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# What have we learnt from Wilkinson microwave anisotropy probe?

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**Abstract.** It has been a little over a year since WMAP produced its dramatic new glimpse of the cosmic microwave background. I review the results of the WMAP mission and the science that has arisen from it, focusing on the qualitatively new features of the data: the temperature-polarization correlation, correlations with large scale structure, the large-scale power deficit and its implications, and the search for non-Gaussianity.

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## 1. What makes the WMAP data so special?

Just over a year ago, the Wilkinson microwave anisotropy probe (WMAP) produced its first pictures of the microwave sky, in a range of frequencies from 20 to 100 GHz [1]. The impact of these data has been tremendous, resulting in more than 300 papers on the archive with 'WMAP' in the title or abstract. In these proceedings, I want to summarize just a few of these results, focusing on the qualitatively new aspects of the WMAP data – those things which simply could not be observed before its arrival.

One of the most surprising things about the WMAP results is how consistent they were with the earlier observations. Accounting for known calibration uncertainties in the data, WMAP in large part agrees with earlier experiments like COBE, Boomerang, MAXIMA, DASI and the VSA [2]. This is most clearly reflected in the fact that the best-fit cosmological model was not dramatically changed by the WMAP data. Like the earlier data, the WMAP data indicate that the universe is nearly flat, but with only about 30% of the matter in the form of baryons and dark matter; the remainder appears to be dominated by some kind of dark energy, such as a cosmological constant [3].

Of the hundreds of citations the WMAP data have received, many of them come in attempts to constrain variations on this model of one kind or another. These have included adding isocurvature perturbations, considering massive neutrinos and modifying the dark energy evolution. To date, no extended model has been found which fits the data significantly better than the simplest cosmological constant model; however, these kinds of quantitative analyses are essential and WMAP has been very effective in tightening the constraints on such alternative physics models.

Perhaps the greatest strength of the WMAP satellite is its ability to map the entire sky. We will see that most of the qualitatively new aspects of the WMAP data arise from this in some way. Foremost, it opens a window on the largest scales we can observe, but there is a number of other advantages. Being sensitive to the large dipole, it provides a natural calibration source, eliminating one nagging systematic of the smaller scale observations. In addition, the full sky coverage guarantees that WMAP overlaps with all the other CMB observations, giving us a common link to compare the various results.

Also, the large sky coverage led to a great improvement on the accuracy at which the spectrum of anisotropies is known. The WMAP errors are dominated by cosmic variance up to $\ell = 350$, and the data have signal-to-noise ratio greater than one for $\ell < 650$. The cosmic variance limit means that the sampling errors introduced by the fact that we see a limited fraction of the universe outweigh any errors in the measurement. Thus, while the observations might be improved, the underlying power spectrum which we are trying to measure will never be better determined (barring the elimination of systematic effects).

## 2. Large-scale polarization

The most dramatic result produced by WMAP was the observation of the large-scale polarization [4]. Polarization is produced causally, and so we expect that any polarization that is created at last scattering will be restricted to scales that were inside the horizon at that time. Polarization correlations on larger scales ($> 2^\circ$) could only have been produced much later. This can happen if a significant fraction of the photons we observe were rescattered relatively recently. However, such rescattering requires a high density of free electrons and thus requires that the neutral hydrogen atoms were reionized at fairly high red-shifts.

The WMAP polarization observations are noise dominated, making direct detection very difficult (though this could potentially be reported with the second year data). However, one of the benefits of having a full sky survey is that one has the statistics to look for weak effects that otherwise would be invisible. WMAP exploited its large coverage by searching for correlations between the polarization and the temperature anisotropies. Such correlations arise naturally in the early universe, since polarization is generated only when there is a net quadrupole in the incident radiation onto the scattering electrons [5]. Besides being easier for WMAP to observe, the temperature-polarization cross-correlation will also be less sensitive to foregrounds, since we believe the temperature fluctuations to be primarily cosmological in origin.

The cross-correlation revealed two important effects. The first was an increase in polarization at very low $\ell$, which can only arise from a rescattering of the CMB radiation. The amplitude of the polarization indicates that about one sixth of the photons were re-scattered, corresponding to a mean optical depth of $\tau = 0.17 \pm 0.04$. This can be translated into a red-shift of reionization if we assume a simple model for the ionization history. In the most extreme model, where the universe instantly becomes totally ionized, this would have happened at a red-shift of $z = 20 \pm 10$; this is somewhat earlier than had been anticipated on theoretical grounds. In less extreme models, reionization would have started at even higher red-shifts.

