SURVEYS OF EXTRAGALACTIC SOURCES WITH PLANCK

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Abstract Although the primary goal of ESA’s PLANCK mission is to produce high resolution maps of the temperature and polarization anisotropies of the Cosmic Microwave Background (CMB), its high-sensitivity all-sky surveys of extragalactic sources at 9 frequencies in the range 30–860 GHz will constitute a major aspect of its science products. In particular, PLANCK surveys will provide key information on several highly interesting radio source populations, such as Flat Spectrum Radio Quasars (FSRQs), BL Lac objects, and, especially, extreme GHz Peaked Spectrum (GPS) sources, thought to correspond to the very earliest phases of the evolution of radio sources. Above 100 GHz, PLANCK will provide the first all-sky surveys, that are expected to supply rich samples of highly gravitationally amplified dusty proto-galaxies and large samples of candidate proto-clusters at \( z \simeq 2–3 \), thus shedding light on the evolution of large scale structure across the cosmic epoch when dark energy should start dominating the cosmic dynamics.

Keywords: Cosmology, galaxy evolution, radio galaxies
1. Introduction

The Planck satellite will carry our high sensitivity all sky surveys at 9 frequencies in the poorly explored range 30–860 GHz (see the contribution by J. Tauber, this volume). At low frequencies, Planck will go several times deeper (and will detect about ten times more sources) than WMAP, that has provided the first all-sky surveys at frequencies of tens of GHz, comprising about 200 objects (Bennett et al. 2003).

Above 100 GHz, Planck surveys will be the first and will remain the only all sky surveys available for many years to come. They will fill an order of magnitude gap in our knowledge of the spectrum of bright extragalactic sources and may discover new populations, not represented, or not recognized, in lower or higher frequencies surveys.

Rather than presenting a comprehensive review of the expected scientific results from Planck measurements of extragalactic sources (see, e.g., De Zotti et al. 1999) we will focus on a couple of frequencies, one of the Low Frequency Instrument, namely 30 GHz, and one of the High Frequency Instrument, namely 350 GHz. The relatively shallow but all-sky Planck surveys will be ideal to study populations which are both very powerful at mm/sub-mm wavelengths, and very rare, such as radio sources with inverted spectra up to $\geq 30$ GHz [extreme GHz Peaked Spectrum (GPS) sources or High Frequency Peakers (HFP)], thought to be the most recently formed and among the most luminous radio sources, and ultra-luminous dusty proto-spheroidal galaxies, undergoing their main and huge episode of star formation at typical redshifts $\geq 2$ (Granato et al. 2001, 2004). And Planck will observe such sources with an unprecedented frequency coverage.

To estimate the detection limit, and the number of detectable sources, we need to take into account, in addition to the instrument noise, the fluctuations due to Galactic emissions, to the Cosmic Microwave Background (CMB), and to extragalactic sources themselves. These fluctuations will be briefly reviewed in Section 2, while in Sections 3 and 4 we will discuss the expected impact of Planck data on our understanding of HFPs and of ultra-luminous proto-spheroidal galaxies, respectively. Our main conclusions are summarized in Sect. 5.

2. Power spectra of foreground emissions

For a very high sensitivity experiment, like Planck, the main limitation to the capability of mapping the CMB is set by contamination by astrophysical sources (“foregrounds”), while CMB fluctuations may be the highest “noise” source for the study of astrophysical emissions at mm wavelengths. The most intense foreground source is our own Galaxy. Because of the different power spectra of the various emission components, the frequency of minimum fore-
Figure 1. Galactic (dot-dashed) and extragalactic (dashed) contributions to the power spectrum of foreground fluctuations, compared with the CMB (dotted horizontal line) for three values of the multipole number $\ell$. The solid lines show the sum, in quadrature, of the two contributions. At $\ell = 100$ the dot-dashed line essentially coincides with the solid line; the two lines largely overlap at high frequencies also for higher $\ell$'s. The Galactic contributions are averages for $|b| \geq 20^\circ$, after having applied the Kp0 mask which include the point source removal, and comprise synchrotron, free-free and thermal dust emissions, whose power spectra are normalized to the K-band (22.8 GHz), V-band (60.8 GHz), and W-band (93.5 GHz) WMAP data, respectively (where each component is best measured). The extrapolation in frequency has been done adopting, for free-free, the antenna temperature spectral index ($T_A \propto \nu^{\beta_{ff}}$) $\beta_{ff} = -2.15$, and for synchrotron the expression proposed by Jackson & Wall (2002) for low-luminosity radio sources ($\log S_{\nu} = \text{const} - 0.6424 \log(\nu) - 0.0692(\log(\nu)^2)$, with $\nu$ in GHz); this formula, which allows for the high-frequency steepening of the synchrotron spectrum due to electron energy losses, is consistent with the steepening observed in WMAP data (Fig. 9 of Bennett et al. 2003). As for thermal dust we have considered two cases: $\beta_d = 2.2$, the best fit value of Bennett et al. (2003), and the more usual value $\beta_d = 2$. With these spectra, an additional component (spinning dust?) is necessary to account for the foreground signal detected by WMAP particularly in the Q-band (40.7 GHz); the solid lines include this component. Power spectra at $\ell = 100$ were derived directly from WMAP data. At higher $\ell$'s we assume $C_\ell = C_{100}(\ell/100)^{-\gamma}$ with $\gamma = 2$ or $\gamma = 3$. The upper dot-dashed curve corresponds to $\gamma = 2$ and $\beta_d = 2.2$, the lower one to $\gamma = 3$ and $\beta_d = 2$. The dashed curve includes, summed in quadrature, the contributions of all classes of extragalactic sources, based on models by De Zotti et al. (2004), including canonical radio sources, starburst galaxies, proto-spheroidal galaxies and Sunyaev-Zeldovich effects. The effect of clustering of proto-spheroidal galaxies has been taken into account as in Negrello et al. (2004a).

