On the Transits of Solar System Objects in the Forthcoming Planck Mission: Data Flagging and Coeval Multifrequency Observations

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Abstract In the context of current and future microwave surveys mainly dedicated to the accurate mapping of Cosmic Microwave Background (CMB), mm and sub-mm emissions from Solar System will represent a potential source of contamination as well as an opportunity for new Solar System studies. In particular, the forthcoming ESA Planck mission will be able to observe the pointlike thermal emission from planets and some large asteroids as well as the diffused Zodiacal Light Emission (ZLE). After a brief introduction to the field, we focus on the identification of Solar System discrete objects in the Planck time ordered data.

1 Introduction

The ESA Planck satellite, scheduled for launch in April 2009, will produce nearly full sky maps at the frequencies of 30, 44, and 70 GHz (Low Frequency Instrument, LFI) and at 100, 143, 217, 353, 545 and 857 GHz (High Frequency Instrument, HFI) with an unprecedented resolution (FWHM from $\approx 33'$ to $\approx 5'$) and sensitivity (in the range of $\approx 10^{-40}$ mJy (1 – 10 $\mu$K) on a FWHM$^2$ resolution element). In order to exploit the scientific targets of the mission even the contamination from faint foreground sources has to be accounted for. External planets, Main Belt asteroids (MBAs), and diffused interplanetary dust will be observed by Planck and will represent a relevant source of contamination but, at the same time, a good opportunity for optical and photometric calibration (in the case of planets) and an interesting subject of scientific analysis. The

1 http://astro.estec.esa.nl/Planck/

2 For a presentation on these topics see e.g. the talk held at the Workshop Future Ground based Solar System Research: Synergies with Space Probes and Space Telescope, held at Portoferraio, Isola d’Elba, Livorno (Italy), September 8–12, 2008, with the original
possibility to observe Solar System sources with PLANCK has been assessed in several works. In particular, [3] shown that it will possible to use the transits of external planets to properly reconstruct the PLANCK main beam shapes and to measure the SED of the planets with a typical photometric accuracy better than $\sim 1\%$ relying on calibration accuracy with dipole. [4] pointed out that PLANCK will be able to observe up to $3 \times 10^2$ MBAs with a $S/N > 1$ and several tens of them with significantly better $S/N$ ratios, and [5] presented a study about the possibility of PLANCK to properly identify and separate the ZLE with a differential, intrinsically unbiased approach. Moreover, [6, 7] discussed the possibility that the thermal emission of trans-Neptunian objects (TNOs) and of comets in the Oort cloud could induce collective distortions in microwave maps, while [8] analyzed in a general way ecliptic plane correlated emissions in the context of large scale anomalies of WMAP maps. In this work we discuss the fundamental recipes needed to plan observations of Solar System objects with ground facilities or space satellites at times almost coeval with the transits of these sources on PLANCK receivers, in the view of multifrequency studies of these objects.

2 Observing the Solar System with the PLANCK satellite

PLANCK is a one–axis stabilized satellite orbiting around the L2 Earth–Sun libration point [2]. It is equipped with a 1.5 m aplanatic Gregorian telescope whose optical axis points at a direction separated by an angle $\beta = 85^\circ$ from the spin axis. During nominal operations the satellite will spin at a rate of 1 r.p.m. allowing the (optical axis of the) telescope to scan each minute a circle on the sky with a semiperture of $85^\circ$. To survey the whole sky the spin axis orientation will be kept constant for about 60 minutes, after which it is drifted of about 2.5 arcmin $^3$. Different ways of drifting defines different scanning strategies [2, 9, 10], provided that the spin axis shall never depart more than some degrees from the instantaneous antisolar direction. In the nominal scanning strategy the spin axis is kept on the ecliptic plane, while in the baseline scanning strategy currently foreseen for PLANCK it will describe a slow precession about the antisolar direction with a semiperture of $7.5^\circ$ and a period of six months in order to have a complete sky coverage will the whole set of receivers. In fact, the two cryogenic instruments hosted in the telescope focal plane, LFI and HFI, form an array of feed–horns (FHs) covering a field–of–view (f.o.v.) of $\simeq 7^\circ$, each FH pointing to a slightly different direction in the sky with respect to the f.o.v. centre defined by the telescope optical axis. In most cases the FHs of a given frequency are arranged to be aligned along the scanning direction as projected on the telescope f.o.v.

