The cosmic background radiation II: The WMAP results

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General Aspects

- WMAP measures temperature fluctuations of the CMB around 2.726 K

- Reason for the temperature fluctuations are density fluctuation in the early universe

- The CMB comes from the age of the decoupling of the photons from the matter

- The CMB data is described with cosmological models
WMAP: Overview

Wilkinson Microwave Anisotropy Probe: WMAP

-Named after Dr. David Wilkinson, pioneer in the study of CMB and member of the science team, died in September 2002

- WMAP weight: 840 kg

- Angular resolution: 0.3°

- Sensitivity: $20 \, \Omega K/(0.3^\circ)^2$
Launch of the Delta II rocket on 30 June 2001
Measuring position

Orbit around the second Lagrange point (L2) of the Earth-Sun system

- 1.5 million km away from earth
- scans ~30% of the sky per day
- full sky coverage after ½ year
WMAP: Detectors I
WMAP: Detectors II

- Two back to back symmetric telescopes
- Differential microwave radiometers
- Angle between opposite feed horns: $\sim 141^\circ$
Frequency Bands

- **K-band**: ~22 GHz (13.6 mm) (1)
- **Ka-band**: ~30 GHz (10.0 mm) (1)
- **Q-band**: ~40 GHz (7.5 mm) (2)
- **V-band**: ~60 GHz (5.0 mm) (2)
- **W-band**: ~90 GHz (3.3 mm) (4)
Thermal spectrum

- **K-band**
- **W-band**
Cosmic Background

charged particles interacting with magnetic fields

hot gas (thermal Bremsstrahlung)

thermal emission
Map making

\[ DT = T(A) - T(B) \]  
\[ T(A) = DT + T(B) \]

\[ T_1(A) = DT_1 + T(B_1) \]
\[ T_2(A) = DT_2 + T(B_2) \]
\[ \vdots \]
\[ T_n(A) = DT_n + T(B_n) \]

Measured signal
Absolute temperature

Iterative procedure
estimated

\[ \langle T(A) \rangle = \frac{1}{n} \sum_{i=1}^{n} T_i(A) \]
Map projection
Scan strategy

Precession rate: 1 rp
22.5° half-angle

Spin rate: 0.464 rpm

A-side line of sight

MAP at L₂

1.5 x 10⁶ km

B-side line of sight

1.5 x 10⁸ km

Earth

Sun

North Ecliptic Pole

South Ecliptic Pole

Sky coverage for 1 spin (Blue)
Centered on X (Blue)
Precession path of Spin Axis (Red)
grey sky coverage pattern in 1 hour (Gray)
www.nasa.gov
Observation Map
Galactic Plane Map
K-band Map (23 GHz)
Ka-band Map (33 GHz)
Q-band Map (41 GHz)
V-band Map (61 GHz)
W-band Map (94 GHz)
Final Map
Comparison COBE-WMAP

53 GHz

94 GHz
(30 times finer)
Spherical harmonics

$l = 2$

$l = 16$
Power Spectrum I

\[ T(\mathbf{n}) = \sum_{l} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\mathbf{n}) \]

\[ C(\Theta) \equiv \langle T(\mathbf{n}_1) \cdot T(\mathbf{n}_2) \rangle \quad \mathbf{n}_1 \cdot \mathbf{n}_2 = \cos(\Theta) \]

\[ \sum_{m=-l}^{l} Y_{lm}^{*}(\mathbf{n}_1) \cdot Y_{lm}(\mathbf{n}_2) = \frac{2l+1}{4\pi} P_l(\mathbf{n}_1 \cdot \mathbf{n}_2) \]

\[ C(\Theta) = \frac{1}{4\pi} \sum_{l} a_l^2 P_l(\cos(\Theta)) \quad a_l^2 = \sum_{m} |a_{lm}|^2 \]
\( C_l = \langle |a_{lm}|^2 \rangle_m = \frac{1}{2l+1} \sum_m |a_{lm}|^2 = \frac{1}{2l+1} a_l^2 \)

\[ C(\Theta) = \frac{1}{4\pi} \sum_l (2l+1) C_l P_l(\cos(\Theta)) \]

\[ \Delta T_l = \sqrt{C_l l(l+1)/2\pi} \]
Power Spectrum III

\[ \Theta \sim \frac{\pi}{l} \]
Primordial fluctuation region

\[ \Theta > 2^\circ \leftrightarrow l < l_{dec} \approx 90 \]

