Cosmic Microwave Background
Introduction

Matt Chasse
casse@hawaii.edu

Department of Physics
University of Hawaii at Manoa
Honolulu, HI 96816
Outline

- CMB, what is it good for?
- Standard Model of Cosmology
- Acoustic Peaks
- Polarization
- WMAP
Lots of Good Stuff

Just a few from WMAP...

- Total matter density, $\Omega_{\text{tot}} = 1.02^{+0.02}_{-0.02}$
- Dark energy density, $\Omega_{\Lambda} = 0.73^{+0.04}_{-0.04}$
- Matter density, $\Omega_{m} = 0.27^{+0.04}_{-0.04}$
- Baryon density, $\Omega_{b} = 0.044^{+0.04}_{-0.04}$
- Hubble constant, $h = 0.71^{+0.04}_{-0.03}$
- Number of light neutrinos
- Neutrino mass
### Parameters Table

“Best” Cosmological Parameters:

Table 3 from *Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results*,

C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;
available at http://lambda.gsfc.nasa.gov/

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>+ uncertainty</th>
<th>− uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total density</td>
<td>$\Omega_{tot}$</td>
<td>1.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Equation of state of quintessence</td>
<td>$w$</td>
<td>$&lt;-0.78$</td>
<td>95% CL</td>
<td>—</td>
</tr>
<tr>
<td>Dark energy density</td>
<td>$\Omega_{\Lambda}$</td>
<td>0.73</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>Baryon density</td>
<td>$\Omega_b h^2$</td>
<td>0.0224</td>
<td>0.0009</td>
<td>0.0009</td>
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<tr>
<td>Baryon density</td>
<td>$\Omega_b$</td>
<td>0.044</td>
<td>0.004</td>
<td>0.004</td>
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<tr>
<td>Baryon density (cm$^{-3}$)</td>
<td>$n_b$</td>
<td>$2.5 \times 10^{-7}$</td>
<td>$0.1 \times 10^{-7}$</td>
<td>$0.1 \times 10^{-7}$</td>
</tr>
<tr>
<td>Matter density</td>
<td>$\Omega_m h^2$</td>
<td>0.135</td>
<td>0.008</td>
<td>0.009</td>
</tr>
<tr>
<td>Matter density</td>
<td>$\Omega_m$</td>
<td>0.27</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Light neutrino density</td>
<td>$\Omega_\nu h^2$</td>
<td>$&lt;0.0076$</td>
<td>95% CL</td>
<td>—</td>
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<tr>
<td>CMB temperature (K)$^a$</td>
<td>$T_{cmb}$</td>
<td>2.725</td>
<td>0.002</td>
<td>0.002</td>
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<tr>
<td>CMB photon density (cm$^{-3})^b$</td>
<td>$n_\gamma$</td>
<td>410.4</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Baryon-to-photon ratio</td>
<td>$\eta$</td>
<td>$6.1 \times 10^{-10}$</td>
<td>$0.3 \times 10^{-10}$</td>
<td>$0.2 \times 10^{-10}$</td>
</tr>
<tr>
<td>Baryon-to-matter ratio</td>
<td>$\Omega_b\Omega_m^{-1}$</td>
<td>0.17</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Fluctuation amplitude in 8h$^{-1}$ Mpc spheres</td>
<td>$\sigma_8$</td>
<td>0.84</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Low-z cluster abundance scaling</td>
<td>$\sigma_8\Omega_m^{0.5}$</td>
<td>0.44</td>
<td>0.04</td>
<td>0.05</td>
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<tr>
<td>Power spectrum normalization (at $k_0 = 0.05$ Mpc$^{-1})^c$</td>
<td>$A$</td>
<td>0.833</td>
<td>0.086</td>
<td>0.083</td>
</tr>
<tr>
<td>Scalar spectral index (at $k_0 = 0.05$ Mpc$^{-1})^c$</td>
<td>$n_s$</td>
<td>0.93</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>
### Parameters Table (con’t)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power spectrum normalization (at (k_0 = 0.05) Mpc(^{-1}))</td>
<td>A</td>
<td>0.833</td>
<td>0.086</td>
<td>0.083</td>
</tr>
<tr>
<td>Scalar spectral index (at (k_0 = 0.05) Mpc(^{-1}))</td>
<td>(n_s)</td>
<td>0.93</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Running index slope (at (k_0 = 0.05) Mpc(^{-1}))</td>
<td>(dn_s/d\ln k)</td>
<td>-0.031</td>
<td>0.016</td>
<td>0.018</td>
</tr>
<tr>
<td>Tensor-to-scalar ratio (at (k_0 = 0.002) Mpc(^{-1}))</td>
<td>(r)</td>
<td>&lt; 0.90</td>
<td>95% CL</td>
<td>—</td>
</tr>
<tr>
<td>Redshift of decoupling</td>
<td>(z_{dec})</td>
<td>1089</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Thickness of decoupling (FWHM)</td>
<td>(\Delta z_{dec})</td>
<td>195</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Hubble constant</td>
<td>(h)</td>
<td>0.71</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Age of universe (Gyr)</td>
<td>(t_0)</td>
<td>13.7</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Age at decoupling (kyr)</td>
<td>(t_{dec})</td>
<td>379</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Age at reionization (Myr, 95% CL))</td>
<td>(t_r)</td>
<td>180</td>
<td>220</td>
<td>80</td>
</tr>
<tr>
<td>Decoupling time interval (kyr)</td>
<td>(\Delta t_{dec})</td>
<td>118</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Redshift of matter-energy equality</td>
<td>(z_{eq})</td>
<td>3233</td>
<td>194</td>
<td>210</td>
</tr>
<tr>
<td>Reionization optical depth</td>
<td>(\tau)</td>
<td>0.17</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Redshift of reionization (95% CL)</td>
<td>(z_r)</td>
<td>20</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Sound horizon at decoupling (°)</td>
<td>(\theta_A)</td>
<td>0.598</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Angular size distance to decoupling (Gpc)</td>
<td>(d_A)</td>
<td>14.0</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Acoustic scale</td>
<td>(\ell_A)</td>
<td>301</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sound horizon at decoupling (Mpc)</td>
<td>(r_s)</td>
<td>147</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>


