EXTRAGALACTIC POINT SOURCES AND THE PLANCK SURVEYOR MISSION

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We review estimates of small scale fluctuations due to extragalactic point sources in the Planck Surveyor frequency bands. While our understanding of the spectral and evolutionary properties of these sources is far from complete, conservative estimates allow us to confidently conclude that, in the frequency range 100–200 GHz, their contaminating effect is well below the expected anisotropy level of the cosmic microwave background (CMB), down to angular scales of at least $\simeq 10'$. Hence, an accurate subtraction of foreground fluctuations is not critical for the determination of the CMB power spectrum up to multipoles $\ell \simeq 1000$. 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 region. New classes of sources may be revealed in these data. The familiar “flat”-spectrum radio sources should show spectral features carrying essential information on their physical properties. 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 extensively tested.

1 Introduction

The multifrequency all-sky maps produced by the Planck Surveyor mission will comprise, in addition to anisotropies which are outgrowths of primordial fluctuations, and whose precision measurements are the main goal of the mission, astrophysical foregrounds, the most important of which, over the frequency range of interest, are those due to emissions in our own Galaxy and to extragalactic radio and mm/sub-mm sources.

We deal here with extragalactic sources, which may be a major limiting factor for experiments, like Planck, aimed at accurately determining the cosmic microwave Background (CMB) power spectrum $C_\ell$ up to multipoles $\ell \sim 2000$, corresponding to angular scales $\theta \sim 5'$. In fact,
a Poisson distribution of sources produce a 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 $\ell \gtrsim 1000$ ($\theta \lesssim 10'$). Hence confusion noise due to discrete sources will dominate at small enough angular scales.

In §2 we summarize the limitations set by fluctuations due to extragalactic sources on Planck measurements of primordial CMB anisotropies. On the other hand, the multifrequency all sky surveys carried out by the Planck Surveyor mission will provide a very rich database for astrophysical studies; their impact on investigations of physical and evolutionary properties of different classes of extragalactic sources is briefly outlined in §3. Our main conclusions are presented in §4.

2 Small scale fluctuations due to extragalactic sources

A detailed discussion of the problem has been recently carried out by Toffolatti et al. Guiderdoni et al. have worked out semi-analytic models for galaxy evolution in the IR/sub-mm range and have presented predictions for source counts in the Planck/HFI bands, among others. The source confusion noise in the same bands has also been estimated by Blain et al.

Due to the steep increase with frequency of the dust emission spectrum in the mm/sub-mm region (the typical spectral index is $\alpha \simeq -3.5$, $S_\nu \propto \nu^{-\alpha}$), the crossover between radio and dust emission components for essentially all classes of extragalactic sources occurs at wavelengths of a few mm; dust temperatures tend to be higher for distant high luminosity sources, partially compensating the effect of redshift. The minimum in the spectral energy distribution of sources is thus roughly coincident with the CMB intensity peak, making the mm region ideal for mapping primordial anisotropies. A further consequence is that there is an abrupt change in the source populations observed in channels above and below $\sim 1$ mm: radio sources dominate at longer wavelengths, while in the sub-mm region the Planck instruments will mostly see dusty galaxies.

2.1 Radio sources

Estimates of the confusion noise due to radio sources do not require extrapolations in flux: the available source counts are more than sensitive enough to include any radio source of the familiar steep and “flat”-spectrum classes, likely to cause detectable fluctuations in any of the Planck maps. The real issue is the spectral behaviour since existing surveys extend only up to 8.4 GHz and hence substantial extrapolations in frequency are required.

The results reported by Toffolatti et al. are based on evolutionary models fitting the observed counts, as well as redshift and luminosity distributions, of both steep- and “flat”-spectrum radio sources at several frequencies up to 8.44 GHz. In the Planck channels one has to deal primarily with “flat”-spectrum sources, mostly at substantial redshifts. These sources appear to keep a spectral index $\alpha \sim 0$ up to $\simeq 100$ GHz. At higher frequencies a steepening or even a spectral break is generally observed. Considerable uncertainties however remain on the high frequency behaviour of these sources. To allow for this, Toffolatti et al. have considered three different values for the mean spectral index of compact radio sources in the range 20–200 GHz: $\alpha = -0.3$, 0, and 0.3; above 200 GHz a steepening to $\alpha = 0.7$ was assumed.

