Articles

New Cosmic Microwave Background Results Strengthen the Case for Inflationary Big Bang Cosmology[1]

Bertram Schwarzschild

With three years of data, the Wilkinson Microwave Anisotropy Probe has finally produced the first all-sky polarization maps of the CMB, despite polarization levels of only a few parts per 10^7 and obscuring galactic foreground.

The launch of NASA's *Wilkinson Microwave Anisotropy Probe* in June 2001 brought a new level of precision to cosmology. Scanning the whole sky, *WMAP* maps the minuscule departures of the cosmic microwave background from a perfectly isotropic, unpolarized 2.725-K blackbody radiator. The CMB's parts-per-10^5 anisotropies and its parts-per-10^7 polarization are mental properties of the cosmos.

Reports of the *WMAP* collaboration's analysis of its first-year data in 2003 (see Physics Today, April 2003, p. 21) confirmed, with unprecedented precision, the emerging "concordance model" inspired by an impressive variety of cosmological observations [1]. The Big Bang expansion, says the model, began with an inflationary epoch of exponential growth that stretched the cosmos by at least 22 orders of magnitude within 10^{-30} seconds. Some 14 billion years later, the model asserts, the cosmic mass-energy budget is now dominated by vacuum energy and nonbaryonic matter—both called "dark" because they are presumed to have no electromagnetic interactions — whose natures remain unidentified.

The analysis of *WMAP*'s first-year data (*WMAP* I) was able to specify that the initial cosmic inflation happened 13.7 $\pm$ 0.2 billion years ago. The CMB is a snapshot of the cosmos a few hundred thousand years later, when it had finally cooled enough to change rather abruptly from an opaque plasma to a transparent gas of neutral hydrogen and helium. *WMAP* I pinpointed that first moment of transparency to $(379 \pm 8)\times 10^3$ years after the Big Bang.

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WMAP I confirmed, with an uncertainty of only 2%, that the mean cosmic mass — energy density has the time-dependent "closure" value required by the inflation scenario, and it sharpened the accumulating evidence that, in the present epoch, more that 70% of that requisite mass — energy is the dark energy that currently accelerates the Hubble expansion. *WMAP* I also confirmed the equally bizarre conclusion that the familiar baryonic matter we know and love accounts for less than a fifth of the mass. Neutrinos, though certainly nonbaryonic, can't account for much of the rest. That's because the dark matter appears to be cold — that is, nonrelativistic — which implies that it consists primarily of particles much heavier than neutrinos.

1. MAPPING POLARIZATION

WMAP III, the collaboration's much-anticipated report on the instrument's second- and third-year data, finally came in March with the release of four fat papers [2-5]. Asked at a press conference why the analysis had taken longer than the community expected, *WMAP* theorist David Spergel (Princeton University) ventured a terse answer: "200 nanokelvin!"

What's principally new in *WMAP* III comes largely from its significantly improved measurement of the CMB's polarization [3]. The polarization is a secondary consequence of the CMB's anisotropy. Anisotropic photon bombardment sets plasma electrons in motion, thus imposing a small net linear polarization on the scattered photons. Because the polarization signal is a hundred times fainter than the temperature-anisotropy signal, which is measured in tens of microkelvin, the group had the formidable task of understanding instrumental and galactic foreground noise well enough to extract a cosmic polarization signal as faint as 200 nK.

At *WMAP*'s heart is a differential radiometer that directly measures the difference in the microwave temperature between small patches 140° apart on the sky in five frequency bands and two orthogonal polarizations. The instrument reads radiant intensity differences directly as temperature differences.

Much of what *WMAP* III reports is only incrementally new. With three times as much data, it confirms and sharpens the three-year-old conclusion that the concordance model with just six free cosmological parameters can fit all the *WMAP* data plus complementary data from large surveys of distant galaxies, supernovae, and intergalactic hydrogen clouds. "As our error bars, and those of the large surveys, have shrunk," says Spergel, "the data points have, if anything, moved closer to the model predictions."

