Galactic radio loops

Philipp Mertsch

*with Subir Sarkar*

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Foregrounds in B-modes

Adam et al., arXiv:1502.01588 (Planck 2015 results X)

Adam et al., 1409.5738 (Planck Int. results XXX)

![Diagram showing the relationship between frequency and multipole for foregrounds in B-modes.](image)
Haslam 408 MHz

Haslam et al., A&AS 47 (1982) 1
The galactic radio background...

... is predominantly synchrotron of CR electrons on the galactic magnetic fields...

\[
P(r; \nu) = \int dE n_e(r; E) \frac{\sqrt{3}e^3 B_\perp(r)}{8\pi^2 \varepsilon_0 c m_e} F\left(\frac{\nu}{\nu_c}\right)
\]

where \( \nu_c = \frac{3}{2} \left( \frac{E}{m_e c^2} \right)^2 \frac{eB_\perp}{2\pi m_e} \)

\[
F(x) = x \int_x^\infty dx' K_{5/3}(x')
\]

... and we look at its line-of-sight projections:

\[
F(l, b; \nu) = \int ds P(r_{\text{LOS}}(s, l, b); \nu)
\]
Ingredients

CR electrons: • sources: SNRs! pulsars? PWNe?
large-scale distribution?!

• conceptual: stochasticity of sources?
• propagation: diffusive! convective?
  reacceleration? energy losses?

Galactic magnetic fields: • large-scale, ordered component

• anisotropic random (also called striated) component

• small-scale, turbulent component
Local e- spectrum and synchrotron

Strong et al., A&A 534 (2011)

40.00 < l < 180.00, 180.00 < l < 320.00
-45.00 < b < -10.00, 10.00 < b < 45.00

$\mathcal{R} = -2.2$
Haslam vs GALPROP

averaging over large parts of the sky...

• assumes factorisation in longitude and latitude
• leads to loss of sensitivity for structures on intermediate scales
Difference: Haslam - GALPROP
Angular power spectrum

1. radio sky:
   \[ \equiv J(\theta, \phi) \]

1. spherical harmonics:
   \[ J(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{l} a_{\ell m} Y_{\ell m}(\theta, \phi) \]

2. angular power spectrum:
   \[ C(\ell) \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2 \]

advantages:
- information ordered by scale
- statistically meaningful quantities
- natural for some applications, e.g. CMB foreground subtraction
1. even/odd structure reflects symmetries of sky map
2. smoother for higher multipoles
3. power-law

\[ C_\ell \propto \ell^{-m} \]

with \( m \sim 11/3 \) (Kolmogorov turbulence)
Smooth component only...

Mertsch & Sarkar, JCAP 06 (2013) 041

- **synchrotron:**
  - smooth emissivity (GALPROP)

- **free-free:**
  - WMAP MEM-template

- **unsubtracted sources:**
  - shot noise
Smooth component only…

Mertsch & Sarkar, JCAP 06 (2013) 041

synchrotron:
smooth emissivity
(GALPROP)

free-free:
WMAP MEM-template

unsubtracted sources:
shot noise
Deficit in RM

Beck et al., JCAP 05 (2016)

Angular Power Spectrum $\log(C_l / C_l^0)$

- Observation O12
- $L_{\text{max}} = 30 \text{pc}$
- $L_{\text{max}} = 100 \text{pc}$
- $L_{\text{max}} = 300 \text{pc}$
- $L_{\text{max}} = 1 \text{kpc}$
- $L_{\text{max}} = 3 \text{kpc}$

Spherical harmonics $l$
plasma perturbations described by MHD modes, e.g. Alfvén waves

two-point correlation function:
\[ \langle B(r_0)B(r_0 + r) \rangle_{r_0} \]

Fourier transform \( \rightarrow \) power spectrum:
\[ P(k) = \int dr \, e^{ik \cdot r} \langle B(r_0)B(r_0 + r) \rangle_{r_0} \]

observed in space plasma and simulations
\[ P(k) \propto k^{-m} \]

for \( k \in [k_1, k_2] \) with \( \sim 11/3 \)
(Kolmogorov turbulence)
Scaling the synchrotron emissivity

- GALPROP assumes a smooth distribution of RMS values for the turbulent field:
  \[ B_{\perp,\text{RMS}}(r^\perp) = \sqrt{\frac{2}{3}} |\vec{B}(r^\perp)| \Rightarrow \varepsilon_{\text{RMS}}(\nu; B_{\perp,\text{RMS}}) \]

- can rescale GALPROP’s volume emissivity
  \[ B(r) \]
  - compute small-scale turbulent field
    \[ \beta(r) \equiv \frac{B_{\perp}(r)}{B_{\perp,\text{RMS}}} \]
  - scaling factor

- exploit scaling of synchrotron emission
  \[ P(r; \nu) = \int dE \, n_e(r; E) \frac{\sqrt{3}e^3 B_{\perp}(r)}{8\pi^2 \varepsilon_0 m_e} F \left( \frac{\nu}{\nu_c} \right) \]
  \[ \nu_c = \frac{3}{2} \left( \frac{E}{m_e c^2} \right)^2 \frac{eB_{\perp}}{2\pi m_e} \]
  to find:
  \[ \varepsilon(\nu; B_{\perp}) = \varepsilon_{\text{RMS}}(\nu; \beta B_{\perp}) = \beta \varepsilon_{\text{RMS}} \left( \frac{\nu}{\beta}; B_{\perp} \right) \]
Turbulence in projection

