The recent announcement by the WMAP satellite team of their landmark measurements of the cosmic microwave background (CMB) anisotropy (1-3) has convincingly confirmed important aspects of the current standard cosmological model. The results show with high precision that space is flat (rather than curved) and that most of the energy in the universe today is “dark energy”, which is gravitationally self-repulsive and accelerates the expansion of the universe. The evidence is independent of supernovae results (4,5).

The measurements strongly indicate that the amplitudes of spatial variations in density and temperature that seeded the formation of galaxies were roughly independent of length scale, adiabatic (all forms of energy have the same spatial variation), and followed a Gaussian distribution — just as predicted by the standard Big Bang inflationary model. WMAP heralds a new age of precision cosmology with careful error analysis, tightly constraining many key parameters (6).

For example, the lifetime of the universe has been determined to be 13,400 ± 300 million years (6). Furthermore, WMAP’s new measurement of the CMB polarization as a function of angular scale shows that the epoch of cosmic reionization — associated with the formation of the first stars — had already occurred when the universe was several hundred million years old.

At the same time we celebrate this triumph, it is important to recognize that important issues remain. For example, it is not yet clear whether the spectrum of temperature fluctuations is truly consistent with inflation. The spectrum is roughly scale-invariant, but there are hints of peculiarities, and a key inflationary prediction — the presence of gravitational wave effects — has not yet been observed.

We also do not know whether dark energy is due to an unchanging, uniform, and inert “vacuum energy” (also known as a cosmological constant) or a dynamic cosmic field that changes with time and varies across space (known as quintessence). “Dark matter”, which is gravitationally self-attractive, also remains mysterious: We do not yet know its nature, nor are we certain about its density or the amplitude of the initial ripples in its distribution.

Today’s standard theoretical paradigm is the inflationary Big Bang model. According to this picture, the universe began in a a state of nearly infinite temperature and density and almost immediately entered a phase of rapid, accelerated expansion (“inflation”). This expansion smoothed out the distribution of energy, flattened initial warp or curvature in space, and created tiny variations in density. To transform these density variations into the gravitationally collapsed, complex structures we see today, it is essential that there be “dark matter” as well as ordinary (baryonic) matter. Finally, we need dark energy to account for the measured total energy density and to explain the current cosmic acceleration.

Some of the WMAP results – the flatness of space, the near scale-invariance, adiabaticity, and Gaussian distribution of the density perturbations (7), the density of baryons, the age of the universe, and perhaps the early formation of the first stars — are based on WMAP alone and are consistent with the standard model. Because the CMB is a direct image of the early universe and its interpretation entails simple, well-understood physical principles, these results are robust.

On the other hand, some important issues can only be addressed by combining WMAP data with other cosmological measurements. These conclusions should be viewed more cautiously because the result depends sensitively on the choice of additional data.

For example, by combining data, a significant deviation from a perfectly scale-invariant ($n = 1$) spectrum was found (8). According to the best-fit WMAP combined analysis (8), $n$ runs from 1.1 on the largest scales to < 0.9 on the smallest scales probed, a deviation that disagrees with the simplest and most natural inflationary models (9). These results cast a pall over the inflationary paradigm at the same time that many of its other important predictions are confirmed. However, it is important to note that WMAP data alone are not inconsistent with the simplest inflationary models, the fit being $n = 0.99 ± 0.04$. The inconsistency only arises when the data are combined with two degree field galaxy redshift survey and quasar absorption line measurements.

Setting aside this issue, we next consider whether the

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**Figure 1:** CMB constraints on $\Omega_m$ and $\sigma_8$. The pink contour corresponds to a “strong prior”, which marginalizes over uncertainties in the Hubble constant, baryon density, and spectral index of primordial fluctuations, but assumes that other parameters are perfectly known, including the optical depth to reionization, $\tau = 0.17$. The other contours are revised limits that include the uncertainty in the equation of state of dark energy (blue, $−1 < w < −0.7$); or $\tau$ [red; in agreement with the WMAP alone constraint from (6), shown by the red cross]]. The “weak prior” (purple) allows both these degrees of freedom. All contours are 95% confidence limits; shading corresponds to the probability. We used WMAP temperature and polarization data (3,3,12) and small scale measurements from (13-15) and performed the calculations with CosmoMC (16).
WMAP data are uniquely consistent with the standard inflationary Big Bang picture. The answer is no, as the WMAP team has itself indicated. There remains room for radical alternatives. An example is the cyclic picture, in which the universe undergoes a periodic sequence of cycles (10): Expansion from a hot big bang is followed by contraction in a “big crunch” and reemergence in a big bang, and the key events that shaped the large-scale structure of the universe occur before the “bang”, a cycle ago. This model offers a very different view of cosmic history, yet it fits all current observations (including the new WMAP results) at least as well as the inflationary picture.

