Primordial Magnetic Fields and CMB Anomalies

(work in progress)

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Outline

1. CMB anomalies.
2. Possible causes.
3. Effects of Primordial Magnetic Fields on CMB.
4. Preliminary results.
5. Conclusions.
Old cosmological Models

Ancient Egypt

Ancient Middle East

1998-2020
\(\Lambda\)CDM model (?)

Dark Ages (and Kansas today)

Ancient South Asia
Tensions in the $\Lambda$CDM model

- high- vs low-z $\sigma_8-\Omega_m$ constraints: clusters, weak lensing
- CMB anomalies: low-$\ell$, hem. anisotropies, ... 
- small scale CDM problems: cusps, too big to...
- high- vs low-z $H_0$ measurements
1. CMB Anomalies

- Several unexpected features were observed in CMB data at large angular scales (WMAP, Planck, COBE).

**Low variance and lack of correlation on large angular scales**

- Variance, skewness and kurtosis (Planck)

- < 0.5 % p-value

\[
C(\theta) = \frac{1}{4\pi} \sum_\ell (2\ell + 1)C_\ell P_\ell(\cos \theta).
\]

Planck2018 (1906.02552)
Planarity and Alignment of the lowest multipole moments.

- In LCDM temperature anisotropies have random phases

- In harmonic space, orientations and shapes of the multipole moments are uncorrelated.

- The octupole is somewhat planar, $p < 5\%$.

- The normal to the quadrupole plane is aligned to the normal to the octupole plane, $p < 1.5\%$

- Quadrupole and octupole plane is orthogonal to the Ecliptic plane, $2\% < p < 4\%$
Hemispherical power asymmetry

- Preference for odd parity modes (p-value < 1%), large cloud spot in the southern hemisphere (p-value < 1.8%)

\[(l, b) = (230^\circ, -16^\circ) \pm 24^\circ\]

- p-value < 1%
- Do the anomalies are independent? Maybe 3 of them \( p \sim 10^{-5} \)

<table>
<thead>
<tr>
<th>feature</th>
<th>p-value</th>
<th>data</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>in angular space</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low variance ( N_{\text{side}} = 16 )</td>
<td>( \leq 0.5% )</td>
<td>Planck 15</td>
<td>Tab. 12 [7]</td>
</tr>
<tr>
<td>2-pt correlation ( \chi^2(\theta &gt; 60^\circ) )</td>
<td>( \leq 3.2% )</td>
<td>Planck 15</td>
<td>Tab. 14 [7]</td>
</tr>
<tr>
<td>2-pt correlation ( S_{1/2} )</td>
<td>( \leq 0.5% )</td>
<td>Planck 15</td>
<td>Tab. 13 [7]</td>
</tr>
<tr>
<td>2-pt correlation ( S_{1/2} )</td>
<td>( \leq 0.3% )</td>
<td>Planck 13 &amp; WMAP 9yr</td>
<td>Tab. 2 [31]</td>
</tr>
<tr>
<td>2-pt correlation ( S_{1/2} ) (larger masks)</td>
<td>( \leq 0.1% )</td>
<td>Planck 13</td>
<td>Tab. 2 [31]</td>
</tr>
<tr>
<td>hemispherical variance asymmetry</td>
<td>( \leq 0.1% )</td>
<td>WMAP 9yr</td>
<td>[31, 32]</td>
</tr>
<tr>
<td>cold spot</td>
<td>( \leq 1.0% )</td>
<td>Planck 15</td>
<td>Tab. 20 [7]</td>
</tr>
<tr>
<td>in harmonic space</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>quadrupole-octopole alignment</td>
<td>( \leq 0.5% )</td>
<td>Planck 13</td>
<td>Tab. 7 [33]</td>
</tr>
<tr>
<td>( \ell = 1, 2, 3 ) alignment</td>
<td>( \leq 0.2% )</td>
<td>Planck 13</td>
<td>Tab. 7 [33]</td>
</tr>
<tr>
<td>odd parity preference ( \ell_{\text{max}} = 28 )</td>
<td>( &lt; 0.3% )</td>
<td>Planck 15</td>
<td>Fig. 20 [7]</td>
</tr>
<tr>
<td>odd parity preference ( \ell_{\text{max}} &lt; 50 ) (LEE)</td>
<td>( &lt; 2% )</td>
<td>Planck 15</td>
<td>Text [7]</td>
</tr>
<tr>
<td>dipolar modulation for ( \ell = 2 - 67 )</td>
<td>( \leq 1% )</td>
<td>Planck 15</td>
<td>Text [7]</td>
</tr>
</tbody>
</table>
Breaking Statistical Isotropy

- In LCDM, CMB is supposed to be Gaussian and Statistically isotropic. i.e multipolar coefficients are statistically independent (correlation matrix is diagonal)

\[
\langle a_{\ell m} a_{\ell' m'}^* \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell
\]

- All information is in the power spectrum and 2PCF.

\[
P(a) = \frac{1}{\sqrt{(2\pi)^3 (l_{\text{max}}+1)^2 \det(M)}} e^{-\frac{1}{2} a^\dagger M^{-1} a}
\]

\[
a = \begin{pmatrix}
a^T_{\ell m} \\
a^E_{\ell m} \\
a^B_{\ell m}
\end{pmatrix}
\]

- Anomalies are related to Violation of Statistical Isotropy (correlation matrix is not diagonal anymore)

- Are necessary more estimators.
2. Possible Causes for Violation of Statistical Isotropy

- **Residual Foregrounds:**
  - Solar System emissions
  - Milky Way emissions
  - Contamination by Sunyaev-Zeldovich effect

- **Cosmological:**
  - Kinetic effects (Earth's motion with respect to CMB)
  - Local large scale structure
  - Broken scale invariance
  - Broken isotropy in Early Universe
  - Topology
  - Primordial Magnetic Fields....
Why Primordial Magnetic Fields?

