Mysteries of the large-angle microwave sky

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Bennett et al. 2003
Lack of power at $\theta > 60$ deg

Bennett et al. 2003
\( \ell = 2, 3 \) are aligned and planar

Tegmark et al. 2003
Multipole Vectors

Spherical Harmonics:

\[
\frac{\delta T}{T}(\theta, \phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi), \quad C_\ell \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2
\]

Multipole Vectors:

\[
\sum_{m=-\ell}^{\ell} a_{lm} Y_{lm}(\theta, \phi) = A^{(\ell)} \left( v^{(\ell)}_1 \cdot e \right) \cdots \left( v^{(\ell)}_\ell \cdot e \right)
\]

\[
\text{“} a^{(\ell)}_{i_1 \ldots i_\ell} \leftrightarrow A^{(\ell)} \left[ v^{(\ell)}_1 \otimes v^{(\ell)}_2 \otimes \ldots \otimes v^{(\ell)}_\ell \right] \text{”}
\]

Copi, Huterer & Starkman, 2004
Multipole Vectors of our sky

L=2  L=3  L=4  L=5
L=6  L=7  L=8
\[ \mathbf{w}_{ij}^{(\ell)} \equiv \pm \left( \mathbf{v}_i^{(\ell)} \times \mathbf{v}_j^{(\ell)} \right) \]

- \[ \mathbf{w}_{12}^{(\ell=2)} \]
- \[ \mathbf{w}_{12}^{(\ell=3)} \]
- \[ \mathbf{w}_{23}^{(\ell=3)} \]
- \[ \mathbf{w}_{31}^{(\ell=3)} \]
(Quad + Oct) map and the ecliptic plane

WMAP Quadrupole and Octopole

Schwarz, Starkman, Huterer and Copi, PRL 2005
(Quad + Oct) map and the ecliptic plane
Found: unexpected alignments

- The four oriented area normals $w_{ij}^{(\ell)} \equiv \pm \left( v_i^{(\ell)} \times v_j^{(\ell)} \right)$ for $\ell = 2, 3$ are mutually close (99.7-99.9% CL)

- $w_{ij}^{(\ell)}$ lie close to the ecliptic plane (99% CL)

- $w_{ij}^{(\ell)}$ are aligned to the dipole and to the equinoxes (99.9% CL)

- Ecliptic plane carefully separates stronger from weaker extrema, running between a maximum and a minimum over most of the sky (93% - 99.6% CL)

Schwarz, Starkman, Huterer and Copi, PRL 2005
N/S power asymmetry

Eriksen et al. 2004; Hansen, Banday & Gorski, 2004
Systematic checks: foreground missubtraction

\[ T_{\text{tot}}(\theta) = T_{\text{CMB}}(\theta) + c T_{\text{for}}(\theta) \sqrt{\frac{\text{Var}(T_{\text{CMB}})}{\text{Var}(T_{\text{for}})}} \]
Systematic checks: sky cut

Copi, Huterer, Schwarz & Starkman, astro-ph/0508047
What about COBE?

Using the COBE MCMC maps from Wandelt, Larson & Lakshminarayanan (2004)
4 classes of explanations:

- **Astrophysical** (e.g. an object or other source of radiation in the Solar System)
  - BUT: we think we know the Solar System. It would need to be a large source and undetected in data cross-checks.

- **Instrumental** (e.g. there is something wrong with WMAP instrument measuring CMB at large scales)
  - BUT: the instruments have been extremely well calibrated and checked. Plus, why would they pick out the Ecliptic plane?

- **Cosmological** (e.g. some property of the universe – inflation or dark energy for example – that we do not understand)
  - This is the most exciting possibility. BUT: why would the new/unknown physics pick out the Ecliptic plane?
  - These alignments are a pure fluke!
  - BUT: they are <0.1% likely!
What could be going on?

- Dipole subtraction?
- Scanning strategy?
- Solar system signal?

or perhaps...

- Anisotropic universe?

Any of the above would have implications for cosmological parameter determination.
Additive and multiplicative errors

Let $T(\hat{n}), A(\hat{n}), B(\hat{n})$ be temperature fields

$$T(\hat{n}) \equiv A(\hat{n}) + f[1 + w(\hat{n})]B(\hat{n})$$

$$\Rightarrow t_{\ell m} = a_{\ell m} + f b_{\ell m} + f \sum_{\ell_1 \ell_2} R_{\ell m}^{\ell_1 \ell_2} b_{\ell_2 m}$$

- $B(\hat{n}) = 1 \Rightarrow \langle t_{\ell m}^* t_{\ell' m} \rangle = \delta_{\ell \ell'} C^{aa}_{\ell} + f^2 w_{\ell} w_{\ell'} \delta_{m0}$ (additive)

- $w(\hat{n}), B(\hat{n})$ depend on $\hat{n}$
  $$\Rightarrow \text{coupling between } \ell, \ell'$$ (multiplicative)

Additive schemes “don’t work”

Double (likelihood) penalty:

- Intrinsic sky is less likely than observed
- Requires a chance cancellation

Same true for all additive schemes: Bianchi templates, Solar System contamination, ...

Multiplicative modulation: example

Conclusions

- We (and others) observe a number of anomalies at large scales in WMAP, including correlations with the Ecliptic.

- Is dark energy or inflation doing something weird? Are there unaccounted-for local contaminants or foregrounds?

- No as-of-yet proposed mechanism works. Multiplicative modulations are promising, additive ones are not.

- Future data:
  - WMAP 2nd year etc temperature maps (but expected to be unchanged)
  - WMAP polarization maps (but expected to be systematics-dominated)
  - Planck