WMAP 5-year data: Let’s test Inflation

During today’s talk, WMAP will survey 1/3 of the sky (again).

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…and thanks to WMAP ‘graduates’ C. Barnes, R. Bean, O. Dore, H. Peiris, L. Verde, and especially to David Wilkinson!
Let’s use the cosmic microwave background intensity as a pedagogic example:

**What epoch does the Planck function probe?**

![Graph of Planck function with residuals and measurements from Gush, Halpern, and Wishnow (1990). The graph shows a best fit Planck function with a temperature of 2.733 Kelvin.]
Scattering time constants increase as the universe expands and cools, and a given process stops once its reaction rate becomes comparable to $1/H$. Photons stopped scattering off electrons at $(1+z)\sim 1000$ and the universe became transparent.

But, among the processes in this plot, only bremsstrahlung and double-compton scattering can change the number of photons and bring light and matter into thermal equilibrium. The photon-to-baryon ratio was ‘frozen’ at $z\sim 10^7$ and the thermal spectrum tells us that there has not been a large energy release since the universe was a week old.
There are seven papers in the WMAP 5-year data release:

- Hinshaw et al., “Data Processing, Sky Maps, and Basic Results” Astro-ph: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

along with an updated WMAP Explanatory Supplement.

The papers, the data and our likelihood code and results are available at http://lambda.gsfc.nasa.gov/
WMAP  5 years: what’s new?

• Improved sensitivity. We are measuring a variance, so some errors drop faster than $t^{-1/2}$.

• Better beam characterization and calibration

• We can use Ka band in polarization along with Q and V.

Our simplest 6-parameter $\Lambda$CDM model still works well. Neither a running spectral index nor massive neutrinos help the fit. Sudden reionization at $z=6$ is rejected, while a cosmic neutrino background is supported at $3\sigma$. 
We have found 390 point sources. The catalogue is complete at 2Jy. The typical WMAP point source is only weakly polarized, while many of them are strongly variable.
Each pixel in the map is fit to a model of Synchrotron, Free-free and thermal Dust brightness, with synchrotron and dust spectral indices as free parameters using a Monte-Carlo Markov chain.
Gold et al. 0803.0715

The procedure produces maps of the sky for each emission mechanism.

In the 85% of the sky masked for CMB analysis the residuals to the fit are consistent with noise at the expected level. The image below shows residuals/noise in W-band.
Hinshaw et al. 0803.0732

The 5-year Internal Linear Combination (ILC) map is a sum of the five single frequency maps which cancels galactic foreground emission.
We will need to understand our beam shapes very well to understand our maps.

Overall normalization, spectral index, tilt and unscrambling matter densities all rely on knowing our beam area and beam shape to high precision.

The two window functions are for 0.1 deg FWHM beams with a 1% difference in solid angle. Only WMAP has achieved anything like this accuracy.
We have more data from Jupiter and better maps of the CMB, which confuse our Jupiter maps.

A major improvement is that we now have high fidelity models of both sides of our optical system. The models let us extend beam integrals beyond the angular range of high S/N Jupiter data.
Our beam uncertainties have dropped by almost a factor of two, while the difference between the beam shape we inferred at Yr-3 and Yr-5 is less than the Yr-3 $1\sigma$ uncertainties.

Notice that the total beam solid angle has gone up for all V and W band by from 0.5% to 1.5%. Much of this change is within the primary beam.

Black: Yr3-Yr5 window functions.
Red: Yr-3 1-σ uncertainties

Hill et al. 0803.0570
The 5-yr TT spectrum is cosmic variance limited to $l = 530$, and the 3rd harmonic is resolved!
Agreement with small angular scale measurements is good
Ground based experiments almost see the 5th harmonic and confirm the slope of the Silk tail.

Red line is $\Lambda$CDM fit to WMAP-5 alone.
Baryons (2.27+/- 0.06) /h^2 %

CDM (10.99+/-0.62)/h^2 %

Optical Depth 0.087+/- 0.017

Spectral Index 0.965+/-0.014

σ_8 0.796 +/- 0.036

Λ 0.742 +/- 0.036

The simple 6-parameter fit still works (yawn). Values are consistent with Spergel et al. (2007) and precision has nearly doubled.

Dunkley et al. 0803.0586
OK--so let’s test inflation.

Inflation was invented to solve the horizon problem (how is the universe so homogeneous on scales larger than the horizon at decoupling) and the flatness problem (why is the universe still here when its natural time constant is the planck time?).
Inflation models predict:

• The universe is nearly flat;
• Primordial fluctuations are gaussian;
• Fluctuations are adiabatic;
• Fluctuations are almost scale invariant. ($n_s$ is just less than unity); and
• There should be a modest level of gravitational radiation.