The signals collected by the FHs are detected independently by the satellite on–board electronics. The instrument output is thus a set of data–streams (time ordered data, TODs) representing the variation of the antenna temperature (or of an equivalent quantity) detected as the telescope scans the sky. When coupled with accurate information about the instantaneous pointing direction of each FH, after proper calibration and data–processing, the TODs are combined to produce multi–frequency maps of the sky.

PLANCK will return at almost the same heliocentric coordinates every 12 months but it will complete a first sky survey in about 8–9 months because of the value of $\beta$...
and the locations of the FHs. It will observe Solar System objects in a narrow range of elongations ($\sim 95^\circ \pm 4^\circ$) so that the objects of the inner Solar System can not be observed. Sources will be observed by PLANCK when they will cross the PLANCK f.o.v. during its scanning of the sky (note that PLANCK is not a space observatory). There is also a certain intrinsic small uncertainty in predicting in advance the exact pointing direction of each FH as a function of time: a precise time / pointing correlation will be established only a posteriori at ground. Also, the same object will not be observed at the same time by all FHs.

As a remarkable example, we consider the observations of MBAs and planets in the case of a mission launch on April 12th, 2009 (JD = 2454935.5), first survey starting 45 days after launch (May 12th, 2009), beginning of second survey 258 days after launch (December 21st, 2009), and end of second survey 471 days after launch (July 28th, 2010). Since few fine details of the current baseline scanning strategy are under definition, we report here results based on the nominal scanning strategy but our results are weakly dependent on the exact scanning strategy. The simulation has been performed by using the JPL Horizons Ephemeris web server\(^4\) which allows to recover the PLANCK orbit for the nominal launch date and to compute the apparent position of any Solar System object as seen by PLANCK. Of course, it is too much time expensive to scan the whole Horizons data base for the whole $4 \times 10^5$ objects. Thus, we limit our search to a sub–sample of MBAs potentially able to produce a non negligible signal in PLANCK receivers.

According to [4], the antenna temperature of an asteroid of radius $R$ observed at a distance $\Delta$ from PLANCK is:

$$T_{\text{ant},\nu} \simeq 4 \ln 2 \ e^{-4 \ln 2 d^2/\nu^2} \ K_\nu \left[ \frac{R}{\Delta} \right]^2 T_{b,\nu}.$$  \hspace{1cm} (1)

here $b_\nu$ is the FWHM of the FH at the considered frequency channel, $K_\nu \leq 1$ the photometric efficiency of the considered FH, $T_{b,\nu}$ the mean surface brightness temperature of the body, $d$ the angular distance of the object from the FH center.

A “detection” threshold with $S/N > 1$ is equivalent to ask to observe asteroid signal with peak $T_{\text{ant},\nu}$ of several $\mu$K and this corresponds to $R/\Delta > 2 \times 10^{-7}$ [4]. On the other hand, even an object below that threshold could cause a non negligible undesired signal. Obviously, the same region of sky will appear different when data of the first and the second survey will be compared. Considering signal differences above an indicative threshold of $\approx 1 \mu$K is equivalent to consider asteroids with $R/\Delta > 5 \times 10^{-8}$. Thus, we selected all the MBAs with $R/\sqrt{R_{\text{per}}} - (1.01 \text{ A.U.})^2 > 5 \times 10^{-8}$, where $R_{\text{per}}$ is the asteroid mean perihelion distance.

In order to illustrate the observability function of asteroids in the PLANCK f.o.v., we use a comoving spin axis reference frame defined as the reference frame having for $X$–axis the spin axis, the $Y$–axis aligned with the drift direction, and the $Z$–axis directed toward the North Ecliptic Pole (NEP).

The polar plot in Fig. 1 represents the position of the selected objects at 00:00 UT of day 407 after the launch. We define the plotting convention used to drawn the figure Planck–eye projection. There the objects are drawn in the $Y, Z$ plane of the Spin–Axis reference frame with $\varphi$ being the azimuthal direction of an object when projected in the same plane. The normalized radial coordinate is defined as:

\(^4\) [http://ssd.jpl.nasa.gov/horizons.cgi](http://ssd.jpl.nasa.gov/horizons.cgi), with code for 500@489 PLANCK.
\[ t = \frac{\theta - \beta}{b_{\text{deg}}} \quad (2) \]

\[ N = \left( 1 - e^{-\left( \frac{180^\circ - \beta}{b_{\text{deg}}} \right) \varpi} \right)^{1/\zeta} - \left( 1 - e^{-\left( \frac{\beta}{b_{\text{deg}}} \right) \varpi} \right)^{1/\zeta} \quad (3) \]

\[ \rho(t) = \frac{1}{N} \left[ 1 + \text{sign}[t] (1 - e^{-|t| \varpi})^{1/\zeta} \right] \quad (4) \]

where \( \text{sign}[t] \) is the sign of \( t \), assumed to be 1 for \( t = 0 \); \( \beta = 85^\circ \) is the angle between the telescope line of sight and the spin axis; \( b_{\text{deg}} \) is a FWHM representative of the instrument; \( \varpi \) and \( \zeta \) are scaling parameters. Here we take \( b_{\text{deg}} = 0.5^\circ, \varpi = \zeta = 0.25 \).

