Morphology of the E and B mode foregrounds

For the “CMB foregrounds for B-mode studies” in Tenerife, Spain, 2018


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Outline

• One way to understand the E & B modes.
• Introduction of two types of real space EB decompositions.
  – Scalar-like ---- E/B maps ---- E(n), B(n)
  – Vector-like ---- E/B families ---- (Q_E, U_E), (Q_B, U_B)
• Polarized emissions from SNe:
  – Full sky.
  – All frequency bands.
  – Dominated by E-mode
  – A “source”, can contain any “components”
    • components: sync, dust, AME...
    • source: Galactic, point source, NPS...
The E, B modes

- There are many different ways to understand the E and B modes.
- Here we provide one way based on rotation sets
  - Direct relationship to the Q and U stokes parameters.
  - Rotational invariant
  - Three keywords:
    - normal vector
    - relative ref. sys.
    - All-in-one

\[ Q \quad E \text{-mode} \quad B \text{-mode} \]
Examples of polarized sky signals in E and B modes

For a good real-space decomposition, we want to have some simple but very useful features:

*) Possibility to get pol-ang & pol-int for E and B
*) Total signal = E + B
*) Possibility to decompose E + B back to E and B

What kind of decomposition can satisfy them?
Scalar-like and vector-like decompositions

- Common basis

\[ a_{\pm 2,lm} = \int (Q(\hat{n}) \pm iU(\hat{n})) \pm 2 Y_{lm}^*(\hat{n}) d\hat{n}. \]

\[ a_{E,lm} = -(a_{2,lm} + a_{-2,lm})/2, \]

\[ a_{B,lm} = i(a_{2,lm} - a_{-2,lm})/2, \]

- Scalar-like decomposition (E/B maps)

\[ E(\hat{n}) = \sum \sqrt{\frac{(l + 2)!}{(l - 2)!}} a_{E,lm} Y_{lm}(\hat{n}), \]

\[ B(\hat{n}) = \sum \sqrt{\frac{(l + 2)!}{(l - 2)!}} a_{B,lm} Y_{lm}(\hat{n}). \]

- Vector-like decomposition (E/B families)

\[ F_{+lm} = -\frac{1}{2}(2Y_{lm} + _{-2}Y_{lm}), \quad F_{-lm} = -\frac{1}{2i}(2Y_{lm} - _{-2}Y_{lm}). \]

\[ Q_E = \sum_{l,m} a_{E,lm} F_{+lm}, \quad U_E = \sum_{l,m} a_{E,lm} F_{-lm}, \]

\[ Q_B = \sum_{l,m} a_{B,lm} F_{-lm}, \quad U_B = \sum_{l,m} a_{B,lm} F_{+lm}. \]

\[ (Q, U) \equiv (Q_E, U_E) + (Q_B, U_B) \]

Proposed by us in Liu et al., 2018, JCAP 05..059L
Main difference of scalar-like and vector-like decompositions

Scalar-like:

Real-space

Spin-2

Harmonic-space

Vector-like:

Real-space

Spin-2

Harmonic-space

Spin-2

This leads to the deformation problem
For a good real-space decomposition, we want to have some simple but very useful features:

*) **Possibility to get pol-ang & pol-int for E and B**
*) **Total signal** = \( E + B \)
*) **Possibility to decompose** \( E + B \) **back to** \( E \) **and** \( B \)

What kind of decomposition can satisfy them?

These can only be satisfied by a vector-like (E/B family) decomposition.

\[
(Q, U) \equiv (Q_E, U_E) + (Q_B, U_B)
\]
One more difference of the two decompositions:
The deformation problem

Model: E-mode loops

K-band, only E-family

$0.00 \leq \mu K^2 \leq 1.0$

$0.0 \leq P_E \leq 100.0$
Deformation of the morphology

Model: E-mode loops

E-family

\[ P_E^2 = Q_E^2 + U_E^2 \]
Deformation of the morphology

Model: E-family loops

E-map output
$E^2(n)$

For better visibility, set the region below 0.5 to green
For foreground removal: do it directly on \((Q,U)\), or on E/B families?

