FM 5:
The Legacy of Planck

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FM5. The Legacy of Planck

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Abstract. This paper is an introduction to Focus Meeting 5 held at the IAU's General Assembly held in Honolulu in August 2015. It describes the rationale for the meeting, and summarizes the introductory talk to FM5, which contained a description of the *Planck* data products released by ESA and the *Planck* Collaboration in the first half of 2015.

Keywords. cosmology, cosmic microwave background, surveys

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1. The Legacy of *Planck*

The *Planck* satellite† (Tauber *et al.* 2010; Planck Collaboration I 2011) was launched on 14 May 2009 and observed the sky continuously from 12 August 2009 to 23 October 2013. *Planck*'s scientific payload contained an array of 74 detectors in nine bands covering frequencies between 25 and 1000 GHz, which scanned the sky with angular resolution between 33′ and 5′. The detectors of the Low Frequency Instrument (LFI; Bersanelli *et al.* 2010; Mennella *et al.* 2011) were pseudo-correlation radiometers, covering bands centred at 30, 44, and 70 GHz. The detectors of the High Frequency Instrument (HFI; Lamarre *et al.* 2010; Planck HFI Core Team 2011) were bolometers, covering bands centred at 100, 143, 217, 353, 545, and 857 GHz. *Planck* was designed to image the whole sky twice in one year, with a combination of sensitivity, angular resolution, and frequency coverage never before achieved. In fact, *Planck* acquired data for a far longer period of time than initially planned, completing 5 full sky surveys with the HFI and 8 surveys with the LFI.

The main objective of *Planck*, defined in 1995, was to measure the spatial anisotropies in the temperature of the cosmic microwave background (CMB), with an accuracy set by fundamental astrophysical limits, thereby extracting essentially all the cosmological information embedded in the temperature anisotropies of the CMB. *Planck* was not initially designed to measure to high accuracy the CMB polarization anisotropies, which encode not only a wealth of cosmological information, but also provide a unique probe of the history of the Universe during the time when the first stars and galaxies formed. However, during its development it was significantly enhanced in this respect, and its polarization measurement capabilities have exceeded all original expectations. *Planck* was also designed to produce a wealth of information on the properties of extragalactic sources, including clusters of galaxies via the Sunyaev-Zeldovich (SZ) effect, and the dust and gas in the Milky Way. The scientific objectives of *Planck* were described in detail in Planck Collaboration (2005).

† *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).*

Planck, its payload, and its performance as predicted at the time of launch are described in 13 papers included in a special issue of Astronomy & Astrophysics (Volume 520). An overview of the scientific operations of the *Planck* mission was given in Planck Collaboration I (2014). Further operational details extending to the end of the mission are presented in the 2015 Explanatory Supplement (Planck Collaboration ES 2015). The first set of scientific data, the Early Release Compact Source Catalogue (ERCSC; Planck Collaboration VII 2011), was released in January 2011. At the same time, initial scientific results related to astrophysical foregrounds were published in a special issue of Astronomy and Astrophysics (Vol. 520, 2011). Since then, 40 "Intermediate" papers have been submitted to A&A containing further astrophysical investigations by the Collaboration. The second set of scientific data, consisting mainly of temperature maps of the whole sky, was released in March of 2013. These data and associated scientific results are described in A&A special issue Vol. 571 (2014).

A third set of scientific data, based on the complete data acquired by *Planck* from 12 August 2009 to 23 October 2013, and containing both temperature and polarisation data, was released to the public between February and July 2015. This data release is accompanied by 28 papers authored by the *Planck* Collaboration, describing the reduction of the data leading to the released products, and the major scientific results obtained from them. One of these papers (Planck Collaboration I 2016) contains a detailed overview of products and results and is the recommended introduction to *Planck*. In addition, an Explanatory Supplement describes the products themselves. All these papers, whose titles begin with "*Planck* 2015 results", have been submitted to the journal Astronomy and Astrophysics for publication in a Special Issue in 2016.

