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The Second *Planck* Catalogue of Compact Sources

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The Second *Planck* Catalogue of Compact Sources is a catalogue of sources detected over the entire sky at nine different frequencies between 30 and 857 GHz. It consists of Galactic and extragalactic objects detected in the *Planck* single-frequency full mission total intensity maps. Compact sources detected in the lower frequency channels are assigned to the PCCS2, while at higher frequencies they are assigned to one of two sub-catalogues, the PCCS2 or PCCS2E, depending on their location on the sky. The PCCS2 covers most of the sky and can be used to produce subsamples at higher reliabilities than the target 80 % integral reliability of the catalogue. The PCCS2E contains sources located in certain regions where the complex background makes it difficult to quantify the reliability of the detections. Both the PCCS2 and PCCS2E include polarization measurements, in the form of polarized flux densities, or upper limits, and orientation angles for all seven polarization-sensitive *Planck* channels.

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1. Introduction

The European Space Agency's *Planck*[1] Mission [1] has observed the microwave and submillimeter sky between August 2009 and October 2013 to study the early Universe through the Cosmic Microwave Background (CMB). The large frequency coverage of *Planck*, 30 – 857 GHz, also allow scientists to study the diffuse and compact emissions of our Galaxy as well as those of very distant galaxies. In 2015 the *Planck* Collaboration has released the second set of products based on the analysis of the full mission data both in total intensity and polarization [2]. One of these products is the Second *Planck* Catalogue of Compact Sources [3], a compilation of sources detected by *Planck* that supersedes previous versions of the *Planck* Compact Source catalogues in terms of sensitivity, completeness and reliability. The main difference between this catalogue and the previous ones, the Early Release Compact Source Catalogue (ERCSC) released in 2011 and the Planck Catalogue of Compact Sources (PCCS) released in 2013, is the division of the frequency catalogues at 100 GHz and above into two sub-catalogues, the PCCS2 and the PCCS2E. This division separates sources for which the reliability can be quantified (PCCS2) from those of unknown reliability (PCCS2E). This separation is primarily based on the Galactic coordinates of the source. The target integral reliability of the entire catalogue, as in the PCCS, is 80% or greater. By setting the reliability target this low we are improving the odds of finding sources with interesting properties which otherwise would have been rejected. However, a very reliable catalogue is also desirable and for this purpose we provide additional information that will allow the user to select subsets of highly reliable sources. In addition, *Planck* has polarization sensitive detectors in the frequency range 30 to 353 GHz and polarization measurements are provided for the sources in the PCCS2 and PCCS2E based on the positions obtained in the analysis of the total intensity maps. Therefore, we do a non-blind analysis at the position of the previously detected sources and do not attempt to search for new compact sources in polarization. In order to produce the PCCS2 we have analysed the full mission data, that for the particular case of the three lowest *Planck* frequencies implies a significant improvement in terms of sensitivity with respect to the PCCS. In figure 1 we compare the sensitivity of the PCCS2 with that of the PCCS, the ERCSC and other surveys in the frequency range covered by *Planck*.

2. The Second *Planck* Catalogue of Compact Sources

The *Planck* full mission data have been transformed into full-sky HEALPix maps [5] by the Data Processing Centres (DPCs) [6, 7]. The LFI DPC produced the 30, 44, and 70 GHz maps after the completion of eight full surveys (spanning the period 12 August 2009 to 3 August 2013). The HFI DPC produced the 100, 143, 217, 353, 545, and 857 GHz maps after five full surveys (12 August 2009 to 11 January 2012). Since the full mission maps contain an average of the eight full surveys for LFI, five full surveys for HFI, the flux densities of the sources as measured in the full-mission maps are an average of several observations of each source over the duration of

[1] *Planck* (http://www.esa.int/Planck) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states and led by Principal Investigators from France and Italy, telescope reflectors provided through a collaboration between ESA and a scientific consortium led and funded by Denmark, and additional contributions from NASA (USA).