Ground fluctuations depends to some extent on the angular scale (see Fig. 1, where $\delta T$ are fluctuations of the CMB thermodynamic temperature, in $\mu$K, related to the power spectrum $C_\ell$ by $\delta T = [\ell(\ell+1)C_\ell/(2\pi)]^{0.5}(e^x-1)^2/(x^2e^x)$, with $x = h\nu/kT_{\text{CMB}}$). So long as diffuse Galactic emissions dominate the fluctuations ($\theta \gtrsim 30^\circ$; see De Zotti et al. 1999), they have a minimum in the 60–80 GHz range (depending also on Galactic latitude; cf. Bennett et al. 2003).
Figure 2. Predicted 30 GHz differential counts. The left-hand panel shows the counts of all the main populations (see De Zotti et al. 2004 for details). The right-hand panel details the contributions of three sub-classes of canonical radio sources: FSRQs, BL Lac objects, and steep-spectrum sources.

But the power spectra of diffuse Galactic emissions decline rather steeply with increasing multipole number (or decreasing angular scale). Thus, on small scales, fluctuations due to extragalactic sources, whose Poisson contribution has a white-noise power spectrum (on top of which we may have a, sometimes large, clustering contribution) take over, even though their integrated emission is below the Galactic one. At high frequencies, however, Galactic dust may dominate fluctuations up to ℓ values of several thousands. Unlike the relatively quiescent Milky Way, the relevant classes of extragalactic sources have strong nuclear radio activity or very intense star formation, or both. Thus, although in many cases their SEDs are qualitatively similar to that of the Milky Way, there are important quantitative differences. In particular, dust in active star forming galaxies is significantly hotter and the radio to far-IR intensity ratio of the extragalactic background is much higher than that of the Milky Way. Both factors, but primarily the effect of radio sources, cooperate to move the minimum of the SED to 100–150 GHz.

3. 30 GHz counts

Figure 2 provides a synoptic view of the contributions of different source classes to the global counts of extragalactic sources. Shallow surveys, such as those by WMAP and Planck, mostly detect canonical radio sources. As shown by the right-hand panel of Fig. 2, detected sources will be mostly flat-spectrum radio quasars (FSRQs), while the second more numerous population are BL Lac objects. Planck will detect about ten times more sources than WMAP, thus allowing a substantial leap forward in the understanding of
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Figure 3. Redshift distributions of WMAP FSRQs (left-hand panel) and BL Lacs (right-hand panel) compared with the model by De Zotti et al. (2004, solid line).

evolutionary properties of both populations at high frequencies, only weakly constrained by WMAP data (Fig. 3).

Planck will also provide substantial complete samples of sources not (yet) represented in the WMAP catalog, such as Sunyaev-Zeldovich (1972) signals and extreme GPS sources or HFPs (Dallacasa et al. 2000).