- There is observational evidence for the presence of large-scale intergalactic magnetic fields, within clusters of galaxies (μG).

- Amplification of Primordial Magnetic Fields (nG) appeared in early times?

- Assumption: There exists a primordial homogeneous magnetic field (nG)

- Recombination epoch
3. Effects of the Magnetic Fields in CMB

- Speed of sound and Acoustic Oscillations:
  \[ c_s^2 \rightarrow c_s^2 + v_A^2 \cos^2 \theta \]
  \[ v_A^2 = \frac{B_0^2}{4\pi(\rho + p)} \]

- Induced vector perturbations and Sachs Wolfe effect corrections
  \[ \frac{\delta T}{T} B_{\hat{n}, k} \approx \hat{n} \cdot \vec{v}_0 \, v_A \, k \, t_{\text{dec}} \, \cos \theta. \]

- In harmonic space
  \[ \langle a_{\ell m} a_{\ell' m'}^* \rangle = \langle a_{\ell m} a_{\ell' m'}^* \rangle_{\Lambda \text{CDM}} + \langle a_{\ell m} a_{\ell' m'}^* \rangle_{B} \]
  \[ \langle a_{\ell m} a_{\ell' m'}^* \rangle_{\Lambda \text{CDM}} = C_{\ell}^{\Lambda \text{CDM}} \delta_{mm'} \delta_{\ell\ell'} \]
  \[ \langle a_{\ell m} a_{\ell' m'}^* \rangle_{B} = \delta_{mm'} [\delta_{\ell\ell'} C_{\ell m}^{B} + (\delta_{\ell+1, \ell' -1} + \delta_{\ell-1, \ell' +1}) D_{\ell m}^{B}] , \]

  \[ C_{\ell m}^{B} = 27.12 \times 10^{-16} \left( \frac{B_0}{1 \, nG} \right)^4 \times \frac{2\ell^4 + 4\ell^3 - \ell^2 - 3\ell + 6m^2 - 2\ell m^2 - 2\ell^2 m^2}{(\ell + 2)(\ell + 1)\ell(\ell - 1)(2\ell - 1)(2\ell + 3)} \]

  \[ D_{\ell m}^{B} = \frac{9\pi}{32} \frac{\sqrt{(\ell + m + 1)(\ell - m + 1)(\ell + m)(\ell - m)}}{2\ell^4 + 4\ell^3 - \ell^2 - 3\ell + 6m^2 - 2\ell m^2 - 2\ell^2 m^2} \frac{\sqrt{(2\ell - 1)(2\ell + 3)(\ell - 1)(\ell + 2)}}{(2\ell + 1)} \]
Simulated maps (Masked with U73)

- LCDM maps (Statistically isotropic)

\[ P(a) = \frac{1}{\sqrt{(2\pi)^3(l_{\text{max}}+1)^2 \det(M)}} e^{-\frac{1}{2} a^\dagger M^{-1} a} \]

- Maps with B = 10 nG

Cholesky decomposition

\[ M = L^\dagger L \]
\[ a = L z \]

\[ P(z) = \frac{1}{\sqrt{(2\pi)^3(l_{\text{max}}+1)^2 |\det(L)|}} e^{-\frac{1}{2} z^\dagger z} \]
Robustness of low variance (in context of LCDM, Planck 2018)

$N_{\text{side}} = 512$:

$N_{\text{side}} = 16$:

<table>
<thead>
<tr>
<th>Method</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commander</td>
<td>0.031</td>
<td>0.246</td>
<td>0.311</td>
</tr>
<tr>
<td>Smica</td>
<td>0.031</td>
<td>0.26</td>
<td>0.256</td>
</tr>
<tr>
<td>SEVEM</td>
<td>0.031</td>
<td>0.304</td>
<td>0.304</td>
</tr>
<tr>
<td>NILC</td>
<td>0.025</td>
<td>0.261</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Robustness of low variance (in context of LCDM)

\[-2\% < p < 4\%\]

\[\text{Consistent with Planck 2018}\]
What about CMB maps with Magnetic Fields?
Conclusions

- There are unexpected features in CMB highly unlikely in context of LCDM. At least 3 of them independents.

- Those unexpected features are caused by broken of statistical isotropy

- There are several scenarios to violation of the statistical isotropy

- Primordial magnetic fields changes the speed of sound and acoustic oscillations, they induced vector perturbations and Sachs Wolfe effect corrections.

- In harmonic space, a magnetic field will induce correlations between different multipolar moments.

- 2019 Planck data present a low variance, 2%<p<4%. this results are robust