

# COSMOGLOBE DR1. III. First full-sky model of polarized synchrotron emission from all WMAP and Planck LFI data

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## ABSTRACT

We present the first model of full-sky polarized synchrotron emission that is derived from all *WMAP* and *Planck* LFI frequency maps. The basis of this analysis is the set of end-to-end reprocessed COSMOGLOBE Data Release 1 sky maps presented in a companion paper, which have significantly lower instrumental systematics than the legacy products from each experiment. We find that the resulting polarized synchrotron amplitude map has an average noise rms of  $3.2\mu\text{K}$  at 30 GHz and  $2^\circ$  FWHM, 30 % lower than the recently released BEYONDPLANCK model that included only LFI+*WMAP*  $Ka-V$  data, and 29 % lower than the raw *WMAP*  $K$ -band sensitivity. The mean  $EE/BB$  power spectrum ratio is  $0.46 \pm 0.03$ , with amplitudes consistent with those measured previously by *Planck* and QUIJOTE. Assuming a power law model for the synchrotron spectral energy distribution, we find a full-sky inverse noise-variance weighted mean of  $\beta_s = -3.07 \pm 0.03$  between *WMAP*  $K$ -band and LFI 30 GHz, in good agreement with previous estimates. In summary, the novel COSMOGLOBE DR1 synchrotron model is both more sensitive and systematically cleaner than similar previous models, and it has a more complete error description that is defined by a set of Monte Carlo posterior samples. We believe that these products are preferable for all synchrotron-related scientific applications compared to the official maps, including simulation, forecasting and component separation.

**Key words.** ISM: general – Cosmology: observations, polarization, cosmic microwave background, diffuse radiation – Galaxy: general

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## 1. Introduction

Understanding the polarization of the cosmic microwave background (CMB) is a primary focus of observational cosmology in the coming decades. Following the success of the satellite-based *COBE* (Smoot et al. 1992; Mather et al. 1994; Hauser et al. 1998), *WMAP* (Bennett et al. 2013), and *Planck* (Planck Collaboration I 2020) experiments, as well as sub-orbital experiments including BICEP (Ade et al. 2021), ACT (Madhavacheril et al. 2023), CLASS (Eimer et al. 2023), SPIDER (SPIDER Collaboration et al. 2021), and many others, the future *LiteBIRD* satellite (LiteBIRD Collaboration et al. 2022) and ground-based Simons Observatory (Ade et al. 2019) and CMB-S4 (Abazajian et al. 2019) experiments will create the most sensitive maps of the polarized sky yet, providing the most stringent constraints on primordial gravitational waves.

In the past decade, uncertainty on cosmological constraints has been limited not only by instrumental sensitivity, but by incomplete knowledge of the sky itself. Uncertainty in the sky model has been mitigated by designing experiments with broad frequency coverage, such as the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) (Bennett et al. 2013) and *Planck* (Planck Collaboration I 2020), or analyzing maps from different experiments jointly, e.g., Bennett et al. (1996), Bennett et al.

(2013), Planck Collaboration X (2016), and BICEP2/Keck Array and Planck Collaborations (2015), among many others. A major impediment to joint analyses is the difficulty of combining data with different survey strategies and incompletely characterized systematics. In order to maximize scientific throughput, one must either design an experiment that can characterize every relevant observable on its own, or jointly analyze different datasets in the same joint framework.

The BEYONDPLANCK project achieved this joint analysis by combining external data, specifically, the Haslam 408 MHz map (Haslam et al. 1982), WMAP  $Ka$ - $V$  bands, Planck 353 GHz in polarization, and Planck 857 GHz in intensity, while analyzing the Planck 30, 44, and 70 GHz time-ordered data (TOD) (BeyondPlanck Collaboration 2023). The Planck LFI experiment showed that raw detector sensitivity was not enough to obtain high-fidelity sky maps; Planck Collaboration II (2020) found that the detector gain solution depended on the assumed polarization and intensity of the sky. To break this circular dependency, the BEYONDPLANCK framework solved for the intrinsic sky signal and instrumental parameters iteratively, providing an accurate model of the entire system with full error propagation. By leveraging the external WMAP, Haslam, and Planck HFI data, BEYONDPLANCK was able to create Planck LFI maps of cosmological quality, while generating a robust model of the foreground sky.

The COSMOGLOBE project<sup>1</sup> expanded the BEYONDPLANCK analysis by processing WMAP  $K$ - $W$ -band TOD jointly with Planck LFI TOD. This framework, fully described in Watts et al. (2023b) and Watts et al. (2023a), not only improved the quality of the WMAP maps themselves, but provided the most robust full-sky model of low frequency polarized emission available to date. In particular, poorly-measured modes due to transmission imbalance (Jarosik et al. 2007) have been effectively marginalized over, in large part due to the use of a global sky model which was not used in the fiducial WMAP analyses. The removal of poorly measured modes alone will improve Galactic modelling for years to come, as the current state-of-the-art models use WMAP  $K$ -band (23 GHz) maps as polarized synchrotron templates for modeling of synchrotron without any mitigation of the poorly-measured modes (Delabrouille et al. 2013; Thorne et al. 2017; Zonca et al. 2021).

In order to make use of the synchrotron model, we require robust estimates of the spectral behavior. Fundamental properties of synchrotron, such as the spectral index as a function of frequency, spatial decorrelation, and even the functional form of the SED, are yet to be fully characterized observationally. Modern attempts have been frustrated by the lack of high signal-to-noise data; de Belsunce et al. (2022), for example, find spectral indices ranging from  $-5$  to  $-1$ , discrepant with predictions from direct measurements of the cosmic ray energy spectrum of  $2$ – $3$  (Rybicki & Lightman 1985; Orlando & Strong 2013; Neronov et al. 2017). This discrepancy is largely due to inadequate data coverage, requiring higher signal-to-noise datasets that have not yet been generated. Therefore, any conclusions about the distribution of the polarized synchrotron spectral index must be verified through multiple independent analysis methods and data choices.

While the combination of as many datasets as possible would help to constrain polarized synchrotron's large-scale properties, long-standing discrepancies between existing datasets complicate this. As shown in, for example, Planck Collaboration X (2016) and Weiland et al. (2018), there are discrepancies in the

polarization measurements of WMAP and Planck, partially due known instrumental effects (Bennett et al. 2013; Planck Collaboration II 2020). BeyondPlanck Collaboration (2023) resolved these issues for LFI, while Watts et al. (2023b) removed the poorly measured modes in WMAP. While Watts et al. (2023a) has demonstrated that the polarized maps from these two experiments are now consistent at the white noise level, the new maps must be validated by a variety of analysis methods. As noted in, for example, Weiland et al. (2022), simply using a different analysis pipelines can result in different estimations of the underlying frequency map. As such, we take care to appropriately marginalize over instrumental effects in our spectral analysis, and attempt to find the physical mechanism for the differences between different pipelines.

With these longstanding discrepancies addressed, the COSMOGLOBE DR1 frequency maps can be used to create the highest signal-to-noise polarized synchrotron map from Planck and WMAP data to date, with no trace of known instrumental effects visible. Moreover, these improved frequency maps can be used to obtain estimates of the polarized synchrotron spectral index using all available full-sky data.

This work is organized as follows. In Sect. 2, we provide a brief overview of the data products and the COSMOGLOBE data processing. Section 3 discusses the polarized amplitude of the COSMOGLOBE synchrotron model, its overall uncertainty, and the power spectrum properties compared to external products. Section 4 estimates the synchrotron spectral index using both the model-independent T-T plot method and Gibbs sampling using Commander, followed by discussions and conclusions in Sect. 5.