- consider two-point correlations on sphere
- power-law in wavenumber reflected by power-law in angle $\theta$ (or multipole $\ell$)

\[ \ell_{\text{br}} \sim \frac{R}{L} \]

\[ C_{\ell} \propto \ell^{-1} \]

\[ C_{\ell} \propto \ell^{-m} \]

...including turbulent component

Mertsch & Sarkar, JCAP 06 (2013) 041

- Synchrotron:
  - Smooth emissivity
  - Power law in wavenumber
  - \( P(k) \propto k^{-m} \)

- Free-free:
  - Reflected by power law in angle or multipole
  - \( C_{\ell} \propto \ell^{-m} \)

- Unsubtracted sources:
  - Shot noise

- WMAP MEM template

Regis, Astropart. Phys. 35 (2011) 170
Radio loops

- probably shells of old SNRs
- can only observe 4 radio loops directly in radio sky
- total Galactic population of up to \( O(1000) \) can contribute on all scales

Radio loops
Haslam et al., A&AS 47 (1982) 1

Haslam 408 MHz
Unsharp masked Haslam

Vidal et al., MNRAS 452 (2015) 656
WMAP9 polarisation

Planck 30 GHz polarisation

Planck collaboration
Modelling individual shells

Mertsch & Sarkar, JCAP 06 (2013) 041

assumption: flux from one shell factorises into angular part and frequency part:

\[ f_{\text{shell} 
}\]

\[ (\nu, \ell, b) = \varepsilon_i(\nu) g_i(\ell, b) \]

frequency part \( \varepsilon_i(\nu) \):
magnetic field gets compressed in SNR shell
electrons get betatron accelerated
emissivity increased with respect to ISM

angular part \( g_i(\ell, b) \):
assume constant emissivity in thin shell:

\[ a^i_{lm} \sim \varepsilon_i(\nu) \int_{-1}^{1} dz' P_l(z') g_i(z') \]
assumption: flux from one shell factorises into angular part and frequency part 

\[ f_{\text{shell}}(\nu, \ell, b) = \varepsilon_i(\nu) g_i(\ell, b) \]

**frequency part** \( \varepsilon_i(\nu) \): 
magnetic field gets compressed in SNR shell 
electrons get betatron accelerated 
emissivity increased with respect to ISM

**angular part** \( g_i(\cos \psi) \): 
assume constant emissivity in thin shell:

\[ a_{\ell m}^i \sim \varepsilon_i(\nu) \int_{-1}^{1} dz' P_l(z') g_i(z') \]

add up contribution from all shells

\[ a_{\ell m}^{\text{total}} = \sum_i a_{\ell m}^i \]
...including ensemble of shells

Mertsch & Sarkar, JCAP 06 (2013) 041

O(1000) shells of old SNRs present in Galaxy we know 4 local shells (Loop I-IV) but others are modeled in MC approach

ey they contribute exactly in the right multipole
Best fit of local shells and ensemble

Mertsch & Sarkar, JCAP 06 (2013) 041

O(1000) shells of old SNRs present in Galaxy

we know 4 local shells (Loop I-IV) but others are modeled in MC approach

they contribute *exactly* in the right multipole
Anomalies in ILC9 ($\ell \leq 20$)

- WMAP 9yr ILC map
- smoothing to $l \leq l_{\text{max}} = 20$
- 4° wide band around Loop I (Berkhuijsen et al., 1971)
- compute $<T>$
- p-values from $10^4$ simulations with WMAP 9yr best-fit APS

p-value: 0.01 (ILC9 and SMICA)
Clustering analysis

- 20° wide band around Loop
- distance modulus map: \( G_j = |\arccos(n_j \cdot n_{ctr}) - \text{radius}| \)
- Pearson’s correlation coefficient
  \[
  C(G, T) = \frac{\sum (G - \mu_G)(T - \mu_T)}{\sqrt{\sum (G - \mu_G)^2 \sum (T - \mu_T)^2}}
  \]
- p-values from \( 10^4 \) simulations with WMAP 9yr best-fit power spectrum

p-value:
\[ 4 \times 10^{-4} \text{ (ILC9)} \ldots 1 \times 10^{-3} \text{ (SMICA)} \]
What do we know about anomaly?

- spatially correlates with Loop I
- unlikely synchrotron (checked with our synchrotron model)
- frequency dependence:
  1. ILC method efficiently suppresses power laws in frequency:

    over most of the sky $\beta \sim -3 \sim 2 \sim 1.7 \ldots 1.8$

    synch free-free  thermal dust

    in the Loop I region $\beta \sim -3 \sim 1.4$

  2. pixelwise correlation between WMAP W- and V-bands with ICL9:

    $\beta \sim 1.3$

Magnetised dust in SMC

thermal dust

typical $\beta \sim 1.6 \ldots 1.7$

spinning dust

low-\nu foreground

magnetic dust

very flat spectra,

$\beta \sim 0$;
dependence on compound, grain size, shape…
Summary

1. Lack of angular power in the Galactic radio background for $\ell = 10 \ldots 100$
2. Small-scale turbulence cannot explain it
3. A population of O(1000) shells from old supernova remnants provides the angular power needed
4. Excess in CMB map. Magnetised dust?