PROCEEDINGS OF SCIENCE

Highlights of Planck results

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The aim of my presentation was to summarize the main cosmological results obtained so far from the *Planck* mission, and to point to the wide variety of data products available from the *Planck* Legacy Archive. I highlighted the concordance of *Planck*'s cosmological model with other independent probes, and noted some of the tensions. A new and higher-quality set of data products based on *Planck* will be released to the community in late 2017. This paper summarizes the presentation and includes the main references to be looked up by anyone interested in *Planck*.

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The *Planck* satellite (`https://www.cosmos.esa.int/web/Planck`) was launched on 14 May 2009 and observed the sky between 12 August 2009 and 23 October 2013. *Planck*'s scientific payload contained an array of 74 detectors in nine bands covering frequencies between 25 GHz and 1000 GHz, which scanned the sky with angular resolution between 33 and 5 arcminutes. The main objective of *Planck*, defined in 1995, was to measure the spatial anisotropies in the temperature of the cosmic microwave background (CMB). The first major set of scientific data from *Planck*, consisting mainly of temperature maps of the whole sky produced from the first 15 months of acquired data, was released to the public in March 2013. These data and associated scientific results were described in a special issue of Astronomy and Astrophysics (vol. 571, 2014); an overview of these results can be found in Planck Collaboration I (2014).

Between February and July 2015, all of the data acquired by *Planck* were released to the public. Processed products included temperature and polarisation all-sky maps (Figs. 1 and 2). This data release was accompanied by 28 papers authored by the *Planck* Collaboration, describing the reduction of the data and the major scientific results. One of these papers (Planck Collaboration I 2016) contains a detailed overview of products and results and is a recommended introduction to *Planck*. All of the papers by the *Planck* Collaboration can be found via `https://www.cosmos.esa.int/web/Planck`, and all of the data products are accessible online via the *Planck* Legacy Archive, `https://www.cosmos.esa.int/web/planck/pla`. Continuing efforts to improve the quality of the data will lead to a third and final release of Planck products in late 2017, which will represent the legacy of the mission.

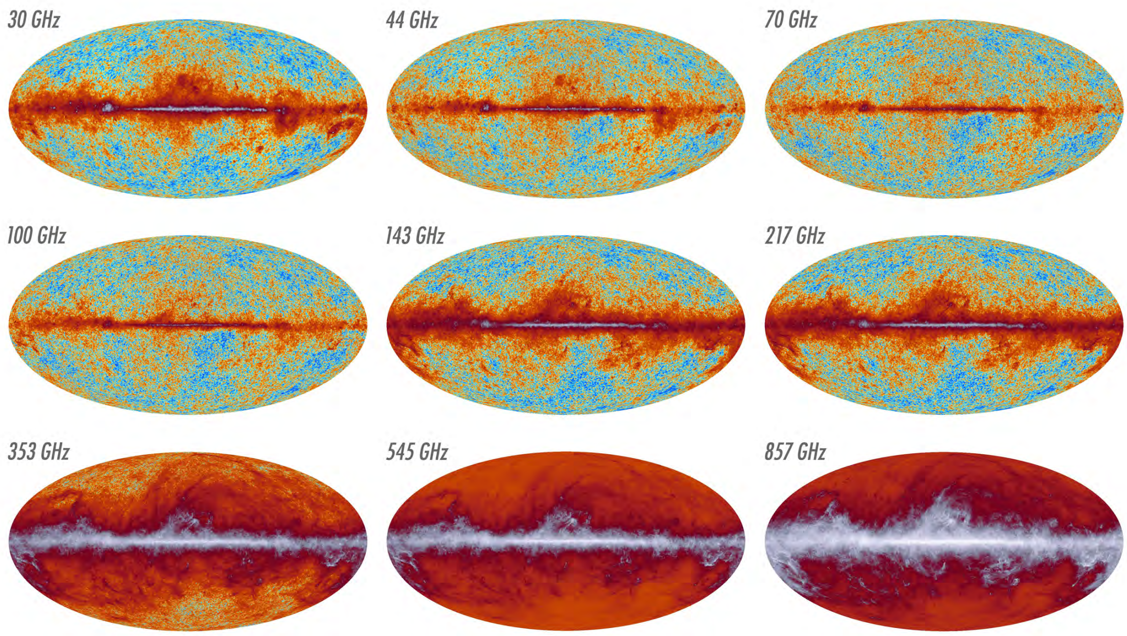

Figure 1: The nine temperature maps from 30 to 857 GHz. The colour scale is tailored to show the full dynamic range of the maps. (credit: ESA and the *Planck* Collaboration).

