Mysteries on universe’s largest observable scales

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How does the universe look at largest observable scales?

ILC map, WMAP collaboration
Outline

Motivation and overview of concurrent findings

Multipole Vectors

Large-scale alignments

Various explanations

Future prospects and conclusions
Low power on large scales

Spergel et al 2003: 0.2% of sims have less power at angles >60 deg
$l=2, 3$ are aligned and planar

\[
\hat{L}_\ell^2 \equiv \sum_{m=-\ell}^{\ell} \frac{m^2 |a_{\ell m}|^2}{\ell^2 \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}
\]

$l=3$ is planar: $P \sim 1/20$

$l=2, 3$ is are aligned: $P \sim 1/60$
N/S power asymmetry

South (ecliptic) has more power than north

Eriksen et al 2004;
Hansen, Banday and Gorski 2004
Multipole vectors!

Spherical Harmonics:

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

Multipole Vectors:

\[
\sum_{m=-\ell}^{\ell} a_{lm} Y_{lm}(\theta, \phi) = A^{(\ell)} \left( v_{1}^{(\ell)} \cdot e \right) \cdots \left( v_{\ell}^{(\ell)} \cdot e \right)
\]

“\(a_{i_1 \ldots i_\ell}^{(\ell)} \leftrightarrow A^{(l)} \left[ v_{1}^{(\ell)} \otimes v_{2}^{(\ell)} \otimes \ldots \otimes v_{\ell}^{(\ell)} \right]''\)"

Lth multipole \(\leftrightarrow\) L (headless) vectors, plus a constant

Copi, Huterer & Starkman 2003;  http://www.phys.cwru.edu/projects/mpvectors/
Multipole vectors of our sky

Copi, Huterer & Starkman 2003;  http://www.phys.cwru.edu/projects/
Why multipole vectors?

- A different representation of the CMB sky than the spherical harmonics, related highly non-linearly
- Well suited for looking for planarity/directionality
- Many interesting properties, theorems (Katz & Weeks 2004, Weeks 2005, Lachieze-Rey 2004, Dennis 2005...)
- (Reviewed in Copi, Huterer, Schwarz & Starkman astro-ph/0508047)

Also:
discussed by J.C. Maxwell in his “Treatise on Electricity and Magnetism” in 1892!!
Maxwell’s multipole vectors

Potential of:

Dipole: \( \nabla v_1 \frac{1}{r} \left[ = -\frac{v_1 \cdot r}{r^3} \right] \)

Quadrupole: \( \nabla v_2 \nabla v_1 \frac{1}{r} \left[ = \frac{3(v_1 \cdot r)(v_2 \cdot r) - r^2(v_1 \cdot v_2)}{r^5} \right] \)

\( \ldots \ldots \)

l’th multipole: \( \nabla v_\ell \ldots \nabla v_2 \nabla v_1 \frac{1}{r} \)

\( v_1 \ldots v_\ell \) are the multipole vectors

Maxwell 1892; Weeks 2004
Normals to multipole vectors

\[ w_{ij}^{(\ell)} \equiv \pm \left( v_i^{(\ell)} \times v_j^{(\ell)} \right) \]

“oriented areas”

\[ L=2 \]

\[ L=3 \]
L=2+3 alignments

(CMB) Dipole

Ecliptic plane

Normals to quad, octopole

Schwarz, Starkman, Huterer & Copi, PRL, 2004
Alignments found at L=2, 3

- The four area vectors are mutually close (99.0-99.9% CL)
- They lie close to ecliptic plane (98%-99% CL)
- They lie close to equinoxes and dipole (99.8% CL)
- Ecliptic plane carefully separates weak from strong extrema (93%-99.6% CL)
Systematic checks: sky cut

Errors increase sharply, but results consistent with full-sky result

Systematic checks: foreground missubtraction

Adding (known) foregrounds leads to galactic, and not ecliptic, alignments

What about COBE?

Using COBE MCMC maps from Wandelt, Larson & Lakshminarayanan 2003

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 \textit{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!
Example: non-linear detector

Suppose that the WMAP detectors are slightly (1%) nonlinear

\[ T_{\text{obs}}(\hat{n}) = T(\hat{n}) + \alpha_2 T(\hat{n})^2 + \alpha_3 T(\hat{n})^3 + \ldots \]

The biggest signal on the sky is the dipole

\[ T(\hat{n}) = 3.3mK \cos(\theta) \]

So with \( \alpha_2 \sim \alpha_3 \sim 10^{-2} \), dipole anisotropy is modulated into a \( 10^{-5} \) quadrupole and octopole with \( m = 0 \) in the dipole frame.

Sadly: doesn’t work since would have been seen when observing \( \sim 1K \) sources (in lab, Jupiter, etc).

Example: Spontaneous Isotropy Breaking

- To explain/model the apparent lack of isotropy on largest scales seen by WMAP

\[ V(\phi) = V_0\left[1 + f \cos(\phi/M_0)\right] \]

\[ \phi(z) = A + Bz \]

Modulates the CMB anisotropy through the ISW effect

Nonlinear modulation \(\Rightarrow\) a range of multipoles affected

Gordon, Hu, Huterer & Crawford 2006
Additive schemes “don’t work”

\[ \hat{T}(\hat{n}) = T_{\text{intr}}(\hat{n}) + T_{\text{extra}}(\hat{n}) \]

Double (likelihood) penalty:

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

True for all additive schemes: Solar System contamination, Bianchi models, etc

Multiplicative modulation can work

\[ \hat{T}(\hat{n}) = T_{\text{intr}}(\hat{n}) [1 + w(\hat{n})] \]

\[ w(\hat{n}) \propto Y_{20}(\hat{n}) \text{ example} \]

Best-fit $L=1,2$ multiplicative modulation from WMAP 123

Spergel et al, 2006
Low power on large scales

Spergel et al 2003: 0.2% of sims have less power at angles >60 deg

Copi, Huterer, Schwarz & Starkman astro-ph/0605135
Future data and prospects

- **WMAP** is probably as good as it will get on large scales (as seen in year 1 vs year 123)
- Nevertheless, understanding of fine details is improving and is crucial.
- **Planck** will provide a great check of these measurements (very different experiment)
- **Polarization maps** with relatively high S/N, when eventually available, will provide even more leverage.
- The level of expected polarization “alignments” is model dependent
- In principle, can map out largest-scale fluctuations from wide-field, large-volume large-scale structure surveys (perhaps LSST)
Conclusions

• Alignments with the ecliptic plane and/or dipole are sufficiently significant to be very interesting despite the a posteriori nature of these observations

• No convincing explanations so far

• Other observed anomalies (N/S asymmetry, L=4-6 etc) very intriguing and possibly related

• Multipole vectors are a great tool to study alignments and directionalities in the CMB

• Pixel-space C(\theta) low at 99.97% CL - even more than in year 1