The coordinate is normalized to have \( 0 \leq \rho(\theta) \leq 1 \), with \( \rho = 0 \) for \( \theta = 0^\circ \), \( \rho = 1 \) for \( \theta = 180^\circ \) and \( \rho \approx 1/2 \) for \( \theta = 85^\circ \). The scaling parameters are chosen to smoothly enlarge the scan circle, allowing a nearly linear scale, compressing the regions far from it. In the plot an example of instantaneous location of the rotating f.o.v. is represented by the gray rectangle, the circles represent the region scanned by the f.o.v.. Dots represents the position of the asteroids outside the scan circle, and then for that pointing of the spin axis, never observed, diamonds the position of observable asteroids. All the objects resides on the ecliptic, corresponding to \( Y \approx 0 \). Due to the polar singularity, there is an apparent divergence of objects near \( \rho = 1 \) (i.e. \( \theta = 180^\circ \)). The spin axis drifts toward the \( Y > 0 \) direction and defines a leading and a trailing edge of the circle. At the trailing edge Mars is already transited while Saturn is going to transit. At the leading edge Neptune is transiting while Jupiter and Uranus are going to transit and are overlapped due to the plot scale. For completeness the apparent positions of L2, Sun, Moon and Earth, all behind the spacecraft, are also marked.

The relative motion of the objects with respect to the telescope axis scan circle is dominated by the drift directed toward the \( Y > 0 \) (or leading) edge of the scan circle. All the objects enters the leading edge of the scan circle and leaves it from the trailing edge more or less moving parallel to the ecliptic. An object crossing the scan circle from the right to the left of the plot will produce a peak in the data–stream with a one minute period and a varying amplitude as it moves through the f.o.v.. Each FH will track a well defined scan circle, relatively close to that identified by the telescope axis scan circle. Each object will cross the scan circles corresponding to the various FHs in a sequence and at different times.

All over the mission, the number of objects in the f.o.v. are in average \( 47 \pm 20 \), i.e. \( \sim (4 \pm 0.15)\% \) of all of the MBAs will enter the PLANCK f.o.v., with an obvious equipartition between the leading and the trailing side of the each scan circle. Among them about 30\% are potentially detectable in at least one frequency channel. About 83\% of the objects are observed twice during the mission, 17\% are observed once, while less than 1\% are never observed or are observed more than twice. In general, double observations refer to objects observed both at the leading and the trailing edge of the scan circle. The average time between the crossing of the leading and the trailing edge is \( \approx (164 \pm 6) \) days. In average, objects take about 8 or 9 days to cross the leading or the trailing side of the scan circle, equivalent to say that they cross the f.o.v. at an averaged speed of about \( \dot{\vartheta}_{\text{fov}} \approx 2 \) arcmin/hour. The fact that \( \dot{\vartheta}_{\text{fov}} \) is smaller than the spacecraft drift rate is due to the relative motion of the objects with respect to PLANCK. Since the FHs are aligned along slightly different scan circles, the average time in which objects could be observed in their main beam is \( \tau_{\text{vis}} \approx b_{\nu}/\dot{\vartheta}_{\text{fov}} \). This ranges
Fig. 1 Planck-eye representation of a PLANCK scan circle (concentric rings) an instantaneous PLANCK f.o.v. (gray region) together with the positions of a selected subset of asteroids and planets. The tilted graduated scale in correspondence of the f.o.v. gives the relation between the normalized radial coordinate $\rho$ and the angular distance from the spin axis $\theta$ according to Eqs (2–4). The spin axis points outside the plot at at $[0, 0]$ and it drifts toward the positive $Y$ direction defining the leading and the trailing directions. The position of the ecliptic poles (North, NEP and South, SEP) are also shown. Red dots represents asteroids outside the f.o.v. while those transiting the f.o.v. are marked with a magenta $\updiamond$.

