The 5-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation

Eiichiro Komatsu (Department of Astronomy, UT Austin)
NUPAC Seminar, Univ. of New Mexico, May 6, 2008
WMAP at Lagrange 2 (L2) Point

June 2001: WMAP launched!

February 2003: The first-year data release

March 2006: The three-year data release

March 2008: The five-year data release

- L2 is a million miles from Earth
- WMAP leaves Earth, Moon, and Sun behind it to avoid radiation from them
WMAP Measures Microwaves From the Universe

- The mean temperature of photons in the Universe today is 2.725 K
- WMAP is capable of measuring the temperature contrast down to better than one part in millionth
Journey Backwards in Time

- The Cosmic Microwave Background (CMB) is the fossil light from the Big Bang
- This is the oldest light that one can ever hope to measure
- CMB is a direct image of the Universe when the Universe was only 380,000 years old

- CMB photons, after released from the cosmic plasma “soup,” traveled for 13.7 billion years to reach us.
- CMB collects information about the Universe as it travels through it.
The Wilkinson Microwave Anisotropy Probe (WMAP)

• A microwave satellite working at L2
• Five frequency bands
  – K (22GHz), Ka (33GHz), Q (41GHz), V (61GHz), W (94GHz)
  – Multi-frequency is crucial for cleaning the Galactic emission

• The Key Feature: Differential Measurement
  – The technique inherited from COBE
  – 10 “Differencing Assemblies” (DAs)
  – K1, Ka1, Q1, Q2, V1, V2, W1, W2, W3, & W4, each consisting of two radiometers that are sensitive to orthogonal linear polarization modes.

• Temperature anisotropy is measured by single difference.
• Polarization anisotropy is measured by double difference. WMAP can measure polarization as well!
WMAP Spacecraft

Radiative Cooling: No Cryogenic System

- Instrument electronics
- Attitude control/propulsion
- Command/data handling
- Battery and power control

Warm spacecraft with:

- Upper omni antenna
- Passive thermal radiator
- Deployed solar array w/ web shielding
- Back to back Gregorian optics, 1.4 x 1.6 m primaries
- Focal plane assembly feed horns
- Secondary reflectors
- Thermally isolated instrument cylinder
- Medium gain antennae
- Line of sight
Galaxy-cleaned Map

WMAP 5-year
WMAP on google.com/sky
WMAP 5-Year Papers

- Hinshaw et al., “Data Processing, Sky Maps, and Basic Results” 0803.0732
- Hill et al., “Beam Maps and Window Functions” 0803.0570
- Gold et al., “Galactic Foreground Emission” 0803.0715
- Wright et al., “Source Catalogue” 0803.0577
- Nolta et al., “Angular Power Spectra” 0803.0593
- Dunkley et al., “Likelihoods and Parameters from the WMAP data” 0803.0586
- Komatsu et al., “Cosmological Interpretation” 0803.0547
WMAP 5-Year Science Team

- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta

Special Thanks to WMAP Graduates!

- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde
WMAP: Selected Results
From the Previous Releases

- **2003: The first-year results**
- Age of the Universe: **13.7 (± 0.2)** billion years
- “Cosmic Pie Chart”
  - Atoms (baryons): **4.4 (± 0.4)** %
  - Dark Matter: **23 (± 4)** %
  - Dark Energy: **73 (± 4)** %
  - Erased lingering doubts about the existence of DE
- “Breakthrough of the Year #1” by Science Magazine
WMAP: Selected Results
From the Previous Releases

- **2006: The three-year results**
  - *Polarization* of the cosmic microwave background measured with the unprecedented accuracy
    - The epoch of the formation of first stars (onset of the “cosmic reionization”)
    - ~400 million years after the Big Bang
  - Evidence for a scale dependence of the amplitude of primordial fluctuations (the so-called “tilt”)
    - Peering into the cosmic inflation (ultra early univ!)
• **Universe today**
  - Age: **13.73 +/- 0.12** Gyr
  - Atoms: **4.62 +/- 0.15 %**
  - Dark Matter: **23.3 +/- 1.3%**
  - Vacuum Energy: **72.1 +/- 1.5%**

• **When CMB was released 13.7 B yrs ago**
  - A significant contribution from the *cosmic neutrino background*
How Did We Use This Map?
The Spectral Analysis

Angular Power Spectrum

$$\ell(l+1)C_\ell^{TT}/2\pi \, [\mu K^2]$$

Multipole moment $\ell$

Measurements totally signal dominated to $\ell=530$

Much improved measurement of the 3rd peak!
The Cosmic Sound Wave

Angular Power Spectrum

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

Multipole moment \( l \)

Note consistency around the 3rd-peak region

- WMAP 5yr
- Acbar
- Boomerang
- CBI
The Cosmic Sound Wave

- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.
How About Polarization?

