 ©ESO 2023

Cosmoglobe II. Preliminary implications for large-scale CMB polarization with improved WMAP sky maps

D. J. Watts[1]⋆, A. Basyrov[1], H. T. Ihle[1], and F. Rahman[2] et al.

[1] Institute of Theoretical Astrophysics, University of Oslo, Blindern, Oslo, Norway
[2] Indian Institute of Astrophysics, Koramangala II Block, Bangalore, 560034, India

January 11, 2023

ABSTRACT

We present the first joint analysis of *WMAP* and *Planck* LFI data, presenting maps that have been generated from a fully consistent joint treatment, including the sampling of sky signals and instrumental properties. The joint analysis approach yields improved *WMAP* data with better treatment of poorly constrained modes, as well as the first fully optimal sampling of all nine years of data. We also improve on the BeyondPlanck analysis, by reducing poorly measured modes in LFI polarization. In particular, we find a $\sim 4\,\mu$K change in the 30 GHz channel as a result of including the higher signal-to-noise *WMAP K*-band maps. The *WMAP* maps we present are free of previously documented systematic effects, and have an *x*% reduction in the white noise level. As the first release of Cosmoglobe products, the maps from this analysis should be considered both a considerable improvement over previous analyses, as well as the first iteration of future joint analyses with other data, including, e.g., the ground-based QUIET experiment and the DIRBE instrument aboard *COBE*.

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

Contents

1. Introduction

A to-do list:

- Find the time it takes for each beam to cross itself.
- Fix AME model (*I'm not sure what motivated this, perhaps not necessary?*
- Fix noise model (*Explained because of the Bessel filter plus linear trend*)

  A table to include

- Spin rate – 0.464 rpm (7.57 mHz), but translations to 2.6 degrees per second in boresight?
- Precession – 1 rev/hour (0.3 mHz)
- Signal bandwidth extends from 0.008–8 Hz (**?**)
- Beam size in degrees – 0.88, 0.66, 0.51, 0.35, 0.22.

The cosmic microwave background (CMB) is the most direct probe of the initial state of the Universe. Since the initial discovery of the CMB (**?**), subsequent experiments have continually refined the measurements, to the extent that the *WMAP* results are generally considered bringing cosmology into the regime of precision science (**?**). Prior to *WMAP*, it was common for CMB experiments to be superseded by more sensitive successors, with the noteworthy exceptions of *COBE*/FIRAS and *COBE*/DIRBE.

The *Planck* experiment, rather than superseding *WMAP*, consistently used *WMAP* data in its calibration, component separation, and cosmological analyses. The most direct comparison between *WMAP* and *Planck* is through analysis of the two experiments' frequency maps, as *WMAP*'s *K*, *Ka*, *Q*, *V*, and *W* maps are interleaved by the *Planck* LFI's 30, 44, and 70 GHz bands. Since the initial *Planck* data release, there have been several analyses comparing the two experiments by members of the *WMAP* team (**?????**) and by the *Planck* team (**???**).

While the *WMAP* low-level analysis has remained stable since **?**, there has been continued work on *Planck* time-ordered data processing, notably BeyondPlanck for the LFI instrument (**?**), `SRoll2` for the HFI instrument (**?**), and *Planck* DR4 for both LFI and HFI (`NPIPE`, **?**). The LFI instrument in particular has had several systematics mitigated by improved analysis, particularly a smoothed gain solution and an improved noise model (**????**). When comparing *WMAP K*-band with the *Planck* LFI data, the residuals are mainly characterized by *WMAP*'s poorly measured modes, which can be seen clearly in Figures 50 and 51 of **?** and Figures 4 and 7 of **?**.

One of the primary outcomes of the BeyondPlanck project is that end-to-end analysis of a dataset with poorly measured modes can be mitigated by a joint analysis with another dataset that measures these modes well. In particular, *Planck* LFI had large scale polarizated modes aligned with the in-

⋆ Corresponding author: D. J. Watts; `duncanwa@astro.uio.no`

Table 1. Difference map χ^2 statistics.

Difference	χ^2_{uncorr}	χ^2_{corr}	$\Delta\chi^2$
0.32×K1 − Ka1 . .	4291	4287	4
Q1 − Q2	4500	4380	120
V1 − V2	4490	4429	61
W1 − W2	4328	4270	68
W3 − W4	4257	4145	112

strument's scan strategy, induced by relative errors between different polarization-sensitive radiometers (?). The BeyondPlanck project mitigated this by using *WMAP*'s polarized *Ka–V* maps for component separation, where these modes were well-measured. In order to properly combine these datasets, the polarized maps were the $N_{\mathrm{side}} = 16$ `HEALPix`[1] products with a pixel-pixel covariance matrix that explicitly projected out the poorly measured modes.