2.2 Evolving dusty galaxies

We are faced here with the need of substantial extrapolations both in frequency and in flux. In fact, there is a 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 $1.3\,\text{mm}/60\,\mu\text{m}$ flux ratios of galaxies span about a factor of $10^{10}$. A tentative estimate of the luminosity function of galaxies at mm wavelengths based on a $1.25\,\text{mm}/60\,\mu\text{m}$ bivariate luminosity distribution has been presented by Franceschini et al. [17]. Furthermore, the observational constraints on evolution of far-IR sources are very poor. IRAS $60\,\mu\text{m}$ counts cover a limited range in flux and are rather uncertain at the faint end [11,2,3].

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 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). On the other hand, according to the hierarchical galaxy formation paradigm, big galaxies are formed by coalescence of large numbers of smaller objects. 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 [8,2,2], and by the intensity of the isotropic sub-mm background [21,22,23], first discovered by Puget et al. [24]. Moreover, the large, negative K-correction strongly amplifies the evolutionary effects, that may thus be appreciable in the relatively shallow Planck surveys, at least in the highest frequency bands.

Toffolatti et al. [25] adopted the luminosity evolution models by Franceschini et al. [17], updated adding a density evolution up to $z = 2$ of late type galaxies [26]. Their reference model (referred to as updated model C), which entails a dust enshrouded phase during the early evolution of spheroidal systems (early type galaxies and bulges of disk galaxies), provides a good fit to the $60\,\mu\text{m}$ IRAS counts, as recently reassessed by Bertin et al. [27], to the far-IR extragalactic background spectrum, and to the preliminary estimates of the counts at $170\,\mu\text{m}$ and at $850\,\mu\text{m}$ [28].

A different approach, directly plugged in current hierarchical scenarios for galaxy formation, has been taken by Guiderdoni et al. [29] who produced a set of models starting from a description of non-dissipative and dissipative collapses of primordial perturbations. The most extreme of these models exceed, even by an order of magnitude, predictions of the updated model C. An extreme evolution in the far-IR to sub-mm bands is indeed indicated by the most recent estimates [21,22,23] indicating a very intense far-IR extragalactic background.

The contributions of AGNs to the counts in the Planck high frequency channels are even more uncertain. The detailed estimates by Granato et al. [21] indicate a detection rate of radio quiet AGNs increasing with increasing frequency, from a few units over the whole sky at $217\,\text{GHz}$ to a few hundreds at the highest frequencies; in any case, their number is expected to be small compared with the number of far-IR galaxies.

### 2.3 Fluctuations due to extragalactic sources and CMB anisotropy measurements

Given the performances of the instruments, the Planck experimental accuracy is effectively limited by astrophysical foregrounds. It is true that, on small angular scales ($\theta < 30'$), on average, the instrumental noise may exceed fluctuations due to extragalactic sources particularly if these are subtracted out down to relatively faint flux levels (on larger scales the dominant foreground fluctuations are due to Galactic emission and generally exceed the instrumental noise). However, much lower than average instrumental noise levels, well below the amplitude of extragalactic source fluctuations, will be reached in regions around the ecliptic poles that will be scanned many times; these regions are large enough to allow a careful determination of...
Figure 1: Temperature fluctuations as a function of frequency for an angular scale of 30′. The horizontal dashed line show the expected level of primordial CMB anisotropies. Average contributions from Galactic free-free, synchrotron and dust (for the two possible dust emission spectra mentioned by Kogut et al.) emissions at |b| > 50° are shown by dots/short dashes, dots-long dashes, long/short dashes, respectively. The dotted line gives the contribution of extragalactic sources. The solid line is the total contribution of astrophysical foregrounds to fluctuations; the filled circles on this line correspond to Planck channels.

