Five Years of WMAP

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ADM-50: A Celebration of Current GR Innovation
Nov 7 2009
WMAP: a mm-wave differencing telescope

- Warm spacecraft with:
  - Instrument electronics
  - Attitude control/propulsion
  - Command/data handling
  - Battery and power control

- Deployed solar array w/ web shielding

- Upper omni antenna
- Passive thermal radiator
- Medium gain antennae
- Focal plane assembly feed horns
- Secondary reflectors
- Thermally isolated instrument cylinder
- Back to back Gregorian optics, 1.4 x 1.6 m primaries
- Line of sight

sun+earth
Scan pattern and sky coverage

- 22.5° half-angle
- 1 hour precession cone
- 3 Months
- 129 sec. (0.464rpm) Spin
- MAP at L2
- 6 Months
- Earth
- Sun
- 1 Day
- 129 sec. (0.464rpm) Spin
- 2 Minute Spin
- 129 sec. (0.464rpm) Spin
- 129 sec. (0.464rpm) Spin
- 129 sec. (0.464rpm) Spin
- 129 sec. (0.464rpm) Spin
- 129 sec. (0.464rpm) Spin
- 129 sec. (0.464rpm) Spin
Why mm?

Axel Mellinger
Why mm?
Why mm?

COBE DIRBE
Why mm? Cosmic Microwave Background
Why difference?

-4mK to +4mK

WMAP
CMB fluctuations

-500μK to +500μK

WMAP
What does WMAP see?

- Afterglow Light Pattern 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion 13.7 billion years
History of the Universe

Key:
- W, Z: bosons
- photon
- q: quark
- g: gluon
- e: electron
- μ: muon
- τ: tau
- n: neutrino
- star
- meson
- baryon
- ion
- galaxy
- atom
- black hole

Accelerators:
- CERN-LHC
- FNAL-Tevatron
- BNL-RHIC
- CERN-LEP
- SLAC-SLC

High-energy cosmic rays

Possible dark matter relics

Inflation

Big Bang

1e-10 s

CMB 370,000 yrs

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
CMB: Plasma Acoustic Oscillations

- perturbation theory on a FLRW background
- plasma physics at accessible energies
- result: acoustic waves
- phase is important
before WMAP
1yr WMAP

(CMB is 1% polarized, polarization is 180° out of phase, cross-correlation is thus 90° out of phase)
3yr WMAP
5yr WMAP
The Concordance Model

- Six parameter curve fits hundreds of independent data points!
- No need (yet) for other interesting parameters
- 2 initial conditions, 2 particle params, 1 astro param, 1 geometric param, plus upper limits/assumptions about others

<table>
<thead>
<tr>
<th>Parameter</th>
<th>5 Year Mean (WMAP only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma/b$ ratio</td>
<td>$100\Omega_b h^2$</td>
</tr>
<tr>
<td>matter density</td>
<td>$\Omega_c h^2$</td>
</tr>
<tr>
<td>distance to LSS tilt</td>
<td>$\Omega_\Lambda$</td>
</tr>
<tr>
<td>pol’n bump amplitude</td>
<td>$n_s$</td>
</tr>
<tr>
<td></td>
<td>$\tau$</td>
</tr>
<tr>
<td></td>
<td>$\Delta^2 R$</td>
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</tbody>
</table>
The Concordance Model

\[ \chi^2_{\nu} = 1.06 \]

- Amplitude
- Matter density
- Tilt
- \( \gamma/b \) ratio

Multipole moment \( l \)

Distance to LSS
What set the initial conditions?

- needs to produce density perturbations “in phase”
- needs to be roughly scale invariant
- would be nice to solve horizon and curvature problems
- might be nice to clean up weird relics (monopoles?)

**Inflation?**
Inflation

• early phase of accelerating expansion solves horizon, flatness, and relic issues

• for inflation to end, use a dynamical entity: a scalar field

• quantum fluctuations become initial density perturbations, with zero velocity

• there are more implications from this model!
Inflation parameters

- gravity wave amplitude is proportional to energy scale of inflation
- large enough gravity waves cause large-scale density fluctuations themselves
- further constraints require polarization
Inflation parameters

no running

with running

(WMAP only)

3yr to 5yr is not just $\sqrt{t}$!
Inflation parameters

- $N < 70$ for post-Planck inflation
- $\phi^4$ very disfavored!
- $r$–$n_s$ combo pushing on theory
Beyond the concordance model

- tensor (gravitational wave) amplitude
- non-Λ dark energy
- scale-invariant scale-invariance (running of the index)
- axionic/other non-inflationary generation of perturbations
- neutrino mass
Non-Λ Dark energy

assume flatness

"phantom" ££

$W$ vs $\Omega_\Lambda$

- WMAP
- WMAP+HST
- WMAP+BAO
- WMAP+SN
- WMAP+BAO+SN
Dark energy

don’t assume flatness

CMB alone constrains “geometry”, combination of curvature and dark energy
Non-$\Lambda$ Dark energy

don’t assume flatness

\begin{align*}
\Omega_k &\sim 0 \\
&\quad \text{WMAP} \quad \text{WMAP+BAO+SN}
\end{align*}

\begin{align*}
\Omega_k &\sim 0 \\
&\quad \text{BAO from SDSS-LRG}
\end{align*}

\begin{align*}
\Omega_k &\sim 0 \\
&\quad \text{WMAP+BAO} \quad \text{WMAP+SN} \quad \text{WMAP+BAO+SN}
\end{align*}
Alternative dark matter

- Axion-like
- Curvaton-like

\[ \alpha_0 (\text{uncorrelated; axion-type}) \]

\[ \alpha_{-1} (\text{anti-correlated; curvaton-type}) \]

Angular Scale

- TT
- TE

Bump
Phase

Multipole moment \( l \)

\[ (l+1)C_l/2\pi [\mu K^2] \]
What if neutrinos weren’t there?

- Neutrino background is cosmologically significant!
- $N_{\text{eff}} > 0$ with 99.5% confidence
- Limit comes primarily from the unique effects of a weakly interacting relativistic “fluid”
- Explaining the CMB without neutrinos would push $\chi^2$ up 8.2, push $H_0 > 75$, and break concordance
Neutrino mass limits

\[ \Sigma m_\nu < 0.67 \text{ eV (with BAO)} \]
Non-Gaussianity
(“Gaussian” here means fluctuations at different wavenumbers are statistically independent)

- CMB is a gaussian random field to 0.1%
- $-9 < f_{NL} \text{ (squeezed)} < 111$ (95% CL)
- $-151 < f_{NL} \text{ (equilateral)} < 253$ (95% CL)
- $27 < f_{NL} \text{ (squeezed)} < 147$ (95% CL) [Yadav & Wandelt 2008]
- $-18 < f_{NL} \text{ (squeezed)} < 80$ (95% CL) [Curto et al. 2009]
- limits improve rapidly as noise and foregrounds come down
Future

- WMAP: 7yr being analyzed, 8yr data for certain, more if funded
- Planck: in progress!
- polarization B-modes -> strong limits on tensor/scalar ratio
Planck First Light

ESA, LFI & HFI consortia, background Axel Mellinger
Planck v3 on 20 arcmin smoothed 5yr W band

WMAP + Planck
courtesy David Larson
Other stuff

Galactic Magnetic Field

Power Anisotropy?

Hansen et al. (2009)

Anomalous Radio Emission?

Kogut et al. (2009)

Interstellar Dust

Dobler et al. (2009)