In principle, the *Planck* experiment can be used to identify *WMAP*'s poorly measured modes in the same way that *WMAP* removed *Planck*'s poorly measured modes. This was shown in **?**, in which *WMAP* data was calibrated against the BeyondPlanck sky model, and the resulting maps differed from the *WMAP9* products mainly through the lack of the poorly measured modes. This work mainly functioned as a demonstration that the `Commander3` framework could be applied to the *WMAP* dataset, and was not a true end-to-end analysis.

In this work, we present the first joint TOD analysis in the Cosmoglobe[2] framework, in which we analyze the full *WMAP* dataset along with time-ordered *Planck* LFI data. In Sect. 2, we review the Cosmoglobe statistical framework and the data processing for *Planck* LFI and *WMAP* in the `Commander3` pipeline. In Sect. **??**, we present the *Planck* and *WMAP* joint frequency maps, and compare these frequency maps with the fiducial analyses in Sect. **??**. We discuss outstanding systematic errors and the propagation of uncertainty in Sect. **??**. We summarize our results and lay a path forward in Sect. 5.

2. Constraining poorly measured modes in WMAP with Cosmoglobe

3. Low-resolution sky maps

4. Likelihood analysis

5. Conclusions

Table 2. Transmission imbalance template amplitudes for each *WMAP* radiometer as estimated by fitting the official templates to low-resolution difference maps between Cosmoglobe and *WMAP*. The templates are provided in mK, and the template amplitudes are therefore dimensionless. The fourth column lists the relative decrease in standard deviation, $\sqrt{\sigma^2_{\mathrm{raw}} - \sigma^2_{\mathrm{corr}}}/\sigma_{\mathrm{raw}}$, after subtracting the best-fit templates in percent.

DA	a_1	a_2	$\Delta\sigma[\%]$
K1	−27.5	−50.6	30
Ka1	−1.4	−1.9	25
Q1	−30.0	−71.6	11
Q2	−7.1	−1.5	20
V1	−32.8	−53.4	6
V2	8.8	−4.1	16
W1	−2.8	4.6	8
W2	−6.9	−3.5	11
W3	29.1	53.4	12
W4	15.5	−6.8	52