All of the papers by the *Planck* Collaboration may be downloaded via a Publications portal (`http://www.cosmos.esa.int/web/Planck`), and all of the data products from the *Planck* Legacy Archive (PLA), accessible from `http://www.cosmos.esa.int/web/planck/pla`. The web interface to the PLA offers the possibility not only to download data products, but also to search for and select parts of them (e.g. a section of a map, a subset of a source catalogue, timelines within time ranges, etc). The PLA interacts seamlessly with powerful visualisation and data processing tools (Aladin, TopCat) which allow many more data manipulation functions.

The polarised CMB data contained in the 2015 release, while a major step forward for many areas of research, still contains unwanted systematics effects at large angular scales which make its use for cosmology very limited. Ongoing efforts are being made to improve the quality of the data, leading to a final release of *Planck* products being planned in the second half of 2016. This release will constitute the Legacy of *Planck*.

As it contains all the *Planck* data, the 2015 release was a major step towards the delivery to the community of the Legacy of Planck. The timing of the IAU's General Assembly in August of 2015 was thus conveniently placed in between the last two major releases of *Planck* data. For this reason, a "Focus Meeting" (FM5) was held whose main aims were to:

- publicize the wide variety of current and potential uses of *Planck* data
- foster exchanges between users of *Planck* data
- get feedback to optimize the last delivery of *Planck* data products.

The programme of FM5 included invited talks reviewing all the major areas of cosmology and astrophysics in which *Planck* data is already having a significant impact, and contributed talks and posters with emphasis on scientific areas where *Planck* data is used on its own and/or together with other sets of data from current or future ground-based, balloon-based or space-based experiments The final programme of FM5 can be

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found at `http://www.cosmos.esa.int/web/planck-legacy-conference/`; most presentations and posters can be downloaded from the same location.

2. Data products in the 2015 release

The 2015 distribution of released products, freely accessible via the *Planck* Legacy Archive interface (PLA, `http://pla.esac.esa.int`) is based on all the data acquired by *Planck* during routine operations, starting on 12 August 2009 and ending on 23 October 2014. The general principle has been to distribute all the intermediate products which are required to produce the official ones (e.g. frequency maps). The distribution contains the following (a more detailed overview of products and results can be found in Planck Collaboration I (2016)).

• Cleaned and calibrated data timelines for each detector, comprising detector data, pointing and time stamps. Detailed descriptions of the cleaning and calibration process can be found in Planck Collaboration II (2016); Planck Collaboration III (2016); Planck Collaboration V (2016); Planck Collaboration VII (2016); Planck Collaboration VIII (2016). The timelines are organized into files containing one Operational Day each. The PLA interface allows to select timelines by detector, time range, and/or sky location; the user may choose to download all OD files corresponding to their selection, or only the selected ranges (in which case the data will be repackaged before download).

• Maps of the sky at nine frequencies in temperature, and at seven frequencies (30–353 GHz) in polarization (see Fig. 1 and Fig. 2). Detailed description and characterization of the maps can be found in Planck Collaboration VI (2016); Planck Collaboration II (2016); Planck Collaboration VIII (2016). The maps are served by the PLA as full-mission maps (which accumulate all the data available at each frequency), or by subsets, i.e. by time range (Survey, Year, Half-Mission, etc) or by Detector and Detector Set. Combinations of time range and Detector are also available. Additional products, such as Half-ring maps, serve to quantify the noise characteristics of the maps to a level adequate for the science results being presented. Bandpass correction maps to be applied to the polarized maps are also made available. Masks based on Galactic emission and Compact sources are provided as well.

• Beam maps (an essential part of the data analysis) are provided in two forms: scanning beams (which represent the optical beam for each detector convolved with the sampling function) and effective beams for each full-mission frequency map (which represent the spatially varying scanning beam convolved with the survey scanning function for each pixel in the map). Scanning beams may be retrieved over a selected grid of pixels. The characterization of *Planck* beams is described in Planck Collaboration IV (2016); Planck Collaboration VII (2016).

• Instrument characteristics are provided in the form of Reduced Instrument Model (RIMO) files, which contain a wide range of average detector properties such as NETs, FWHMs, window functions, etc etc. A software package is also provided that calculates unit conversion and color correction of maps.