• Polarization is a rank-2 tensor field.
• One can decompose it into a divergence-like “E-mode” and a vorticity-like “B-mode”.

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky, Stebbins (1997)
5-Year E-Mode Polarization Power Spectrum at Low $l$

5-sigma detection of the E-mode polarization at $l=2-6$. (Errors include cosmic variance)

Black Symbols are upper limits
Polarization From Reionization

• CMB was emitted at $z=1090$.
• Some fraction (~9%) of CMB was re-scattered in a reionized universe: erased temperature anisotropy, but created polarization.
• The reionization redshift of ~11 would correspond to 400 million years after the Big-Bang.

First-star formation

$z=1090, \tau \sim 1$

$z \sim 11, \tau \sim 0.09$

$z=0$
Assuming an instantaneous reionization from $x_e=0$ to $x_e=1$ at $z_{\text{reion}}$, we find $z_{\text{reion}}=11.0 \pm 1.4$ (68% CL).

The reionization was not an instantaneous process at $z \sim 6$. (The 3-sigma lower bound is $z_{\text{reion}}>6.7$.)
Tilting = Primordial Shape $\rightarrow$ Inflation

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

Multipole moment $l$
“Red” Spectrum: $n_s < 1$
“Blue” Spectrum: $n_s > 1$
• WMAP-alone: $n_s=0.963 \pm 0.014$ (Dunkley et al.)

• 2.5-sigma away from $n_s=1$, “scale invariant spectrum”

• $n_s$ is degenerate with $\Omega_b h^2$; thus, we can’t really improve upon $n_s$ further unless we improve upon $\Omega_b h^2$
Cosmic Neutrino Background

• How do neutrinos affect the CMB?
  • *Neutrinos add to the radiation energy density*, which delays the epoch at which the Universe became matter-dominated. The larger the number of neutrino species is, the later the matter-radiation equality, $z_{\text{equality}}$, becomes.
  • This effect can be mimicked by lower matter density.
  • *Neutrino perturbations* affect metric perturbations as well as the photon-baryon plasma, through which CMB anisotropy is affected.
Multiplicative phase shift is due to the change in $z_{\text{equality}}$

- **Degenerate with** $\Omega_m h^2$

Suppression is due to neutrino perturbations

- **Degenerate with** $n_s$

Additive phase shift is due to neutrino perturbations

- **No degeneracy**

(Bashinsky & Seljak 2004)
Cosmic/Laboratory Consistency

- From WMAP+BAO+SN (I will explain what BAO and SN are shortly)
  - $N_{\text{eff}} = 4.4 \pm 1.5$
- From the Big Bang Nucleosynthesis
  - $N_{\text{eff}} = 2.5 \pm 0.4$
- From the decay width of Z bosons measured in LEP
  - $N_{\text{neutrino}} = 2.984 \pm 0.008$
• **BAO** helps determine the neutrino mass by giving $H_0$.

• **$\text{Sum}(m_\nu) < 0.61 \text{ eV}$** (95% CL) -- independent of the normalization of the large scale structure.
Testing Cosmic Inflation

~5 Tests~

• Is the observable universe flat?
• Are the primordial fluctuations adiabatic?
• Are the primordial fluctuations nearly Gaussian?
• Is the power spectrum nearly scale invariant?
• Is the amplitude of gravitational waves reasonable?
How Do We Test Inflation?

• The WMAP data alone can put tight limits on most of the items in the check list. (For the WMAP-only limits, see Dunkley et al.)

• However, we can improve the limits on many of these items by adding the extra information from the **cosmological distance measurements**:
  
  • *Luminosity Distances* from Type Ia Supernovae (SN)
  
  • *Angular Diameter Distances* from the Baryon Acoustic Oscillations (BAO) in the distribution of galaxies
Example: Flatness

- WMAP measures the angular diameter distance to the decoupling epoch at $z=1090$.

- The distance depends on curvature AND other things, like the energy content; thus, we need more than one distance indicators, in order to constrain, e.g., $\Omega_m$ and $H_0$.
From these measurements, we get the **relative** luminosity distances between Type Ia SNe. Since we marginalize over the absolute magnitude, the current SN data are **not** sensitive to the absolute distances.