Even if the standard picture is proven to be correct, the model is incomplete. The initial conditions that led to inflation and the identity of the “inflaton” field (the cosmic field that causes inflationary expansion) remain unknown and the nature of dark matter is unsettled.

An important uncertainty is the nature of the gravitationally self-repulsive dark energy. Whether it consists of vacuum energy or quintessence depends on w, the ratio of pressure to energy density. The WMAP combined analysis concluded that the best fit corresponds to vacuum energy. But their own closer examination of WMAP results at large angular scales shows that the enhanced fluctuations expected for vacuum energy are missing. This discrepancy could be a first sign that dark energy is quintessential (11). The combined analysis washed out the effect, but this could be hiding a very important hint about the true nature of dark energy and confounding measurements of parameters.

WMAP has produced impressive constraints on many fundamental cosmic parameters [see (6) for extensive tables], but there remain open frontiers. Perhaps most important is the uncertainty in the density of dark matter, $\Omega_\text{m}$, and the amplitude of density fluctuations labeled by $\sigma_8$, as represented in the figures. These parameters are critical because they describe the amount and distribution of the matter that clusters to form all of the structure in the universe.

The WMAP data alone determine some combination of $\Omega_\text{m}$ and $\sigma_8$, represented by the narrow pink contour in the first figure, if one takes into account the uncertainties in just three other cosmological parameters but assumes the rest are perfectly known (“strong prior”). Even with these over optimistic assumptions, the range of $\Omega_\text{m}$ and $\sigma_8$ is large. As we progressively relax the assumptions by including empirical uncertainties, the range of degeneracy balconies until we get to the more realistic purple contour (the “weak prior”).

To reduce the uncertainty, the WMAP team has presented results obtained by combining with the two degree field galaxy redshift survey and quasar absorption line measurements. We agree with the mathematical conclusions obtained by the WMAP team when combining these data sets. On the other hand, it is worth considering the broader range of available data shown in the second figure, which reveals three different directions of degeneracy: vertical strips from methods that measure the matter density alone; constraints on the combination $\sigma_8 \Omega_\text{m}^{0.6}$, obtained by measuring the number of galaxy clusters observed today and the apparent distortion of galaxy images due to the bending of light by dark matter; and a roughly orthogonal constraint from the WMAP data. Here we see that the high likelihood regions (solid lines) do not all overlap well, suggesting a problem with one or more of the measurements, or their interpretation, or, more interestingly, that the underlying model may be wrong.

Perhaps adding only select measurements to WMAP data will prove to be the correct strategy. On the other hand, given the issues raised in the second figure, it may be that the real uncertainty is much greater. We will have to wait for forthcoming observations to substantially reduce the current uncertainty.

Thus, even after the historic WMAP breakthrough, there remain unresolved issues, and so there is plenty of room for surprises. Only 5 years ago, breakthroughs in technology and astronomical technique led to the discovery that the expansion of the universe is accelerating. The future holds promise of even greater technological advances that will uncover further cosmological surprises.

![Figure 2: Comparison with other constraints.](image)

Figure 2: Comparison with other constraints. The “strong prior” (pink) and “weak prior” (purple) WMAP constraints (from first figure) are compared to other cosmological probes (95% confidence limits). Red, mass-to-light ratio in galaxies and clusters of galaxies (17). Orange, ratio of baryons to total matter content in clusters of galaxies (18). Blue, observed numbers of galaxy clusters (18) [blue arrow indicates scatter in results from different groups, as reviewed in (19)]. Green, alignment of galaxy shapes in random directions in the sky due to gravitational lensing [results from (20); spread of results reviewed in (21)]. Other than the purple WMAP contour, all constraints are based on the assumption that the Hubble constant, primordial spectral index, and dark energy parameter are well known.

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