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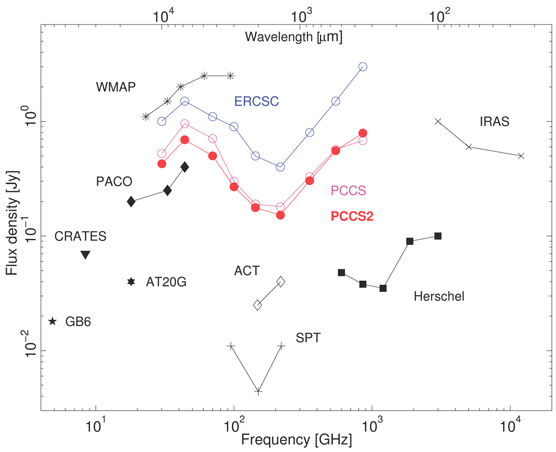

Figure 1: Sensitivity (the flux density at 90 % completeness) of the PCCS2, compared with PCCS, ERCSC, WMAP and others. The sensitivities displayed for the LFI channels are for the full sky. For the HFI channels, the 90 % completeness limits plotted for the PCCS2 were evaluated in the extragalactic zone as defined in [4]. The regions of sky to which the 90 % completeness limits apply are therefore similar but not identical to those of the PCCS2.

the mission. The flux density of the sources could be measured in the single survey maps, but this would not guarantee a single epoch observation, and is out of the scope of the PCCS2. The beam sizes of the *Planck* instruments range from 32.4 arc minutes at 30 GHz to 4.6 arc minutes at 857 GHz. More details about the beams can be found in table 2 of the PCCS2 article [3]. The detection of the compact sources in the catalogue has been done at each frequency independently using improved versions of the detection pipelines used to create the PCCS. These pipelines are based on the Mexican Hat Wavelet 2 algorithm [8, 9]. This is a cleaning and denoising algorithm used to convolve the maps, preserving the amplitude of the sources while greatly reducing the large scale structures visible at gigahertz frequencies (e.g., diffuse Galactic emission) and small scale fluctuations (e.g., instrumental noise) in the vicinity of the sources. The analysis is performed after projecting the full-sky maps onto square patches. The size of the patches and the overlap between them have been chosen in such a way that the full sky is effectively covered. Sources above a fixed signal-to-noise ratio (S/N) threshold are selected and their positions are translated from patch to spherical sky coordinates. Because the patches overlap, multiple detections of the same object can occur, these must be found and removed, keeping the detection with the highest S/N for inclusion in the catalogue. The reason for having slightly different estimations of the S/N of a source in different patches is related to the fact that the diffuse Galactic emission varies across the sky and the background that one can find in one patch is slightly different from the patch next to it. Therefore, after filtering out the small scale noise and the large scale diffuse emission, the statistical properties of the local noise are similar from one patch to the next, but not identical, and we keep the source that has been detected with the highest S/N. In this release of the *Planck* Compact Source Catalogue we provide two sub-catalogues for six of the nine frequencies and a parameter for each source which gives the highest reliability catalogue to which the source belongs (e. g., a source with a $HIGHEST\_RELIABILITY\_CAT = 95$ meaning that this source can be

Channel	Flux density 90% completeness [mJy]	No. of sources		Polarized sources	
		PCCS2	PCCS2E	PCCS2	PCCS2E
30	427	1560	–	122	–
44	692	934	–	30	–
70	501	1296	–	34	–
100	269	1742	2487	20	43
143	177	2160	4139	25	111
217	152	2135	16842	11	325
353	304	1344	22665	1	666
545	555	1694	31068	–	–
857	791	4891	43290	–	–

Table 1: Characteristics of the PCCS2 and PCCS2E catalogues: flux density at 90% completeness in total intensity; number of sources detected in each catalogue in total intensity; number for which polarized signal is measured above a 99.99% confidence level.

included in a catalogue with a reliability up to 95%, but should not be included in a catalogue where the sources are expected to have a reliability greater than 95%). Those sources for which we do not evaluate this parameter are placed in the PCCS2. Figure 2 shows the distribution of the PCCS2 and PCCS2E sources across the sky for three of the *Planck* frequency channels (30, 143, and 857 GHz). Table 1 summarizes the properties of the nine frequency sub-catalogues of the current release, additional information can be found in tables 10 and 11 of the PCCS2 article [3].