For four of the six cosmological parameters — the Hubble constant, the densities of dark and baryonic matter, and the amplitude scale of fluctuations in the spatial distribution of energy at the end of inflation — the *WMAP* III improvements, albeit impressive, are indeed incremental. But for the other two — n, the spectral index that describes the dependence of the fluctuations on length scale, and τ, the optical depth of the cosmos between us and the CMB — the improvements are substantive. The spectral index describes the cosmos just as inflation comes to an end, and the optical depth tells us about the reionization of the cosmos by the first generation of stars a few hundred million years later.

2. A SPECTRAL TILT

The spatial density fluctuations that emerged form inflation are thought to be the seeds of all later structure. A perfectly homogeneous beginning would preclude the existence of galaxies today. Inflation is presumed to have expanded a preinflation spectrum of quantum fluctuations to astronomical size in an instant. In the anisotropies of the CMB, we see these fluctuations, further stretched by the Hubble expansion and deepened by gravitational clustering over the next 4×10^5 years, at the dawn of transparency. Since then, the ongoing Hubble expansion has stretched them another thousandfold.

Before Alan Guth and others developed the idea of cosmic inflation in the early 1980s, it was attractive to believe that the primordial fluctuation spectrum is "flat," with equal power on all spatial scales. That turns out to be a good first approximation in inflation theory. The dependence of the fluctuation power spectrum at the end of inflation on wavenumber k (the reciprocal of wavelength) is parameterized by k^{n-1}. For a flat primordial spectrum, $n = 1$. But the inflation scenario, considered in detail, predicts that n must be slightly less than 1. The precise "spectral tilt" prediction depends on the detailed dynamics presumed to have driven inflation, and theorists have come up with many conjectures. But quite generally, inflationary predictions for $1–n$ are not far from 0.05.

WMAP I could only specify $n = 0.99 \pm 0.04$, completely consistent with the unwanted flat spectrum [1]. The new *WMAP* III results, however, yield an n of 0.951 ± 0.015, more than three standard deviations from flatness. The evidence for the predicted tilt is strengthened by including in the fits improved data from galaxy surveys and fine-resolution CMB anisotropy measurements of small patches of sky by ground-based microwave telescopes (see Physics Today, July 2001, p. 16). But the principal factor in the better determination of the spectral index is the *WMAP* III polarization data, which made it possible to disentangle the effects of n and τ on the CMB.

In *WMAP* I, with no polarization maps and only preliminary power spectra of correlations between polarization and temperature, the likelihood functions that determine the best parameter estimates from the data were badly degenerate in n and τ. That is, without adequate polarization data, a tilt in primordial fluctuation spectrum was hard to distinguish from the amplification of CMB anisotropy at large angular scales by reionized hydrogen.

Near the equatorial plane of the Milky Way, the CMB polarization signal is swamped by galactic foreground, especially in *WMAP*'s lower-frequency observing bands (20-40 GHz). The *WMAP* III polarization map in Fig. 1 shows that, even at 60 GHz, the foreground contamination is still prominent. For a reliable determination of CMB polarization and its correlation with anisotropy temperature, one has to deal with the galactic foreground. That was done in *WMAP* III by masking off the most offending regions of sky and by using the observed

