Recent CMB Results

by

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• http://www.astro.ucla.edu/~wright/intro.html
• http://www.astro.ucla.edu/~wright/cosmolog.htm
• http://www.astro.ucla.edu/~wright/CMB-DT.html
• http://map.gsfc.nasa.gov
A Big Media Splash in 1992:

THE TIMES

25 April 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.”
Large $\Lambda$ & exponential growth during inflation
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.
Inflationary Scenario

- The exponential growth during the period when there was a non-zero vacuum energy is called “inflation”.
- Inflation “postdicts” solutions to the flatness-oldness and horizon problems.
- It also solves the “monopole” problem.
- Does it predict anything that we can test?
Quantum Fluctuations get Very Big

- QFs occur uniformly throughout space-time.
- Their future light-cones expand beyond the observable Universe.
- New QFs continue to add small-scale structure.
“Chi-by-eye” suggests that the “Equal Power on All Scales” prediction of inflation is correct.
COBE View was Blurry

Sometimes higher resolution...

reveals the secret of the Universe
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 mass density of baryons
  – Pressure of photons = $u/3 = (1/3)\rho \ c^2$
  – Sound speed is about $c/\sqrt{3} = 170,000 \text{ km/sec}$
Traveling Sound Wave: $c_s = \frac{c}{\sqrt{3}}$
Stay at home Dark Matter
Interference at last scattering

- For the wavelength illustrated \([1/2 \text{ period between the Big Bang and recombination}]\), the denser = hotter effect and potential well = cooler effect have gotten in phase.
- For larger wavelengths they are still out of phase at recombination.
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.
Accelerating Universe: 1998

High $z$ supernovae fainter than expected: see talks by Arlin Crotts & Peter Garnavich.
Acceleration causes Faintness

Without CC, Universe is younger, hence light travel time is smaller to any z, so SNe at z=1 are closer & thus brighter.

\( \Omega = 1 \)

\( \Omega = 0.25, \lambda = 0.75 \)
Smaller Scale Experiments

- COBE
  - SASKATOON 3 YEAR DATA
  - COBE DMR 4 YEAR DATA

- HACME
  - HACME γ UMI
  - HACME α Leo

- QMAP
  - QMAP FLIGHTS 1 & 2
  - COBE DMR 4 YEAR DATA
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

At the South Pole where it’s very cold & dry

26-36 GHz
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, $n=1$; $\omega_b = 0.021$, $\omega_c = 0.196$, $H_o = 47$; $\omega_b = 0.022$, $\omega_c = 0.132$, $H_o = 68$, $\Lambda = 2/3$
• Uniform comoving dust density is ruled out by highest $z$ supernovae, but uniform physical density dust or $\exp(\alpha t)$ evolution are better fits than $\Lambda$CDM.
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.
A New Cosmology Satellite
WMAP Science Working Group
WMAP Status on 30 Jun 2001
and WMAP has a NED Controller!

S/A Deployment NED Control
Systematic Error Control

**SPIN-SYNCHRONOUS NON-SKY SIGNALS ARE THE LEADING CONCERN**

- Minimize sensitivity of experiment to non-sky signals
  - Minimize all observatory changes
    - L2 orbit; constant survey mode operations
    - Minimize transmitter time; use make up heater
  - Symmetric, rapidly switched, differential radiometers
  - Rapid sky scanning (30% of sky per hour)

- Multiple modulation periods to isolate & identify systematic effects

- Distinguish cosmic from non-cosmic sky signals
  - 5 frequencies to model and remove galactic signals
  - Minimize stray diffracted signals from Earth, Sun, Moon
    - Large edge taper; diffraction shielding
    - L2 orbit
WMAP’s Scan Pattern like COBE’s
Combination to remove foreground
Effects on Peak Position: $l_{pk}$

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

+ High matter density gives smaller wavelength
With WMAP replacing COBE
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>
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</thead>
<tbody>
<tr>
<td><strong>Pre-WMAP</strong></td>
<td>1.18(11)</td>
<td>1.04(4)</td>
<td>1.02(3)</td>
<td>1.02(2)</td>
</tr>
<tr>
<td><strong>With WMAP</strong></td>
<td>1.16(9)</td>
<td>1.04(3)</td>
<td>1.03(3)</td>
<td>1.02(2)</td>
</tr>
</tbody>
</table>
Info from peak & trough heights

- Overall Amplitude of the perturbations
  - Agrees with large scale structure if almost all the dark matter is COLD dark matter

- Primordial power spectrum power law spectral index: $n = 0.99 \pm 0.04$ without running index.
  - EPAS inflationary prediction is $n = 1$

- 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$^3$  
    $\omega \equiv \Omega h^2 = \rho / \{18.8$ yg/m$^3]\}$
Results With WMAP