[1] http://healpix.sourceforge.net (?)
[2] cosmoglobe.uio.no

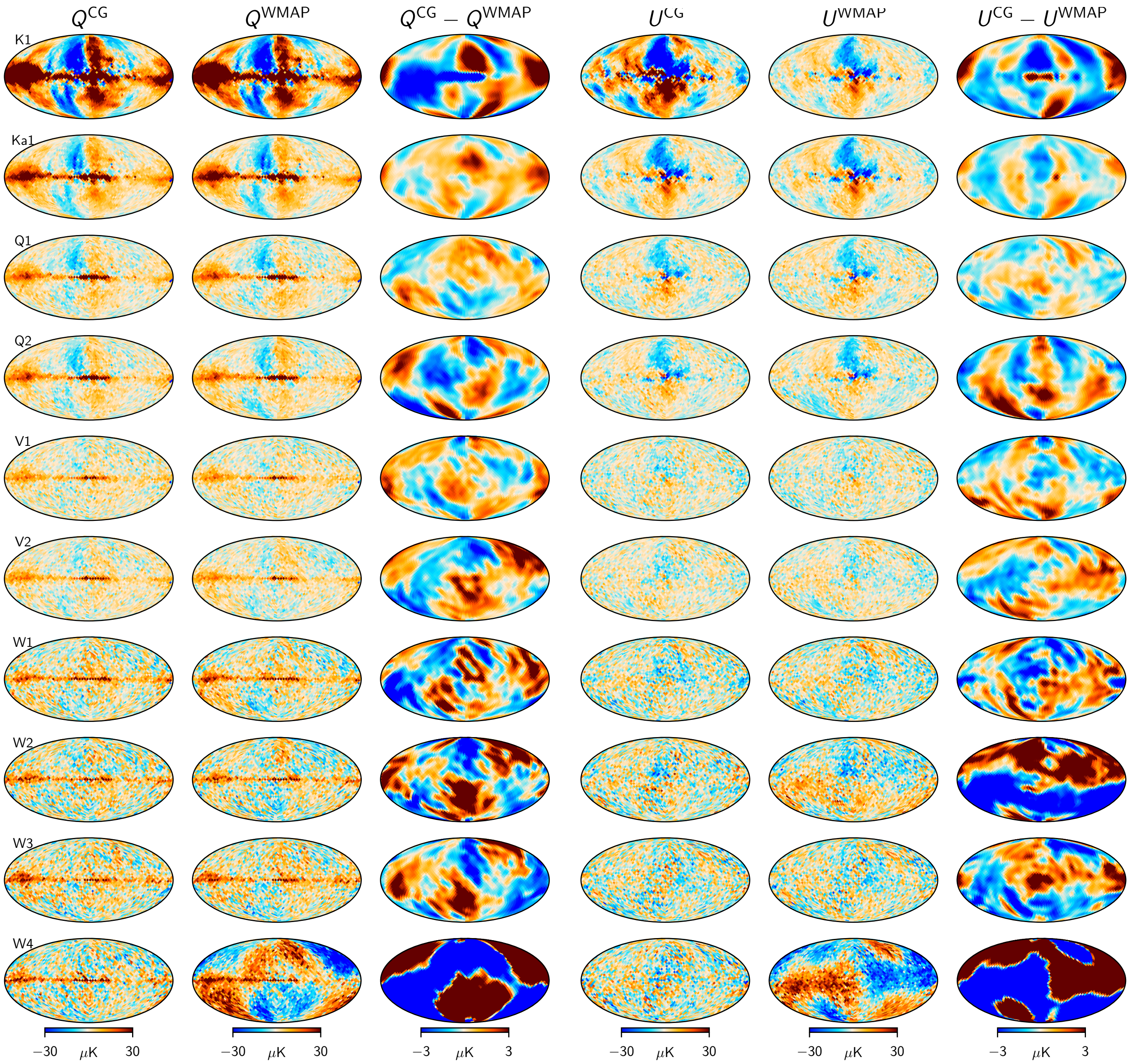

Fig. 1. Sky maps

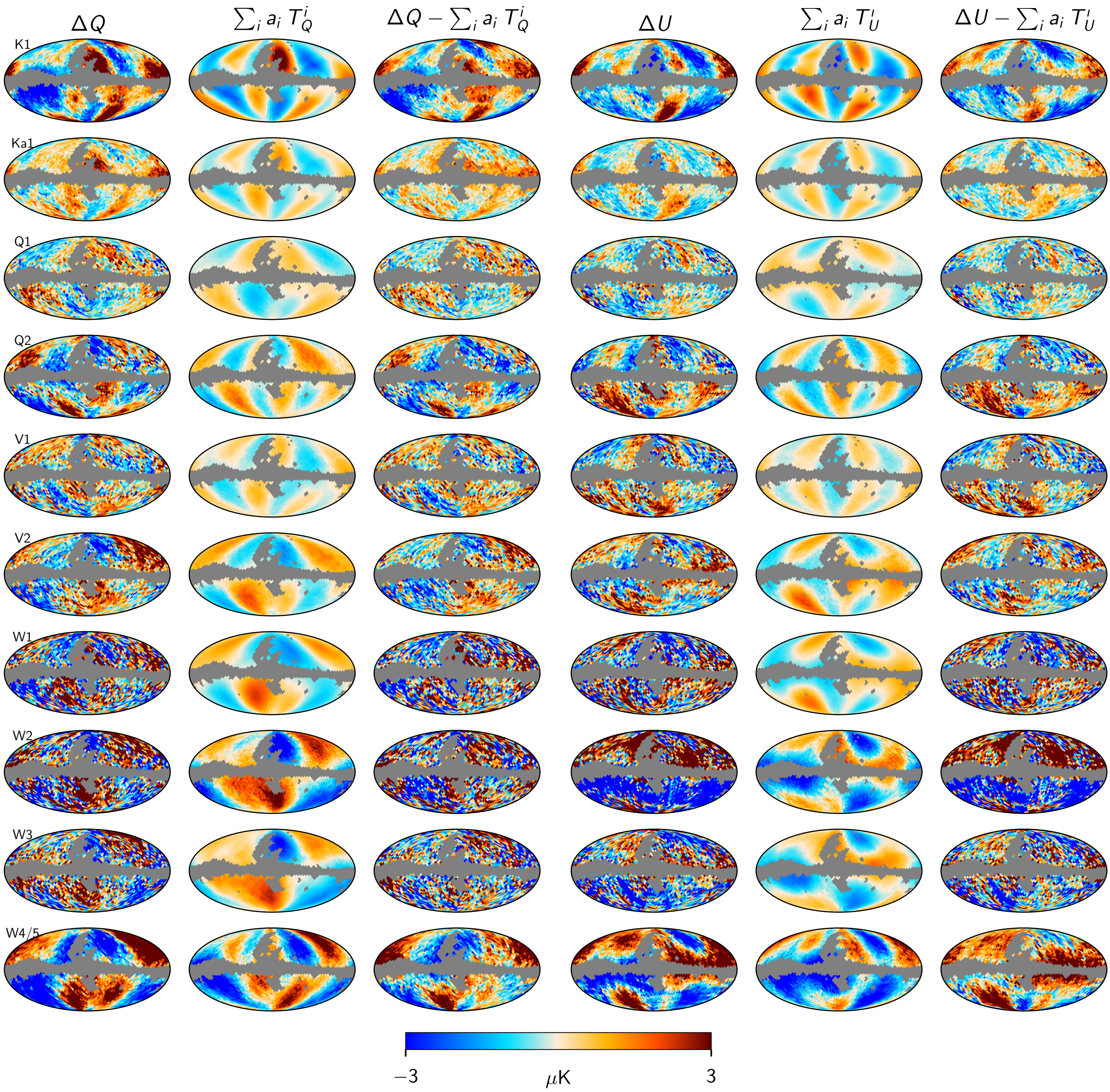