The second crucial result was the cross-correlation on degree scales, generated by the largest modes at last scattering. On these scales the polarization was generated primarily by the divergence of the fluid velocity, and so offers a direct probe of the motion fluid on the largest scales. Not only was the velocity seen to be out of phase with the density fluctuations, as expected, but the sign of the cross-correlation revealed the direction of the motion. The overdensities were seen to collapse upon entering the horizon, consistent with the expectations of adiabatic fluctuations and contrary to what one expects in isocurvature or defect-dominated models.

## 3. Correlation with other surveys

Since the CMB fluctuations were discovered by COBE, studies have searched for correlations between the CMB and maps in other frequencies. The primary purpose of these was to use the lack of correlations to establish that the temperature anisotropies were truly of cosmological origin and not from some more local sources. However, in most models, some part of the CMB anisotropies does arise locally, and this has now been established with the precision data of WMAP.

There are a number of possible local sources of CMB fluctuations, but the only one that arises in linear theory is the integrated Sachs–Wolfe effect (ISW). In the ISW effect, fluctuations arise gravitationally as CMB photons travel toward us. When the photons fall into a gravitational well, they gain energy, but they lose that energy on climbing out. However, if the depth of the gravitational well changes, then the energy shifts will not balance and the photons end up with a net increase or decrease of energy. The amplitude of the temperature fluctuations produced in this way depend on the gravitational potential, which is reflected in the over- or under-density of galaxies. Thus we expect to see correlations between the galaxy density and the CMB temperature [6].

Recently, such correlations have been discovered with the WMAP data. They were first seen in correlations with the X-ray background and with the distribution of radio galaxies [7,8]. The correlations have an angular profile, amplitude and sign consistent with the signal expected for the present best cosmological model and were seen with a significance of about three sigma. The large angular scale of the correlations and their independence of the masking of foreground sources argue strongly for an ISW origin. Subsequent analyses have detected correlations with optical galaxy surveys, including the APM and SDSS, and with the 2-MASS near-infrared survey [9–11].

Integrated Sachs-Wolfe effect (ISW) correlations can have important implications for determining the cosmological model. While the universe is matter dominated, the gravitational potentials are expected to be constant, so that no ISW effect is produced. However, once another component – such as a cosmological constant or the curvature of the universe – becomes important dynamically, the ISW effect can begin to arise. The observation of the ISW effect shows that there has been a change in the dynamics of the universe at recent times.

Another way CMB fluctuations can be produced locally is if the photons are re-scattered off hot gas in clusters, which is known as the Sunyaev–Zeldovich effect. This effect would also lead to correlations between the CMB and local surveys, particularly if the surveys are good indicators of clusters of galaxies. The correlations are clearly distinguishable from the ISW effect because they are expected to be on smaller angular scales. In addition, they should have the opposite sign, because in low-frequency surveys like WMAP, the galaxy clusters should actually appear cooler. The amplitude expected depends on the so-called 'Compton-$y$ parameter'; this gives a measure of the probability of rescattering (and thus the density of free electrons) as well as the temperature of the cluster.

The situation with regard to the measurement of cross-correlations resulting from the Sunyaev–Zeldovich effect is as yet unresolved. Some analyses have seen hints of the cross-correlation [9–13], while others have only been able to place upper bounds [14]. This is in part due to the different kinds of surveys being looked at and how well they reflect the density of clusters.

## 4. Deficit of power on large scales?

The WMAP data fit a simple cosmological constant model quite well. However, the fit is not perfect, and there are particular regions in multipole space where the data and the model differ significantly. These tend to dominate the contribution to the $\chi^2$ of the fits and stand out visually: $\ell < 6$, $\ell \sim 40$ and $\ell = 210$.

If some alternative model is to be a viable alternative to the simplest model, it should fit the data better, which means improving the fits to these features. For the deviations at high $\ell$, this is a considerable task, primarily because the features are fairly sharp and this is difficult to explain from fundamental physics.