• A full set of simulations of the sky as observed by *Planck*, including Monte Carlo realizations, are described in Planck Collaboration XII (2016). Considering the huge data volume of the entire set of simulated realizations (10000) used by the *Planck* Collaboration, the PLA makes only a small fraction of them (1000) available for download. However, the entire set is available for local use at the NERSC supercomputing facility in Berkeley (USA). Instructions for accessing this facility are available from the PLA.

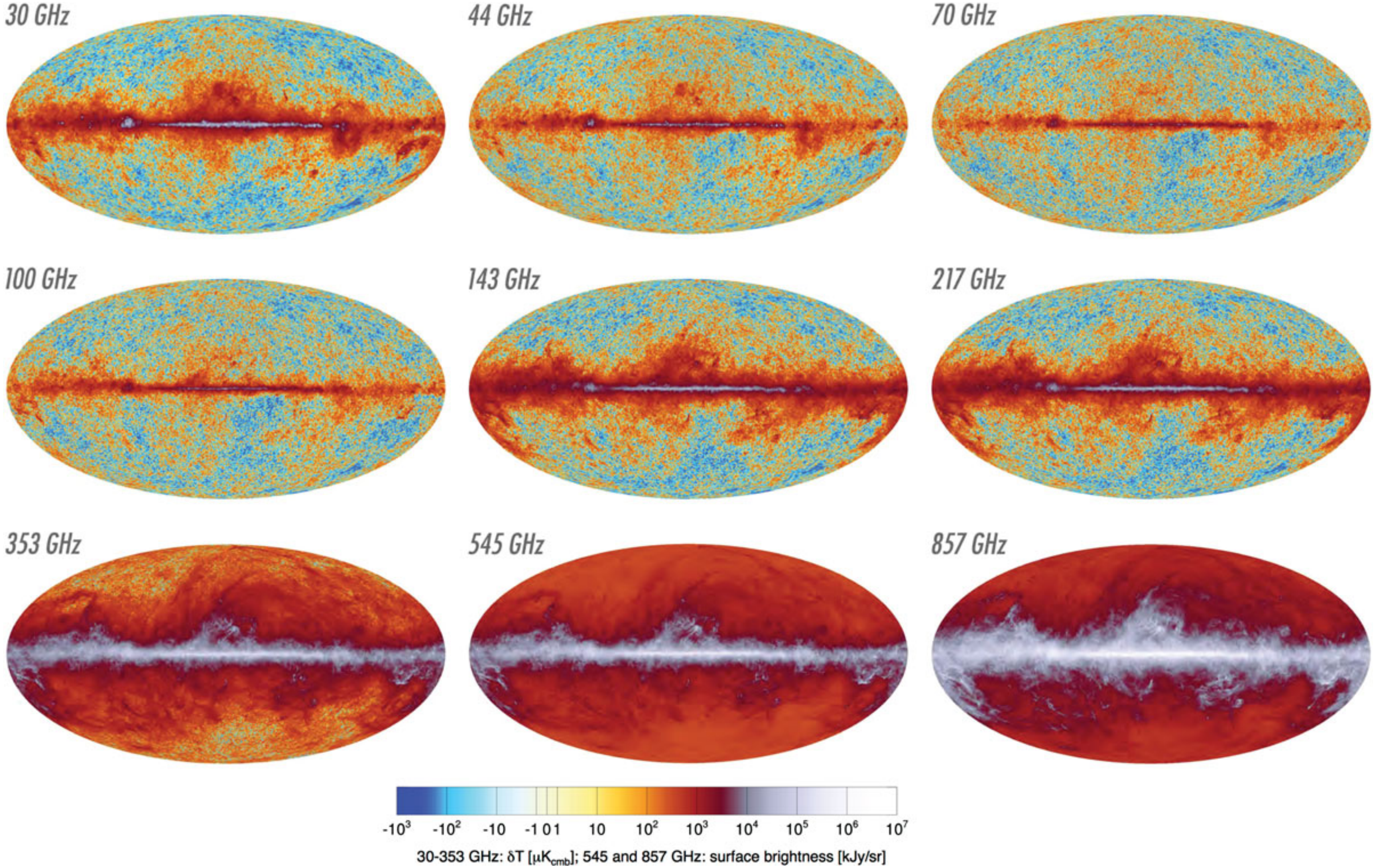

Figure 1. The nine *Planck* frequency maps from 30 to 857 GHz. The colour scale, based on inversion of the function $y = 10^x - 10^{-x}$, is tailored to show the full dynamic range of the maps.