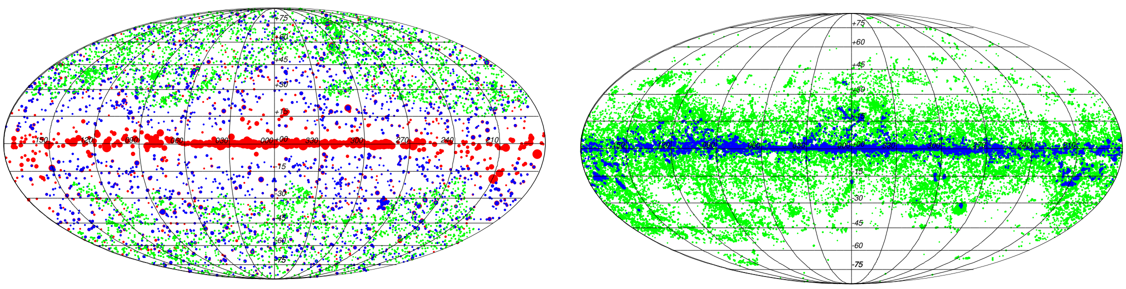

Figure 2: Left: Distribution of the sources from the PCCS2. Red, blue, and green circles show sources from the 30, 143, and 857 GHz catalogues, respectively. Right: Distribution of the sources in the 143 and 857 PCCS2E. The figure is a full-sky Mollweide projection with the Galactic equator horizontal; longitude increases to the left with the Galactic centre in the centre of the map. The size of the filled circles gives an idea of the relative flux densities of the sources per frequency, with larger circles corresponding to larger flux densities. A different size range has been used for each channel.

2.1 Photometry in total intensity and polarization

In the PCCS2, as in previous *Planck* catalogues of compact sources, we provide four different measures of the flux density for each source. They are determined by the source detection algorithm

(DETFLUX), aperture photometry (APERLUX), point spread function (PSF) fitting (PSFFLUX), and Gaussian fitting (GAUFLUX). Only the first is obtained from the filtered maps; the other measures are estimated from the full-sky maps at the positions of the sources. The source detection algorithm photometry, the aperture photometry, and the PSF fitting use the *Planck* band-average effective beams, calculated with FEBeCoP (Fast Effective Beam Convolution in Pixel space) [10, 11, 12]. Note that only PSFFLUX takes into account the variation of the PSF with position on the sky.

In the *Planck* polarization maps, the polarized sources are embedded in a background which is the combination of instrumental noise and Galactic diffuse emission. The nature of the diffuse emission depends on the observation frequency; for example, polarized synchrotron emission in the lower frequency channels and infrared and zodiacal light emission in the higher frequency channels. In both regimes the polarization degree of the compact sources (the ratio between their polarized flux densities and total intensity) is typically lower than $1-2\%$. This presents a challenge in terms of disentangling the true polarized flux density of a source from the background. In order to tackle this problem, a two-step process has been proposed [13]. First, a maximum-likelihood filter is applied, reducing the noise and enhancing the S/N of the sources embedded in the Q and U maps [14]. Second, the significance of each detection is assessed based on the statistics of the local background in the vicinity of the source. Several significance levels were investigated and we concluded that, for the typical polarization backgrounds present in the *Planck* polarization maps, a significance threshold of 99.99 % successfully distinguishes the polarized emission of a compact source from a peak in the background. This approach has been used in the present catalogues to attempt to measure the polarized flux densities and uncertainties of all sources found in the temperature maps. Polarization measurements are provided for all sources where the significance of the detected polarized signal reaches or exceeds the limit of 99.99%; for the remaining sources we provide the 99 % upper limit. Figure 3 shows the distributions of the significantly polarized sources in the LFI.