## 2. Data products

In this paper, we investigate the spatial variation of the polarized synchrotron spectral index, with an emphasis on the comparison between legacy maps against the COSMOGLOBE results. The data products used are the WMAP and Planck LFI maps, with most of the statistical weight coming from 23–33 GHz, or the WMAP  $K$  and  $Ka$  bands and LFI's 30 GHz band. These frequencies are low enough that we can treat them as synchrotron tracers and hence ignore thermal dust and the CMB, but not so low that we need to take into account effects like Faraday rotation (Fuskeland et al. 2021). We describe the legacy data products and the data products from the COSMOGLOBE WMAP reanalysis in the following subsections.

### 2.1. WMAP and Planck legacy products

WMAP was a NASA-funded satellite mission that observed from August 2001 to August 2010, designed to characterize the microwave sky well enough to measure the primary CMB anisotropies across the full sky down to a resolution of  $13'$ . Using a differential scanning strategy inspired by COBE/DMR, WMAP produced maps of the sky at 23 ( $K$ ), 33 ( $Ka$ ), 41 ( $Q$ ), 61 ( $V$ ), and 94 GHz ( $W$ ) in both polarization and intensity (Bennett et al. 2013), with angular resolutions of  $53'$  at 23 GHz to  $13'$  at 94 GHz. The maps are available on the LAMBDA website.<sup>2</sup>

The Planck Low Frequency Instrument (LFI) produced 30, 44, and 70 GHz maps in both intensity and polarization, while the High Frequency Instrument (HFI) produced 100, 143, 217, 353 GHz maps in polarization and intensity, and 545 and 857 GHz maps in intensity alone. The LFI data are similar to the

<sup>1</sup> [cosmoglobe.uio.no](http://cosmoglobe.uio.no)

<sup>2</sup> [https://lambda.gsfc.nasa.gov/product/wmap/dr5/m\\_products.html](https://lambda.gsfc.nasa.gov/product/wmap/dr5/m_products.html)



**Fig. 1.** Polarized intensity of (top): *WMAP* *K*-band, (middle): *Planck* 30 GHz, and (bottom): synchrotron amplitude from the COSMOGLOBE Gibbs chain, all evaluated at 30 GHz with a resolution of 72'. The leftmost column is a 10° width square centered a low signal-to-noise regions highlighted by a red square in the top middle panel, while the rightmost column shows the rms noise for the frequency maps and the posterior standard deviation of the synchrotron amplitude.

*WMAP* data, with higher angular resolutions of 30', 20', and 13' for 30, 44, and 70 GHz, and with lower white noise. Although the detector design was similar, LFI observed with a single horn, and observed in rings closely aligned with the ecliptic longitude. The legacy datasets, PR3 ([Planck Collaboration I 2020](#)) and PR4 ([Planck Collaboration Int. LVII 2020](#)), are both publicly available on the *Planck* Legacy Archive (PLA).<sup>3</sup>

## 2.2. COSMOGLOBE products

The goal of COSMOGLOBE is to perform joint end-to-end analyses on several data sets jointly, preferably beginning from raw TOD. Doing this can help to break the degeneracies of the different data sets, and in general reduces the amplitude of systematic effects. The analysis in [BeyondPlanck Collaboration \(2023\)](#) and [Watts et al. \(2023a\)](#) was performed on raw TOD, producing cosmological parameters using the Bayesian Gibbs sampler, Commander3 ([Galloway et al. 2023](#)). The data products produced in this analysis accounts for the complex interactions between the instrument, the microwave sky, and its constituent components self-consistently.

COSMOGLOBE DR1 produced a sky model and instrumental parameters for each Gibbs sample, allowing for complete characterization of the dependence of low-level instrumental parameters on the sky model. The sky model includes all relevant components in *WMAP* and LFI's frequency range, specifically the CMB, synchrotron, thermal dust, free-free emission, anomalous microwave emission, and radio point sources, the first three of which we model as polarized in our sky model. The full products from this analysis and individual maps are available on the COSMOGLOBE website.<sup>4</sup>

This paper makes use of COSMOGLOBE end products produced by the reanalysis of the *WMAP* and *Planck* LFI TODs ([Watts et al. 2023a](#)). COSMOGLOBE DR1 produced improved *WMAP* and *Planck* LFI maps, which we will use to compare our results to those produced by legacy data. Although most of the results in [Watts et al. \(2023a\)](#) use the posterior mean of the Gibbs chain, here we perform our analysis on each of the 500 frequency map samples individually. This allows us to fully marginalize over the low-level systematic parameters, quantifying the extent to which instrumental processing propagates to the synchrotron spectral index determination.

## 3. Polarized synchrotron amplitude

When using external data for polarized foreground cleaning, the choices for high signal-to-noise full sky constraints are either

<sup>4</sup> <https://www.cosmoglobe.uio.no/products/cosmoglobe-dr1.html>

<sup>3</sup> <https://pla.esac.esa.int/>



**Fig. 2.** COSMOGLOBE posterior standard deviation divided by BEYONDPLANCK posterior standard deviation.

*WMAP* *K*-band, *Planck* LFI 30GHz, or models derived from combinations of these data, as in COSMOGLOBE. From the perspective of pure statistical uncertainty, a combination of multiple independent datasets would yield component maps that are more sensitive than each individual component. However, unmodeled systematic uncertainties in the underlying datasets, left untreated, can induce map effects that can leak into astrophysics and cosmological constraints. As shown in Watts et al. (2023a), a single sky model that all datasets are calibrated against improves the low-level instrumental processing, and allowing for degeneracies, such as transmission imbalance uncertainty in *WMAP* and differential gain uncertainty in LFI, to be broken. Within the COSMOGLOBE DR1 framework, the polarization maps from *WMAP* and *Planck* LFI are consistent with each other at the  $10\,\mu\text{K}$  level, consistent with the instrumental white noise of the datasets.

The COSMOGLOBE DR1 frequency maps are free from previously reported systematics, and are consistent between different frequencies and instruments. Therefore, a coherent model of polarized synchrotron emission can be made by combining these two different datasets. The polarized spectral amplitude determined from COSMOGLOBE fully utilizes the *Planck* and *WMAP* joint reprocessed data, as shown in Fig. 1. We plot the total polarized amplitude  $P = \sqrt{Q^2 + U^2}$  for ease of comparison. The visible noise bias from plotting this positive definite quantity highlights the reduction in the noise level in the COSMOGLOBE synchrotron map as compared to the *K*-band and 30GHz maps. This is especially relevant in the leftmost column of Fig. 1, an inset of a high Galactic latitude, low signal region.

The *WMAP* *K*-band data and LFI 30GHz data, as the highest signal-to-noise full-sky polarized maps of Galactic synchrotron emission, are the main contributors to our knowledge of the polarized amplitude. The slightly higher angular resolution 30GHz map has lower signal-to-noise than the *K*-band data, but by combining the multi-resolution maps we are able to produce a clean map of the synchrotron emission evaluated at 30GHz with a FWHM of  $1^\circ$ .

BEYONDPLANCK and COSMOGLOBE data products are both created using the Commander3 pipeline, but COSMOGLOBE benefits from using the *K*-band data. Therefore, the synchrotron map from BEYONDPLANCK has lower resolution and higher noise; the COSMOGLOBE synchrotron map has a mean posterior rms of  $3.4\,\mu\text{K}$ , a marked improvement over the BEYONDPLANCK map. Much of the improvement can be seen when taking the ratio of the posterior rms maps, as in Fig. 2. As expected, the regions with the lowest ratios correspond to the deep *WMAP* observa-

tions and the Galactic plane, which benefit from the high signal-to-noise of the *K*-band data. Regions with nearly identical rms include regions with the highest *Planck* depth, such as the ecliptic poles, and regions less deeply observed by *WMAP*, corresponding to planet crossings and artifacts from the processing mask. Notably, stripes corresponding to the *Planck* scan strategy also show improvement respect to BEYONDPLANCK. This is due to the interaction between the sky model and LFI's instrumental parameters – with the high signal-to-noise *K*-band data, the sky model becomes more stable, and LFI's relative gain solution becomes better determined.

