The S-PASS view of Synchrotron at 2.3 GHz

https://arxiv.org/abs/1802.01145
Krachmalnicoff et al., A&A, in press

CMB foregrounds for B-mode studies
Tenerife - October 17th, 2018

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COSMOS
The **S-PASS survey**
see E. Carretti talk

**PARKES radio telescope**: 64 m  
Frequency: **2.3 GHz** (224 MHz BW)  
**Sky coverage ~ 50%** (South hemisphere)  
Angular resolution ~ **9 arcmin**

**S-PASS science:**
- Galactic Magnetic field
- Fermi Bubbles and Galactic structure
- ISM turbulence
- Gum Nebula
- ICM of galaxy clusters
- Extragalactic source properties
- CMB foregrounds
- ...
S-PASS polarized intensity map @2.3 GHz

Tenerife, October 17th 2018

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WMAP-K polarized intensity map

@23 GHz
Overview of the analysis

- S-PASS auto power spectra
- Synchrotron Spectral Energy Distribution (SED)
- Constraint on synchrotron curvature
- Synchrotron spectral index map
- Correlation between synchrotron and thermal dust emission
- Contamination to CMB B-modes
In order to describe the spectral behavior as a function of angular scales, the sky emission is dominated by different masks, for the whole range of considered sky region, with spectra computed at higher angular scales (Fig. 2). Given the highly non-stationarity and non-Gaussianity of the thermal dust emission, on the basis of Planck observation region. Therefore, the fit may result in a poor correspondence with the model and data. Gross statistical indicators, like all contamination of foregrounds, but are far from constituting a physical explanation of this feature.

As for the parameter, representing the power of point sources effects on the Galactic plane, spectra are almost flat in the whole considered multipole range with similar amplitude for different masks, for the sets of six masks are plotted in Figure 2. The fitted power spectra are shown in Figure 2. We fitted the model in Equation EE$^2$ + BB$^2$, separately for isotropic cases, together with the synchrotron radiation model (although being a typical one for this kind of studies). As for the polarization maps computed on the set of iso-latitude masks described in Section 3.1. Fitting, it is worth noticing that, in all the considered cases where we not apply the fit in this case, the model characterizes the diurnal behavior as a function of the amplitude of S-PASS$^2$.

\[ C_\ell = A_s \ell^\alpha + A_p \]
Fig. 6. Upper panel: amplitude of computed power spectra on data for different multipole bins and sky masks (the color scheme is the same of Figure 4) as a function of the effective frequency. Filled points refers to $EE$ spectra, empty ones to $BB$. Curves represent the best model we obtain when fitting Equation (2) to data (solid and dashed lines for $E$ and $B$-modes respectively). Lower panel: residuals of the fits normalized to the 1 error. In both upper and lower panel the points inside the grey shaded area come from the correlation of S-PASS with WMAP/Planck data which, as described in the text, are not considered in the fitting.
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**Synchrotron SED**

Fig. 4. Best fit values for the synchrotron SED spectral index $\beta_s$ (upper panel) and PTE coefficients (lower panel), obtained by fitting the model of Equation (2) to S-PASS, WMAP, and Planck data. Different point colors and shapes refer to the different sky regions. The black line and grey area in the upper plot show the retrieved average value $\beta_s = -3.22 \pm 0.08$.

Fig. 5. Retrieved $\beta_s$ parameter obtained by fitting synchrotron SED model on simulated spectra. Point colors and shapes follow the same scheme of Figure 4.

We fit the model of Equation (2) to the mean value of the spectra obtained from the simulations. We stress that the synchrotron signal in our simulations is rigidly rescaled at the different frequencies considering a constant spectral index $\beta_s = 3.1$. Any possible cause of de-correlation among frequencies (other than noise) is excluded. Therefore differently to what we have described previously for data, we fit the SED model on simulations, considering the full set of ten frequencies, including therefore also the cross spectra among S-PASS and WMAP/Planck.

Results of the fit are shown in Figure 5. We are able to recover the input value of the $\beta_s$ parameter in all the considered cases.

4.3. Correlation between S-PASS and WMAP/Planck polarization maps

In the upper panel of Figure 6 we show the amplitude of EE and BB spectra we get from data, for all the multipole bins and sky masks, together with the best fit curves. The lower panel of the same figure shows the residuals of each fit. In all these plots the points inside the grey shaded area come from the cross correlation between the S-PASS polarization maps and the other three maps at higher frequencies from WMAP and Planck data.

As described in the previous Section, we did not consider these points while performing the fit. The reason of excluding them appears clear while looking at the residuals: the majority of them show a lack of power with respect to the best synchrotron SED model. In particular, residuals can be more than 4 away from the best fit curve for the largest masks. On the other hand, at high latitudes deviations are generally within 2, and therefore not statistically significant. This indicates that S-PASS and WMAP/Planck maps do not properly correlate in the sky regions close to the Galactic plane and that, here, some kind of mechanism causing de-correlation is present.