from 16 − 17 hours for a 30 GHz beam down to 2 − 3 hours for a 857 GHz beam. When combined with the number of FH forming each frequency channel, $N_{d tc}$, the total integration time is:

$$\tau_{int, \nu} \approx \frac{b_\nu}{\theta_{fov} \tau_{point}} \frac{b_\nu N_{spin} N_{d tc}}{\omega_{spin}} N_{obs};$$  

(5)

here $N_{obs}$ is the number of observations, $N_{spin} \approx 55$ the number of useful spin rotations during a pointing period of $\tau_{point} = 3600$ seconds, and $\omega_{spin}$ is the satellite spin-rate. With the PLANCK parameters reported in [4], $\tau_{int, \nu}$ ranges from 350 sec for the 30 GHz channel down to 15 sec for the 857 GHz frequency channel, with a typical
Table 1  Epochs of transits for planets and some large asteroids through the Planck f.o.v., L: transit at the leading edge of the scan circle. T: transit at the trailing edge.

| Object | L: Dates | T: Dates |
|--------|----------|----------|
| Mars   | L:2009-Oct-27 ÷ 2009-Nov-8 | T:2010-Apr-20 ÷ 2010-May-1 |
| Jupiter| T:2009-Oct-29 ÷ 2009-Nov-6 | L:2010-Jun-24 ÷ 2010-Jul-2 |
| Saturn | T:2009-May-28 ÷ 2009-Jun-4 | L:2009-Dec-26 ÷ 2010-Jan-2 | T:2010-Jun-10 ÷ 2010-Jun-17 |
| Uranus | L:2009-Jun-18 ÷ 2009-Jun-25 | T:2009-Dec-4 ÷ 2009-Dec-11 | L:2010-Jun-23 ÷ 2010-Jun-30 |
| Neptune| T:2009-Nov-4 ÷ 2009-Nov-12 | L:2010-May-21 ÷ 2010-May-28 |
| Ceres  | L:2010-Mar-24 ÷ 2010-Apr-1 |
| Pallas  | L:2010-Feb-10 ÷ 2010-Feb-19 | T:2010-Jul-15 ÷ 2010-Jul-26 |
| Vesta  | T:2009-Nov-22 ÷ 2009-Dec-1 | L:2010-May-7 ÷ 2010-May-16 |

spread of ±40% because of detailed FWHM of the considered FH, exact beam centre angular distance from the spin axis direction, and, obviously, object motion. To a first approximation, useful for practical estimates, \( \tau_{\text{int},\nu} \approx 10^{3.94 - 0.97 \log_{10}(\nu_{\text{GHz}})} \) sec.

As an example of the output of our tool, Tab. 1 gives the epochs for the Planck observation of planets and three large asteroids, specifying also if the object transit in the Planck receiver scan circle occurs at its leading or trailing edge. Changes in the final orbit, as well as spin axis precessions, may displace the observation windows of up to about a week with respect to the table.

3 Conclusion

We have presented a method to characterize when and how Solar System discrete objects, such as asteroids and planets, will be observed by the Planck satellite, aimed at planning almost coeval observations of these sources on a wide frequency coverage, including data from Planck and observational facilities. Of course, our method can be also used to flag those Planck data samples that, being affected by the signals from Solar System discrete objects, have to be excluded in other astrophysical and cosmological analyses. The main limitation for coeval multifrequency observations comes from the fact that Planck will just observe each object more or less in quadrature with the Sun. For comets this does not pose any serious constrain given the large eccentricity of their orbits. However, up to now, there is not a robust constraint on the physical properties of a comet to be detectable by Planck. On the contrary, a similar analysis for planets and MBAs is relatively well assessed. In average planets and MBAs will be observed at least twice during the nominal mission. For asteroids this means that in average they will be seen at a distance of about 2.3 AU from Planck and that only asteroids with radii larger than some tens of kilometers will be observed with a sufficiently high S/N. Our simple simulations indicate that in average at least one or two of such objects will be in the Planck f.o.v. each day. The need for Planck to keep its spin axis within some degrees from the Sun allows a simple planning of almost coeval observations, by looking at the elongation of the objects with respect to the Sun. More refined calculations could be obtained with relatively small efforts by using on–the–shelf ephemerids calculators and the available information about Planck focal plane and scanning strategy.
Acknowledgements

This work has been partially supported by the Italian ASI Contract “PLANCK LFI Activity of Phase E2” and by the “Fondi FFO ricerca libera 2009”. We thank Thomas Mueller for constructive discussions.

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