Cosmologists have concentrated on the low $\ell$ difference for a number of reasons. One is that the usual way of plotting exaggerates its importance; in fact, the larger $\ell$ features tend to dominate the $\chi^2$ of the fits. Another reason is that while the other features are constrained on each side, at higher and lower $\ell$, the low power deficit is not; it could well continue on even larger scales. In addition, the scale at which it occurs is somewhat special. The fluctuations are very near the horizon size, and correspond to the largest scale that we are able to probe. If some causal mechanism, such as a defect, is affecting things, the horizon is where it is likely to be acting.

The first attempt to quantify the effect was by Spergel *et al* [3], who pointed out that on large angular scales, the CMB correlations are of a much lower amplitude than expected. They showed that a fourth-order statistic, the square of the correlation function integrated from 60° to 180°, was considerably smaller than expected and that such a small value occurred in their Monte Carlo simulations only 0.15% of the time. Many suggestions have been put forward to explain this, usually relating to a lack of underlying power at large scales compared to a scale invariant spectrum. Possibilities include a running spectral tilt, oscillations in the underlying power spectrum, and a suppression of power on scales sufficiently close to the curvature scale.

But just how significant is the power deficit? Is some twist to the simplest model really required, or is it consistent within the errors? Efstathiou argues that the case has been overstated for a number of reasons [15]. First, the statistic Spergel *et al* considered was determined *a posteriori*, after having seen the data, making it harder to evaluate its significance. In addition, the quadrupole and octupole amplitudes are subject to large uncertainties due to the galactic contamination. The particular values used by Spergel *et al* were somewhat lower than those found in other analyses which treated the galaxy slightly differently, and this considerably changes the likelihood of the observations. In particular, Efstathiou argues that the estimator used by the WMAP team is non-optimal, and that using a maximum likelihood estimator instead leads to higher values (up to 100% higher) for the quadrupole and octupole amplitudes [16]. Finally, he also argues that in this case, using frequentist statistics tends to give higher significance than a Bayesian approach, and that the true likelihood of seeing the low power is closer to one in 10 or 20, rather than the one in 700 claimed by Spergel *et al*.

Overall the data appear to be consistent with the simple 'concordance' model. The deficit of power on large scales remains a very interesting and real feature of the data, and any theory which naturally gives a suppression of power on these scales should and will receive significant attention. However, the statistical significance of the feature is not so strong that we should feel obliged to force it into the model.

## 5. Topology of the universe

Among the most interesting of the proposals to explain the lack of large-scale power is the possibility that we may be seeing the effects of a finite universe. The size of space itself could be imposing a cut-off on the very long wavelength modes.

Perhaps the simplest finite model to consider is a closed universe. The complication to this is that the position of the Doppler peaks seen in WMAP strongly constrains the curvature of the universe, $\Omega_0 = 1.02 \pm 0.02$. The curvature scale must be significantly larger than the present horizon size meaning that the effects of curvature would be unlikely to greatly affect the CMB observations. For the effect to work, somehow modes much smaller than the curvature scale need to be suppressed. Efstathiou has investigated this, by introducing a rather ad hoc means of suppressing modes near the curvature scale [17].

Another way out of this difficulty is if the universe has a non-trivial topology; for example, a flat universe could have a toroidal topology with a size of the order of the present horizon. Alternatively, the universe could be closed, but arranged such that there are many copies in a given curvature radius. Luminet *et al* proposed one such solution, where the universe is closed but has a dodecahedral topology [18]. One hundred and twenty spherical dodecahedra are needed to tile the surface of the hypersphere, providing the needed lever to make the radius of the universe smaller than the curvature radius. They showed that this model, for an acceptable total density, can suppress the power of the quadrupole and octupole significantly.

Whether flat or closed, if the universe is small enough to suppress the CMB, then one expects to be able to see this in more than the power spectrum. There should be other, more specific signatures to test. One which is currently being sought is the existence of 'matched circles on the sky' [19]. If the radius of the universe is smaller than the distance to the last scattering surface, then the scattering surface in one direction can intersect with the scattering surface in another direction. These will intersect on circles in the sky, and on these circles we are able to see the same volume of space from two directions. As long as the main contribution to the temperature anisotropy is from the density of the baryon–photon fluid, these circles will have matching CMB patterns. (However, the ISW and Doppler effects can complicate matters, particularly on smaller scales.)