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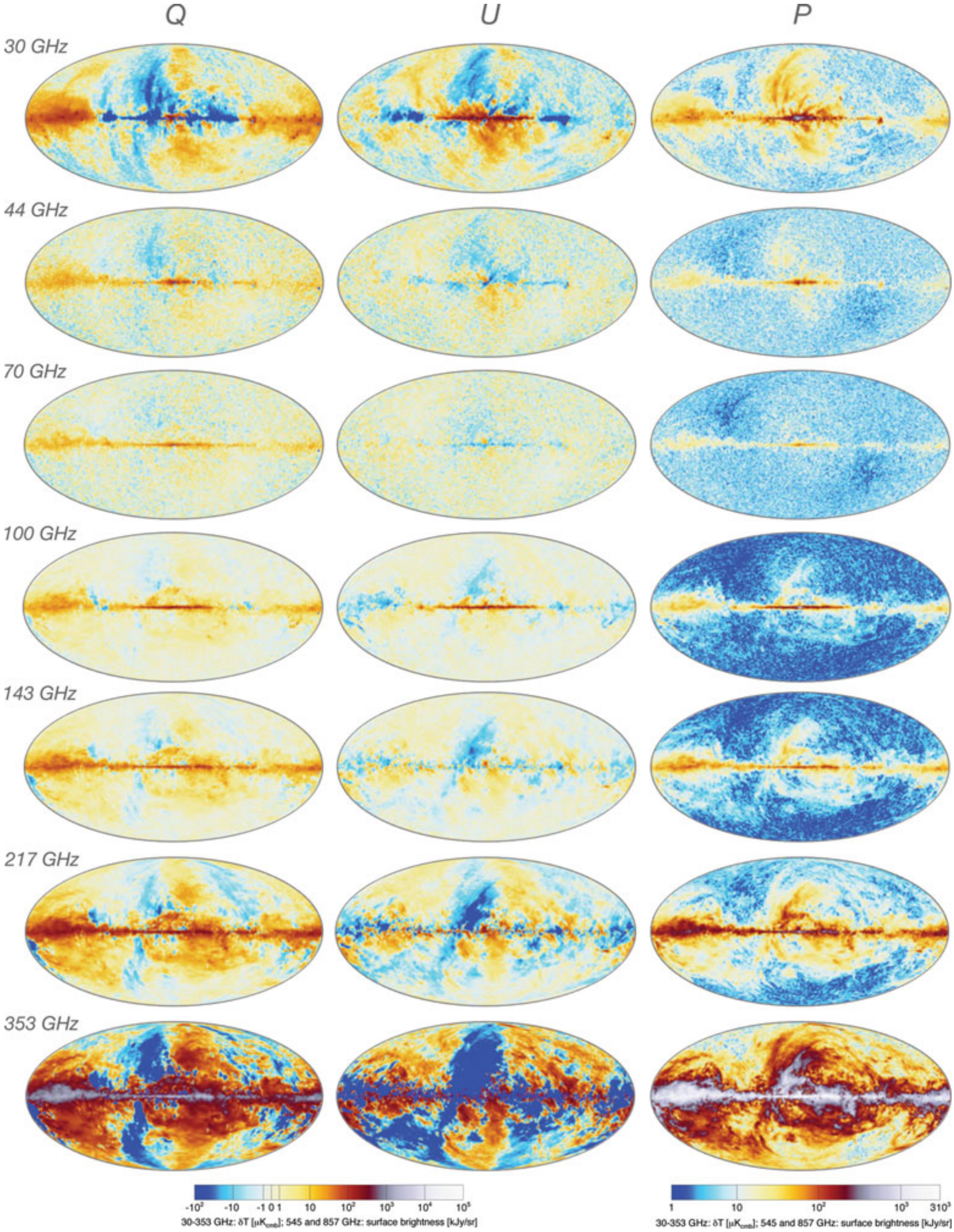

Figure 2. The seven *Planck* polarization maps from 30 to 353 GHz, shown in Stokes Q and U, and in total polarized intensity (P). Note: the LFI maps are not corrected for temperature–to-polarization leakage due to bandpass mismatch; the HFI maps are. The colour scale uses the same function as in Fig. 1, but the range limits have been adjusted.