Fig. 2. Transmission imbalance templates

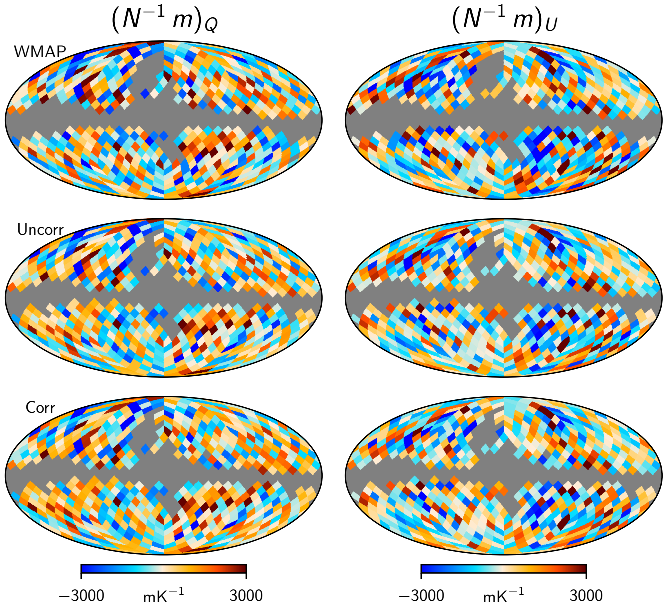

Fig. 3. Noise-weighted likelihood input maps.

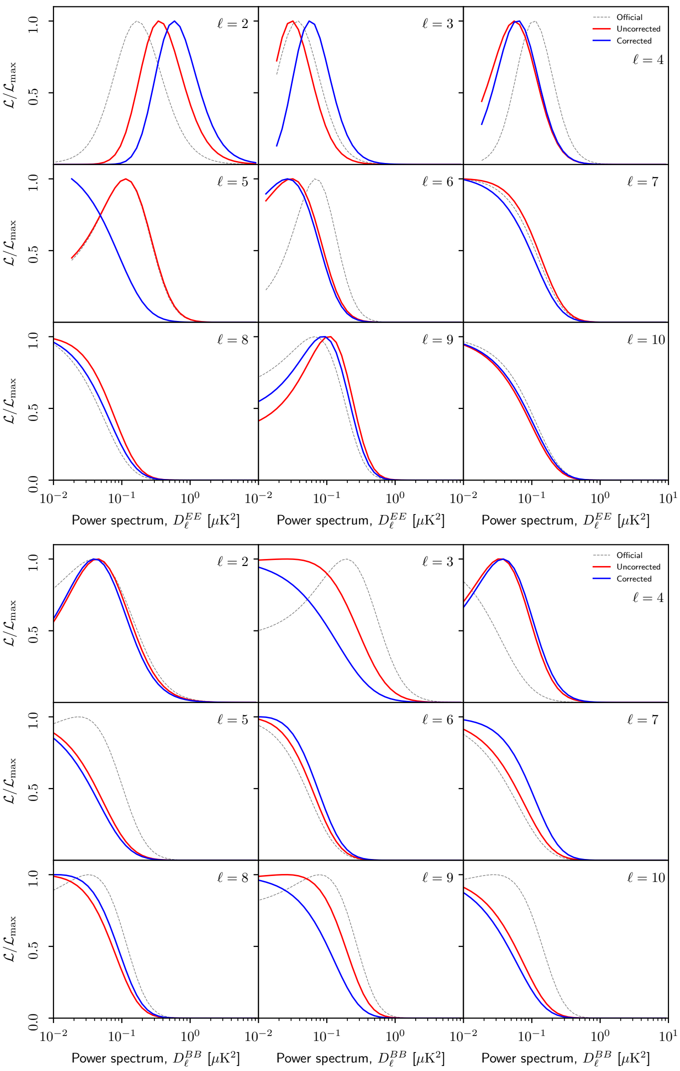

Fig. 4. Likelihood slices