In general, de-correlation may originate either from instrumental effects or physical motivations. In our case, systematic effects can not be the primary source since they would cause stronger de-correlation where the signal is weaker, i.e. at high Galactic latitudes, which is opposite to what we find. For WMAP and Planck, residual intensity...
Constraints on curvature

\[ D_\ell(\nu_1 \times \nu_2) = A_s \left( \frac{\nu_1}{\nu_0} \right)^{\beta_s + s_{\text{run}}} \log(\nu_1/\nu_0) \left( \frac{\nu_2}{\nu_0} \right)^{\beta_s + s_{\text{run}}} \log(\nu_2/\nu_0) \]

- Strong degeneracy between \( \beta_s \) and \( s_{\text{run}} \)
- **Gaussian prior on spectral index** from WMAP and Planck: \( \beta_s = -3.13 \pm 0.13 \)
- \( s_{\text{run}} \) compatible with zero, with 1\( \sigma \) errors between 0.07 and 0.14
- More data at intermediate frequencies are needed (C-BASS in south, QUIJOTE and C-BASS in north)

\( D_\ell(\nu_1 \times \nu_2) \) vs multipole \( \ell \) for EE and BB power spectra.
Synchrotron spectral index map

- Power law fit in range 2.3 - 33 GHz
- Fit in each pixel in total polarized intensity taking into account the noise bias
- Angular resolution of 2°
- Sky coverage ~ 30%
- No prior

\[ \hat{\beta}_s \approx -3.20 \]
\[ \sigma(\hat{\beta}_s) \approx 0.15 \]
Power spectrum of spectral index map

Noise realizations:

- S-PASS maps @ 2.3 GHz
- Extrapolate in frequency using $\beta$ map at WMAP-K/Ka, LFI-30 frequencies
- Add noise on extrapolated maps
- Estimate $\beta^*$
- Compute spectrum of $(\beta^* - \beta)$

**PySM**

$\beta$ map auto spectrum

Unbiased spectrum

Power law fit

$D_\ell \propto \ell^{\alpha}$

$\alpha = -0.6 \pm 0.2$

Multipole $\ell$

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Power spectrum of spectral index map

\[ \Delta \beta_s \]

\[ \alpha = -0.6 \pm 0.2 \]

\[ D_\ell \propto \ell^\alpha \]
Synch x Dust

\[ \rho_\ell = \frac{C_\ell(2.3 \times 353)}{\sqrt{C_\ell(2.3)C_\ell(353)}} \]

Level of correlation between 2.3 and 353 GHz is compatible with what measured with WMAP and Planck channels.

![Graphs showing correlation between 2.3 and 353 GHz](image)
Synch contamination to CMB B-modes

CMB maps - only B-modes
(Total polarized intensity)$^2$

$\ell \approx 40$
Synch contamination to CMB B-modes

Synchrotron @ 90 GHz * + CMB B-modes
(Total polarized intensity)$^2$

\[ \ell \approx 40 \]

* extrapolated with $\beta_s = -3.2$, BB/EE = 0.5
Synch contamination to CMB B-modes

CMB maps - only B-modes
(Total polarized intensity)$^2$

$r = 10^{-2}$

$\ell \approx 80$

$r = 10^{-3}$
Synch contamination to CMB B-modes

Synchrotron @ 90 GHz * + CMB B-modes
(Total polarized intensity)$^2$

\[ \ell \approx 80 \]

* extrapolated with $\beta_s = -3.2$, BB/EE = 0.5
FG contamination to CMB B-modes

- Foreground minimum as sum of synch and dust amplitudes at \( \ell = 80 \) neglecting correlation between the two
Conclusions and prospective

**S-PASS** is an **excellent dataset** for investigating synchrotron emission in **southern hemisphere** at **high Galactic latitudes** ($|b| > 30^\circ$)

**High S/N power spectra**: steep decay at small angular scales

- $C_\ell \propto \ell^\alpha$ with $\alpha < -3$

**Synchrotron SED** for E and B-modes as a function of multiple spectral indices

- $\beta_s = -3.22 \pm 0.08$

**First constraints on synchrotron curvature** in polarization

- compatible with zero, more data at intermediate frequencies are needed (C-BASS South)

**First spectral index map in polarization** allowing extrapolation of fluctuation at small angular scales

- test on component separation

**Better characterization of contamination to CMB B-modes**

- Important to optimize instrument sky scanning strategy

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Backup Slides
Synchrotron SED: residuals

\begin{figure}
\centering
\includegraphics[width=\textwidth]{residuals.png}
\caption{Upper panel: amplitude of computed power spectra on data for different multipole bins and sky masks (the color scheme is the same of Figure 4) as a function of the effective frequency. Filled points refers to EE spectra, empty ones to BB. Curves represent the best model we obtain when fitting Equation (2) to data (solid and dashed lines for E and B-modes respectively). Lower panel: residuals of the fits normalized to the 1σ error. In both upper and lower panel the points inside the grey shaded area come from the correlation of S-PASS with WMAP/Planck data which, as described in the text, are not considered in the fitting.}
\end{figure}
Minimizing:
\[
\sum_{\nu_i} (\tilde{P}_{\nu_i} - P_{\nu_i})^2
\]

with:
\[
\tilde{P}_{\nu_i} = \sqrt{\left[ Q_{2.3} \left( \frac{2.3}{\nu_i} \right)^{\beta_s} + n_{\nu_i}^Q \right]^2 + \left[ U_{2.3} \left( \frac{2.3}{\nu_i} \right)^{\beta_s} + n_{\nu_i}^U \right]^2}
\]