- We see from above that EB-family is better than EB-map in foreground removal.
- However, can we do foreground removal directly on \((Q,U)\)?
- Simple criterion: Is there at least one source of foreground emission that is mainly in E- or B-family?
  - No: We can do foreground removal directly on \((Q,U)\).
  - Yes: It's better to work on E/B families respectively.
E-mode emission from SNe & Galactic loops

SNe suppress the magnetic field and makes it perpendicular to the normal vectors (which is well-known, like: Whiteoak & Gardner 1968; Milne 1987; Dubner & Giacani 2015; Petruk et al. 2016)
Ratio of the E/B families

\[ P_E = \sqrt{Q_E^2 + U_E^2} \]
\[ P_B = \sqrt{Q_B^2 + U_B^2} \]

\[ \rho = \frac{P_E}{P_B} \]

Value of rho for the loop and non-loop regions

<table>
<thead>
<tr>
<th></th>
<th>Median inside (outside)</th>
<th>Mean inside (outside)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-band</td>
<td>2.6 (1.9)</td>
<td>5.4 (2.8)</td>
</tr>
<tr>
<td>353 GHz</td>
<td>1.9 (1.3)</td>
<td>3.0 (2.1)</td>
</tr>
</tbody>
</table>
Pol-ang comparison

Model and data (Note: the model has no free parameter)

Regions for comparison

$$\delta_\theta = |\arcsin(\sin(\delta'_\theta))|$$
$$\equiv 90^\circ - |90^\circ - \arccos[\cos(\delta'_\theta)]|,$$
$$\langle \delta_\theta \rangle = \arctan2 \left( \sum \sin(\delta_\theta), \sum \cos(\delta_\theta) \right),$$
Important message 1:
polarized emissions from SNe exist everywhere.
Pol-ang comparison

For other frequency bands, Planck 2015 data, lists the model-to-data mean-pol-angle-difference, lower than 45-deg means the data is correlated with Loop I model.

<table>
<thead>
<tr>
<th>Band</th>
<th>K</th>
<th>30</th>
<th>Ka</th>
<th>Q</th>
<th>44</th>
<th>V</th>
<th>70</th>
<th>W</th>
<th>100</th>
<th>143</th>
<th>217</th>
<th>353</th>
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<tr>
<td>$\nu$ (GHz)</td>
<td>22.8</td>
<td>28.4</td>
<td>33.0</td>
<td>40.7</td>
<td>44.1</td>
<td>60.8</td>
<td>70.4</td>
<td>93.5</td>
<td>100</td>
<td>143</td>
<td>217</td>
<td>353</td>
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<tr>
<td>In &amp; Out</td>
<td>15.6</td>
<td>26.9</td>
<td>16.5</td>
<td>16.7</td>
<td>28.3</td>
<td>29.6</td>
<td>31.7</td>
<td>22.0</td>
<td>17.1</td>
<td>20.0</td>
<td>18.6</td>
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</tr>
<tr>
<td>Inside</td>
<td>16.2</td>
<td>25.0</td>
<td>16.6</td>
<td>16.4</td>
<td>26.1</td>
<td>27.4</td>
<td>28.7</td>
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<tr>
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<td>14.3</td>
<td>31.1</td>
<td>16.2</td>
<td>17.3</td>
<td>32.5</td>
<td>34.5</td>
<td>36.8</td>
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<td>16.8</td>
<td>20.6</td>
<td>19.3</td>
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<tr>
<td>BICEP2</td>
<td>9.7</td>
<td>53.5</td>
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<td>6.8</td>
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<td>21.8</td>
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<td>4.1</td>
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Same but with the Planck 2018 data (better systematics control). The suspicious value (in blue) becomes apparently lower.

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<td>19.5</td>
<td>8.7</td>
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<td>5.6</td>
<td>5.2</td>
</tr>
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Important message 2: polarized emissions from SNe exist for all frequencies.
Properties of the polarized Loop I emission

- At least part of the loop I (NPS) emission is from a local bubble.

- The size of Loop I is bigger than the distance to its center (we are inside the bubble).

- Polarized emissions from SNe provides a natural explanation to the E-mode excess problem reported by Planck (Planck, 2016, A&A, 586, A133), which means a huge contribution to the total polarized emission

- This also provides possible constraint on the interstellar magnetic field:
  - Turbulent background $\mathbf{B} + \text{SNe} + \text{LOS integration} \equiv \text{regular appearance of } \mathbf{B}
The morphologies of the E/B families are completely different.
Conclusion

- All frequency bands and almost all-sky region contain significant polarized foreground from supernova explosion, which is mainly in E-mode.

- Polarized emissions from supernova come from different distances than Galactic emissions, so they can certainly have different frequency spectra.

- The input map should be separated in terms of E/B families before foreground removal, which certainly helps to reduce the complexity of foreground emissions.

- To the best of our expectation, pol-emission from SNe can be removed by EB-family separation, but small residual B-mode can exist when:
  - Asymmetric of the SNe (Very likely!)
  - Properties of the background magnetic field
Thanks!