To quantify the noise improvement in the synchrotron maps over pure templates based on either *K*-band or 30GHz maps, we compare the posterior standard deviation of the COSMOGLOBE synchrotron map with the frequency maps' rms values. The posterior standard deviation maps are  $\lesssim 1\,\mu\text{K}$  for *K*-band, while temperature-to-polarization uncertainty in 30GHz contributes at the  $2\,\mu\text{K}$  level (see, e.g., Watts et al. 2023a and Basyyrov et al. 2023 for further details). An informative prior of  $D_\ell = 200 e^{-\ell(\ell+1)\sigma^2(30')} \mu\text{K}^2$  is applied during polarized synchrotron amplitude fitting, essentially downweighting low signal-to-noise fluctuations at angular scales  $\lesssim 30'$ , or  $\ell \gtrsim 360$  (Svalheim et al. 2023a). Therefore, the rms noise contributions are relevant at roughly  $N_{\text{side}} = 128$ . To compare the COSMOGLOBE white noise level with the *K*-band and 30GHz white noise levels, we simulate realizations of the expected white noise smoothed to  $72'$  and scale the maps to 30GHz assuming  $\beta_s = -3.1$ , consistent with the post-processed synchrotron map. We display these smoothed rms maps in the right column of Fig. 1.

At these resolutions, the mean rms for *K*-band and 30GHz are  $4.8\,\mu\text{K}$  and  $4.7\,\mu\text{K}$  respectively, compared to the mean value of  $3.4\,\mu\text{K}$  for the COSMOGLOBE DR1 synchrotron map; this is consistent with adding the scaled maps in quadrature. While this may seem obvious on its face, the combination of *WMAP* *K*-band and *Planck* 30GHz is not straightforward due to instrumental effects that remain in the maps, notably poorly measured modes in *WMAP* (Bennett et al. 2013; Weiland et al. 2018) and gain uncertainty in *Planck* (Planck Collaboration II 2020). These effects remain in the official *WMAP9* (Bennett et al. 2013) and *Planck* PR3/PR4 (Planck Collaboration II 2020; Planck Collaboration Int. VII 2020) maps, making combination of these datasets unsuitable for Galactic science and cosmological analyses. However, the end-to-end BEYONDPLANCK (BeyondPlanck Collaboration 2023) products effectively removed the gain uncertainty modes from the *Planck* LFI maps, and the COSMOGLOBE DR1 results (Watts et al. 2023a) are free from the poorly measured modes. As shown in Fig. 46 of Watts et al. (2023a), the *Planck* 30GHz and the *WMAP* *K*-band are consistent with each other at the  $10\,\mu\text{K}$  level, indicating that the maps are consistent with each other down to the white noise level.

This polarized synchrotron map, derived from consistent datasets, has a white noise level 29 % lower than both the *K*-band map and the 30GHz map, with minimal systematic uncertainties in the posterior standard deviation. Therefore, the synchrotron map derived from the COSMOGLOBE DR1 Gibbs chain should be used for the characterization and removal of polarized synchrotron emission between 23–90GHz.

### 3.1. Comparison with independent datasets

As a check on the polarized synchrotron amplitude, we compare the COSMOGLOBE polarized synchrotron map with the frequency maps produced in the main DR1 chain, paying special

attention to maps with the highest polarized synchrotron signal-to-noise ratio;  $K$ ,  $Ka$ , 30 GHz, and 444 GHz. These maps should agree by virtue of being produced in the same analysis framework. We compare with the *WMAP9* and PR3 maps. Of these, the *WMAP9* results can be considered the most independent, as the results were produced with no sky model assumptions, and were produced before the *Planck* polarized maps were publically available, thus making the analysis completely unbiased. The PR3 maps should also be independent of the *WMAP9* results, although the *WMAP9* results were available during PR3 production, so this analysis cannot be truly considered blinded to existing *WMAP* data. The PR4 analysis was performed using both the LFI and HFI dataset in a joint processing framework, conceptually similar to the framework in COSMOGLOBE DR1. Since we are highlighting the differences between joint processing and independent processing frameworks, we leave out PR4 in this specific comparison.

Using the polarized synchrotron model generated in the main COSMOGLOBE DR1 chain, we can evaluate the synchrotron emission at each frequency and compare it with the maps produced by various different processing pipelines. We evaluate the COSMOGLOBE sky model using the `cosmoglobe` Python package to evaluate the sky model using the full bandpass information of each instrument.<sup>5</sup> Visual inspection of the data with the sky model subtracted and smoothed to a common  $5^\circ$  Gaussian beam provides a robust check on the quality of the model and the underlying data.

The first and third rows of Fig. 3 show the *WMAP9* and PR3 residuals with respect to the COSMOGLOBE sky model. These residuals match previously-documented observational effects in both experiments. In particular, the *WMAP* maps show artifacts of the poorly-measured modes due to transmission imbalance in the differential horns (Jarosik et al. 2007; Bennett et al. 2013), while the PR3 differences are mostly due to relative gain errors (Planck Collaboration II 2020; Planck Collaboration Int. LVII 2020). In contrast, the synchrotron model matches the COSMOGLOBE DR1 frequency maps within  $5\mu\text{K}$  across the sky, with few observational artifacts.

Most of the residuals are associated with the Galactic plane and diffuse structures uncorrelated with the *WMAP* and *Planck* observation strategies. The positive excess in the  $Ka$  Stokes  $Q$  map could be due to as yet unmitigated data processing artifacts. While a similar large-scale excess can also be seen in the LFI 30 and 44 GHz Stokes  $Q$  maps, the signature strongly resembles the bandpass correction in *WMAP K*-band, suggesting incomplete treatment of bandpasses could be contributing to this large-scale signal. The LFI residuals, while much improved, still show trace residuals, especially near the Galactic center, that are somewhat correlated with the gain correction templates, but not at a level that high Galactic latitude features can be identified.

As the scale of instrumental residuals have been reduced to below the white noise level for each of the synchrotron-dominated full-sky polarization maps, we are now able to associate the residuals with potential modifications to the sky model. Specifically, the COSMOGLOBE DR1 processing sampled a spatially constant  $\beta_s$  with a final mean of  $\beta_s = -3.15$ . In Sec. 4, we will determine the extent to which true on-sky variation can be determined based on these maps.

**Table 1.** Best-fit power law parameters to the synchrotron estimates evaluated at 30 GHz, using half-mission splits with NaMaster.

	PR3	COSMOGLOBE
$A_s^{\text{EE}} [\mu\text{K}^2]$ . . .	$2.39 \pm 0.07$	$2.35 \pm 0.05$
$A_s^{\text{BB}} [\mu\text{K}^2]$ . . .	$1.09 \pm 0.06$	$0.94 \pm 0.04$
$A_s^{\text{BB}}/A_s^{\text{EE}}$ . . . .	$0.46 \pm 0.03$	$0.40 \pm 0.02$
$\alpha_s^{\text{EE}}$ . . . . .	$-0.81 \pm 0.02$	$-0.87 \pm 0.02$
$\alpha_s^{\text{BB}}$ . . . . .	$-0.80 \pm 0.03$	$-0.81 \pm 0.03$

### 3.2. Power spectra

Due to the importance of foreground removal for precise primordial gravitational wave measurement, the ratio of synchrotron B-modes to E-modes has long been studied, and has been consistently noted to be less than one (Page et al. 2007; Planck Collaboration X 2016; Planck Collaboration IV 2018). The physical mechanism for this has been discussed in the context of Galactic magnetic fields and polarized thermal dust, but similar mechanisms are likely to be in play for synchrotron polarization.

