Testing the Isotropy of the Cosmic Microwave Background

Starring ‘The Axis of Evil’!

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POWER SPECTRUM FROM WMAP
MOTIVATION: Common Assumptions

- ‘The Cosmological Principle’: The universe is Homogeneous and Isotropic, on large scales.
  ➔ Statistical Isotropy

- Gaussianity - as predicted by simple inflationary models

These issues are often mixed
MULTIPOLES

\[ T(n) = \sum_{l} \sum_{m} a_{lm} Y_{lm}(n) = \sum_{l} T_{l}(n) \]

SI  \(\rightarrow\)  \[ \langle a_{lm} a_{l'm'} \rangle = \sum_{ll'} \sum_{mm'} C_{l} \]

Gaussian  \(\rightarrow\)  \( C_{l} \) contains all info

Degrees of freedom
\[(2l + 1) = 3 \text{ rotational} \ & \ (2l - 2) \text{ invariants} \]
ASSUMPTIONS MADE

• ‘The Cosmological Principle’:
The universe is Homogeneous and Isotropic, on large scales.

⇒ Statistical Isotropy

\[ C(n_1, n_2) \langle T(n_1)T(n_2) \rangle = f(\cos \theta) \]

\[ T(n) = \sum a_{lm} Y_{lm}(n) \]

\[ \langle a_{lm} a_{l'm'} \rangle = C_l \]

No \( l \) correlations
ASSUMPTIONS MADE

• **Gaussianity** - as predicted by simple inflationary models

\[ C_l \text{ contains all information} \]

Odd order functions = 0

The issues are often mixed.

Multipoles:

\[ T_l(n) = \sum_m a_{lm} Y_{lm}(n) \]

Degrees of freedom

\[ (2l + 1) = 3 \text{ rotational} \quad \& \quad (2l - 2) \text{ invariants} \]
THE CMB

Gaussianity

\( a_{lm} \) from GAUSSIAN RANDOM FIELD

\[
\langle a_{lm} \rangle = 0
\]

\[
\langle a_{lm} a_{lm} \rangle = C_l
\]

Isotropy

STATISTICALLY ISOTROPIC CMB

\( l \) independence

\( m \) equality

\[
T(n) = \sum_{lm} a_{lm} Y_{lm}(n) = \sum_l T_l(n)
\]

Degrees of freedom

\[
(2l + 1) = 3 + (2l - 2)
\]
“Intriguingly, both the quadrupole and the octopole are seen to have power suppressed along a particular spatial axis, which lines up between the two, roughly towards

\((l, b) \sim (-110, 60)\)

in Virgo.”
**PLANARITY**

Oliveira et al. 0307282

\[
\sum_m m^2 |a_{\ell m}(\hat{n})|^2
\]

**MAX**

\[
\hat{n}
\]

Axis of maximum planarity

\[
\hat{n}_2 = (-0.1145, -0.5265, 0.8424),
\hat{n}_3 = (-0.2578, -0.4207, 0.8698),
\]

i.e., both roughly in the direction of \( (l, b) \sim (-110^\circ, 60^\circ) \) in Virgo.
MULTIPOLe FRAMES II

When does a multipole look most like a pure m-mode?

\[
    r_l = \max_{m,n} \frac{2|a_{lm}|^2}{\sum_{m'}|a_{lm'}|^2}
\]

- **RATIO** - how much 'm preference'
- **SHAPE** - which m
- **DIRECTION**

Land & Magueijo PRL(95)071301
$l = 2$ (Quadrupole)

SHAPE $m = 2$

RATIO 0.957
$l = 3$ (Octopole)

SHAPE $m = 3$
RATIO 0.942
$l = 4$

SHAPE $m = 2$
RATIO 0.875
$l = 5$

SHAPE $m = 3$
RATIO 0.895
$l = 6$

SHAPE $m = 1$

RATIO 0.802
RESULTS

• SHAPES $m_l$
  Not just favouring one shape. Not always planar.

• RATIOS $r_l$
  Not significant – some ‘$m$ preference’ is normal.

• DIRECTIONS $n_l$
  Highly correlated for $l = 2,3,4,5$

  All find direction $(l,b)\sim(-110,60)$

  Rejected by 99.9%
MULTIPOLE VECTORS

\[ T_l(n) = A_l(n \cdot v_1) \ldots (n \cdot v_l) + R_l(n) \]

Will highlight directions

Simple form for pure m-mode

\[ T_l = Y_{lm}(n) \]

\( m \) ‘disc’

\( (l-m) \) ‘handle’
MULTIPOLE VECTORS

Copi, Huterer, Starkman PRD(70)043515. Copi &al. astro-ph/0508047

\[ T_l(n) = A_l (n.v_l) \ldots (n.v_l) + R_l(n) \]

\{a_{lm}\} \quad A_l \& \{v_i\}

Land & Magueijo MNRAS(362)838
MULTIPOLE VECTORS

Will highlight directions
More intuitive
Simple form for pure m-mode

\[ T_l = Y_{lm}(n) \]