In addition to solving the horizon and flatness problems and imprinting super-horizon scale motion,
The CMB alone can not establish flatness.

Additional astrophysical data are required to set a distance scale.
Baryon Acoustic Oscillations (BAO) measured in surveys of nearby galaxies set an angular-diameter distance. Here, data from Percival et al. (2007) are compared to our best fit $\Lambda$CDM model.

(Strictly speaking, the acoustic peaks in the CMB are also baryon-acoustic oscillations, but the term ‘BAO’ is typically restricted to very low-z situations.)
Type 1A supernovae set a luminosity distance. Here, data from HST, Essence and SNLS, as binned by Wright (2007), are compared to our $\Lambda$CDM model

![Graph showing comparison of data with model.](image)
The combined result: The Universe is flat: $-0.018 < \Omega_k < 0.007$

Komatsu et al., 803.0547

In this particular case, BAO provides the tighter constraint because its distance scale is absolute.

(We have only used relative intensities of the supernovae.)
The WMAP maps are Gaussian.

We find

$-137 < f_{NL}^{\text{local}} < 2 \ (68\%)$

from Minkowski, and

$-9 < f_{NL}^{\text{local}} < 111 \ (95\%)$

from the bi-spectrum.

These numbers mean primordial iso-curvature fluctuations are gaussian to 0.1%.
The 5-year TE power spectrum confirms Adiabatic fluctuations. The green curve above $l=30$ is obtained from TT via super-horizon flow, with no free parameters.

“Non-adiabatic” power would fill in the trough at $l>100$.

Green curve is NOT fit to these data.
Entropic perturbations not correlated with curvature, such as axions, are adiabatic to within 8.6% [Komatsu et al., 803.0547]

Generically, for adiabatic fluctuations,

\[
\frac{\delta \rho_x}{\dot{\rho}_x} = \frac{\delta \rho_y}{\dot{\rho}_y}
\]

so we search for entropic perturbations of the form

\[
\frac{1}{3} \delta S = \frac{\delta \rho_C}{3 \rho_c} - \frac{\delta \rho_\gamma}{4 \rho_\gamma}
\]

Axions, a good dark matter candidate invented to solve the strong CP problem, were not in equilibrium with radiation “before”, and can generate entropic perturbations during inflation.
Gravitational radiation is expected to be present at the end of inflation and de-couples right away. It produces tensor perturbations and a unique polarization signature.

Pedagogical illustration of searching for $r$, the ratio of tensor to scalar perturbations: the low $l$ TT spectrum does most of the work once redundancy with tau is broken.
The spectral index is less than 1, and gravitational radiation is not excessive.

As the universe “lingers” in inflation the spectral index is driven to unity and the amplitude of tensors to 0. Some popular models have survived, others have not.
...and don’t forget neutrinos. Once again, the distance scale set by BAO is helpful. It sharpens the resolution of the neutrino mass.

There is still an order of magnitude between the mass lower limit set at SNO and Kamiokande and the upper limit set astro-physically. Precise data on $\sigma_8$ would help a lot.

Komatsu et al., 030547
There is a Cosmic Neutrino Background! (cnb)

The red curve is for 3 relativistic, weakly interacting species which de-couple at 2 Mev (z~10^{10}).

This is a treat, but not a surprise.
The number of relativistic species is very correlated with matter density. We constrain the ratio better than the amount. But the likelihood vanishes as one approaches zero.

The power of this constraint does not depend on including the distance scales from supernovae or the BAO.

..and we are consistent with the obvious correct answer!