To estimate the power spectra without a noise bias, we performed a Commander3 run using half-mission splits with odd-numbered scans and even-numbered scans being analyzed in runs labeled HM1 and HM2, analogous to the *Planck* “half-mission” splits. Each of these chains were performed using the same data as in the main COSMOGLOBE chain, with 200 samples each.<sup>6</sup> The highest quality similar half-mission splits that are publically available are from the *Planck* PR3 analysis, as discussed in Planck Collaboration IV (2018). We therefore compute power spectra from the PR3 results and compare them directly with the COSMOGLOBE HM splits.

We performed power spectrum estimation using NaMaster (Alonso et al. 2019) with the *Planck* 2018 common polarization mask with  $f_{\text{sky}} = 0.78$  and  $1^\circ$  apodization. To quantify the uncertainty, we take the cross spectrum for each pair of Gibbs samples from HM1 and HM2 respectively, and report the 68 % confidence intervals on this posterior. The power spectra are displayed in Fig. 4, and the standard deviation is computed using the within-bin variance of each bin, with the posterior standard deviation of the Gibbs chain added in quadrature for the COSMOGLOBE spectra. Other than the very lowest and very highest multipole bins, there is good per-multipole agreement between both the PR3 and COSMOGLOBE DR1 spectra.

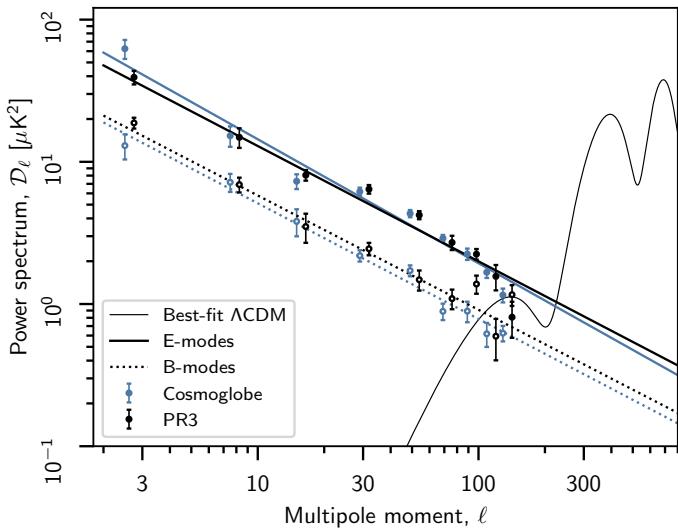
Following Planck Collaboration IV (2018), we perform power law fits to the power spectra of the form  $\mathcal{D}_\ell^{\text{EE}/\text{BB}} = A_s^{\text{EE}/\text{BB}}(\ell/80)^\alpha$ , using multipoles  $\ell \in [2, 140]$ . The 68 % confidence intervals for each quantity, including the  $A_s^{\text{BB}}/A_s^{\text{EE}}$  ratio, are reported in Table 1. The primary differences between the fits to the two datasets are  $\sim 2\sigma$  discrepancies in the  $A_s^{\text{BB}}$  and  $\alpha_s^{\text{EE}}$  fits, while all others are consistent within  $\simeq 0.5\sigma$ . The primary drivers of these differences are lower  $\mathcal{D}_\ell^{\text{BB}}$  and higher  $\mathcal{D}_\ell^{\text{EE}}$  in the lowest bins. These fit parameters yield a  $\lesssim 2\sigma$  lower  $A_s^{\text{BB}}/A_s^{\text{EE}}$  value of 0.40. While this is higher than the published value of 0.34 using the same procedure as in Planck Collaboration IV (2018), we obtained a higher value of 0.46. Despite the discrepancies between the processing in this paper and Planck Collaboration IV (2018), it is clear that the COSMOGLOBE DR1 ratio is lower than that of *Planck* PR3 when processed in our framework.

<sup>5</sup> <https://cosmoglobe.readthedocs.io/en/latest/tutorials/skymodel.html>

<sup>6</sup> These products can be found at [cosmoglobe.uio.no](http://cosmoglobe.uio.no).



**Fig. 3.** Residuals with respect to the COSMOGLOBE DR1 sky model evaluated at  $5^\circ$ . COSMOGLOBE maps are labeled CG, *Planck* 2018 maps are labeled PR3, and the legacy WMAP9 maps are labeled WMAP.



**Fig. 4.** Half-mission splits of synchrotron for *Planck* PR3 (black) and COSMOGLOBE DR1 (blue). Filled circles correspond to E-modes, while empty circles correspond to B-modes.

#### 4. Polarized synchrotron spectral indices

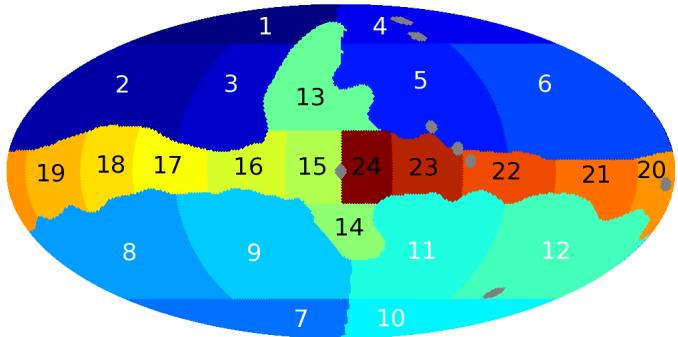
The determination of polarized synchrotron spectral index variation across the sky has been studied in detail using several different data combinations. Although the small-scale details vary, nearly every analysis has found  $\beta_s \approx 2.8$  in the Galactic plane and  $\beta_s \sim -3.3$  in high Galactic latitudes (Fuskeland et al. 2014;

Krachmalnicoff et al. 2018; Fuskeland et al. 2021; Weiland et al. 2022), with the exception of QUIJOTE (Rubiño-Martín et al. 2023; de la Hoz et al. 2023), who find a slightly flatter spectral index along the Galactic plane. However, true spatial variations beyond the high-latitude and low-latitude regions have been difficult to determine. Both Fuskeland et al. (2014) and Weiland et al. (2022) report oscillations with Galactic longitude close to the Galactic plane, but high-latitude regions variations are more difficult to determine, and tend to depend on the specific dataset chosen and the analysis method chosen.

A fundamental challenge in spectral index estimation is due to the fact that every difference between two channels can be associated with a spectral index variation if not accounted for fully. Therefore, it is necessary to not only make sure that results are robust towards data selection, but also to ensure that differences between results are not due to instrumental effects.

While the COSMOGLOBE pipeline produces samples of polarized synchrotron emission, the spatial variation of the spectral index is poorly determined within the Gibbs chain. To mitigate the poor Monte Carlo Markov Chain (MCMC) convergence of the spectral indices, the COSMOGLOBE DR1 sampled the spectral index from a prior distribution,  $\beta_s \sim \mathcal{N}(-3.15, 0.05)$ . Improvements within the Commander3 framework will require more high signal-to-noise data.

