the simple recipe adopted by Danese et al. (1987) and taken up by Toffolatti et al. (1998) (spectral index $\alpha = 0$ for “flat”-spectrum sources up to 200 GHz, and a subsequent steepening to $\alpha = 0.75$) turns out to be rather successful. In fact, it 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. It is also consistent with the estimates of 90 GHz counts obtained by Holdaway et al. (1994) from sensitive 90 GHz observations of a large sample of “flat”-spectrum sources selected at 5 GHz. Actually, the numbers of sources brighter than 0.1 Jy and 1 Jy estimated by Holdaway et al. (1994) are almost a factor of 2 below the predictions by Toffolatti et al. (1998). However, the former results are really lower limits since they may underestimate the number of sources with strongly inverted spectra which are underrepresented at 5 GHz.

On the other hand, 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 keeping a flat or inverted spectrum up to 1000 GHz. The results presented in Figs. 1 and 2 are obtained adopting the latter value for the break frequency. At $\nu \gtrsim 300$ GHz, however, counts are probably dominated by dusty galaxies.

### 2.2 Fluctuations due to 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. 1998), to the preliminary counts at 850 $\mu$m with SCUBA on JCMT (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1998) 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 (cf. Table 1).

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). A bivariate 60 $\mu$m/1.3 mm luminosity distribution has been obtained by Franceschini et al. (1998).

### 2.3 Power spectrum of foreground fluctuations at different frequencies
As pointed out in the proposals submitted to ESA for the High Frequency and Low Frequency Instruments (HFI and LFI), due to their high sensitivity, the experimental accuracy is effectively limited by astrophysical foregrounds. On angular scales \( \gtrsim 30' \), foreground fluctuations are dominated by Galactic emissions. COBE data indicate that these reach a minimum between 50 and 90 GHz (Kogut et al. 1996; Kogut 1996). The models by Toffolatti et al. (1998) imply that the minimum in the foreground fluctuation spectrum moves to higher frequencies with increasing Galactic latitude and decreasing angular scale; for \( |b| > 50^\circ \) and \( \theta \simeq 30' \) it occurs at about 100 GHz. The angular power spectrum of Galactic emission, however, falls rapidly at small angular scales \( (C_\ell \propto \ell^{-3}) \) (Gautier et al. 1992, Kogut 1996, Wright 1998; somewhat flatter slopes have been reported for some regions of the sky, cf. Lasenby 1996, Schlegel et al. 1998), while a Poisson distribution of extragalactic point sources produces a white-noise power spectrum, with the same power on all multipoles (Tegmark & Efstathiou 1996). The estimates by Toffolatti et al. (1998) indicate that, at high galactic latitude, foreground fluctuations are dominated by extragalactic sources for scales \( \lesssim 30' \). The minimum moves to somewhat higher frequencies. Our calculations indicate that, for fluctuations in a beam of width \( \theta \lesssim 30' \) the minimum is close to 100 GHz while the minimum in the temperature power spectrum for the corresponding multipoles \( (\ell > 300) \) is close to 150 GHz (see Figs. 1 and 2). The figures also show that at \( \ell \simeq 2000 \) the amplitude of the power spectrum of primordial CMB fluctuations is expected to be close or below that of foreground fluctuations and the situation worsens at larger values of \( \ell \) (angular scales smaller than 5', which are beyond the angular resolution reachable by Planck instruments). On the other hand, for smaller values of \( \ell \) foreground fluctuations are not a severe hindrance for measurements of CMB anisotropies for frequencies around 100 GHz.

Fluctuations due to clustering are generally negligible in comparison with Pois-
FIGURE 1. Frequency dependence of CMB brightness fluctuations \( \delta T_\ell = \left[ \ell (\ell+1)C_\ell(\nu)/4\pi \right]^{1/2} \) for the multipole \( \ell = 1000 \) corresponding to an angular scale \( \theta \approx 180^\circ/\ell \approx 0.18^\circ \approx 10'. \)

The dots+long dashes, dots+short dashes, and long+short dashes correspond to the mean contributions from Galactic foregrounds (synchrotron, free-free, and interstellar dust, respectively), at \( b > 50^\circ \). The total rms foreground fluctuations (solid curve) are, however, dominated, for small angular scales, by extragalactic sources. For radiogalaxies we have exploited the baseline model by Toffolatti et al. (1998), except that the steepening of the spectral indices to \( \alpha = 0.75 \) has been assumed to occur at \( \nu = 1000 \) GHz. The dotted lines show the contributions of radiogalaxies plus dusty galaxies, adopting, for the latter, the baseline model of Toffolatti et al. (1998; lowest curve), model E by Guiderdoni et al. (1998) and the model by Blain et al. (1998). The predictions of the last two models are very close to each other; those by Guiderdoni et al. (1998) are slightly lower except at the highest frequencies. Fluctuations were computed assuming that sources brighter than 1 Jy can be identified and removed. In order to compute the total foreground fluctuations we have adopted the model by Blain et al. (1998). The filled circles on the solid curve identify the central frequencies of Planck channels. The horizontal line shows, for comparison, the rms fluctuation amplitude predicted by the standard CDM model.

