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Beyond the Standard cosmological model with CMB

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Abstract. Measurements of CMB anisotropy and, more recently, polarization have played a very important role in cosmology. Besides precise determination of various parameters of the 'standard' cosmological model, observations have also established some important basic tenets that underlie models of cosmology and structure formation in the universe – 'acausally' correlated, adiabatic, primordial perturbations in a flat, statistically isotropic universe. These are consistent with the expectation of the paradigm of inflation and the generic prediction of the simplest realization of inflationary scenario in the early universe. Further, gravitational instability is the established mechanism for structure formation from these initial perturbations. Primordial perturbations observed as the CMB anisotropy and polarization is the most compelling evidence for new, possibly fundamental, physics in the early universe. The community is now looking beyond the parameter estimation of the 'standard' model, for subtle, characteristic signatures of early universe physics.

Keywords : cosmology – cosmic microwave background – early universe

The 'standard' model of cosmology must not only explain the dynamics of the homogeneous background universe, but also satisfactorily describe the perturbed universe – the generation, evolution and finally, the formation of large scale structures in the universe.

The transition to precision cosmology has been spearheaded by measurements of CMB anisotropy and, more recently, polarization. Our understanding of cosmology and structure formation necessarily depends on the rather inaccessible physics of the early universe that provides the stage for scenarios of inflation (or, related alternatives). The CMB anisotropy and polarization contains information about the hypothesized nature of random primordial/initial metric perturbations – (Gaussian) statistics, (nearly scale invariant) power spectrum, (largely) adiabatic vs. iso-curvature and (largely) scalar vs. tensor component. The 'default' settings in brackets are motivated by inflation.

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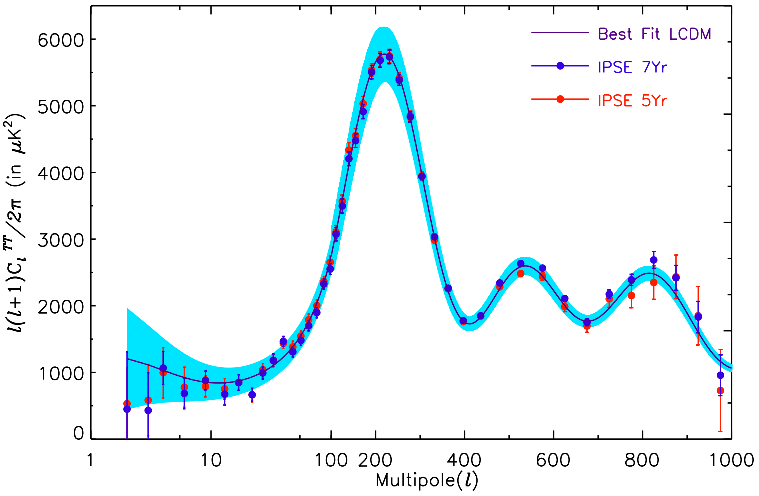

Figure 1. The angular power spectrum estimated from the multi-frequency five and seven year WMAP data. The result from IPSE a self-contained model free approach to foreground removal [6] matches that obtained by the WMAP team. The solid curve showing prediction of the best fit power-law, flat, ΛCDM model threads the data points closely.[Fig. courtesy: Tuhin Ghosh]

The angular power spectrum of the Cosmic Microwave Background temperature fluctuations ($C_\ell^{\rm TT}$)have become invaluable observables for constraining cosmological models. The position and amplitude of the peaks and dips of the $C_\ell^{\rm TT}$ are sensitive to important cosmological parameters, such as, the relative density of matter, Ω_m; cosmological constant, Ω_Λ; baryon content, Ω_B; Hubble constant, H_0 and deviation from flatness (curvature 'density'), Ω_K.

The angular spectrum, $C_\ell^{\rm TT}$, has been measured with high precision on up to angular scales ($\ell \sim 1000$) by the WMAP space mission [1], while $C_\ell^{\rm TT}$ at even smaller angular scales have been measured (at somewhat coarse multipole space resolution) by ground and balloon-based CMB experiments such as ACBAR, QuaD and ACT [7, 8]. These data are largely consistent with a ΛCDM model where the Universe is spatially flat and is composed of radiation, baryons, neutrinos and, the exotic, cold dark matter and, at present, dominated by the cosmological constant. Figure 1 shows the angular power spectrum of CMB temperature fluctuations obtained from the 5 & 7-year WMAP data [6]. Most recent estimates of the cosmological parameters are available and best obtained from recent literature, eg. Ref.[1] and, hence, is not given in the article.