Komatsu et al., 803.0547
<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>WMAP-only</th>
<th>WMAP+BAO+SN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hinshaw et al.</strong> 0803.0732 Parameters for Standard ΛCDM Model**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age of universe</td>
<td>$t_0$</td>
<td>$13.69 \pm 0.13 \text{ Gyr}$</td>
<td>$13.73 \pm 0.12 \text{ Gyr}$</td>
</tr>
<tr>
<td>Hubble constant</td>
<td>$H_0$</td>
<td>$71.9^{+2.6}_{-2.7} \text{ km/s/Mpc}$</td>
<td>$70.1 \pm 1.3 \text{ km/s/Mpc}$</td>
</tr>
<tr>
<td>Baryon density</td>
<td>$\Omega_b$</td>
<td>$0.0441 \pm 0.0030$</td>
<td>$0.0462 \pm 0.0015$</td>
</tr>
<tr>
<td>Physical baryon density</td>
<td>$\Omega_b h^2$</td>
<td>$0.02273 \pm 0.00062$</td>
<td>$0.02265 \pm 0.00059$</td>
</tr>
<tr>
<td>Dark matter density</td>
<td>$\Omega_c$</td>
<td>$0.214 \pm 0.027$</td>
<td>$0.233 \pm 0.013$</td>
</tr>
<tr>
<td>Physical dark matter density</td>
<td>$\Omega_c h^2$</td>
<td>$0.1099 \pm 0.0062$</td>
<td>$0.1143 \pm 0.0034$</td>
</tr>
<tr>
<td>Dark energy density</td>
<td>$\Omega_\Lambda$</td>
<td>$0.742 \pm 0.030$</td>
<td>$0.721 \pm 0.015$</td>
</tr>
<tr>
<td>Curvature fluctuation amplitude, $k_0 = 0.002 \text{ Mpc}^{-1}$</td>
<td>$\Delta_R^2$</td>
<td>$(2.41 \pm 0.11) \times 10^{-9}$</td>
<td>$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$</td>
</tr>
<tr>
<td>Fluctuation amplitude at $8h^{-1} \text{ Mpc}$</td>
<td>$\sigma_8$</td>
<td>$0.796 \pm 0.036$</td>
<td>$0.817 \pm 0.026$</td>
</tr>
<tr>
<td>$l(l+1)C_{220}^{TT}/2\pi$</td>
<td>$C_{220}$</td>
<td>$5756 \pm 42 \mu\text{K}^2$</td>
<td>$5748 \pm 41 \mu\text{K}^2$</td>
</tr>
<tr>
<td>Scalar spectral index</td>
<td>$n_s$</td>
<td>$0.963^{+0.014}_{-0.015}$</td>
<td>$0.960^{+0.014}_{-0.013}$</td>
</tr>
<tr>
<td>Redshift of matter-radiation equality</td>
<td>$z_{eq}$</td>
<td>$3176^{+151}_{-150}$</td>
<td>$3280^{+88}_{-89}$</td>
</tr>
<tr>
<td>Angular diameter distance to matter-radiation eq.</td>
<td>$d_A(z_{eq})$</td>
<td>$14279^{+186}_{-189} \text{ Mpc}$</td>
<td>$14172^{+141}_{-130} \text{ Mpc}$</td>
</tr>
<tr>
<td>Redshift of decoupling</td>
<td>$z_*$</td>
<td>$1090.51 \pm 0.95$</td>
<td>$1091.00^{+0.72}_{-0.73}$</td>
</tr>
<tr>
<td>Age at decoupling</td>
<td>$t_*$</td>
<td>$380081^{+5843}_{-5841} \text{ yr}$</td>
<td>$375938^{+3148}_{-3115} \text{ yr}$</td>
</tr>
<tr>
<td>Angular diameter distance to decoupling</td>
<td>$d_A(z_*)$</td>
<td>$14115^{+188}_{-191} \text{ Mpc}$</td>
<td>$14006^{+142}_{-141} \text{ Mpc}$</td>
</tr>
<tr>
<td>Sound horizon at decoupling</td>
<td>$r_s(z_*)$</td>
<td>$146.8 \pm 1.8 \text{ Mpc}$</td>
<td>$145.6 \pm 1.2 \text{ Mpc}$</td>
</tr>
<tr>
<td>Acoustic scale at decoupling</td>
<td>$l_A(z_*)$</td>
<td>$302.08^{+0.83}_{-0.84}$</td>
<td>$302.11^{+0.84}_{-0.82}$</td>
</tr>
<tr>
<td>Reionization optical depth</td>
<td>$\tau$</td>
<td>$0.087 \pm 0.017$</td>
<td>$0.084 \pm 0.016$</td>
</tr>
<tr>
<td>Redshift of reionization</td>
<td>$z_{reion}$</td>
<td>$11.0 \pm 1.4$</td>
<td>$10.8 \pm 1.4$</td>
</tr>
<tr>
<td>Age at reionization</td>
<td>$t_{reion}$</td>
<td>$427^{+88}_{-65} \text{ Myr}$</td>
<td>$432^{+90}_{-67} \text{ Myr}$</td>
</tr>
</tbody>
</table>
Nolta et al. 0803.0593  Hill et al. 0803.0570

Wright et al., 0803.0577

Komatsu et al., 0803.0547

Gold et al. 0803.0715

Dunkley et al. 0803.0586

Hinshaw et al. 0803.0732