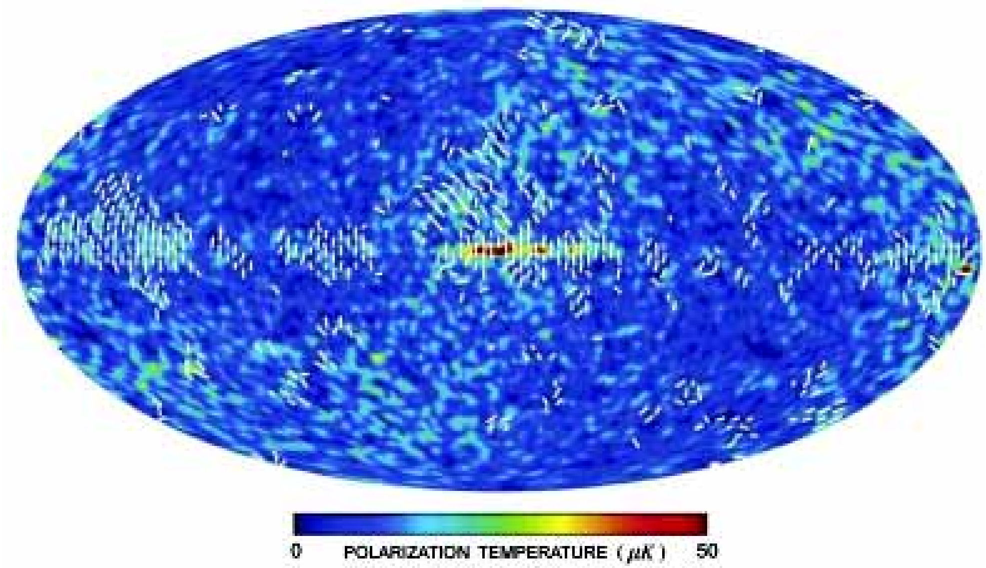

Fig. 1: All-sky polarization map of the cosmic microwave background in galactic coordinated, as measured in WMAP's 60-GHz band. The true CMB linear polarization, typically a few hundred nanokelvin, is obscured in the equatorial plane by galactic-foreground polarization and in undersampled regions such as the diagonal swath from 7 to 1"o'clock" by noise. Polarization direction is indicated by lines only where signal exceeds noise.

dependence of polarization on microwave frequency to make a model of the remaining foreground polarization.

3. COSMIC REIONIZATION

The much improved polarization data break the degeneracy between n and τ. In doing so, they not only confirm the anticipated tilt of the primordial spectrum of density fluctuations; they also make the one disturbing surprise in the old *WMAP* I analysis go away. The optical depth τ can be thought of as the probability that a CMB photon liberated from the opaque plasma at the moment of first transparency will be scattered on its way here. That probability would be negligible if the intergalactic gas were still overwhelmingly neutral. But we know that the hydrogen was largely reionized by ultraviolet radiation from the first generation of stars. The time of that reionization can be estimated from τ.

WMAP I's best estimate of τ was 0.17. That suggested, albeit with big error bars, significant reionization by 200 million years after the Big Bang — uncomfortably early for theorists of star formation. "There may well have been some stars that early," says Cambridge University's Martin Rees. "But most of us thought that not enough of their UV could have escaped the dense circumstellar gas of that epoch." *WMAP* III reports $\tau = 0.09 \pm 0.03$. The new result pushes significant cosmic reionization forward to about 400 million years after the Big Bang, in much better accord with astrophysical expectations.

4. ANGULAR POWER SPECTRA

To extract cosmological information from the anisotropy and polarization maps, and form the anisotropy-polarization correlation function, one decomposes them into spherical harmonics $Y_{lm}(\theta, \phi)$ of the celestial coordinates and plots the mean squares of the expansion coefficients (averaged over m) against the multipole index l. At a given l, these "power spectra" reveal correlations between points on the CMB sky separated by angles of order π/l. The so-called acoustic peaks predicted for the spectra follow from the elastic properties of CMB plasma (gravitational attraction versus radiation pressure) and the abrupt beginning and end of the plasma epoch.

The curves in Fig. 2 show concordance-model fits with the best estimates of the six cosmological parameters. For the temperature anisotropy spectrum — already very well measured and fitted in *WMAP* I — the measurement errors for all points up to $l = 400$ are now smaller than the so-called cosmic variance, the irreducible random scatter of spectral coefficients perfectly measured by observers cosmologically far apart. The apparently errant point at $l = 2$ might be thought to indicate a topologically confined finite cosmos. But *WMAP* leader Charles Bennett of Johns Hopkins University says that it is completely consistent with the scatter expected from cosmic variance at low l.

