Final Performace Report for NASA NAG5-8084 "Primary and Secondary Anisotropies of Cosmic Microwave Background"

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April 26, 2002

This is the final report of NASA NAG5-8084 grant covering the period 3/99-1/02. During this period the PI and collaborators have completed several projects which were supported in part or fully by this grant. Below are described the projects which are most directly related to the proposal topic. Three main topics we proposed to do are linear calculations (continuing development of CMBFAST), nonlinear calculations of gas physics relevant to CMB (Sunyaev-Zeldovich effect etc.) and nonlinear effects on CMB due to dark matter (gravitational lensing etc.). We describe each of these topics below, as well as additional topics PI and his group worked on that are related to the topics in the proposal.

Linear calculations:

Together with Matias Zaldarriaga PI has completed the implementation of closed universe models into the widely used CMBFAST code. The method is based on the line of sight integration over the sources and it is accurate to about 1%. It has become a standard code to use when computing cosmic microwave background (CMB) anisotropies, but until recently did not allow for closed models. The accuracy of the implementation has been carefully tested, specially in the regime around zero curvature, where open, flat and closed versions of the code agree with each other with sufficient accuracy to make the interpolation between them smooth, achieved at the required 1% level of accuracy. PI also implemented the more accurate recombination model developed by Saeger, Sasselov and Scott (1999). There have been many additional improvements of the code, including making it faster, making it parallel, allowing for newly proposed theoretical models (warm dark matter, tilted models, quintessence etc.) etc. Reference: M. Zaldarriaga and U. Seljak, "CMBFAST for spatially closed universes", ApJS 129, 431 (2000).

A postdoc, Sergei Bashinsky, has worked on the dynamics of CMB. Together with Ed Bertschinger they demonstrated that the linear dynamics of cosmological perturbations can be described by coupled wave equations, allowing their efficient numerical and, in certain limits, analytical integration in real space with the Green's function method. Prior to photon decoupling, neglecting neutrino perturbations, and taking isentropic (adiabatic) initial conditions, the Green's functions for all metric, density, and velocity perturbations vanish beyond the acoustic horizon. A localized primordial cosmological perturbation expands as an acoustic wave of photon-baryon density perturbation with narrow spikes at its acoustic wavefronts. These spikes provide one of the main contributions to the cosmic microwave background radiation anisotropy on all experimentally accessible scales. Due to the gravitational interaction between cold dark matter and baryons, the CMB temperature Green's function has a central dip, responsible for the acoustic peak heights alternation pattern. The diffusive corrections due to finite photon mean free path smear the sharp features in the photon and baryon density Green's functions over the scale of Silk damping. This work was submitted to Phys.Rev.D.

Nonlinear calculations: dark matter

With B. Jain and S. White PI has developed a method to ray trace through cosmological N-body simulations to produce maps of weak lensing. These maps of a few degree in size are useful for upcoming weak lensing observations from deep exposures on large telescopes, as well as from weak lensing distortions of CMB. It was shown that the power spectrum can be measured accurately from realistically noisy data on scales corresponding to 1-10 Mpc/h. Reference: B. Jain, U. Seljak and S. White, "Ray Tracing Simulations of Weak Lensing by Large-Scale Structure", ApJ 530, 547 (2000).

With M. Zaldarriaga PI has shown that clusters of galaxies induce step-like wiggles on top of the CMB. The direction of the wiggle is parallel to the large scale gradient of CMB allowing one to isolate the effect from other small scale fluctuations. The effect is sensitive to the deflection angle rather than its derivative (shear or magnification) and is thus tracing outer parts of the cluster with higher sensitivity than some other methods. A typical amplitude of the effect is $10\mu K(\sigma_v/1400kms^{-1})^2$ where σ_v is the velocity dispersion of the cluster and several μK signals extend out to a fraction of a degree. Detection of this effect is within reach of the next generation of small scale CMB telescopes and could provide information about the cluster density profile beyond the virial radius. Reference: U. Seljak and M. Zaldarriaga, "Lensing Induced Cluster Signatures in Cosmic Microwave Background", ApJ, 538, 57 (2000).