Figure 2: Same as in Fig. 1 but for an angular scale of 10′.

the power spectrum of CMB anisotropies on small scales. On moderate to large angular scales (θ ≳ 30′), foreground fluctuations are minimum at frequencies ≃ 70 GHz (see Fig. 1) while on smaller scales the minimum moves to ≃ 100 GHz (Fig. 2).

In the frequency range 100–200 GHz CMB anisotropies are expected to dominate over foreground fluctuations at least up to ℓ ≃ 1000. Only a tiny fraction of pixels is expected to be contaminated by extragalactic sources which can be efficiently identified thanks to the multifrequency observations carried out during the mission. If only the brightest (S > 1 Jy) sources are removed, the contribution of clustering to fluctuations is small compared with the Poisson term. However, the effect of clustering may show up in the case of source subtraction down to below 100 mJy, introducing a modest feature in the angular power spectrum at θ ≃ 20′ at high frequencies (clustering of galaxies) and θ ≃ 80′ at low frequencies (clustering of radio sources).

The separation of CBR fluctuations from those due to extragalactic sources is further eased by the substantial difference between the power spectra of the two components. Also, in principle, it is possible to discriminate fluctuations due to discrete sources from primordial CMB anisotropies on the basis of their quite different angular size, by means of higher resolution observations. Thus, contamination by extragalactic sources does not set a critical limitation to Planck mapping of primordial CMB anisotropies.

3 Studies of extragalactic sources with the Planck Surveyor mission

3.1 “Flat”-spectrum radio sources

According to the estimates by Toffolatti et al., the Planck surveys will provide multifrequency data for a relatively large (from several hundred to a few thousand sources), complete sample
of “flat-”spectrum radio sources (compact radio galaxies, radio loud QSOs, BL Lacs, blazars), allowing investigation of a number of interesting issues.

The available observations of the spectral energy distributions of these sources generally have a gap at mm/sub-mm wavelengths. Those sources which have data in this interval frequently show a dip in the mm region, indicative of a cross-over of two components. This spectral feature, that Planck can observe, 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 a frequency at which the radiative cooling time equals the outflow time \( t \); 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, which has been 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 \( \nu_b \approx 96(30 \mu G/B)^{3/2} \) GHz. 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). These models strongly differ in the form of the falloff above \( \nu_b \). Also, many compact sources are observed to become optically thin at \( \nu \gtrsim 10 \) GHz. Correspondingly, their spectral index steepens to values (\( \alpha \approx 0.7 \)) typical of extended, optically thin sources. Thus, the systematic multifrequency study at the Planck frequencies will provide a statistical estimate of the radio source ages and measurements of the high frequency spectral behaviour and of its evolution with cosmic time: these are pieces of information of great physical importance.

In the case of blazars, the component dominating at cm wavelengths is rather “quiescent” (variations normally occur on time of years) and has a spectral turnover at \( \sim 2-5 \) 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 self-absorption break at mm/sub-mm wavelengths. The mm/sub-mm region is thus crucial to understanding the mechanisms responsible for variability in radio loud active nuclei.

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 frequencies which are higher for the denser knots. The mm/sub-mm region is unique for studying sub-parsec scale, high density regions, including the radio core. 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.

Excess far-IR/sub-mm emission, possibly due to dust, is often observed from local radio galaxies. 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.

### 3.2 Inverted-spectrum radio sources

The predictions of Toffolatti et al. do not explicitly include sources with strongly inverted spectra, peaking at mm wavelengths, that would be either missing from, or strongly under-represented in low frequency surveys and be very difficult to distinguish specrally from fluctuations in the CMB.