\(^{c}\)\(l_{eff} \approx 700\)

\(^{d}\)\(\ell_A \equiv \pi \theta_A^{-1}\), \(\theta_A \equiv r_s d_a^{-1}\)
Before recombination the cosmic plasma is nearly homogeneous, isotropic, and in thermal equilibrium. The emitted radiation follows an almost perfect blackbody spectrum. As the temperature of the plasma drops below $2967^0 K$ it becomes optically transparent.

The baryon-photon fluid is believed to be initially perturbed by small variations in curvature introduced in inflation and oscillates on a cold dark matter background. But it can also develop disturbances due to its own gravitational instabilities; there are isocurvature models which use this as the sole source.
Surface of Last Scattering

The cosmic microwave background Radiation’s “surface of last scatter” is analogous to the light coming through the clouds to our eye on a cloudy day.

Source "NASA/WMAP Science Team"
Acoustic Horizon

Surface of Last Scatter

Acoustic Horizon

Matt Chasse, CMB Intro, May 3, 2005 – p. 9/29
After dipole moment is removed, the temperature variations are 1:100,000 (2.7K:10μK). Dipole variation is 1:1000.
Spherical Harmonics

The angular temperature distribution is described using spherical harmonics.

\[ \Delta T(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi) \]

When there is no preferred direction in space the temperature distribution can be described by just the \( l \)-values. The correlation between parts of the CMB sky with angular separation \( \theta \approx 2\pi/l \) is described by \( C_l \).

\[ C_l = \sum_{m} |a_{lm}|^2 / (2l + 1) \]
Baryon loading adds effective mass and shifts the equilibrium point of the oscillations, enhancing the odd numbered peaks in the spectrum. It also decreases the speed of sound, which shifts the power spectrum to higher $l$-values.
Baryon Loading

(a) $\Omega_b h^2$ Dependence

$\Omega_b h^2$
- 0.025
- 0.015
- 0.0075
- 0.0025

$\Omega_0 = 1 \ h = 0.5$

Source "Wayne Hu's website"
Diffusion Damping

The photons aren’t perfectly coupled to the baryons. As the mean free path for the photons overtakes the wavelength of the oscillations, they spread energy from the hot areas to the cold ones and create damping.
Diffusion Damping

Source "Wayne Hu’s website"
When $\Omega_{tot} = 1$, the density of the universe is such that it is spatially flat. For a closed ($\Omega_{tot} > 1$) universe the CMB anisotropies will subtend larger angles in the sky for a given length scale, shifting the power spectrum to lower $l$-values.
Power Spectrum and $\Omega_{tot}$

(b) $\Omega_0 h^2$ Dependence

- $\Omega_0 h^2 \quad h$
  - ---- 0.09 0.3
  - ------- 0.25 0.5
  - ------ 0.64 0.8

$\Omega_b h^2 = 0.015 \quad \Omega_0 = 1.0$

Source "Wayne Hu’s website"
Polarization

The differences in intensity in the CMB cause polarization at small scales.

Source "Wayne Hu’s website"
Polarization

The polarization distribution gives information on quadrupole anisotropies that can be used to find gravity waves in the CMB. Polarization distributions also give information on scattering that can help to further constrain the power spectrum.
Conditions Effecting Observation

- Sachs-Wolfe Effect - Photons from denser regions are gravitationally red-shifted. Net result is that hotter, denser regions in the CMB appear cooler.

- Integrated Sachs-Wolfe (ISW) Effect - As photons travel through changing gravitational potentials they acquire a net red/blue-shift.

- Doppler Shift - Shows up in dipole moments.

- Secondary Scattering from intervening material - Reionization. Secondary scattering has less of an effect on lower multipoles.
Systematics are reduced by taking the difference between the signals from the opposite facing dishes.
Far Away from Noisy Earth

WMAP Orbits around the L2 lagrange point.

Source "NASA/WMAP Science Team"
The galaxy signal and random noise are partially removed by cross correlating different channels (frequencies from "most red"): 23GHz (K-Band), 33GHz (Ka-Band), 41GHz (Q-Band), 61GHz (V-Band), 94GHz (W-Band).
But foreground still remains and the area around the galaxy needs to be masked out. WMAP uses several masks for the galaxy: Kp0 leaves 76.8% of the sky, Kp2 leaves 85.0%, Kp12 leaves 95%. Known point sources also have to be masked out.

Source "NASA/WMAP Science Team"
The masking has a larger impact on lower $l$-values. If a fraction of the sky $f_{\text{sky}}$ is sampled then the errors scale up by $f_{\text{sky}}^{-\frac{1}{2}}$. For each $l$ there are $m$ statistically independant samples which produces an error of:

$$\Delta C_l = \sqrt{\frac{2}{2l + 1}} C_l$$

A more conservative mask reduces random errors but introduces more systematic error.
Conclusion

- Very accurate measurement of the cosmic microwave background anisotropies has enabled very accurate measurement of many cosmological parameters and information on almost all of them.

- Measurement of the polarization will yield even more information.
Thanks to Istvan Szapudi, John Tonry, and John Learned.

References