- Riess et al. (2004; 2006) HST data
- Astier et al. (2006) Supernova Legacy Survey (SNLS)
- Wood-Vasey et al. (2007) ESSENCE data
• The same acoustic oscillations are hidden in this galaxy distribution...
• BAO measured from SDSS (main samples and LRGs) and 2dFGRS (Percival et al. 2007)

• Just like the acoustic oscillations in CMB, the galaxy BAOs can be used to measure the **absolute** distances
As a result,

- \(-0.0181 < \Omega_k < 0.0071\) (95% CL) for \(w=-1\) (i.e., dark energy being a cosmological constant)

- The constraint driven mostly by WMAP+BAO
Fun Numbers to Quote

• The curvature radius of the universe is given, by definition, by
  
  \[ R_{\text{curv}} = \frac{3h^{-1}\text{Gpc}}{\sqrt{\Omega_k}} \]

• For negatively curved space \((\Omega_k > 0)\): \(R > 33h^{-1}\text{Gpc}\)

• For positively curved space \((\Omega_k < 0)\): \(R > 23h^{-1}\text{Gpc}\)

• The particle horizon today is \(9.7h^{-1}\text{Gpc}\)

• The curvature radius of the universe is at least 3 times as large as the observable universe.
Implications for Inflation?

• Details aside...

• Q. How long should inflation have lasted to explain the observed flatness of the universe?

• A. $N_{\text{total}} > 36 + \ln(T_{\text{reheating}}/1 \text{ TeV})$

• A factor of 10 improvement in $\Omega_k$ will raise this lower limit by 1.2.

• Lower if the reheating temperature was $< 1 \text{ TeV}$

• This is the check list #1
What If Dark Energy Was Not Vacuum Energy (w/-1)...

- WMAP+BAO -> Curvature; WMAP+SN -> w
- WMAP+BAO+SN -> Simultaneous limit
- -0.0175 < Ω_k < 0.0085; -0.11 < 1+w < 0.14 (95% CL)
Check List #2: Adiabaticity

- The adiabatic relation between radiation and matter:
  - \[ 3\delta\rho_{\text{radiation}}/(4\rho_{\text{radiation}}) = \delta\rho_{\text{matter}}/\rho_{\text{matter}} \]

- Deviation from adiabaticity: A simple-minded quantification
  - Fractional deviation of A from B = \((A - B) / [(A + B)/2]\)
    - \[ \delta_{\text{adi}} = [3\delta\rho_{\text{radiation}}/(4\rho_{\text{radiation}}) - \delta\rho_{\text{matter}}/\rho_{\text{matter}}]/\{[3\delta\rho_{\text{radiation}}/(4\rho_{\text{radiation}}) + \delta\rho_{\text{matter}}/\rho_{\text{matter}}]/2\} \]
  - Call this the “adiabaticity deviation parameter”
    - “Radiation and matter obey the adiabatic relation to \((100\delta_{\text{adi}})\%\) level.”
• The negative TE at l~100 is the distinctive signature of super-horizon adiabatic perturbations (Spergel & Zaldarriaga 1997)

• Non-adiabatic perturbations would fill in the trough, and shift the zeros.
Axion Dark Matter?

- CMB and axion-type dark matter are adiabatic to 8.6%
  - This puts a severe limit on axions being the dominant dark matter candidate.

\[
\frac{\Omega_a}{\Omega_c} < \frac{3.0 \times 10^{-39}}{\theta_a \gamma^6} \left( \frac{0.01}{r} \right)^{7/2}
\]
Check list #3: Gaussianity

• In the simplest model of inflation, the distribution of primordial fluctuations is close to a Gaussian with random phases.

• The level of non-Gaussianity predicted by the simplest model is well below the current detection limit.

• A convincing detection of primordial non-Gaussianity will rule out most of inflation models in the literature.

  Detection of non-Gaussianity would be a breakthrough in cosmology
Angular Bispectrum

• Non-zero bispectrum means the detection of non-Gaussianity. **It’s always easy to look for deviations from zero!**

• There are many triangles to look for, but...
  • Will focus on two classes
    • “Squeezed” parameterized by $f_{NL}^{\text{local}}$
    • “Equilateral” parameterized by $f_{NL}^{\text{equil}}$
No Detection at >95%CL

-9 < f_{NL}(local) < 111 (95% CL)
-151 < f_{NL}(equilateral) < 253 (95% CL)

These numbers mean that the primordial curvature perturbations are Gaussian to 0.1% level.

