CMB Anisotropy

Ned Wright, UCLA
True Contrast CMB Sky

33, 41 & 94 GHz as RGB, 0-4 K scale
• Conklin 1969 - 2σ
• Henry 1971 - 3σ
• Corey & Wilkinson 1976 - 4σ
• Smoot et al. 1977 - 6σ
I have analyzed the preliminary 1 year DMR maps by making a linear combination to give a "no galaxy" map. The results are presented here, and are quite consistent with unbiased CDM. There is probably a real quadrupole in the data.

Chuck,

I have been working on the new 1 year maps. I include a bunch on analyses following this message. It looks like a 10 sigma detection of an Harrison-Zeldovich spectrum with an amplitude corresponding to a quadrupole of 15 microK. The "No Galaxy" map is noisier but agrees with the 53A+B.

-Ned Wright-
A Big Media Splash in 1992:

Prof. Stephen Hawking of Cambridge University, not usually noted for overstatement, said: “It is the discovery of the century, if not of all time.”

25 April 1992
Solving Horizon & Flatness-Oldness

• A small patch grows to be bigger than the observable Universe. $T=\text{const}$ is explained.

• Whatever the curvature of the patch may be, it will look flat. Density=critical is explained.
Animated View of Inflation

- Quantum fluctuations occur uniformly throughout space-time
- Future light cones have radii of $(c/H)[\exp(H\Delta t) - 1]$
- As small circles become large, new small circles are formed.
- Equal Power on All Scale - EPAS
“Chi-by-eye” suggests that the “Equal Power on All Scales” prediction of inflation is correct.
Sachs-Wolfe Effect

\[ \frac{\Delta T}{T} = \frac{\phi}{3c^2} \]

\( \phi(x) \)
Measured $\Delta \phi$ Leads to Structure
Prediction of Doppler Peaks:

(a) adiabatic h=0.75
(b) isocurvature h=0.75

Two Fluids in the Early Universe

• Most of the mass is dark matter
  – 80-90% of the density
  – Zero pressure
  – Sound speed is zero

• The baryon-photon fluid
  – baryons are protons & neutrons = all ordinary matter
  – energy density of the photons is bigger than $c^2$ times the density of baryons
  – Pressure of photons = $u/3 = (1/3)\rho \ c^2$
  – Sound speed is about $c/\sqrt{3} = 170,000$ km/sec
Traveling Sound Wave: \( c_s = \frac{c}{\sqrt{3}} \)
Stay at home Dark Matter
Interference at last scattering

• For the wavelength illustrated [1/2 period between the Big Bang and recombination], the denser = hotter effect and potential well = cooler effect have gotten in phase.

• For larger wavelengths they are out of phase at recombination:
Density contrast vs $a(t)$
Contrast at last scattering vs $\kappa$
Potential survival vs $\kappa$

\(k \cdot R_{ls} = 50\) plane wave
$99 \, k^*R_1 = 50$ plane waves
Spherical Harmonic Decomposition
Conversion from k to l

- Mean $l$ is $(\pi/4)kR_{LS}$ for density effects, and $(3\pi/16)kR_{LS}$ for velocity effects.
- Velocity effects give a broad spectrum in $l$ and contribute little to the peaks in the angular power spectrum.
Many parameters to measure

Careful measurements of the power at various angular scales can determine the Hubble constant, the matter density, the baryon density, and the vacuum density.
COBE View was Blurry

Sometimes higher resolution... reveals the secret of the Universe
Observations pour in after COBE

• By 1994 Scott & White give > 95% confidence that the Doppler peaks are present: 9407073
Observations since 1994

• More Saskatoon
• QDMAP – Saskatoon on a balloon
• TOCO – Saskatoon on a truck (Mobile Anisotropy Telescope) in Chile + D band (150 GHz channel)
• BOOMERanG
• MAXIMA
• DASI
• ARCHEOPS
• CBI
Smaller Scale Experiments
BOOMERanG

- First acoustic peak was well established and position known before BOOMERanG:
  \[ l_{pk} = 210 \pm 15 \] (L. Page, 2 Jan 2000)

- The Italian-American BOOMERanG balloon-borne experiment announced “the flat Universe” in April 2000:
  \[ l_{pk} = 197 \pm 6 \]

- BOOMERanG was a big improvement in sky coverage and sensitivity, and thus reduced the first peak position uncertainty to about 3% (unfortunately 4σ off the true \[ l_{pk} = 220 \])
DASI: Degree Angular Scale Interferometer
At the South Pole where it’s very cold & dry

26-36 GHz
2000 Power Spectrum
2001 Power Spectrum

Angular Scale [Degrees]

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

$\ell_{eff}$

Ned Wright - 6 May 2001
The Very Small Array

- 14 antennae
- 4.5° or 2° FOV
- 0.5° or 0.2° res
- 26-36 GHz
- 1.5 GHz bandwidth
- Teide on Tenerife
Cosmic Background Imager

- Chile @ 5.08 km
- 13 antennae
- 26-36 GHz
- 10 GHz band
- 0.75° FOV
- 0.075° res
- Mosaic many FOV’s together
Pre-MAP Power Spectrum