GPS sources are powerful ($\log P_{1.4\ GHz} \gtrsim 25$ W Hz$^{-1}$), compact ($\lesssim 1$ kpc) radio sources with a convex spectrum peaking at GHz frequencies. It is now widely agreed that they correspond to the early stages of the evolution of powerful radio sources, when the radio emitting region grows and expands within the interstellar medium of the host galaxy, before plunging into the intergalactic medium and becoming an extended radio source (Fanti et al. 1995; Readhead et al. 1996; Begelman 1996; Snellen et al. 2000). Conclusive evidence that these sources are young came from measurements of propagation velocities. Velocities of up to $\simeq 0.4c$ were measured, implying dynamical ages $\sim 10^8$ years (Polatidis et al. 1999; Taylor et al. 2000; Tschager et al. 2000). The identification and investigation of these sources is therefore a key element in the study of the early evolution of radio-loud AGNs.

There is a clear anti-correlation between the peak (turnover) frequency and the projected linear size of GPS sources. Although this anti-correlation does not necessarily define the evolutionary track, a decrease of the peak frequency as the emitting blob expands is indicated. Thus high-frequency surveys may be able to detect these sources very close to the moment when they turn on. The self-similar evolution models by Fanti et al. (1995) and Begelman (1996) imply that the radio power drops as the source expands, so that GPS’s evolve into lower luminosity radio sources, while their luminosities are expected to be very high during the earliest evolutionary phases, when they peak at high frequencies. De Zotti et al. (2000) showed that, with a suitable choice of the
parameters, this kind of models may account for the observed counts, redshift and peak frequency distributions of the samples then available. The models by De Zotti et al. (2000) imply, for a maximum rest-frame peak frequency $\nu_{p,i} = 200$ GHz, about 10 GPS quasars with $S_{30\text{GHz}} > 2\text{Jy}$ peaking at $\geq 30\text{GHz}$ over the 10.4 sr at $|b| > 10^\circ$. Although the number of candidate GPS quasars (based on the spectral shape) in the WMAP survey is consistent with such expectation, when data at additional frequencies (Trushkin 2003) are taken into account the GPS candidates look more blazars caught during a flare optically thick up to high frequencies. Furthermore, Tinti et al. (2004) have shown that most, perhaps two thirds, of the quasars in the sample of HFP candidates selected by Dallacasa et al. (2000) are likely blazars.

Thus, WMAP data are already providing strong constraints on the evolution of HFPs. PLANCK will substantially tighten such constraints and may allow us to directly probe the earliest phases (ages $\sim 100\text{yr}$) of the radio galaxy evolution, hopefully providing hints on the still mysterious mechanisms that trigger the radio activity.

We note, in passing, that contrary to some claims, we do not expect that PLANCK can detect the late phases of the AGN evolution, characterized by low accretion/radiative efficiency (ADAF/ADIOS sources).

At faint flux densities, other populations come out and are expected to dominate the counts. In addition to SZ effects, we have active star-forming galaxies, seen either through their radio emission, or through their dust emission, if they are at substantial redshift. The latter is the case for the sub-mm sources detected by the SCUBA surveys if they are indeed at high redshifts (see below).

Such sources may be relevant in connection with the interpretation of the excess signal on arc-minute scales detected by CBI (Mason et al. 2003; Readhead et al. 2004) and BIMA (Dawson et al. 2002) experiments at 30 GHz, particularly if, as discussed below, they are highly clustered, so that their contribution to fluctuations is strongly super-Poissonian (Toffolatti et al. 2004). In fact, to abate the point source contamination of the measured signals, the CBI and BIMA groups could only resort to existing or new low frequency surveys. But the dust emission is undetectable at low frequencies. Although our reference model (Granato et al. 2004), with its relatively warm dust temperatures yielded by the code GRASIL (Silva et al. 1998), imply dusty galaxy contributions to small scale fluctuations well below the reported signals, the (rest-frame) mm emission of such galaxies is essentially unknown and may be higher than predicted, e.g. in the presence of the extended distribution of cold dust advocated by Kaviani et al. (2003) or of a widespread mm excess such as that detected in several Galactic clouds (Dupac et al. 2003) and in NGC1569 (Galliano et al. 2003). This is another instance of the importance of a multi-
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Figure 4. Left-hand panel: contributions of different populations to the 350 GHz counts. Central panel: effect of lensing on counts of proto-spheroidal galaxies. Right-hand panel: estimated counts of “clumps” of proto-spheroids observed with Planck resolution.

frequency approach, like Planck’s, capable of keeping under control all the relevant emission components, with their different emission spectra.

4. 350 GHz counts

The 350 GHz counts of extragalactic sources have been determined in the range from \( \simeq 10 \, \text{mJy} \) to \( \simeq 0.25 \, \text{mJy} \) by surveys with the SCUBA camera, covering small areas of the sky (overall, a few tenths of a square degree). These surveys have led to the discovery of very luminous high-z galaxies, with star-formation rates \( \sim 10^3 \, M_\odot/\text{yr} \), a result confirmed by 1.2mm surveys with MAMBO on the IRAM 30m telescope. These data proved to be extremely challenging for semi-analytic galaxy formation models, and have indeed forced to reconsider the evolution of baryons in dark matter halos.