son fluctuations. However, if discrete sources can be subtracted out to flux limits < 100 mJy, the effect of clustering on the power spectrum can show up at several tens of arcmin (Toffolatti et al. 1998).

3. STUDYING EXTRAGALACTIC POINT SOURCES WITH PLANCK

Just because Planck is designed and optimized to measure CMB anisotropies, its sensitivity to compact sources is poor compared to ground based instruments, as well as to space-based missions such as FIRST. Nevertheless, because of the sensitivity near fundamental physical limits, freedom from systematic errors, full sky coverage, accurate calibration from the motion of the Earth around the Sun, its images at 9 frequencies, between 30 and 860 GHz will be a unique resource for studying both Galactic and extragalactic foregrounds over an essentially unexplored, broad frequency range.

From several hundreds to many thousands of sources will stand out in each
Planck channel at more than 5σ (Toffolatti et al. 1998; Guiderdoni et al. 1998). By applying suitable filters, exploiting the point-like nature of sources as opposed to the extended CMB and Galactic signals, it is possible to suppress by a substantial factor the latter components, thus strongly increasing the number of discrete sources that can be detected (Tegmark & de Oliveira-Costa 1998). The detectability of discrete sources can be further enhanced by exploiting their different spectral properties, in comparison with the CMB, i.e. by combining the information from Planck maps at different frequencies.

### 3.1 Evolution of galaxies

Measurements of the far-IR to mm extragalactic background intensity, deep ISO counts at 175 µm, and counts at 850 µm with SCUBA on JCMT indicate extreme evolution of galaxies in this region, much stronger than in the optical band. This implies that a large fraction (perhaps > 80%: see Hughes et al. 1998) of the star formation activity in the high redshift Universe may have been missed by optical studies.

This conclusion is further supported by evidences of strong dust obscuration of z > 2 Lyman break galaxies in the Hubble Deep Field found by analyses of their optical-IR spectral energy distribution (Sawicki & Yee 1998; Mobasher & Mazzei 1998; Meurer et al. 1997). It follows that far-IR to mm surveys are essential to provide true measurements of the early cosmic star formation history (Guiderdoni et al. 1997, 1998; Franceschini et al. 1997; Burigana et al. 1997; De Zotti et al. 1998; Rowan-Robinson et al. 1997).

As mentioned above, current models give widely different predictions for counts in the high frequency Planck channels. Correspondingly large differences come out in the predicted redshift distributions of detected sources (see, e.g., Fig. 19 of Guiderdoni et al. 1998). Thus, Planck will provide valuable data, complementary to
the deeper surveys from the ground or from the ESA FIRST mission, to discriminate among the various evolutionary scenarios.

3.2 Physics of radio sources

Large area radio continuum surveys above 30 GHz are not feasible from the ground (the beam area of a given telescope scales as $\nu^{-2}$) and no space-borne survey experiment operating at frequencies below several hundred GHz is foreseen. Thus, the information provided by Planck surveys will be unique.

Planck covers the frequency range where the shape of the spectral energy distribution of Active Galactic Nuclei is least known and where important spectral features, carrying essential information on physical conditions of sources, show up. We will briefly mention some examples.

Synchrotron self-absorption frequency in compact regions. As already mentioned, observations at mm/sub-mm wavelengths often reveal the transition from optically thick to optically thin radio emission in the most compact regions and therefore provide quantitative information on their physical conditions. Planck will, for example, allow to investigate if there are systematic differences in the synchrotron turnover frequencies between e.g. BL Lacs and quasars, as would be expected if BL Lacs are angled closer to our line of sight so that their turnovers are boosted to higher frequencies, and if there are correlations between turnover frequency and luminosity, which is also boosted by relativistic beaming effects.

Early phases of radio flares. Major high radio frequency flares have been observed in several compact radio sources. The radio emission peak frequency of the quasar PKS 0528+134 has increased, in 1992, from $\simeq 7$ GHz to $\simeq 60$ GHz (Zhang et al. 1994). The peak frequency of 3C 345 has been observed to decrease with time from $\simeq 50$ GHz to $\simeq 10$ GHz. Planck might detect the rise of the flare at the highest frequencies, generally missed by ground based observations.