In order to test for and mitigate potential instrumental effects, we perform two analyses, a temperature-temperature (T-T) plot analysis in Sect. 4.1 and a Gibbs sampling analysis using Commander1 in Sect. 4.2. Section 4.1 focuses on pairs of channels to better isolate potential unmodeled systematic effects, while Sect. 4.2 uses all WMAP and LFI channels plus *Planck*



**Fig. 5.** Spectral index regions as defined in Fuskeland et al. (2014). The most prominent point sources are masked out and shown in grey circular areas.

353 GHz to maximize the joint statistical weight of all available data.

#### 4.1. T-T plot analysis

The T-T plot analysis can be used for pairs of datasets in a model-independent way, allowing for us to probe the difference between different datasets without making strong assumptions on the underlying physical model. This method can also easily be adapted to probe the dependence on polarization angle. This can be used to determine both the orientation dependence of  $\beta_s$ , as well as identify the magnitude of unmodeled instrumental effects, such as beam asymmetries, as discussed in Wehus et al. (2013).

##### 4.1.1. Method

Following Fuskeland et al. (2014) and Fuskeland et al. (2021), we apply linear regression via the T-T plot method, in which spectral indices can be estimated over extended regions with approximately constant spectral indices. Here we use the regions labeled in Fig. 5. In this approach, our data model for two frequencies is

$$\mathbf{m}_\nu = \mathbf{m}_{\nu_0} \left( \frac{\nu}{\nu_0} \right)^\beta + c_\nu + \mathbf{n}_\nu, \quad (1)$$

where  $\mathbf{m}_\nu$  is a spatially varying amplitude map at frequency  $\nu$ ,  $\nu_0$  is the reference frequency,  $\beta$  the power law between the two frequencies,  $c_\nu$  the spatially constant offset per band, and  $\mathbf{n}_\nu$  the noise. In the case of noiseless data with no offset, the spectral index may be estimated using a simple ratio,

$$\frac{m_{\nu_1,p}}{m_{\nu_2,p}} = \left( \frac{\nu_1}{\nu_2} \right)^{\beta_{s,p}} \Rightarrow \beta_{s,p} = \frac{\ln(m_{\nu_1,p}/m_{\nu_2,p})}{\ln(\nu_1/\nu_2)}. \quad (2)$$

In the case where one map is much noisier than the other, the standard T-T plot method involves performing a linear regression  $\mathbf{m}_{\nu_1} = a\mathbf{m}_{\nu_2} + b$ , and associates  $\beta_s$  with  $\ln a / \ln(\nu_1/\nu_2)$ . More care must be taken when the noise amplitudes in both maps are comparable to each other, so we adopt the effective variance method of Orear (1982) as implemented by Fuskeland et al. (2014).

For the T-T plot analysis, we focus exclusively on bands between 23 and 33 GHz. As in Fuskeland et al. (2014), we use the WMAP  $K$  and  $Ka$  band Stokes  $Q$  and  $U$  parameter maps at 23 GHz and 33 GHz. The respective effective frequencies used are 22.45 GHz and 32.64 GHz. The maps originally at a HEALPix pixelization of  $N_{\text{side}} = 512$  are downgraded to  $N_{\text{side}} = 64$  and smoothed to a common resolution of 1° FWHM.



**Fig. 6.** Spatial variation of the synchrotron spectral index, computed using T-T plot between the (from top to bottom) WMAP9 23 GHz and Planck 2018 30 GHz, WMAP9 23 GHz and Planck DR4 30 GHz, WMAP9 23 GHz and BEYONDPLANCK 30 GHz, and COSMOGLOBE 23 GHz and COSMOGLOBE 30 GHz. The spectral index is inverse variance weighted over rotation angle, and in the COSMOGLOBE case also samples.

The Planck data products used are the 30 GHz Stokes  $Q$  and  $U$  maps, with an effective frequency of 28.4 GHz. Both the BEYONDPLANCK and COSMOGLOBE products are natively at  $N_{\text{side}} = 512$ , while for the Planck PR4, it is 1024.



**Fig. 7.** Synchrotron spectral index as a function of region number, computed using T-T plot between the 9-yr *WMAP* 23 GHz and *Planck* 2018 30 GHz (red), 9-yr *WMAP* 23 GHz and *Planck* DR4 30 GHz (blue), 9-yr *WMAP* 23 GHz and BEYONDPLANCK 30 GHz (purple), and COSMOGLOBE 23 GHz and COSMOGLOBE 30 GHz (black). The spectral index is inverse variance weighted over rotation angles, and samples. The horizontal line in the high latitude regions corresponds to the estimated spectral index values from the *Planck* 2018 likelihood analysis (Planck Collaboration V 2020).

As in Fuskeland et al. (2021), a systematic uncertainty that takes into account the variation of  $\beta$  over rotation angle,  $[\max(\beta_\alpha) - \min(\beta_\alpha)]/2$ , is added in quadrature to the statistical uncertainty. The uncertainty of the spectral indices is calculated as the minimum of the uncertainties in each rotation angle and region. For the COSMOGLOBE analyses we have a whole suite of maps represented by the individual samples instead of just one mean map. Here the standard deviation of the spectral indices of the samples is also added in quadrature to represent an additional systematic uncertainty. This enables us to have a better propagation of uncertainties from the maps to the final spectral indices.

#### 4.1.2. Results

We start by looking at the results from the T-T plot method applied to the  $K$ -band and 30 GHz maps. We apply the method to the 24 regions to see the spatial variation of the polarized synchrotron spectral index. The top three maps in Fig. 6 show the T-T plot results using *WMAP9*  $K$ -band and three incarnations of the *Planck* 30 GHz maps; PR3, PR4, and BEYONDPLANCK. The bottom map shows the results using the improved maps from the COSMOGLOBE analysis; COSMOGLOBE  $K$ -band and 30 GHz. The spectral indices are inverse variance weighted over rotation angle, and in the COSMOGLOBE case also samples. Some of the brightest point sources have been masked out using grey. We see an overall improvement in the results of the spectral index, from regions with extreme values in the top map represented by dark red and blue values, with colors gradually fading in the lower figures. The range in the plot is quite wide for spectral indices, and goes from  $-5$  to  $-1$ . This improvement in the value of the spectral index is especially prominent in the high Galactic regions, as well as region number 22 along the Galactic plane.

The same results are also shown in Fig. 7, with the spectral indices plotted as a function of region number. The different datasets are shown in different colors, and with the same order as the four maps in Fig. 6. Here we have also included one sigma uncertainties as errorbars as described in Sect. 4.1.1. We also plot

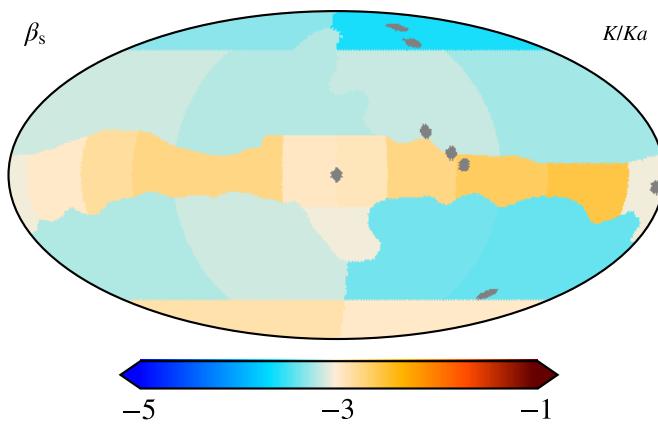


**Fig. 8.** Synchrotron spectral index computed using T-T plot with the COSMOGLOBE 23 GHz and 30 GHz data versus COSMOGLOBE 23 GHz and 33 GHz data for the 24 regions.

the estimated spectral index range for high Galactic regions, in our case represented by regions 1–12, as forecasted by the likelihood analysis in Figure 22 of Planck Collaboration V (2020). We see with each iteration of the data processing, the region estimates draw closer to this line. For a more detailed study of each of the regions, we refer the reader to the Appendix, where we have shown the corresponding T-T scatterplots (Fig. A.1) and the spectral index as a function of rotation angle (Fig. A.2) for all 24 regions.