Flat, n=1; $\omega_b = 0.021$, $\omega_c = 0.196$, $H_0 = 47$; $\omega_b = 0.022$, $\omega_c = 0.132$, $H_0 = 68$, $\Lambda = 2/3$
Some definitions

- $T(l,b) = T_o + \Delta T_d \cos \theta + \sum a_{lm} Y^{lm}(l,b)$
- $C_l = \langle |a_{lm}|^2 \rangle$
- Baryon density $\omega_b = \Omega_b h^2$ or the density relative to the critical density for $H_o = 100$ which is $18.8 \times 10^{-30}$ grams/cm$^3$ or 18.8 yoctograms per cubic meter in SI.
- Cold Dark Matter density $\omega_c = \Omega_c h^2$
- Vacuum energy density $\Lambda = \Omega_\Lambda$ or energy density $= 10.5 \Omega_\Lambda h^2$ keV/cm$^3$
Calibration Uncertainties

• Each experiment (except for COBE and later WMAP) has amplitude uncertainty of several percent that is correlated across all the data from that experiment.

• I have done fits and plots that solve separately for calibration adjustment “nuisance parameters” which are included in the $\chi^2$ but not in the errorbars.

• Combining data from many experiments gives a “flexible” observed spectrum due to these calibration errors.
WMAP Science Working Group
The MAP RF plumbing is very complex with 10 horns per side, 20 DA’s, 40 amplifier chains.
Seeing WMAP at L2

• You need a pretty big telescope.
• These pictures were taken on 16 Nov 2001 with the KPNO 4m by Ian Dell’Antonio
• The 3 stars are mag 15.2, 15.4 & 17.3
• FOV is 115” wide.
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First map from WMAP, day 01186
Combination to remove foreground
Foreground vs CMB Power

![Graph showing the comparison between foreground and CMB power](image)

- **Antenna Temperature (µK, rms)**
- **Frequency (GHz)**
- **K, Ka, Q, V, W**
- **CMB Anisotropy**
- **Synchrotron**
- **Free-free**
- **Dust**

Legend:
- 85% Sky (Kp2)
- 75% Sky (Kp0)
Nobs for K, Q & W
Remove $v_{SS}$, 2000x contrast
Remove Galaxy, 19000x Contrast
QVW as RGB
No Galaxy on same scale
Effects on Peak Position: $l_{pk}$

+ Open or vacuum dominated Universes give larger distance to last scattering surface

+ High matter density gives smaller wavelength
What We Have Learned: pre-WMAP
With WMAP replacing COBE
Info from peak & trough heights

• Overall Amplitude of the perturbations
  – Agrees with large scale structure if sum of neutrino masses is < 0.7 eV

• Primordial power spectrum power law spectral index: $n = 0.99 \pm 0.04$ without running index.
  – Agrees with inflationary prediction

• Baryon/photon and DM/baryon density ratios
  – $\rho_b = 0.42$ yoctograms/$m^3 = 0.42 \times 10^{-30}$ gm/cc
  – $\rho_{cdm} = 2.1$ yg/$m^3$ \quad [\omega \equiv \Omega h^2 = \rho/\{18.8 \text{ yg/m}^3\}]
Pre-WMAP densities
With WMAP replacing COBE

Note the new BBNS value from astro-ph/0302006
Key to Models

$H_0: 30 \ 40 \ 50 \ 60 \ 70 \ 80 \ 90 \ 100$

Diagram showing the relationship between $\Omega_M$ and $\Omega_A$ with various color bands representing different $H_0$ values. The diagram also includes a line for a flat universe and regions labeled as open and closed.
$\Lambda$CDM is a Good Fit

\[ H_0 = 71, \Omega_{\Lambda} = 0.73, \Omega_b h^2 = 0.0224, \Omega_m h^2 = 0.135, \Omega_{\text{tot}} = 1 \]
Super-Sandage is Closed

\[ H_0 = 32, \quad \Omega_\Lambda = 0, \quad \Omega_b h^2 = 0.0232, \quad \Omega_m h^2 = 0.139, \quad \Omega_{\text{tot}} = 1.3 \]
Best Fit: Two Many Tooth Fairies

\[ H_0 = 50, \ \Omega_{\Lambda} = 0.51, \ \Omega_b h^2 = 0.0233, \ \Omega_m h^2 = 0.141, \ \Omega_{\text{tot}} = 1.08 \]
Einstein – de Sitter Model Fails

\[ H_0 = 50, \, \Omega_\Lambda = 0, \, \Omega_b h^2 = 0.0236, \, \Omega_m h^2 = 0.25, \, \Omega_{\text{tot}} = 1 \]
Can this model be saved?

• Einstein – de Sitter fails because it is off the “degeneracy line”.
• To get the peak positions right the densities have to be pushed out of the “sweet spot”.
• As a result the amplitude, especially at low $l$, is wrong. An $8\sigma$ discrepancy on $C_l$
• Blanchard et al. astro-ph/0304237 fix this with a broken power law primordial $P(k)$. They use a mixed dark matter approach to get the Large Scale Structure right.
• Their EdS model is still $3\sigma$ off on $H_0$ and $10\sigma$ off on the accelerating Universe data from supernovae.
Is the Universe Really Flat?