Note the new BBNS value from astro-ph/0302006
ΛCDM is a Good Fit

$H_0 = 71, \Omega_\Lambda = 0.73, \Omega_b h^2 = 0.0224, \Omega_m h^2 = 0.135, \Omega_{\text{tot}} = 1$
Closed super-Sandage is a good fit

\[ H_0 = 32, \ \Omega_\Lambda = 0, \ \Omega_b h^2 = 0.0232, \ \Omega_m h^2 = 0.139, \ \Omega_{\text{tot}} = 1.3 \]
Einstein – de Sitter Model Fails

\[ H_0 = 50, \quad \Omega_\Lambda = 0, \quad \Omega_b h^2 = 0.0236, \quad \Omega_m h^2 = 0.25, \quad \Omega_{\text{tot}} = 1 \]
ARCHEOPS vs WMAP

- ARCHEOPS observed same $\Delta T$ at 143 & 217 GHz.
- Also consistent with WMAP at 94 GHz.
- Therefore thermal Sunyaev-Zeldovich effect is insignificant at $l < 500$.

from Hamilton et al., astro-ph/0310788
ACBAR: also at South Pole
ACBAR Power Spectrum at 150 GHz

from Kuo et al., astro-ph/0212289
Latest CBI High $l$ Excess is Lower
If SZ, a high $\sigma_8$ is wanted

- CBI:ACBAR ratio is 1:1 but should be 4:1 for SZ. However the error bars allow an SZ model.
- Predicted SZ $C_l$ is insignificant at $l < 500$.
- To have a high $\sigma_8$, a higher $\tau$ is wanted.
Latest Results

- BOOMERanG long duration 2003 flight, published 2.5 year later in summer 2005.
- Polarization sensitive bolometers.
- Power spectrum consistent with earlier results.
- Polarization consistent with electron scattering at recombination – see talk by Bruce Winstein.
Late ISW Effect: Another test for $\Lambda$

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

- This late ISW effect occurs on our past light cone so the $\Delta T$ we see is due to structures we also see.
- Correlation between WMAP and LSS seen by:
  - Boughn & Crittenden (astro-ph/0305001) at $2.75\sigma$ with hard X-ray background and $2.25\sigma$ with NVSS
  - Nolta et al. (astro-ph/0305097) at $2\sigma$ with NVSS
  - Ashfordi et al (astro-ph/0308260) at $2.5\sigma$ with 2MASS
I am the PI on a MIDEX called WISE, an all-sky survey in 4 bands from 3.3 to 23 μm. WISE will find and study the closest stars to the Sun, the most luminous galaxies in the Universe, and also map the large-scale structure out to redshift z=1, covering the era when the late ISW effect should be generated. WISE will fly in 2009.
Spreading Sphere of Sound

The baryon-photon fluid spreads out in an expanding spherical shell surrounding the cold dark matter which does not move. After recombination, the Universe becomes transparent and the photons exit the shell, leaving a spherical density enhancement which should show up as a sharp feature in the 3D two-point correlation function at a radius equal to the distance sound could travel before recombination.

This is the same scale involved in the acoustic peaks of the CMB angular power spectrum.
Baryonic Oscillations in SDSS LRGs

\[ s^2 \xi(s) \]

\[ s \ [h^{-1} \text{Mpc}] \]

Eisenstein et al. 2005 Figure 3
Implications for $\Omega_M$, $\Omega_\Lambda$
The Three Simplicities

- $\Lambda = 0$ but this probably is not correct.
- $\Omega_{\text{tot}} = 1$ due to inflation.
- $w = -1$ if there is dark energy.
  - Note that if $w = -1$, the dark energy is Lorentz invariant, but if $w \neq -1$ observers can measure their velocity with respect to the dark energy so it has to be a dynamical thing that will react to inhomogeneities in the Universe. Thus $w$ will be a function of space \textit{and time}, not a function of redshift $w(z)$. 
We should prove flatness.

- The success of the flat model with $w = -1$ cannot be used to justify assuming flatness when trying to find $w$ and $w'$.
- Certainly $\Omega_{\text{tot}} = 1$ is simpler, but
  - $\Omega_X = 0$ is simpler, no CDM is simpler & $w = -1$ is simpler
- But the model consistent with both the CMB and SNe data moves as $w$ is varied, and is most consistent with the Hubble constant from the HST Key Project when $w$ is close to -1. So $w$ can be measured using all data combined but be suspicious of priors on $\Omega_{\text{tot}}$ or $\Omega_M$. 
Search for Two Numbers?

- Allan Sandage in 1970 was searching for $H_o$ and $q_o$.
- Now we are searching for $w$ and $w'$ but $H_o$ and $q_o$ have not been chiseled into a stone tablet by God (or by Sandage).
- We still need to measure $H_o$, $\Omega_M$ and $\Omega_V$ while we search for $w$ and $w'$.
- A majority of theoretical analyses of $w$ and $w'$ on astro-ph use unreasonable priors and thus obtain unreasonable results.
If $w = -1$, then flat $\Lambda$CDM is a good fit to all the data. If $\Omega = 1$, then $w = -1$ is a good fit to all the data.
We (and all of chemistry) are a small minority in the Universe.
Conclude: Big Cosmic News of 2003

- A flat $\Lambda$CDM model gives a good fit to CMB, SNe, $H_0$, late ISW, baryon oscillation, and age data.
- This model is $13.7\pm0.2$ Gyr old.
- More than 95% of this model is “dark energy” [or “smooth tension”] and cold dark matter. Finding the nature of these dark components gives cosmologists plenty to work on.