Angular scales larger than the causal horizon size at decoupling as observed today (primordial fluctuation spectrum)
Acoustic Peak Region

$2^\circ > \Theta > 0.2^\circ \leftrightarrow 90 < l < 900$

This region can be described by the physics of a 3000 K plasma with a number density of $n_e = 300 \text{ cm}^{-3}$ responding to fluctuation in the gravitational potential of dark matter (acoustic peak region)
Silk Damping Tail

\[ \Theta < 0.2^\circ \leftrightarrow l > 900 \]

The structure is produced by the diffusion of the photons from the potential fluctuations, and the washing out of the net observed fluctuations by the large number of cold and hot regions along the line of sight (Silk damping tail)
Interpretation of the peaks

Interpretation in terms of a flat adiabatic $\Lambda$CDM-cosmological-model

Only the position of the peaks and their ratios are considered

Physics of the acoustic peaks may be understood in terms of:

\[
\Omega_b h^2 \quad \Omega_m h^2 \quad \omega_m = \omega_b + \omega_c
\]

baryon density

matter density

spectral index

angular scale of the sound horizon at decoupling

optical depth at reionization

\[\omega_b, \omega_m, n_s, \tau, \Theta_A\]
Peak ratios

For $l>40$ the peak ratios are insensitive to the intrinsic amplitude of the power spectrum and $\tau$ due to:

Scattering of free electrons from reionization ($z=20$) with CMB photons -> lowering the fluctuation by nearly a constant factor
The first acoustic peak

- The peaks arise from adiabatic compression of the photon-baryon-fluid as it falls into preexisting wells in the gravitational potential

- The potential wells are the result of some primordial field fluctuation (e.g. inflation field)

- The wells are enhanced by the dark matter (does not scatter off the baryons and photons)

- The first peak corresponds to the scale of the mode that has compressed once in the age of the universe (the photons decoupled from the electrons, $t=379$ kyr after Big Bang)
Angular scale of the peaks

\[ \Theta_A = \frac{r_s(z_{dec})}{d_A(z_{dec})} \]

- Comoving size of the sound horizon at decoupling
- Angular diameter distance to the decoupling surface
Geometric degeneracy

\( \omega_m, \omega_b \) Are well measured (affect the spectrum at early times) (assumption: flat geometry)

Geometric degeneracy: Same \( \Omega_A \) for different \( \omega_m, \omega_b \) and \( h \)

\[
\omega_m = \Omega_m h^2 \\
\omega_b = \Omega_b h^2
\]

It can be shown that \( \Omega_A \) is the same for constant \( \Omega_m h^{3.4} \).
Age of the Universe

\[ \Omega_m h^3.4 = \text{const} \left( \Theta_A \right) \]

\[ t_0 = 6.52 h^{-1} (1 - \Omega_m)^{-1/2} \ln \left( \frac{1 + \sqrt{1 - \Omega_m}}{\sqrt{\Omega_m}} \right) \text{ [Gyr]} \]
# Basic Results