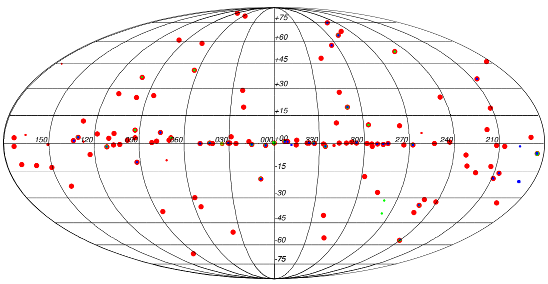

Figure 3: Distribution of the polarized sources in the lowest channels of the PCCS2. Red, green, and blue circles show sources from the 30, 44, and 70 GHz catalogues, respectively. As in the previous figure, the size of the filled circles give a qualitative idea of the relative polarized flux densities of the sources.

The polarized flux density of a source, P, is evaluated using

$$P = \sqrt{Q^2 + U^2}, \tag{2.1}$$

where Q and U are the flux densities in the Q and U maps, measured at the position of the source detected in the I map. We follow the $IAU/IEEE$ convention [15], for defining the angle of polarization of a source: polarization angles are taken as increasing anticlockwise (north through east). In this paper, however, position angle zero is taken as the direction of the north Galactic pole. The polarization angle is defined by

$$\Theta = \frac{1}{2}\arctan(-U/Q). \tag{2.2}$$

The minus sign is necessary to correct from the HEALPix convention for position angles used in the *Planck* Stokes parameter maps, in which position angle increases clockwise. Polarization angles are given in degrees in the range -90 deg to 90 deg.

3. Validation of the PCCS2

The sources in the PCCS2 and the four different flux-density estimates have been validated using simulations (internal validation) and comparing with other astrophysical data (external validation). The validation of the low-frequency sources can be performed in part by using the large number of existing catalogues. Detections identified with known sources have been flagged as such in the catalogues. In contrast, the validation of sources at higher frequencies must be done using simulations; specifically through a Monte Carlo quality assessment process in which artificial sources are injected into both real and simulated maps. Further details about the validation of the catalogues, in particular the completeness and reliability assessments, can be found in section 3 of the PCCS2 article [3].

4. Accessing the PCCS2

The PCCS2 is available from the *Planck* Legacy Archive[2]. It is composed of 15 single frequency catalogue FITS files, one per LFI channel and two per HFI channel. Additional information about the catalogue content and format can be found in the Explanatory Supplement[3], in the FITS file headers, and in the first PCCS paper [4].

5. Conclusions

The Second *Planck* Catalogue of Compact Sources has been produced using the *Planck* full mission data. The catalogue lists sources detected in total intensity in each of its nine frequency bands between 30 and 857 GHz and polarization measurements at the positions of these sources for seven of the frequencies, between 30 and 353 GHz. Its format has changed with respect to the ERCSC and the PCCS. We have divided the catalogue into two, the PCCS2 and PCCS2E, based on our ability to provide a measure of the reliability of each source detected at 100 GHz and above, where the available external catalogues of compact sources are not enough to fully assess the reliability of the detections. Sources located inside the defined Galactic plane masks and/or sitting along dusty filamentary structures as defined in the cirrus masks provided with the

[2] http://archives.esac.esa.int/pla

[3] http://wiki.cosmos.esa.int/planckpla2015

catalogue are in the PCCS2E. The new catalogue is more complete than the PCCS, in particular for the LFI channels, due to the large increase in the data available, eight sky surveys as compared with the two and a half sky surveys of PCCS. The division of the HFI catalogues into the PCCS2 and PCCS2E has allowed the addition of a parameter in the PCCS2 catalogue that will allow a user to define subsets of the catalogue with higher reliabilities than the target integral reliability of 80 %. This added functionality gives the users of the PCCS2 the option of extracting high-reliability sub-catalogues, and, in addition, provides a much more complete full catalogue, allowing studies of more sources and to fainter flux densities.

Acknowledgments

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