J. Guzik, PI and M. Zaldarriaga have investigated the gravitational lensing effect on the CMB polarization. Specific combinations of Stokes Q and U parameters were identified that correspond to spin 0,$\pm$2 variables and can be used to reconstruct the projected matter density. The expected signal to noise was computed as a function of detector sensitivity and angular resolution. With Planck satellite the detection would be at a few σ level. Several times better detector sensitivity would be needed to measure the projected dark matter power spectrum over a wider range of scales, which could provide an independent confirmation of the projected matter power spectrum as measured from other methods. Reference: J. Guzik, U. Seljak and M. Zaldarriaga, "Lensing effect on polarization in microwave background: extracting convergence power spectrum", PRD 6204, 3517 (2000).

PI, together with D. Holz, has investigated the magnification distribution of high redshift supenovae, which can be a powerful discriminator between smooth dark matter and dark matter consisting of compact objects. Using high resolution N-body simulations in combination with the results of simulations with compact objects the magnification distribution was determined for a Universe with an arbitrary fraction of the dark matter in compact objects. Using these distributions the number of type Ia SNe required to measure the fraction of matter in compact objects was determined. It was shown that it is possible to determine a 20% fraction of matter in compact objects with 100-400 well measured SNe at $z \sim 1$. Reference: U. Seljak, D. Holz, Astronomy and Astrophysics Letters, 351, L10 (1999).

Nonlinear calculations: gas physics

With graduate student J. Burwell and U. Pen PI wrote a paper on Sunyaev-Zeldovich (SZ) effect from hydrodynamical simulations. They ran several popular cosmological models and produced simulated maps for them. Several statistics have been applied to these maps, including mean, power spectrum and one-point distribution function. They have also been correlated with the external maps, such as those from weak lensing or galaxy catalogs. Reference: U. Seljak, J. Burwell and U. Pen, "Sunyaev-Zeldovich effect from hydrodynamical simulations: maps and low order statistics", PRD, 6306, 3001 (2001).

With a postdoc, E. Komatsu, PI investigated analytic models of galaxy clusters that are routinely observed in X-rays and will be observed in SZ. They showed that such models, based on dark matter distribution found in simulations, can be useful in describing the nature of clusters and should superseed the models that are often adopted to describe these observations. In particular, the models developed show that observations are in a good agreement with theoretical predictions of CDM models. This model should be particularly useful to predict SZ observations, which are more sensitive to the outer parts of the cluster, where deviations from isothermal temperature profile and so called β-profile of intensity are important. Work currently in progress extends this work by comparing the analytical models to hydrodynamical simulations. This comparison is important since different simulations do not agree with each other, but it is not clear whether this is because of differences in models or in the simulations themselves. We find a good agreement between simulations once they are adjusted for the differences in cosmological parameters, with the residuals at a level of less than 10% in overall amplitude of primordial fluctuations. Reference: E. Komatsu and U. Seljak, "Universal gas density and temperature profile", MNRAS, 327, 1353 (2001).

In a separate publication PI used empirical determinations of cluster mass-cluster temperature relation to determine the amplitude of fluctuations extracted from the local abundance of galaxy clusters as a function of the density parameter. He showed that this approach leads to a lower amplitude than previously obtained, which is in a.good agreement with the other independent methods such as CMB or Lyman alpha forest observations. This result has implications for the proposed SZ observations, which are mostly sensitive to the amplitude of fluctuations and less to the density of the universe. This work has been submitted for publication in MNRAS.

Another postdoc, Patrick McDonald, together with Jordi Miralda-Escudé, and Renyue Cen investigated gravitational evolution of primordial density perturbations, which leads to fluctuations in the neutral hydrogen density in the intergalactic medium, which are observed through their Lyman-α absorption in high-redshift quasar spectra. This fluctuating absorption is called the Lyman-α forest. They presented predictions, based on simulations of structure formation in Cosmological Constant plus Cold Dark Matter models, for the correlation between the Lyα forest absorption and the mass within $\sim 5h^{-1}$Mpc (comoving). Observations of galaxies near quasar lines of sight where the Lyα forest is observed can be directly compared to our predictions. These comparisons should provide tests of our ideas on the nature of the Lyα forest, the relation between galaxies and mass, and the power spectrum of the primordial density perturbations. This will improve our understanding of gas physics at high redshift in general and its influence on the secondary sources of CMB (SZ, point sources...). This work was submitted for publication to ApJ.