As a second part of this T-T plot analysis we apply the method on  $K$ -band and  $Ka$ -band maps. For the *WMAP* data, this analysis was already performed in Fuskeland et al. (2014), so here we only present results using the new COSMOGLOBE data. First, as a consistency check, in Fig. 8 we plot the spectral indices for all 24 regions in the form of COSMOGLOBE  $K/30$  GHz versus COSMOGLOBE  $K/Ka$ . We see that for the regions in the north and south Galactic spurs, and along the Galactic plane (regions 13–24), there is a good agreement between the spectral indices obtained by the two pairs of datasets. Regions 1–12, all of which are high-latitude regions with low signal-to-noise, are all consistent with the two data combinations. The most prominent outliers, regions 6 and 12, are the regions with the lowest signal-to-noise ratio, and hence most prone to unmodeled effects and noise fluctuations.

In Fig. 9 the value of the spectral indices is shown for the 24 regions. We see here that the colors are even fainter than the COSMOGLOBE  $K$ -band versus 30 GHz values (the bottom figure in Fig. 6), meaning there are fewer outliers with respect to a standard value in the range around  $-3$ . This is especially visible in the regions with lowest signal to noise, like regions 6, 8 and 12, at high latitude.



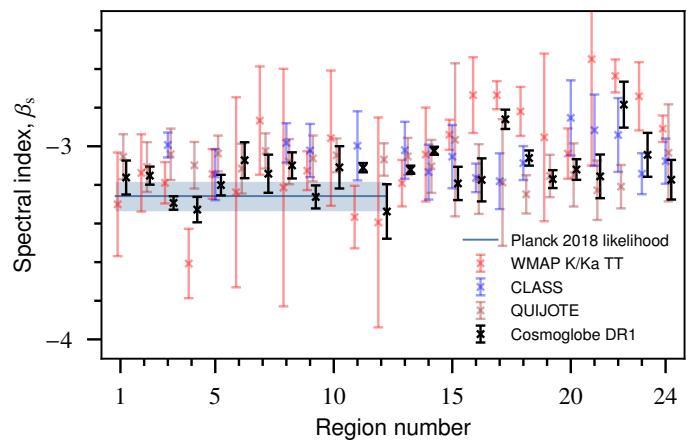
**Fig. 9.** Spatial variation of the synchrotron spectral index, computed using T-T plot between the COSMOGLOBE WMAP  $K$ - and  $Ka$ -band. The spectral index is inverse variance weighted over rotation angle and samples.

#### 4.2. Parametric component estimation

Here we use Commander<sup>7</sup> to perform pixel-based component separation on maps smoothed to a common resolution of  $5^\circ$  and at  $N_{\text{side}} = 64$ . For this analysis, we perform 100 pixel-based Commander1 Gibbs samples on each of the 500 COSMOGLOBE DR1 Gibbs samples produced by Commander3. This allows us to decompose the pure statistical error assuming white noise alone for each of the 100 Commander1 samples, while changes between each main DR1 sample show the effects of low-level instrumental processing. In these analyses, we use the same polarized bands as in the main CG DR1 analysis, namely *WMAP*, *Planck* LFI, and *Planck* 353 GHz. We use a prior  $\beta_s \sim \mathcal{N}(-3.1, 0.1)$  for the synchrotron spectral index, while for dust we use a constant spectral index of  $\beta_d = 1.55$  and the dust map  $T_d$  from *Planck Collaboration X* (2016).

We used the same data model as in COSMOGLOBE DR1, but allowed for spatially varying  $\beta_s$  in two different forms. First, we allow  $\beta_s$  over the same regions as in the T-T analysis. We find that for such large regions, there is very little effect due to the prior, and in particular find a maximum shift of 0.3 between a prior of  $\mathcal{N}(-3.5, 0.1)$  and  $\mathcal{N}(-2.7, 0.1)$ . We add this difference in quadrature to the uncertainty due to statistical and systematic errors. We also compare the reported  $\beta_s$  maps from QUIJOTE (de la Hoz et al. 2023) and CLASS (Eimer et al. 2023). We choose these maps because they are to this date the best publicly available synchrotron spectral index maps that are not affected by Faraday rotation off the Galactic plane, as in S-PASS (Krachmalnicoff et al. 2018; Fuskeland et al. 2021). The delivered  $\beta_s$  maps are pixelized at  $N_{\text{side}} = 64$  and 32, respectively, with associated uncertainty maps taking into account the expected instrumental noise levels. We take an inverse-weighted average of the respective maps and report the weighted standard error within each region, displayed in Fig. 10.

In general, the uncertainties in our analysis are smaller than each of the other published results, each for slightly different reasons. First, the T-T analyses will inherently have less constraining power than a full likelihood analysis, as this approach only uses two frequency channels via a linear regression, so the uncertainty is determined by the noise level in each frequency channel and the inherent variation within a given sky region. Be-



**Fig. 10.** Spectral index from COSMOGLOBE DR1 spectral index estimation, T-T plots with  $K/Ka$ , the QUIJOTE estimates, and the CLASS estimates.

yond that, the T-T plot in this paper marginalizes over dependence on the polarization angle  $\alpha$ , and by design accentuates systematic effects, predominantly beam ellipticity. Finally, the QUIJOTE analysis is most similar in data choice (MFI 11/13 GHz, *WMAP9 K/Ka*, *Planck PR4*) and methodology (B-SeCRET; de la Hoz et al. 2022), but still yields higher uncertainty than the Commander1 spectral index region analysis. This is most likely due to different spatial resolution and modeling choices; the Commander1 analysis presented here is performed at  $5^\circ$  resolution versus the  $2^\circ$  resolution per-pixel analysis in de la Hoz et al. (2023). In addition, de la Hoz et al. (2023) sampled for  $\beta_d$  and  $T_d$  with priors  $\mathcal{N}(1.55, 0.1)$  and  $\mathcal{N}(21, 3)$  while using a relatively wide prior on  $\beta_s$  of  $\mathcal{N}(-3.1, 0.3)$ .

At high Galactic latitudes (regions 1–12), there is good agreement between each of the treatments, and all values are consistent with a single constant value. In the north and south polar spur (regions 13 and 14) there is excellent agreement between all of the pipelines, while along the Galactic plane (regions 15–24), there are mild discrepancies between the methodologies, in particular a less distinct amount of periodic structure as a function of Galactic latitude.