\( m \) ‘disc’

\( (l-m) \) ‘handle’
$l = 3$ (Octopole)

SHAPE $m = 3$
$l = 5$

SHAPE $m = 3$
POSITIVE MIRROR PARITY: \((l + m)\) even

Preferred Axis 99.9\% + Mirror Parity 90\% = 99.99\%
MIRROR PARITY

- Reflections through a plane

\[(l+m) \text{ even: Positive} \quad (l+m) \text{ odd: Negative}\]
POINT PARITY

- Reflections through the centre $n \rightarrow -n$
  
  $l$ even: Positive  
  $l$ odd: Negative
ASYMMETRIES – POWER SPECTRUM


(l,b) = (57,10) maximises asymm
ASYMMETRIES - 3 POINT CORRELATION F’NS

Surprisingly Featureless

Land & Magueijo MNRAS(357)994
ASYMMETRIES - BISPECTRUM

\[ B_{l_1 l_2 l_3} = \sum_{m_1 m_2 m_3} \left( \begin{array}{ccc} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{array} \right) \langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle \]

- All-sky WMAP Bispectrum consistent with Guassianity, but...
\((l, b) = (57, 10)\) maximises asymm
ASYMMETRIES – LOCAL CURVATURE

LAKE COUNTS


$(l,b) = (57,10)$ maximises asymm
ANOMALIES SUMMARY

★ Max asym axis (57,10)
★ Ecliptic pole (96,30)
★ SG pole (47,6)
★ Axis of Evil ~ (260,60)
★ Dipole (264,48)
★ Virgo ~ (260,70)

Low power on large scales

Cold spot (209,-57)

Cruz & al. MNRAS(356)29
HUNTING CULPRITS

• SYSTEMATICS
  Satellite, data pipeline, …

• ASTROPHYSICAL EFFECT
  Foregrounds, local lensing, …

• COSMOLOGICAL FEATURE
  Non-FLRW models, non-trivial topology, …

• IT JUST IS!
  Have we over-done the analysis?
Bielewicz, Gorski, Banday MNRAS(355)1283
BIANCHI VII$_h$ MODELS

A class of anisotropic cosmological models. Have shear and rotation about preferred axis.
**TEMPLATE FITTING**

Data contaminated with template \( d = a + t \)

\[-2\ln L = \chi^2 + \ln|\mathbf{M}|\]

\[\chi^2 = (d - t)^T \mathbf{M}^{-1} (d - t)\]

Maximising Likelihood \( \rightarrow \) Minimising \( \chi^2 \)

\[= \frac{t^T \mathbf{M}^{-1} d}{t^T \mathbf{M}^{-1} t}, \quad \chi^2 = \frac{d^T \mathbf{M}^{-1} d -(t^T \mathbf{M}^{-1} d)^2}{t^T \mathbf{M}^{-1} t}\]

WILL ALWAYS REDUCE THE \( \chi^2 \)
Angular Scale

TT Cross Power Spectrum

\[ I(l+1)C_l/2\pi \ (\mu K^2) \]

Multipole moment \( (l) \)

\( \Lambda - CDM \) All Data

WMAP

CBI

ACBAR
TEMPLATE FITTING

Base Likelihood on $\chi^2$ instead:

$$-2\ln L = \chi^2 + \ln |M| + D \ln \chi^2$$

Maximise $L \rightarrow$

2 Solutions

If $\chi^2_0 < D \rightarrow$ always 2 solutions to $\chi^2 = D$
TEMPLATE FITTING

To select best template – marginalise over

$$P(\text{template}) \propto (\chi^2)^{-D/2} \exp\left(-\frac{1}{2} \chi^2\right)$$

$$\chi^2 = d^T M'^{-1} d$$

$$M'^{-1} = \lim_{\sigma \to \infty} \left( M + \sigma^2 t^T t \right)^{-1}$$

$$\chi^2 = d^T M^{-1} d - \frac{(t^T M^{-1} d)^2}{t^T M^{-1} t}$$
BIANCHI VII\textsubscript{h} MODELS

Land & Magueijo astro-

Axis of Evil removed + Low power restored
But chance alignment is needed
LENSING FROM LOCAL STRUCTURE


MONPOLE

DIPOLE

POWER LEAKS TO HIGHER MULTIPOLES
OTHER IDEAS…

- Non-trivial topology
- Lemaitre-Tolman-Bondi model Moffat astro-ph/0502110
- Dominating long wavelength modes
- Eccentric universe Berera, Buniy, Kephart JCAP(0410)016
- Other Bianchi models
- Anisotropic $P(k)$ Armendariz-Picon astro-ph/0509893

AND THE MORE MUNDANE…

- Contamination
  - Look for correlations with local structure (work in progress)
SUMMARY

- It is important to test our assumptions of Isotropy and Gaussianity
- There is evidence of such deviations in first year WMAP data
- Culprit(s) not known

Work in progress...