The bright portion of observed counts appears to be declining steeply with increasing flux density, probably reflecting the exponential decline of the dark-halo mass function at large masses implied by the Press & Schechter formula, so that one would conclude that Planck cannot do much about these objects, but rather detect brighter sources such as blazars and relatively local star-forming galaxies, or SZ signals. There are, however, two important effects to be taken into account, that may change this conclusion: gravitational lensing and clustering.

We refer here to the model by Granato et al. (2004) according to which SCUBA sources are large spheroidal galaxies in the process of forming most of their stars. Forming spheroidal galaxies, being located at relatively high redshift, have a substantial optical depth for gravitational lensing, and the effect
of lensing on their counts is strongly amplified by the steepness of the counts. This is illustrated by the left-hand panel of Fig. 4, based on calculations by Perrotta et al. (2003). Strong lensing is thus expected to bring a significant number of high-$z$ forming spheroids above the estimated Planck $5\sigma$ detection limit.

If indeed SCUBA galaxies are massive spheroidal galaxies at high $z$, they must be highly biased tracers of the matter distribution, and must therefore be highly clustered. There are in fact several, although tentative, observational indications of strong clustering with comoving radius $r_0 \simeq 8h^{-1}$ Mpc (Smail et al. 2004; Blain et al. 2004; Peacock et al. 2000), consistent with theoretical expectations.

But if massive spheroidal proto-galaxies live in strongly over-dense regions, low resolution experiments like Planck unavoidably measure not the flux of individual objects but the sum of fluxes of all physically related sources in a resolution element.

This is an aspect of the “source confusion” problem, whereby the observed fluxes are affected by unresolved sources in each beam. The problem was extensively investigated in the case of a Poisson distribution, particularly by radio astronomers (Scheuer 1957, Murdoch et al. 1973, Condon 1974, Hogg & Turner 1998). The general conclusion is that unbiased flux measurements require a $S/N \geq 5$.

Not much has been done yet on confusion in the presence of clustering (see however Hughes & Gaztanaga 2000). The key difference is that, for a Poisson distribution, a bright source is observed on top of a background of unresolved sources that may be either above or below the all-sky average, while in the case of clustering, sources are preferentially found in over-dense regions.

Clearly, the excess signal (over the flux of the brightest source in the beam) depends on the angular resolution. For a standard $\xi(r) = (r/r_0)^{-1.8}$ the mean clustering contribution is $\propto r_0^{-0.8}r_{\text{beam}}^{1.2}$. The Planck beam at this frequency corresponds to a substantial portion of the typical clustering radius at $z \simeq 2$–3, so that Planck will actually measure a significant fraction of the flux of the clump, which may be substantially larger than the flux of any member source. The effect on counts depends on the joint distribution of over-densities and of $M/L$ ratios. The former depends on both the two- and the three-point correlation function, while the latter depends on the luminosity function.

Preliminary estimates of the distribution of excess luminosities due to clustering around bright sources have been obtained by Negrello et al. (2004b). The right-hand panel of Fig. 4 shows the estimated counts of clumps observed with Planck resolution for three models for the evolution of the coefficient $Q$ of the three-point correlation function. Obviously Planck can provide information only on the brightest clumps, and, except in the extreme case of $Q = 1$ at all cosmic times, the clumps will only show up as $< 5\sigma$ fluctuations.
On the other hand, such fluctuations will provide a rich catalogue of candidate proto-clusters at substantial redshifts (typically at $z \approx 2–3$), very important to investigate the formation of large scale structure and, particularly, to constrain the evolution of the dark energy thought to control the dynamics of the present day universe.

5. Conclusions

Although extragalactic surveys are not the primary goal of the mission, Planck will provide unique data for several particularly interesting classes of sources. Examples are the FSRQs, BL Lac objects, but especially extreme GPS sources that may correspond to the earliest phases of the life of radio sources, and proto-spheroidal galaxies. Thus Planck will investigate not only the origin of the universe but also the origin of radio activity and of galaxies. Sub-mm surveys will provide large samples of candidate proto-clusters, at $z \approx 2–3$, shedding light on the evolution of the large scale structure (and in particular providing information on the elusive three-point correlation function) and of the dark energy, across the cosmic epoch when it is expected to start dominating the cosmic dynamics.

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