To more finely probe the spatial variation of  $\beta_s$ , we perform a second Commander1 analysis with identical data and model choices, except the  $\beta_s$  are allowed to vary with a prior of  $\mathcal{N}(-3.1, 0.1)$  and spatially vary along an  $N_{\text{side}} = 16$  grid. We found that this was the highest resolution grid in which the spectral index was not prior dominated across all high-latitude regions. In Fig. 11, we display the mean of all of the Gibbs samples, along with the standard deviation evaluated per CG1 Gibbs sample,  $\sigma_{\beta_s}^{\text{stat}}$ , and the standard deviation over all CG1 samples and Commander1 samples,  $\sigma_{\beta_s}^{\text{sys+stat}}$ . Put concretely,  $\sigma_{\beta_s}^{\text{stat}}$  is the standard deviation when the input maps themselves are static, and  $\sigma_{\beta_s}^{\text{sys+stat}}$  includes variations in the frequency maps themselves, corresponding to underlying instrumental effects, including gain, noise characterization, and baseline estimation. The uncertainty due to white noise alone traces the high signal-to-noise regions of the polarized synchrotron, especially the prominent loops and spurs and the Fan region. At high Galactic latitudes, the standard deviation is 0.1, indicating that the posterior uncertainty is limited by the prior. To further test this, we performed additional Commander1 runs with priors of  $\mathcal{N}(-3.2, 0.1)$  and  $\mathcal{N}(-3.0, 0.1)$ , and used the deviation from the mean in the fiducial analysis as an estimate of the extent of prior domination,

<sup>7</sup> <https://github.com/Cosmoglobe/Commander1>

$\sigma_{\beta_s}^{\text{prior}} \equiv (\langle \beta_{-3.0} \rangle - \langle \beta_{-3.2} \rangle)/2$ . Adding this in quadrature gives the total uncertainty, which we display in the bottom panel of Fig. 11.

The uncertainty across the entire Gibbs chain does not merely trace high signal-to-noise regions, and in fact there are variations that exceed the prior surrounding the Galactic center. These variations are primarily due to gain and bandpass uncertainties. It therefore makes sense that gain variations in  $K$ ,  $Ka$ , and 30 GHz around the brightest region of the sky would induce large variations. Despite the relative increase in noise level when including instrumental effects, the brightest Galactic loops, the Cygnus region, and Tau A regions are well-constrained by the data.

As a final quality check, we display the residuals with respect to the Commander1 sky model in Fig. 12, as well as the total scaled and normalized  $\chi^2$ . In all bands but  $K$ , 30 GHz, and  $Ka$ , there are no visible artifacts due to instrumental uncertainty, with each map showing fluctuations consistent with the estimated white noise level calculated in the DR1 processing. In addition, many of the residuals visible in Fig. 3 have been reduced, demonstrating that polarized synchrotron spectral index variation provides meaningful improvements to the sky model fit.

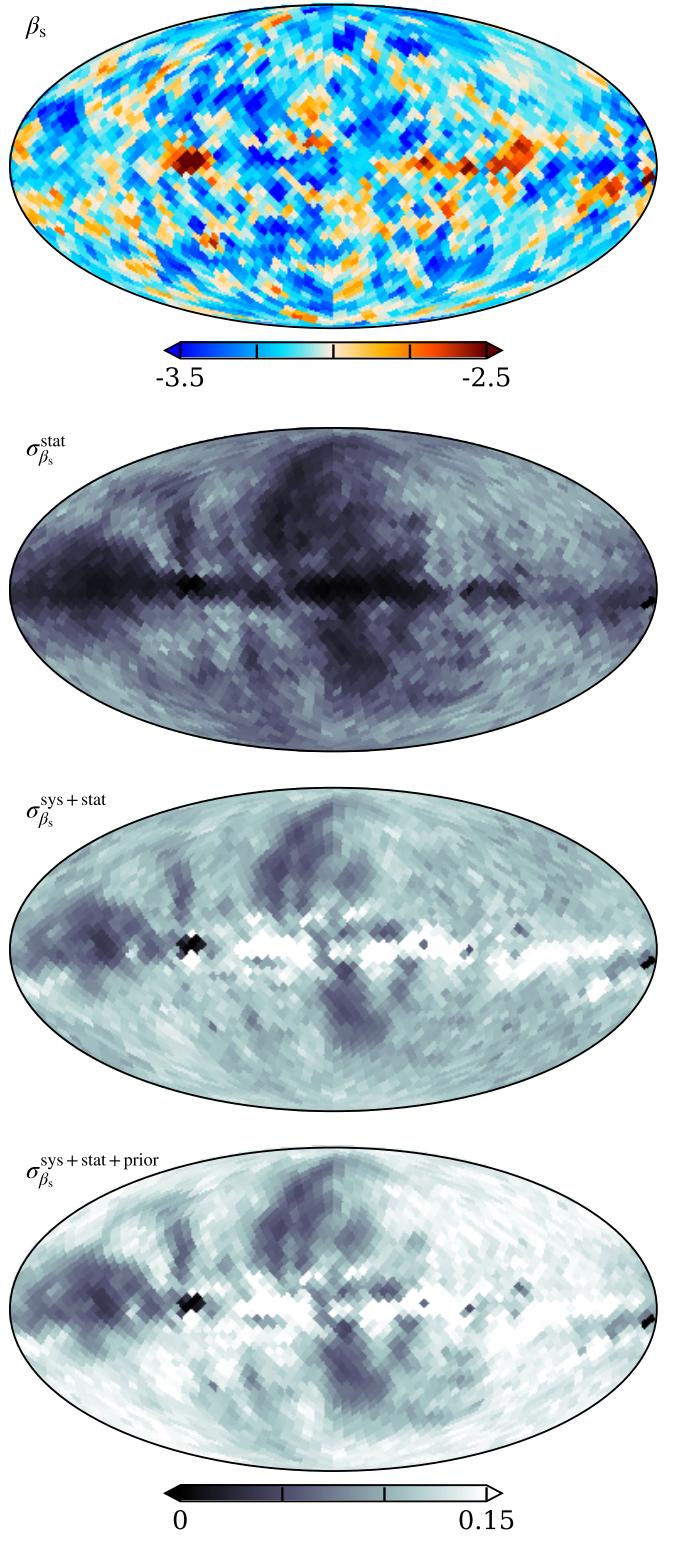
The most salient remaining residuals are in  $K$ , 30 GHz, and  $Ka$ .  $K$ -band and 30 GHz are anticorrelated surrounding Galactic center, indicating tension between these two high signal-to-noise datasets. This could either be due to genuine mismodeling of the sky, or be due to incompletely modelled instrumental parameters. In particular, the signature is reminiscent of bandpass leakage corrections, which are shown, e.g., in Fig. 9 of Svalheim et al. (2023b).

A more persistent residual is found in the Stokes  $Q$   $K$ -band map. This feature has appeared in several different analyses, e.g., Fig. 4 of Svalheim et al. (2023a) and Fig. 8 of Weiland et al. (2022), but was not as clear without full removal of the poorly measured modes in the final map. The lack of this feature in the corresponding Stokes  $U$  map suggests that the effect is not a true Galactic effect, and is in some way due to instrumental processing, or unmodeled systematics. We discuss potential sources of this signal in Sec. 5.

## 5. Discussion and conclusion

We have presented the state-of-the-art model of polarized synchrotron model using the COSMOGLOBE DR1 data products. The polarized synchrotron map as delivered in Watts et al. (2023a) has an effective white noise level of  $3.4 \mu\text{K}$ , a 29 % improvement over the white noise levels of the *WMAP*  $K$ -band and LFI 30 GHz maps. Using the fully consistent reprocessed *WMAP* and *Planck* LFI data, we have been able to leverage the full statistical power of both datasets. We have additionally verified that this model characterizes the polarized sky signal to within  $5 \mu\text{K}$  at all bands. We have also reproduced the previously-reported  $E$ -to- $B$ -mode ratio in the polarized synchrotron power spectrum. Furthermore, we have shown that physically reasonable spectral indices can be recovered using a variety of methods, which are consistent with both the methods presented in this paper and with previously published results from CLASS and QUIJOTE, confirming variation in  $\beta_s$  along the Galactic plane and constant at high Galactic latitudes.

Our improved processing of the *WMAP* and LFI data in conjunction with improved polarized synchrotron modeling has allowed us to dig deeper into the underlying differences between



**Fig. 11.** COSMOGLOBE DR1  $\beta_s$  constraints. (*First*): Mean spectral index over all samples, (*second*): standard deviation over a single CG DR1 sample, (*third*): standard deviation over all Commander1 and CG DR1 samples, and (*fourth*): difference due to prior choice added in quadrature.



