Opening A New Window to the Early Universe

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The big news at the recent Cosmo ’02 workshop in Chicago [1] was the announcement of the first detection of polarization in the cosmic microwave background (CMB), the 2.726 K radiation left over from the big bang [2].

In 1968, Rees predicted that the CMB must be polarized if it is a relic from the early universe [3]. Ever since, astronomers have sought observational evidence. The race for detection heated up after precise measurements of temperature fluctuations [4] provided increased confidence in our ability to understand the CMB. The new discovery, reported by the Degree Angular Scale Interferometer (DASI) collaboration, not only confirms our theoretical grasp of the CMB, but also opens a whole new window to the early universe.

Early-universe cosmology merges the search for new laws of fundamental physics, beyond the standard model of particle physics and Einstein’s gravity, with the search to understand the origin and evolution of the universe. The mean thermal energies of particles in the primordial soup that filled the universe microseconds after a big bang greatly exceed those accessible with our most powerful terrestrial particle accelerators. The early universe thus provides a test bed for new ideas for ultra high-energy physics – if it has left a trace in today’s universe, the big bang’s cosmic debris. Fortunately, a truly pristine cosmological relic exists: the CMB.

To a very good approximation, the temperature of the CMB radiation is the same in all directions in the sky. However, at the level of 1 part in 10⁵, there are small variations. The CMB radiation was emitted ∼14 billion years ago when electrons and nuclei first combined to form atoms, at a time when the universe was only ∼400,000 years old. Thus, the angular temperature variations reflect variations in properties (such as density, pressure, temperature and velocity) of the primordial universe.

The temperature patterns at the CMB surface of last scatter were probably inscribed even earlier, just fractions of a microsecond after the big bang (see Fig. 1). Particle theories suggest that in the extreme temperature that existed then, gravity may have briefly become a repulsive, rather than attractive, force. The enormously accelerated expansion during the ensuing period of “inflation” can explain the remarkable smoothness of the CMB and produce the primordial mass inhomogeneities imprinted in the CMB temperature.

Existing CMB temperature maps allow the temperature power spectrum, which quantifies the size distribution of hot and cold spots, to be determined. Comparisons with predictions of inflation models for primordial inhomogeneities then provide constraints for several cosmological parameters (such as the mass density, the geometry of the universe and its expansion rate). Moreover, the oscillatory pattern seen in the CMB power spectrum [5] confirms that the primordial inhomogeneities are consistent with inflation.

The CMB polarization contains yet more cosmological data than that provided by the temperature maps alone. Most light is unpolarized (the orientation of the oscillating electric field that makes up the electromagnetic wave is random). But light can also be linearly polarized (the field is more likely to oscillate in a given direction). In the CMB, the polarization indicates a direction at the surface of last scatter. However, the polarization amplitude is very small – just ∼7% of the temperature-fluctuation amplitude for the polarization from primordial inhomogeneities. Inflationary models make many predictions for the statistical properties of the polarization [6].

The current DASI results (see the figure) are not yet nearly precise enough to test the inflationary predictions fully, but they are a dramatic first step. They detect the polarization with high confidence (5σ), and the measured amplitude is consistent with that expected.

Far more will be learned with more precise polarization maps. First, the polarization will provide much more precise velocity maps because it is due primarily to the velocity at the surface of last scatter. In contrast, the temperature pattern is due to a combination of the mass inhomogeneity and velocity. Second, the polarization

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provides a test for inflation theories, which predict a unique polarization pattern [7]. Third, polarization might map the mass distribution in the more recent universe through the effects of weak gravitational lensing [8]. The galaxies between us and the surface from which the CMB radiation was emitted induce a gravitational bending of light that leads to an identifiable distortion to the CMB polarization pattern. Finally, polarization with large coherence patches is generated by rescattering of CMB radiation from intergalactic debris produced by the onset of star formation.

DASI has ended a 34-year quest to detect the CMB polarization, sounding the starting gun for a new race to peer further back in time, with more precision than ever before. Many more CMB polarization experiments are in progress or planned. NASA’s recently launched Microwave Anisotropy Probe (MAP) [9] should detect the large-angle polarization induced by early star formation. This should be followed by increasingly precise ground and balloon experiments leading to the Launch of the European Space Agency’s Planck satellite [10] in 2007. If the recent past is any indication, studies of the CMB will continue to advance cosmology, even after Planck.

Figure 1: From smooth to structured. The big bang may have been followed by a period of rapid inflation, during which the resulting “soup” of particles coalesced into nucleons and lighter elements. Matter and radiation eventually became decoupled, the former gravitationally clumping into the structure of the modern universe and the latter yielding the microwave background we see today. The seeds from which galaxies grew should be apparent in the variations in the radiation background.
Figure 2: **Current and future polarization data.** The polarization power spectrum determines the correlation of polarization over patches of sizes indicated on the top axis. (Top curve) Prediction for the polarization from primordial inhomogeneities produced by inflation. The large-angle bump in this curve is the enhancement from early star formation. (Lower curves) Inflationary gravitational-wave and gravitational-lensing signals. These can be distinguished from the larger mass-inhomogeneity signal with geometric properties of the polarization. DASI data points are shown in red. Future experiments will go beyond DASI in sensitivity to detect some of the other signals. We show the data points that experimentalists hope to achieve with some of these new experiments [11].
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