One of the firm predictions of this working 'standard' cosmological model is a linear polarization pattern (Q and U Stokes parameters) imprinted on the CMB at the last scattering surface. The polarization pattern on the sky can be decomposed in the two kinds, E–(gradient) mode and B– (curl) mode. For Gaussian CMB sky four power spectra that characterize the CMB signal :

$C_\ell^{\rm TT}, C_\ell^{\rm TE}, C_\ell^{\rm EE}, C_\ell^{\rm BB}$. The expected absence of parity violating physics rule out, $C_\ell^{\rm TB}$ & $C_\ell^{\rm EB}$ in usual considerations, however, these are potential probes of exotic parity violating phenomena. The CMB polarization spectra complement $C_\ell^{\rm TT}$ by isolating the effects at the last scattering surface from that along the line of sight. Also $C_\ell^{\rm EE}$ provide an important test on the adiabatic nature of primordial scalar fluctuations. A clear evidence of adiabatic initial conditions for primordial density fluctuations is that the compression and rarefaction peaks in the temperature anisotropy spectrum are 'out of phase' with the gradient (velocity) driven peaks in the $C_\ell^{\rm EE}$.

The first detection of $C_\ell^{\rm EE}$ was achieved by the Degree Angular Scale Interferometer (DASI) on ($\ell \sim 200 - 440$) in late 2002 [9]. First full sky E-mode maps are from WMAP [10, 11]. The best measurements of $C_\ell^{\rm TE}$ and $C_\ell^{\rm EE}$ and upper limits on $C_\ell^{\rm BB}$ come from QUaD and BICEP [7, 12]. $C_\ell^{\rm BB}$ is clean probe of early universe scenarios and required sensitivities at tens of nK level pose stiff challenges for ongoing and future experiments.

Besides precise determination of various parameters of the 'standard' cosmological model, observations have also begun to establish (or observationally query) some of the important basic tenets of cosmology and structure formation in the universe. The recent cosmological observations have queried and, in some cases, established fundamental tenets of cosmology and structure [1].:

- **Statistical Isotropy (SI) of the universe:** The *Cosmological Principle* that led to the idealized FRW universe found its strongest support in the discovery of the (nearly) isotropic, Planckian, Cosmic Microwave Background. The exquisite measurement of the temperature fluctuations in the CMB provide an excellent test bed for establishing the statistical isotropy (SI) in the universe. The observed CMB sky is a single realization of the underlying correlation, hence detection of SI violation, or correlation patterns, pose a great observational challenge. The Bipolar harmonic representation of CMB sky is emerging as method of choice for quantifying SI violations [3].

- **Gravitational instability mechanism for structure formation:** Cosmological perturbations excite acoustic waves in the relativistic plasma of the early universe. For baryonic density comparable to that expected from Big Bang nucleosynthesis, acoustic oscillations in the baryon-photon plasma will also be observably imprinted onto the late-time power spectrum of the non-relativistic matter. This has been established (coupled to adiabaticity from CMB polarization results) through measurements of the subtle Baryon Acoustic Oscillations (BAO) in large galaxy surveys [4].

- **Origin of primordial perturbations from Inflation:** What has been truly remarkable is the extent to which recent cosmological observations have been consistent with and, in certain cases, even vindicated the simplest set of assumptions for the initial conditions for the (perturbed) universe.While the simplest generic inflationary models predict that

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[1] Due to the page limit, these sections are not expanded upon in this article, for fuller discussion, see [2]. Citations to work carried out in IUCAA and other important references have, however, been provided.

the spectral index varies slowly with scale, specific physics in a inflationary model can predict strong scale dependent fluctuations. Search for subtle features in primordial power spectrum are being hunted as signatures of new physics [5].

The past few years has seen the emergence of a ‘concordant’ cosmological model that is consistent both with observational constraints from the background evolution of the universe, as well as, that from the formation of large scale structures [13]. The community is now looking beyond the estimation of parameters of a working ‘standard’ model of cosmology. There is increasing effort towards establishing the basic principles and assumptions. The upcoming results from the Planck space mission will radically improve the CMB polarization measurements. There are already proposals for the next generation dedicated satellite mission in 2020+ for CMB polarization measurements at best achievable sensitivity. The next decade would see increasing efforts to observationally test fundamental tenets of the cosmological model and also search for subtle deviations from the same using the CMB anisotropy and polarization measurements and related LSS observations, such as, galaxy surveys and gravitational lensing.

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