The 2015 *Planck* CMB temperature maps have significantly lower noise than those produced in 2013. Between 2013 and 2015 the understanding of *Planck* beams, pointing, calibration and

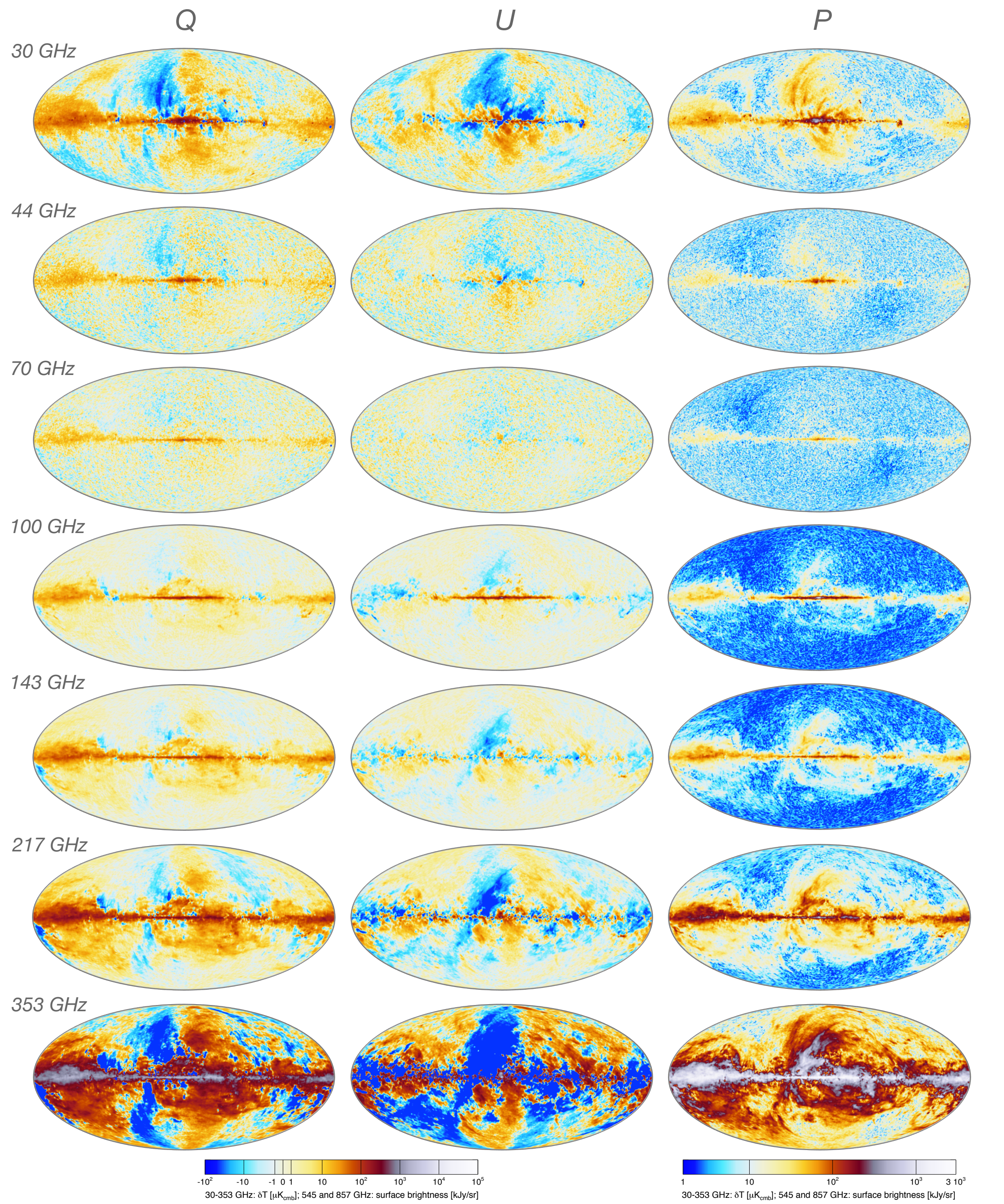

Figure 2: The seven Planck polarisation maps from 30 GHz to 353 GHz, shown in Stokes Q and U, and in total polarised intensity (P). The colour scale is tailored to show the full dynamic range of the maps. (credit: ESA and the *Planck* Collaboration).

systematic errors has significantly advanced. All of these factors have led to improvements in the cosmological results of *Planck*. The all-sky polarisation maps between 30 GHz and 353 GHz (see Fig. 2) are a major new release of 2015 and provide an entirely new view of the sky. They allow the extraction of maps of the polarised CMB anisotropies, which not only carry new cosmological information, but also provide a unique probe of the thermal history of the Universe during the time when the first stars and galaxies formed. In addition, the polarisation data can be used to estimate cosmological parameters independently of temperature, in effect constituting important confirmation of the *Planck* temperature-based results.

The best-fit 2015 cosmological parameters (Table 1, from Planck Collaboration XIII (2016)) confirm the basic 6-parameter Lambda cold dark matter scenario that was first established in 2013, with reduced uncertainties. There is no compelling evidence for any extensions to the 6-parameter model, or any need for new physics. Depending somewhat on the precise data combinations used, five of the six parameters have now been measured to better than 1% precision. At large angular scales, it is now possible to use *Planck*-only products to carry out polarisation-based cosmological analysis. Specifically, the optical depth of re-ionisation, τ, can be estimated independently of other experiments. A preview of the improved quality of the forthcoming Legacy polarisation data can be appreciated in Planck Collaboration Int. XLVI (2016) and Planck Collaboration Int. XLVII (2016). The value of τ found in these papers (0.055 ± 0.009) is lower and more precise than in previous determinations (still consistent with the 2015 estimate), implying later and faster re-ionisation, which resolves important open questions related to the formation of the first ionizing objects (Planck Collaboration Int. XLVII 2016).