Establishing the peak of the synchrotron emission is crucial also to understand if the emission at higher energies is to be attributed to Compton scattering of the same synchrotron photons (synchrotron self-Compton, SSC) or of seed photons external to the synchrotron emitting region, EC).

Steepening of the synchrotron spectrum due to radiation energy losses by the relativistic electrons. 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 (e.g. Carilli et al. 1991): $\nu_b \simeq 96(30 \mu G / B)^3 t_s^{-2}$ GHz. Thus, the systematic multifrequency study at the Planck frequencies will provide a statistical estimate of the radiosource ages.

Excesses due to cold dust emission. 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 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.

Thus, while lower frequency surveys provide much more detailed information relevant to define phenomenological evolution properties, surveys at mm wavelengths are unique to provide information on the physical properties.

3.3 Inverted spectrum sources
Planck/LFI will also provide the first complete samples of the extremely interesting classes of extragalactic radio sources characterized by inverted spectra (i.e. flux density increasing with frequency), which are difficult to detect, and therefore are either missing from, or strongly underrepresented in low frequency surveys. Strongly inverted spectra up to tens of GHz can be produced in very compact, high electron density regions, by optically thick synchrotron emission or by free-free absorption. Examples are known also among galactic sources.

**GHz Peaked Spectrum (GPS) radio sources.** These 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).

**High frequency free-free self absorption cutoffs in AGNs.** Ionized gas in the nuclear region free-free absorbs radio photons up to a frequency

\[
\nu_{ff} \approx 50 (g/5) \left( n_e / 10^5 \text{ cm}^{-3} \right) \left( T / 10^4 \text{K} \right)^{3/4} \ell_{\text{pc}}^{1/2} \text{ GHz},
\]

where \( g \) is the Gaunt factor. Free-free absorption cutoffs at frequencies > 10 GHz may indeed be expected in the framework of the standard torus scenario for unifying type 1 and type 2 AGNs, for radio cores seen edge on, and may have been observed in some cases (see Barvainis & Lonsdale 1998). Thus Planck's high radio frequency observations can provide constraints on physical conditions in the parsec scale accretion disk or infall region for the nearest AGNs.

**Advection-dominated sources.** In the case of a low accretion rate into a massive black hole, the radiative cooling rate becomes smaller than the viscous heating rate. As a result, the dissipated accretion energy is not efficiently radiated away but kept as internal heat and advected inward with the accreted plasma (Yi & Boughn 1998 and references therein). The radio spectra of ADS sources are characterized by a synchrotron self absorption frequency:

\[
\nu_s \approx 300 \left( M_{\text{BH}} / 10^8 M_\odot \right)^{-1/2} \left( \dot{M} / \dot{M}_{\text{Edd}} \right)^{1/2} \left( T / 10^4 \text{K} \right)^2 \left( R / R_S \right)^{-5/4} \text{ GHz}.
\]

The luminosities, however, are rather low, so that Planck may eventually see only the nearest sources of this class.

4. CONCLUSIONS

Although current estimates of fluctuations due to extragalactic sources are still affected by considerable uncertainties, particularly in the case of far-IR/sub-mm sources, conservative estimates allow to conclude that, in the frequency range 100–200 GHz, foreground fluctuations over much of the sky are well below the expected amplitude of CMB fluctuations on all angular scales covered by the Planck mission (\( \theta \geq 5' \)).

Foreground temperature fluctuations in a Gaussian beam of width \( \theta \) are minimum between 60 and 100 GHz, higher frequencies corresponding to higher Galactic latitudes and smaller values of \( \theta \). The minimum in the foreground power spectrum is estimated to occur at about 150 GHz for \( \ell \gtrsim 300 \).
The contribution due to clustering is generally small in comparison with the Poisson term; however, the relative importance of clustering increases if sources are subtracted from the Planck maps down to faint flux levels.

Planck will carry out calibrated all sky surveys at 9 frequencies between 30 and 860 GHz, covering an essentially unexplored spectral region. Sub-mm Planck channels will detect a large number of galaxies up to substantial redshifts and will thus provide information on the star formation history of galaxies. Planck will also provide 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); on the frequency of sub-mm excesses due to dust; on the population properties of inverted spectrum sources: GPS, sources with high frequency free-free self absorption, ADS, ...

In conclusion, extragalactic sources will not be a threat to Planck's cosmological investigations. At the same time, Planck will provide extremely interesting data for astrophysical studies.

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