GHz Peaked Spectrum radio sources (GPS) appear to have 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 with peak at high frequency. It is very hard to guess how common such sources may be. Snellen exploited the sample of de Vries et al. to estimate a count of $22 \pm 10 \, \text{Jy}^{-3/2} \, \text{sr}^{-1}$ 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 the Planck experiment. Thus, although these rare sources will not be a threat for studies of CMB anisotropies, we may expect that the Planck surveys will provide crucial information about their properties. GPS sources are important because they may be the younger stages of radio source evolution 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.

Planck/LFI may also allow to study another very interesting class of radio sources, powered by advection-dominated accretion flows. These may correspond to the final stages of accretion in large elliptical galaxies hosting a massive black hole. Their radio emission is characterized by an inverted spectrum with spectral index $\alpha \sim -0.4$ up to a frequency of 100–200 GHz, followed by fast convergence.

### 3.3 Evolving dusty galaxies

As shown by Toffolatti et al. and Guiderdoni et al., the Planck high frequency channels will detect the dust emission from a large number of evolving galaxies. A spectacular breakthrough has been achieved in the last couple of years, in the optical/UV, with the long sought detection of large samples of galaxies at $z \sim 3$, allowing to get a direct insight into the history of the cosmic star and metal formation. On the other hand, several lines of evidence indicate that optical/UV data are offering a very incomplete view of the galaxy evolution at high $z$. Indeed, there are indications that most of the starlight emitted during early phases of the evolution of spheroidal systems may be essentially invisible in the optical-UV region. This may not be surprising since active star formation is generally observed to occur in dusty environments. The very strong, negative K-correction due to the steep rise with frequency of the dust emission spectrum in the mm/sub-mm wavelength range, makes this spectral region particularly well suited for detecting high-$z$ galaxies. In fact, models predict that most sources detected in the Planck high frequency channels are at $z \geq 1$; in some cases, substantial tails up to $z \simeq 3–4$ are expected. Planck high frequency surveys may thus provide a wealth of data essential to understand the the cosmic star and metal formation history.

### 4 Conclusions

Luckily enough, both for galaxies and active galactic nuclei, the crossover between the radio and the dust emission components, determining a minimum in the spectral energy distribution, is roughly coincident with the CMB intensity peak. The dust temperature tends to be higher for bright distant objects, moving the minimum to higher frequencies in the rest frame and thus partially compensating for the effect of redshift. This situation makes the mm region ideal for mapping primordial anisotropies.

Although our understanding of foregrounds at Planck frequencies is far from complete, estimates using worst-case parameters in extrapolating existing measurements to Planck frequencies or angular scales, allow us to safely conclude that, in the frequency range 100-200 GHz, the foreground fluctuations, which are dominated, on small scales ($\theta \lesssim 30'$), by extragalactic sources,
are well below the expected amplitude of CMB anisotropies over much of the sky. Hence, the removal of foreground contamination is not critical for accurate determinations of the power spectrum of CMB anisotropies up to multipoles of at least $\ell \sim 1000$.

On the other hand, while only a small fraction of high Galactic latitude pixels are strongly contaminated by astrophysical foregrounds, the Planck surveys at 9 frequencies will provide sufficiently rich complete samples for astrophysical studies. Spectral information will be provided for “flat”-spectrum radio sources (compact radio galaxies, radio loud QSOs, BL Lacs, blazars) over a frequency region where spectral features carrying essential information on their physical conditions show up (breaks due to energy losses of relativistic electrons, self-absorption turnovers of flaring components, ...). Planck surveys will be unique in providing complete samples of bright radio sources with inverted spectra, essentially undetectable in radio-frequency surveys. Important classes of sources of this kind are GHz peaked spectrum sources, which may be the youngest stages of radio source evolution and may thus provide insight into the genesis of radio sources, and advection dominated sources, corresponding to final stages of accretion in giant elliptical galaxies hosting a massive black hole. The high frequency Planck channels will detect thousands of dusty galaxies, a large fraction of which at substantial redshifts, allowing to extensively test scenarios for galaxy evolution. The increasing evidence that a large, and perhaps dominant fraction, of star formation at high redshifts may be hidden by dust, makes far-IR to sub-mm surveys an essential complement to optical data.

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