- CMB data alone give some limits but adding $H_0$ and SNe priors gives much better limits.
- Replacing COBE by WMAP does not dramatically change the limits on $\Omega_{\text{tot}}$.

<table>
<thead>
<tr>
<th></th>
<th>CMB only</th>
<th>CMB+SNe</th>
<th>CMB+$H_0$</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-WMAP</td>
<td>1.18(11)</td>
<td>1.04(4)</td>
<td>1.02(3)</td>
<td>1.02(2)</td>
</tr>
<tr>
<td>With WMAP</td>
<td>1.16(9)</td>
<td>1.04(3)</td>
<td>1.03(3)</td>
<td>1.02(2)</td>
</tr>
</tbody>
</table>
More Restrictions on Models

• Quintessence is restricted: \( w = P/\rho c^2 \leq -0.78 \) in the dark energy

• Neutrino masses add up to less than 0.7 eV
  – \( \Delta P(k)/P = -8 \Omega_v/\Omega_m \) (Hu et al. astro-ph/9712057)
  – So this limit, about 7% of the CDM density, gives a 50% reduction in small-scale power
Going Flat Out with LSS & Ly\(\alpha\)

- Assuming a flat, \(\Omega_{\text{tot}} = 1\), Universe gives:
  - \(H_0 = 71 \pm 3.5\) km/s/Mpc
  - \(t_o = 13.7 \pm 0.2\) Gyr
  - \(\Omega_\Lambda = 0.73 \pm 0.04\)
  - \(\Omega_b h^2 = 0.0224 \pm 0.001\) or 0.25 baryons/m\(^3\)
  - \(\Omega_m h^2 = 0.135 \pm 0.009\) or 2.54 yoctograms/m\(^3\)
  - \(\sigma_8 = 0.84 \pm 0.04\)
Late ISW Effect

Potential only changes if $\Omega_m \neq 1$ (or in non-linear collapse, but that’s another story [Rees-Sciama effect]).
Potential decays at $z \approx 0.6$
Correlated with Observed LSS

- This late ISW effect occurs on our past light cone so the $\Delta T$ we see is due to structures we also see.
- Search for correlation between LSS at $z=0.6$ and the CMB anisotropy: see Boughn & Crittenden, astro-ph/0111281
  - Expected 0.035 cross-correlation between NVSS sources and COBE DMR
  - observed -0.003 ± 0.025
Correlation is seen with WMAP

- Correlation between WMAP and LSS seen by:
  - Boughn & Crittenden (astro-ph/0305001) at $2.75\sigma$ with hard Xray background and $2.25\sigma$ with NVSS
  - Nolta et al. (astro-ph/0305097) at $2\sigma$ with NVSS
$\Lambda$CDM is OK, sSSCDM fails at $3\sigma$
Possible Improvements?

- Less noisy and higher resolution CMB data.
- Use a better tracer of LSS. IR surveys trace old stars and thus are close to a mass survey.
2MASS Galaxies at $z \approx 0.15$

To get a deeper sample, use:

Milky Way stars
WISE will provide an all-sky survey from 3 to 23 \( \mu m \) with three orders of magnitude better sensitivity than IRAS. The survey will help search for the origins of planets, stars, and galaxies and will be a valuable precursor for JWST.

**WISE will**
- Find the most luminous galaxies in the Universe.
- Find the closest stars to the sun.
- Detect most main belt asteroids larger than 3km.

**Mission Overview**
- Circular 500-km Sun-synchronous orbit.
- 7-month mission including a 1-month checkout.
- Four 1024\(^2\) focal plane arrays.
- 40-cm telescope cooled by a two-stage solid-hydrogen cryostat.
- Scan mirror to stabilize the line-of-sight while the spacecraft scans the sky.
“Nothing” really funny

• Where the hell does it all come from?
• And where does the vacuum energy come from?
• Why 3.9 keV/cc?
We (and all of chemistry) are a small minority in the Universe.
CONCLUSION

• The basic $\Lambda$CDM model for the Big Bang with inflation is confirmed:
  – The baryon density is measured to an accuracy of 4% from the CMB and agrees with the value from BBNS (9% accuracy) to within 5%.
  – Flat model fit only to CMB data matches the Hubble constant, supernova and large scale structure data.
  – Age of the Universe in a flat $\Lambda$CDM model is $13.7 \pm 0.2$ Gyr

• Get more information at http://map.gsfc.nasa.gov
WMAP Status

• At L2, having completed of 4th full year of observations.

• Approved for an extended mission of 8 years total at L2 if the spacecraft and instrument continue to work and we ever get the polarization data out.

• WMAP has already greatly exceeded the “minimum space mission” goal discussed at Snowmass in 1994 of measuring the anisotropy to the cosmic variance limit for all scales larger than a degree.

• More integration will greatly improve the SNR on polarization and l’s up to 1000.