• High-resolution maps of the CMB sky in temperature and polarization obtained by four different component separation methods, and accompanying characterization products. Fig. 3 shows one of the temperature maps and Fig. 4 shows the corresponding (high-pass-filtered) Stokes Q and U maps. Comparison of the four maps allows the user

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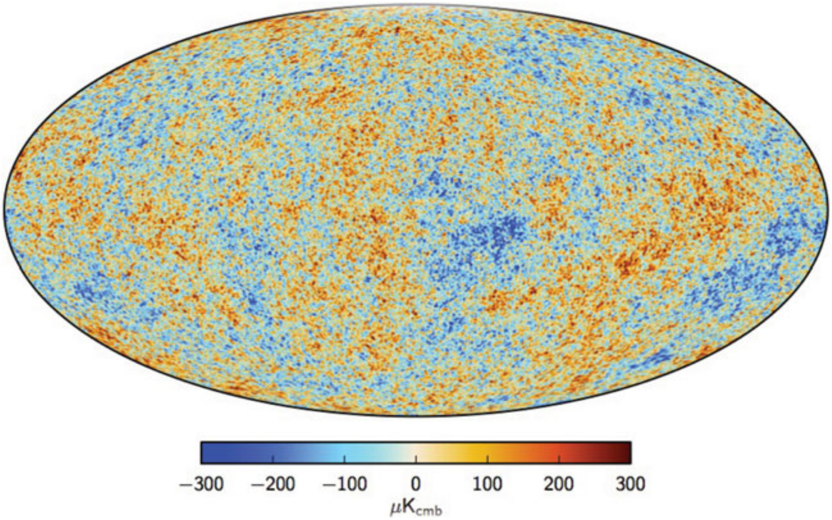

Figure 3. Maximum posterior CMB intensity map at 5′ resolution derived from the joint baseline analysis of *Planck*, WMAP, and 408 MHz observations. A small strip of the Galactic plane, 1.6 % of the sky, is filled in by a constrained realization that has the same statistical properties as the rest of the sky (Planck Collaboration IX 2016).

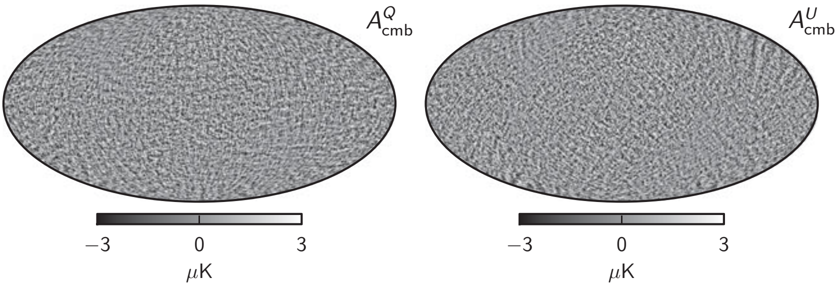

Figure 4. Maximum posterior amplitude Stokes Q (*left*) and U (*right*) maps derived from *Planck* observations between 30 and 353 GHz. These maps have been highpass-filtered with a cosine-apodized filter between $\ell = 20$ and 40, and a 17 % region of the Galactic plane has been replaced with a constrained Gaussian realization (Planck Collaboration IX 2016). From Planck Collaboration X (2016).

to characterize the uncertainties in the CMB extraction process. A detailed description of the production and characterization of these maps is available in Planck Collaboration IX (2016). The maps are used to constrain the statistics, gaussianity, and isotropy of the CMB fluctuations (Planck Collaboration XVI 2016; Planck Collaboration XVII 2016). Constraints on the geometry and topology of the Universe are described in Planck Collaboration XVIII (2016). Extraction of the Integrated Sachs-Wolfe effect from the CMB maps is described in Planck Collaboration XXI (2016).

• A low-resolution CMB temperature map used in the low-ℓ likelihood code, with an associated set of foreground temperature maps produced in the process of separating the low-resolution CMB from foregrounds, with accompanying characterization products.