While the *Planck* ΛCDM model is in good agreement with many other cosmological probes (Planck Collaboration I 2016), some mild tensions exist. One of these, which has received a good deal of attention in the literature, relates to the Hubble constant H_0. Indeed, the value of H_0 derived from *Planck* CMB analysis is in tension with the most precise local-distance-ladder determination (Riess et al. 2016) at the level of $\sim 3\sigma$. The dichotomy between totally independent estimates points either to new physics or to unaccounted systematic effects in one of the two measurements (Freedman 2017). Addison et al. (2016) noted that limiting the *Planck* CMB data only to the largest angular scales (those accessible to WMAP) brought the estimate of H_0 into consistency with the local value, and suggested that the current tension could be due to systematic effects in the *Planck* data at small angular scales. However, Planck Collaboration LI (2016) showed that the effect noted by Addison et al. (2016) can be largely attributed to the well-known "low-ℓ anomaly" or deficit of power in the CMB temperature angular power spectrum at $\ell \sim$10-30, which biasses significantly the determination of cosmological parameters based on measurements limited to $\ell <1000$. In effect, it is required to measure a very wide range of angular scales (only accessible to *Planck* so far) in order to counteract this bias. A more recent paper by Addison et al. (2017) confirms that the tension between the *Planck* CMB analysis and the distance-ladder estimate cannot be due to systematic effects in the *Planck* data at high-ℓs. It therefore remains a distinct possibility that the local value of H_0 is influenced by additional physics (Riess et al. 2016) or possibly by local effects e.g. our situation within a void (Hoscheit & Barger 2017; Keenan et al. 2016).

In addition to their value for cosmology, the *Planck* data are an important resource for astrophysics. The 2015 data allow the production of high-quality maps of synchrotron, free-free, spinning dust, thermal dust and carbon monoxide emissions from the Milky Way; and for the first time, polarised synchrotron and dust emission maps of our Galaxy are available for detailed investigation (Planck Collaboration X 2016; Planck Collaboration XXV 2016). In addition, catalogues of galactic and extragalactic compact sources have been produced (Planck Collaboration XXVI 2016; Planck Collaboration XXVII 2016; Planck Collaboration XXVIII 2016), allowing a wide variety of astrophysical studies.

Table 1: Column 2 shows parameter best-fit values and 68 % confidence levels for the base ΛCDM cosmology, computed from the 2015 *Planck* CMB temperature ("TT") and low-*ell* ("lowP") polarisation power spectra, in combination with the *Planck* CMB lensing likelihood ("lensing"). In the third column, the addition of CMB high-ℓ polarisation data and a compilation of external data sets ("ext") leads to reduced uncertainties. While we see no evidence that systematics in the high-ℓ polarisation are biasing parameters in the base ΛCDM model, a conservative choice would be to take the parameters listed in column 2. The first 6 rows contain the base ΛCDM model parameters, all others being derived from them. For more details see Planck Collaboration I (2016) and Planck Collaboration XIII (2016).

Parameter	PlanckTT+lowP+lensing	PlanckTT,TE,EE+ lowP+lensing+ext
$\Omega_b h^2$	0.02226 ± 0.00023	0.02230 ± 0.00014
$\Omega_c h^2$	0.1186 ± 0.0020	0.1188 ± 0.0010
$100\theta_{MC}$ . . .	1.04103 ± 0.00046	1.04093 ± 0.00030
τ	0.066 ± 0.016	0.066 ± 0.012
$\ln(10^{10} A_s)$.	3.062 ± 0.029	3.064 ± 0.023
n_s	0.9677 ± 0.0060	0.9667 ± 0.0040
H_0	67.8 ± 0.9	67.74 ± 0.46
Ω_Λ	0.692 ± 0.012	0.6911 ± 0.0062
Ω_b	0.0484 ± 0.0010	0.04860 ± 0.00051
Ω_c	0.258 ± 0.011	0.2589 ± 0.0057
Ω_m	0.308 ± 0.012	0.3089 ± 0.0062
$\Omega_m h^2$	0.1415 ± 0.0019	0.14170 ± 0.00097
$\Omega_m h^3$	0.09591 ± 0.00045	0.09598 ± 0.00029
σ_8	0.815 ± 0.009	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088	0.4535 ± 0.0059
Age[Gyr] . .	13.799 ± 0.038	13.799 ± 0.021
r_{drag}	147.60 ± 0.43	147.50 ± 0.24
k_{eq}	0.01027 ± 0.00014	0.010288 ± 0.000071

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been involved, can be found at `https://www.sciops.esa.int/index.php?project=planck&page=Planck_Collaboration`.

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