Some preliminary searches have been performed, thus far yielding negative results [20,21]. For the models covered by the searches, the topology scale has been shown to be larger than 24 Gpc. However, the searches have focused on back-to-back circles, with a straightforward reflection. This has not yet ruled out the dodecahedral model above, because it predicts a twist relative to the image. These searches are continuing, as are other types of searches which focus more generally on testing for symmetries and statistical isotropy [20,22].

## 6. Large-scale Gaussianity

The final topic I wish to discuss is the evidence for the data being non-Gaussian. Most inflationary models predict the primordial fluctuations to be very close to Gaussian, with deviations far below the present sensitivities. The WMAP data give us a chance to test this on the largest scales.

The results of initial searches for non-Gaussianity in the WMAP data were mostly negative, confirming the inflationary prediction [23–25]. The first tests focused on 3-point statistics such as the bispectrum, or topological tests such as the genus or the Minkowski functionals. Galactic foregrounds constitute a serious source of contamination for any non-Gaussian test. After attempting to remove these, Komatsu *et al* [23] found that WMAP was consistent with Gaussianity, improving the upper limits for bispectrum kinds of non-Gaussianity by a factor of 20–30. The small non-Gaussianity they were able to detect was consistent with that expected from the radio point sources which they had not been able to remove. The consistency with Gaussianity was also confirmed by other authors looking at similar kinds of tests [24,25]. In addition, a potentially non-Gaussian feature of the COBE data was seen to have disappeared in the new data [26].

However, a number of interesting features of the data have been noted which hint at non-Gaussianity. Tegmark *et al* [27] noted that not only were the quadrupole and octupole lower, but they also seemed to be suppressed along the same spatial axis. Interesting features also appeared when the data were separated into different hemispheres. Eriksen *et al* [28] saw that, in ecliptic coordinates, the southern hemisphere has significantly higher power than the northern hemisphere, as well as greater three- and four-point moments. Similarly, Park [29] saw differences in genus statistics between the northern and southern galactic hemispheres, and that the southern hemisphere is itself somewhat anomalous. Also, the analysis of Vielva *et al* [30] detected a non-Gaussian signal related to the statistics of Mexican hat wavelets, also in the southern galactic sky. Taken together, these suggest the possibility of an unremoved foreground (or even a signal) lying in the southern ecliptic or galactic sky.

Other studies have focused on the statistics of the full sky multipole moments, either looking for phase correlations or non-linear combinations which might indicate a lack of isotropy [31–33]. These have given indications of possible non-Gaussianity on small and large angular scales. While these hints might be further confirmation of the other signs mentioned above, they might also be the result of unremoved point sources (small scales) or remnants of the galaxy (large scales).

It is too early to take the present evidence as any kind of conclusive proof of non-Gaussianity. Any particular map drawn from a Gaussian ensemble is going to appear to be non-Gaussian in some way. Given that we are always more likely to emphasize the unexpected, we do not know how many tests of non-Gaussianity were performed yielding negative results that simply have not been reported. Without knowing this, interpretation of these kinds of tests is very difficult.

Even if non-Gaussianity is proven, it is much more likely to be due to foregrounds or systematics with the instrument than from the primordial fluctuations. Indeed, non-Gaussian studies are probably the best way to search for such unexpected problems. This was clearly demonstrated in the case of COBE, when non-Gaussianities discovered in the data were eventually traced to contaminated data from the satellite passing through the Earth's shadow [34,35].

## 7. Conclusions

With three more years of data, there is still much to come from WMAP. The additional data will likely reduce the instrumental errors by a factor of two, and should see the first detection of the large-scale polarization autocorrelation. While the temperature spectrum on the largest scales should not be greatly affected, improvement will be seen at higher $\ell$. In addition, further progress should be made in understanding the foreground contaminants like the galaxy and removing them from the cosmological signal. Finally, greatest improvement will likely be in the study of non-Gaussianities in the data, in order to reduce any residual systematics and to probe for remnants from the early universe.

Already though, WMAP has to be considered an unqualified success. Not only has it increased the amount of CMB data dramatically (with nearly one million independent pixels), but it has also opened new windows into the development of our universe. It has shown that the late universe has played a key role in changing the microwave background, both by rescattering the photons and by the ISW effect. It has also hinted at new directions, and presented us with puzzles on the largest scales we can see. Most importantly, the quantity and quality of the WMAP data have truly propelled us into an era of 'precision cosmology'.

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