• Maps of thermal dust, carbon monoxide (CO), synchrotron, free-free, and spinning dust temperature emission, plus maps of dust temperature and opacity. Maps of polarized synchrotron and dust emission are also included in the release. The production and

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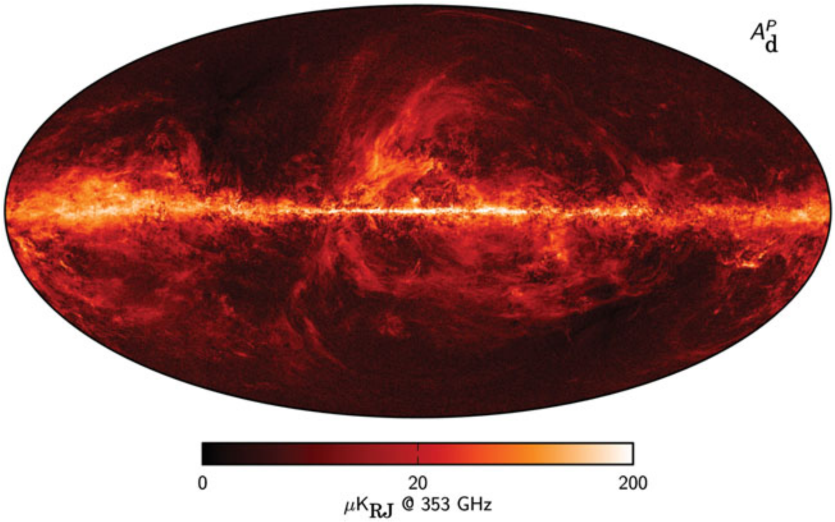

Figure 5. Dust polarization amplitude map, $P = \sqrt{Q^2 + U^2}$, at 353 GHz, smoothed to an angular resolution of $10'$, produced by the diffuse component separation process described in (Planck Collaboration X 2016) using *Planck* and WMAP data.

characterization of these maps is described in Planck Collaboration X (2016). As an example, Fig. 5 shows polarized dust intensity across the sky. A detailed analysis of the low-frequency sky observed by *Planck* is described in Planck Collaboration XXV (2016).

• A map of the estimated CMB lensing potential over 70 % of the sky. The production of this map and its constraints on cosmology are described in Planck Collaboration XV (2016).

• A map of the Sunyaev-Zeldovich effect Compton parameter, whose production is described in Planck Collaboration XXII (2016), and its correlation with Cosmic Infrared background tracers in Planck Collaboration XXIII (2016).

• The Second *Planck* Catalogue of Compact Sources (PCCS2), comprising lists of compact sources over the entire sky at the nine *Planck* frequencies. The PCCS2 (described in Planck Collaboration XXVI (2016) includes polarization information, and supersedes the previous Early Release Compact Source Catalogue (Planck Collaboration XIV 2011) and the PCCS1 (Planck Collaboration XXVIII 2014). See Fig. 6 to get an impression of the contents of PCCS2.

• The Second *Planck* Catalogue of Sunyaev-Zeldovich Sources (PSZ2), comprising a list of sources detected by their SZ distortion of the CMB spectrum. The PSZ2, described in Planck Collaboration XXVII (2016), supersedes the previous Early Sunyaev-Zeldovich Catalogue (Planck Collaboration XXIX 2014) and the PSZ1 (Planck Collaboration XXIX 2014). Constraints on cosmology derived from a selected subset of PSZ2 sources are described in Planck Collaboration XXIV (2016).

• The *Planck* catalogue of Galactic Cold Clumps (PGCC; Planck Collaboration XXVIII 2016), providing a list of Galactic sources selected on the basis of their low dust temperature. The PGCC supersedes the previous Early Cold Core Catalogue (ECC), part of the Early Release Compact Source Catalogue (ERCSC; Planck Collaboration VII 2011).