This result provides the strongest evidence for quantum origin of primordial fluctuations during inflation.
Check List #4: Scale Invariance

- For a power-law power spectrum (no $dn_s/d\ln k$):
  - WMAP-only: $n_s=0.963 \pm 0.014$ (-0.015)
  - WMAP+BAO+SN: $n_s=0.960 \pm 0.014$ (-0.013)

  **2.9 sigma away from $n_s=1$**

- No dramatic improvement from the WMAP-only result because neither BAO nor SN is sensitive to $\Omega_b h^2$
Check List #5: Gravitational Waves

- How do WMAP data constrain the amplitude of primordial gravitational waves?

- We use “r” to parameterize the amplitude of GWs relative to the density fluctuations (or the scalar curvature (metric) perturbations)
  - When r=1, we have equal amount of scalar and tensor metric perturbations.
• If all the other parameters ($n_s$ in particular) are fixed...
  
  • Low-l polarization gives $r < 20$ (95% CL)
  
  • + high-l polarization gives $r < 2$ (95% CL)
  
  • + low-l temperature gives $r < 0.2$ (95% CL)
Since the limit on $r$ relies on the low-$l$ temperature, it is strongly degenerate with $n_s$.

The degeneracy can be broken partially by BAO&SN.

- $r<0.43$ (WMAP-only) $\rightarrow$ $r<0.20$ (WMAP+BAO+SN)
\( n_s > 1.0 \) is Disfavored, Regardless of \( r \)

- The maximum \( n_s \) we find at 95% CL is \( n_s = 1.005 \) for \( r = 0.16 \).
Lowering a “Limbo Bar”

- $\lambda \varphi^4$ is totally out. (unless you invoke, e.g., non-minimal coupling, to suppress $r$...)

- $m^2\varphi^2$ is within 95% CL.
  - Future WMAP data would be able to push it to outside of 95% CL, if $m^2\varphi^2$ is not the right model.

- N-flation $m^2\varphi^2$ (Easther&McAllister) is being pushed out

- PL inflation $[a(t) \sim t^p]$ with $p<60$ is out.

- A blue index ($n_s>1$) region of hybrid inflation is disfavored
Grading Inflation

• **Flatness:** $-0.0175 < \Omega_k < 0.0085$ (not assuming $w=-1$!)

• **Non-adiabaticity:** $<8.6\%$ (axion DM); $<2.0\%$ (curvaton DM)

• **Non-Gaussianity:** $-9 < \text{Local} < 111; -151 < \text{Equilateral} < 253$

• **Tilt** (for $r=0$): $n_s=0.960$ ($+0.014$) ($-0.013$) [68% CL]

• **Gravitational waves:** $r < 0.20$
  
  • $n_s=0.968$ (+/- 0.015) [68% CL]

  • $n_s>1$ disfavored at 95% CL regardless of $r$
Summary

- A simple, yet mysterious $\Lambda$CDM still fits the WMAP data, as well as the other astrophysical data sets.

- **We did everything we could do to find deviations from $\Lambda$CDM, but failed.**
  - Bad news... we still don’t know what DE or DM is.
  - Significant improvements in limits on the deviations
    - Most notably, $r<0.2$ (95% CL), and $n_s>1$ is now disfavored regardless of $r$.

- **Good News:** Many popular inflation models have been either ruled out, or being in danger!

- Significant improvements in $\Lambda$CDM parameters.
Looking Ahead...

• With more WMAP observations, exciting discoveries may be waiting for us. Two examples for which we might be seeing some hints from the 5-year data:
  
  • Non-Gaussianity: If $f_{\text{NL}} \sim 50$, we will see it at the 3 sigma level with 9 years of data.
  
  • Gravitational waves ($r$) and tilt ($n_s$) : $m^2\varphi^2$ can be pushed out of the favorable parameter region
    
    • $n_s > 1$ would be convincingly ruled out regardless of $r$.  

Dark Energy EOS:
\[ w(z) = w_0 + w'z/(1+z) \]

- Dark energy is pretty consistent with cosmological constant: \( w_0 = -1.09 \pm 0.12 \) & \( w' = 0.52 \pm 0.46 \) (68%CL)
• Parity violating interactions that rotate the polarization angle of CMB can produce TB and EB correlations.
These are simpler relations when there was no primordial B-mode polarization.

- How much rotation would WMAP allow?
\[ \Delta \alpha = (-1.7 \pm 2.1) \text{ degrees (68\% CL)} \]

- Comparable to the astrophysical constraint from quasars and radio galaxies
  - \[ \Delta \alpha = (-0.6 \pm 1.5) \text{ degrees (68\% CL) (Carroll 1998)} \]
  - But, note the difference in path length!