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total density</td>
<td>*_{\text{tot}}</td>
<td>1.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Dark energy density</td>
<td>*_{\text{\textbullet}}</td>
<td>0.73</td>
<td>0.04</td>
</tr>
<tr>
<td>Baryon density</td>
<td>*_{\text{\textbullet}b}</td>
<td>0.044</td>
<td>0.004</td>
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<tr>
<td>Matter density</td>
<td>*_{\text{\textbullet}m}</td>
<td>0.27</td>
<td>0.04</td>
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<tr>
<td>Light neutrino density</td>
<td>*<em>{\text{\textbullet}m</em>{\nu}}</td>
<td>&lt;0.015</td>
<td>95% CL</td>
</tr>
<tr>
<td>CMB Temperature (K)</td>
<td>\text{t}_{\text{cmb}}</td>
<td>2.725</td>
<td>0.002</td>
</tr>
<tr>
<td>Redshift at decoupling</td>
<td>\text{z}_{\text{dec}}</td>
<td>1089</td>
<td>1</td>
</tr>
<tr>
<td>Hubble constant</td>
<td>\text{h}</td>
<td>0.71</td>
<td>0.04</td>
</tr>
<tr>
<td>Age of universe (Gyr)</td>
<td>\text{t}_{0}</td>
<td>13.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Age at decoupling (kyr)</td>
<td>\text{t}_{\text{dec}}</td>
<td>379</td>
<td>8</td>
</tr>
<tr>
<td>Age at reionization (Myr)</td>
<td>\text{t}_{r}</td>
<td>180</td>
<td>+220 (-80)</td>
</tr>
</tbody>
</table>

- Standard model of cosmology: flat \( \star \)-dominated universe seeded by a nearly scale-invariant adiabatic Gaussian fluctuation fits the data

\[ m_{\nu} < 0.23 \text{ eV} \]
Future: Planck

- Start in the first quarter of 2007

- Frequencies from 30 GHz to 857 GHz

- Angular resolution: 5.0 arcmin to 33 arcmin
  (WMAP: 13.8 arcmin – 55.8 arcmin)
References

- The Cosmic Microwave Background Data and their Implications for Cosmology, V. Tudose, Romanian Reports in Physics, Volume 55, Number 2, P.116-142, 2003

- First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results, C.L. Bennett et al. Astrophysical Journal


- WMAP-Homepage: http://map.gsfc.nasa.gov

- PLANCK-Homepage: http://www.rssd.esa.int/index.php?project=PLANCK


- First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters
Angular scale of the peaks II

\[ r_s(z_{\text{dec}}) = 3997 \sqrt{\frac{\omega_\gamma}{\omega_m \omega_b}} \ln \frac{\sqrt{1 + R_{\text{dec}}} + \sqrt{R_{\text{dec}} + R_{\text{eq}}}}{1 + \sqrt{R_{\text{eq}}}} \]

\[ R(z) = 3 \rho_b(z) / 4 \rho_\gamma(z) \]

\[ 1 + z_{\text{eq}} = \frac{5464 \left( \frac{\omega_m}{0.135} \right)}{\left( T_{\text{CMB}} / 2.725 \right)^4 \left( 1 + \rho_v / \rho_\gamma \right)} \]

redshift at matter-radiation equality
Angular scale of the peaks III

\[ d_A = \int_{0}^{z_{\text{dec}}} \frac{H_0^{-1} dz}{\sqrt{\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_\Lambda}} \]

angular diameter distance
to the decoupling surface
for a flat geometry

\[ \Omega_\Lambda = 1 - \Omega_m - \Omega_r \]

matter density  current radiation density
Age of the Universe I

- First acoustic peak in the CBM power spectrum: known acoustic size:
  \[ r_s = 147 \pm 2 \text{ Mpc} \]

  at redshift: \[ z_{\text{dec}} = 1089 \pm 1 \]

Decoupling surface:

\[ d_A = 14.0^{+0.2}_{-0.3} \text{ Gpc} \]

\[ t_0 = 6.52 h^{-1} (1 - \Omega_m)^{-1/2} \ln \left( \frac{1 + \sqrt{1 - \Omega_m}}{\sqrt{\Omega_m}} \right) \text{ [Gyr]} \]

\[ \rightarrow \text{Age: } t_0 = 13.7 \pm 0.2 \text{ Gyr} \]