5. PRIMORDIAL GRAVITY WAVES

To get the polarization power spectrum of Fig. 2, Bennett and

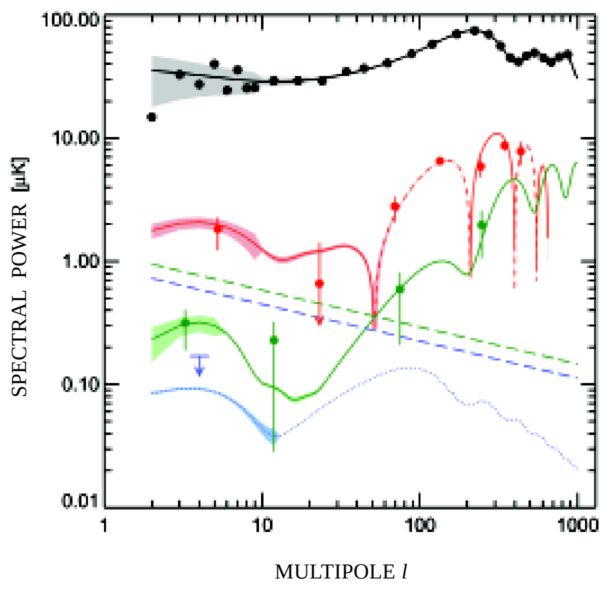

Fig. 2: WMAP III angular power spectra of CMB temperature anisotropy (black), temperature-polarization correlation (red), and E-mode polarization (green). Only an upper limit (blue) is shown for B-mode polarization, which would signal the effect of primordial gravity waves. Power at multipole l indicates correlation between points on the sky separated by angles of order π/l. Curves show best cosmological fits. Their shaded widths indicate irreducible cosmic variance. The dashed parts of the red curve indicate anticorrelation. The dashed green and blue lines show estimates of galactic-foreground E- and B-mode polarization that has been removed.

company separated the polarization map (after foreground subtraction) into two constituent vector fields, one curl-free and the other divergence-free. These in turn are derived, respectively, from a scalar and a pseudoscalar field, denoted *E* and *B* for their mathematical resemblance to electromagnetic fields.

Polarization resulting from temperature anisotropies at the end of the plasma epoch, with or without later amplification by reionized intergalactic hydrogen, contributes only to the *E*-mode. Any *B*-mode polarization (assuming that galactic fore ground effects have been adequately scrubbed) would signal the much-sought-after primordial gravity waves predicted by all the inflation models. The primordial waves — very different from the astrophysical gravity waves being sought by LIGO — are attributed to inhomogeneities in the primordial metric of space-time itself. Such a signal could determine whether the "inflation" field that presumably drove inflation had the energy scale suggested by attempts at a grand unified theory of elementary-particle interactions.

As shown in Fig. 2, *WMAP* III, having seen no *B*-mode polarization, can set only an upper limit on the gravity-wave contribution to CMB polarization. That limit, for now, is 30% of the observed *E*-mode signal. If, as some inflation models predict, the actual ratio is about 10%, more *WMAP* observing time is unlikely to reveal it. But the European Space Agency's *Planck* satellite, scheduled for launch in 2008, may be able to detect *B*-mode polarization at that level.

Next-generation CMB probes designed to detect a 1% *B*-mode signal are already being planned. That's a sensitivity level at which many theorists [6], but not all [7], believe that primordial gravity waves are bound to show up if inflation really did happen.

REFERENCES

[1] D. Spergel *et al.*, Astrophys. J. **148**, 175 (2003).
[2] D. Spergel *et al.*, http://arXiv.org/abs/astro-ph/0603449.
[3] L. Page *et al.*, http://arXiv.org/abs/astro-ph/0603450, to be published in the Astrophys. J. Supplement.
[4] G. Hinshaw *et al.*, http://arXiv.org/abs/astro-ph/0603451.
[5] N. Jarosik *et al.*, http://arXiv.org/abs/astro-ph/0603452.
[6] See, for example, L. Boyle, P. Steinhardt and N. Turok, http://arXiv.org/abs/astro-ph/0507455.
[7] G. Efstathiou and S. Chongchitnan, http://arXiv.org/abs/astro-ph/0603118.