2.7 Epilogue: CMB science in the 21st Century

Since this course was first run in 2002, observational cosmology made substantial progress. Many groups raced to get their results out before the release of data from the MAP satellite. The major highlights were:

April 2002
The 2dF Surveys of Galaxy and Quasar Redshifts were formally completed, having measured the redshifts of 221,283 galaxies and 23,424 quasars.

May 2002
The Cosmic Background Imager (CBI), releases the first measurements of the damping tail of CMB fluctuations in the multipole range $300 \leq l \leq 3500$. As well as confirming the expected damping at $l > 1000$, they report higher-than expected fluctuations on very small scales of $l > 2000$.

June 2002
Early results from the Sloan Digital Sky Survey, which will eventually measure redshifts of 1 million galaxies.

September 2002
The DASI team announce that their interferometer at the South Pole has made the first detection of CMB polarization.

October 2002
The French balloon-borne experiment ARCHEOPS releases a map of the CMB fluctuations covering about 30% of the sky. The instrument is a prototype of the *Planck* HFI, and the excellent results obtained in just 19 hours promises that the 1-year long *Planck* sky maps will be truely stunning. The ARCHEOPS results provide the best measurement of the first acoustic peak (but not for long).

December 2002
The ACBAR instrument, a bolometer array mounted on the Viper telescope at the South Pole, releases high-quality measurements of the damping tail of the CMB fluctuations, in the l range 150-3000. They see less excess power on large scales than the CBI. This is not necessarily inconsistent because the two instruments operate at different wavelengths: 1 cm for the CBI and 2 mm for ACBAR. This suggests that the excess seen by the CBI does not have a black-body spectrum, supporting speculation that it is due to the Sunyaev-Zel'dovich effect, from an unexpectedly large population of of distant clusters of galaxies.

December 2002
The BOOMERanG team report their third and final analysis of their 1998 balloon flight, using some data originally rejected due to calibration problems, to give slightly better results than before.

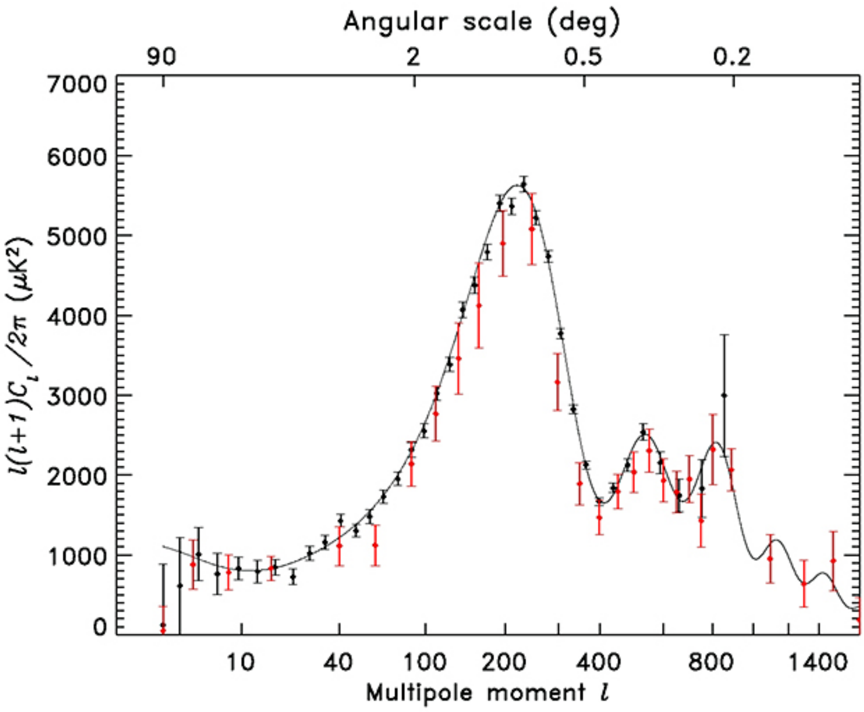
January 2003
The VSA team (including yours truly) report new measurements on smaller scales than before, now extending to $l = 1500$. This confirms the damping previously seen by CBI and ACBAR in this range.

February 2003
NASA releases the results from the first year of observations with the MAP satellite, now re-named the Wilkinson Microwave Anisotropy Probe (WMAP) in honour of the late David T. Wilkinson. With good sensitivity and 100% sky coverage, WMAP data now provides the definitive measurement of the first acoustic peak (the errors are limited by cosmic variance and so cannot be improved), and by far the best measurements of the second peak. They also detected CMB polarization from the acoustic peaks, slightly more clearly than the original detection by DASI. Despite the much higher quality of the measurements than any previously available, the 'concordance model universe' still matches the data well. The one significant change is that WMAP seems to detect much higher polarization on very large angular scales (> 20°) than expected. This suggests that the first stars or quasars formed, and re-ionized the Universe, much earlier than previously thought, at a redshift of about $z \approx 17$, only a few hundred million years after the Big Bang.

The WMAP team got their most precise results by combining the WMAP data with other measurements of fluctuations on smaller scales: the ACBAR measurements of high-l CMB fluctuations, the 2DF Galaxy Redshift Survey for the present-day power spectrum of the large-scale structure, and data from the forest of hydrogen absorption lines found in the spectra of distant quasars, which measures fluctuations in the intergalactic gas on scales equivalent to l of several thousand. Together, these data provide remarkably tight constraints on the parameters of the Universe: for instance the age of the Universe is calculated to be 13.7±0.2 billion years (almost exactly three times the age of our Solar System). These numbers should be treated with a pinch of salt, since they rely on **all** the different experiments being correct within their quoted uncertainties, i.e. no systematic errors. There is tantalizing evidence that the initial spectrum of fluctuations produced by inflation (or whatever) is not a pure power law; if true this would, for the first time, allow us to go beyond the vague predictions of inflation as a scenario and begin to test some specific physical theories of how it happened.

Finally, the WMAP results confirm an earlier result from COBE, that there is surprisingly little structure in the CMB on the very largest scales, measured by the all-sky quadrupole (l = 2) and maybe octopole. This has prompted some fascinating speculation that we do indeed live in a topologically compact universe; but the smoking gun of identical circles on the sky has not (yet) been found.

Figure 2.42: The 2003 observed angular power spectrum of the CMB from WMAP (the black symbols with very small error bars) and a combination of earlier data (the larger red symbols).



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This was a relatively quite year for CMB results. The VSA and the CBI have both released new, more precise measurements which continue to confirm the WMAP results, including the hint of a more complicated initial spectrum of fluctuations than a pure power law. See the VSA press release on the Jodrell Bank web site for more details. Meanwhile, a number of ground- and balloon-based experiments are beginning to take data for detailed studies of the CMB polarization.

The future

WMAP will continue to observe until late 2005, along with more than a dozen ground and balloon-based experiments. Many new results are expected, especially on CMB polarization and the mysterious 'excess' small-scale fluctuations detected by the CBI. At a recent conference on the CMB, Professor Joe Silk of Oxford University chose to deliberately mis-quote Winston Churchill:

"This is not the end. It is not even the beginning of the end. But it is the end of the beginning."