• A likelihood code and data package used for testing cosmological models against the *Planck* data, including both the CMB and CMB lensing, and the Monte Carlo chains

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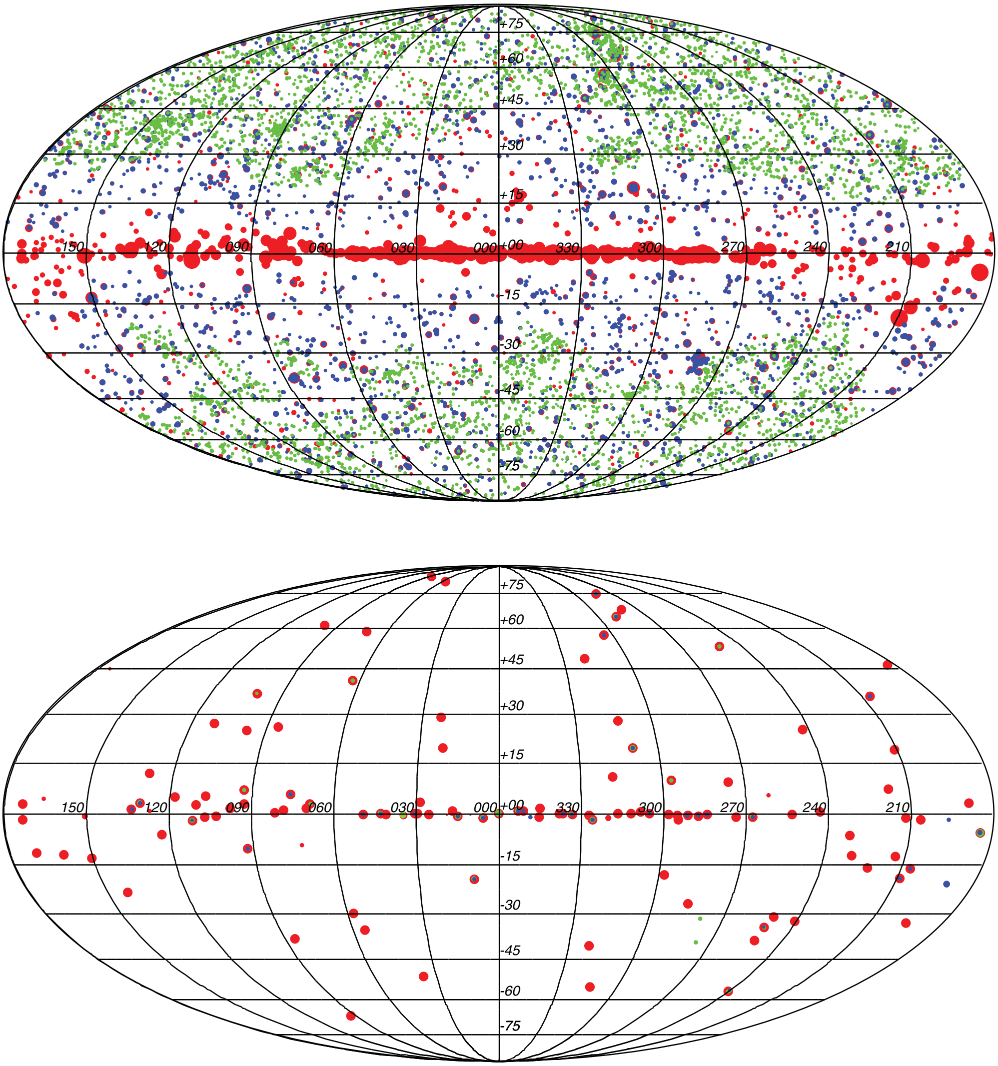

Figure 6. *Top*: Distribution of the validated sources from the PCCS2. Red, blue, and green circles show sources from the 30, 143, and 857 GHz catalogues, respectively. *Bottom*: Distribution of the polarized sources in the lowest channels of the PCCS2. Red, green, and blue circles show sources from the 30, 44, and 70 GHz catalogues, respectively. 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. Note that a different size range for each channel was necessary for visualization purposes.

used in determining cosmological parameters. The likelihood code and its characterization are described in Planck Collaboration XI (2016), and the estimation of cosmological parameters in Planck Collaboration XIII (2016). A more specialized extraction of parameters related to Dark energy and modified gravity is described in Planck Collaboration XIV (2016), and one dedicated to primordial magnetic fields in Planck Collaboration XIX (2016). More general constraints on inflation, combining likelihood-based analysis and map-based analysis, are described in Planck Collaboration XX (2016).