**Fig. 12.** Residual maps and normalized  $\chi^2$ . Panels are organized with LFI channels in rows 1–2, WMAP in rows 3–7, and the total reduced  $\chi^2$  in row 8.

the two datasets. We have shown agreement between the  $\beta_s$  values derived using the T-T plot method that are in agreement within the expected uncertainties using  $K/30\text{ GHz}$  and  $K/Ka$  data combinations, further evidence that these datasets are now consistent with each other. The remaining unexplained differences between the sky maps and our derived model are primarily in the Galactic center, and have morphologies consistent with bandpass errors and SED complexities.

The least well-understood residual is in the  $Ka$ -band, specifically Stokes  $Q$ . Of all the known instrumental effects in both *WMAP* and *Planck* LFI, the only one that morphologically resembles this residual is the bandpass correction in  $K$ -band, which was previously presented in Figure 12 of Watts et al. (2023a). The bandpass correction term depends solely on laboratory measurements, presented in Jarosik et al. (2003). The high statistical weight of  $K$ -band for determining polarized synchrotron could easily lead to an undersubtraction in the  $Ka$ -band maps. Conversely, the bandpass correction to  $Ka$ -band itself is negligible, as all of the  $Ka$ -band radiometers were reported to have nearly identical bandpasses. A full accounting of this effect, including sampling of bandpass differences in the *WMAP* TODs (not performed in Watts et al. 2023a) will be performed in future work.

The estimation of  $\beta_s$  is difficult precisely because the quantity is dependent on differences between different frequencies, which can often exacerbate systematic effects and processing choices. The differences between a sky model and datasets is best determined in the timestreams – much of the improvement demonstrated in this analysis would not have been possible through a purely map-based analysis. Beyond pure improvement of data quality, this approach allowed for a natural end-to-end propagation of errors, and demonstrated that some of the brightest regions of the sky in fact do not have well-determined spectral indices, despite their high signal-to-instrumental noise ratio. As increasingly stringent uncertainty constraints are becoming necessary in order to measure a non-zero tensor-to-scalar ratio, the use of joint information between experiments with complementary observation strategies will increasingly become a necessity. Future joint analysis, including for example QUIJOTE and CLASS data, will continue to improve our knowledge of the polarized sky.

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<sup>8</sup> <http://healpix.sf.net>

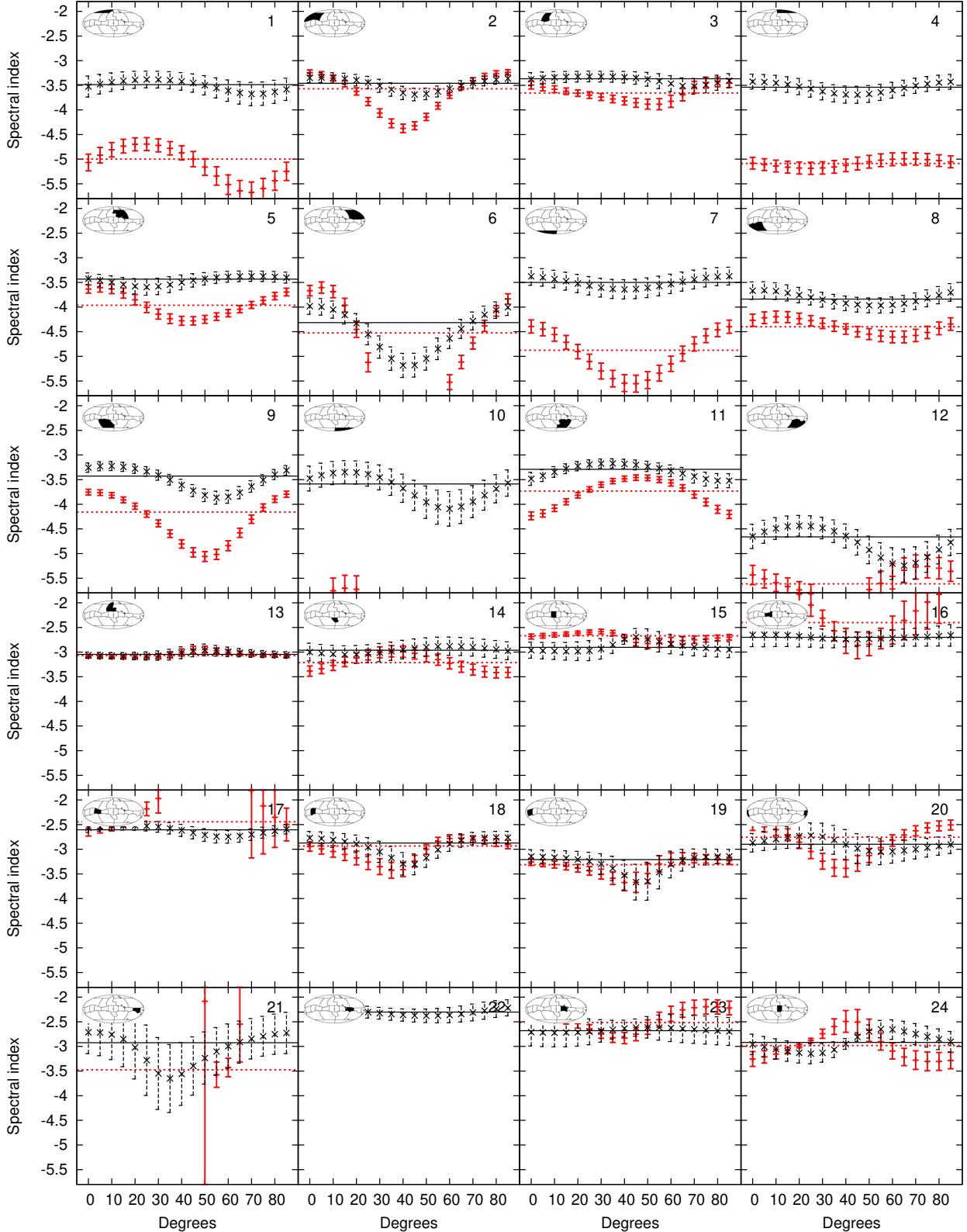
<sup>9</sup> <http://www.astropy.org>

## Appendix A: T-T Plots

This section shows two intermediate results in the T-T plot analysis. Figure A.1 shows the scatter plots within each individual region for both the *WMAP9* and COSMOGLOBE DR1 results, while Fig. A.2 shows the measured spectral index as a function of polarization angle  $\alpha$ . For more details, the interested reader can consult [Fuskeland et al. \(2014\)](#).



**Fig. A.1.** T-T plots for Stokes Q and U maps of the COSMOGLOBE 23 GHz versus the COSMOGLOBE 30 GHz (black) and the 9 yr *WMAP* 23 GHz versus *Planck* 2018 30 GHz (red) for all regions. The horizontal (solid and dotted) lines indicates the corresponding inverse variance weighted values of the spectral index, averaged over rotation angle, and in the COSMOGLOBE case also samples.



**Fig. A.2.** Synchrotron spectral index as a function of rotation angle, computed using T-T plot between the COSMOGLOBE 23 GHz and the COSMOGLOBE 30 GHz (black) compared to the spectral index using the 9 yr WMAP 23 GHz and *Planck* 2018 30 GHz (red) for all regions. The horizontal (solid and dotted) lines indicates the corresponding inverse variance weighted values of the spectral index, averaged over rotation angle, and in the COSMOGLOBE case also samples.