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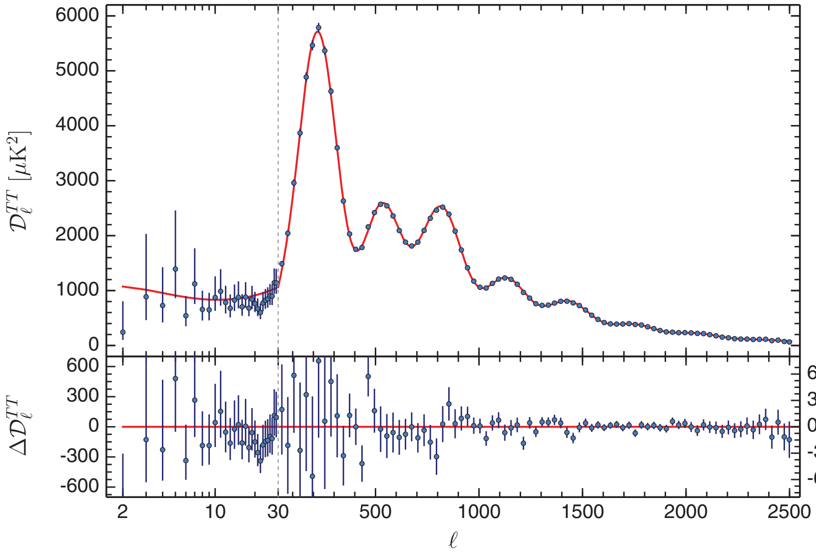

Figure 7. The *Planck* 2015 CMB temperature angular power spectrum. At multipoles $\ell \geqslant 30$ we show the maximum likelihood frequency-averaged temperature spectrum computed from the cross-half-mission likelihood with foreground and other nuisance parameters determined from the MCMC analysis of the base ΛCDM cosmology. In the multipole range $2 \leqslant \ell \leqslant 29$, we plot the power spectrum estimates from the `Commander` component-separation algorithm computed over 94 % of the sky. The best-fit base ΛCDM theoretical spectrum fitted to the PlanckTT+lowP likelihood is plotted in the upper panel (in red). Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1\,\sigma$ uncertainties. From Planck Collaboration XIII (2016).

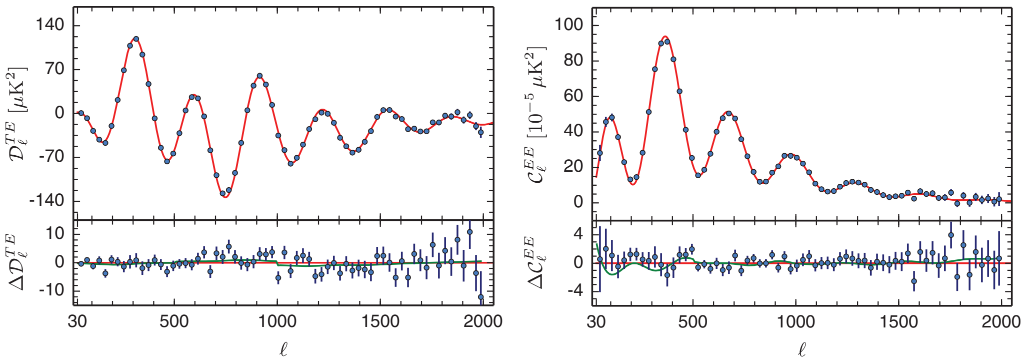

Figure 8. Frequency-averaged TE (*left*) and EE (*right*) spectra (without fitting for T–P leakage). The theoretical TE and EE spectra plotted in the upper panel of each plot are computed from the best-fit model of Fig. 7. Residuals with respect to this theoretical model are shown in the lower panel in each plot. The error bars show $\pm 1\,\sigma$ errors. The green lines in the lower panels show the best-fit temperature-to-polarization leakage model, fitted separately to the TE and EE spectra. From Planck Collaboration XIII (2016).

- A subset of cosmological results, e.g. CMB angular power spectra, best-fit models, and sets of cosmological parameters extracted using the *Planck* likelihood. Spectra and best-fit models for the “vanilla” 6-parameter cosmology are shown in Fig. 7 and Fig. 8.

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