OBSERVATION OF THE COSMIC MICROWAVE BACKGROUND ANISOTROPY

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ABSTRACT

Recent precise observations of the cosmic microwave background (CMB) isotopy and experiments in progress are summarized. The current measurements on all angular scales are approaching sensitivities of the order of $\Delta T/T \approx 10^{-5}$. Nearly all experiments are observing positive detections. Most assume the detection to be due to galactic emission or other foregrounds or systematics and not due to primordial anisotropies in the CMB. The context and significance of these observations are discussed.

1. INTRODUCTION

In standard cosmology, the Big Bang theory, the cosmic microwave background (CMB) is the relic radiation from the hot early universe. It is generally thought that the CMB last interacted significantly with matter by Thompson scattering at a redshift near 1100 ($\pm 4\%$ rms) when the universe was roughly 300,000 years old. At this time there are a number of angular scales (projected comoving sizes) that are naturally significant. One is the particle horizon size, the region of causal connectivity, for a matter or radiation dominated universe. It is roughly three times the speed of light times the age of the universe at last scattering and corresponds to an angle of about 1 to 2 degrees on the sky. This corresponds to about 100 to 200 Mpc in present physical size. Any structure observed on the surface of last scattering with angular size larger than a few degrees has been out of causal contact with itself since the very earliest times and must have been generated in those early times during the era of quantum cosmology.

The next scale of interest is the horizon size at the time of matter and radiation equality. That corresponds to a current physical size of approximately $13(\Omega_o h^2)^{-1}$Mpc, where $h = H_o/100kms^{-1}Mpc^{-1}$ and H_o is the current value of the Hubble constant and Ω is the ratio of the density of the universe to the critical density. This physical size corresponds to an angle of approximately $8h^{-1}$ arcminutes. This is the natural scale of structure formation.

This angular scale also happens to be about the range of one optical depth for Thompson scattering at a redshift of 1100. Thus objects smaller than about 8 arcminutes (0.1 degrees) are blurred by the finite thickness of the surface of last scattering. Anisotropies on much smaller scale are expected to arise from foreground effects rather than at the surface of last scattering.

The causes of anisotropy versus angular scale are illustrated in figure 1. Large angular scale anisotropies are due to primordial fluctuations in the universe and manifest themselves through the Sachs-Wolfe (primarily gravitational redshift) mechanism. On intermediate angular scales ($0.1 < \theta < 2$ degrees) the dominant effect tends to be CMB

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Doppler shift from scattering with matter falling into density perturbations, while on the smaller scales scattering washes out these effects and the Rees-Sciama effect produces the anisotropy. Other effects and foreground objects lead to anisotropies and some of these are also indicated in Figure 1.

2. OBSERVATIONS

Many experiments have been performed to measure the anisotropy of the CMB. The recent results are also displayed in Figure 1.

The observed signal is comprised of components from the cosmic microwave background, from Galactic synchrotron, bremsstrahlung and dust emission, from atmospheric emission, and from instrument sidelobes seeing the ground. Galactic contributions are separated by comparing sky maps at multiple wavelengths and fitting models. The wavelength range from 0.1 to 1 cm provides the best window in galactic emission between the falling synchrotron and bremsstrahlung and rising dust emission. One must also be concerned about unresolved sources (Franceschini et al. 1989) which fortunately also point to this wavelength range. Still for small angular scale observations, the experimenter must select the region to be observed carefully.

The anisotropy experiments divide into types according to angular scale. Atmospheric variation is quite significant on large angular scales or short wavelengths so that those observations are done by satellite (*COBE* & Relict) or balloon-borne instruments. At medium angular scale the atmosphere is still very troublesome and the measurements are made either from balloons or from high, dry sites (Antarctica, northern Canada in the winter). Only the small and fine scale experiments can be done from more conventional radioastronomical ground-based sites. This is fortunate because diffraction dictates the size of the receiving aperture is inversely proportional to the observing wavelength times angular scale. Thus the size of the instrument is inversely proportional to the distance it must be away from a conventional site.

2.1 Large Angular Scale Observations:

Observations of the large angular scale isotropy of the CMB began with its discovery by Penzias and Wilson in 1965. Limits improved over time and the dipole anisotropy (at the 10^{-3} level) was detected by aircraft (Smoot, Gorenstein, and Muller 1977) and balloon-borne (Cheng, et al. 1979) detectors. Detectors and limits have continued to improve and the current best limits are from new balloon-borne measurements (Meyer, Cheng, & Page 1991; Boughn et al. 1991) and satellite-based instruments (Relict: Strukov et al. 1988; and *COBE*: Smoot et al. 1990, 1991). The *COBE*-DMR instrument continues to operate and the noise continues to average down with time. These instruments have produced full sky maps at multiple frequencies. This provides the means to separate the potential CMB anisotropies from the foreground galactic and celestial emissions.

Other than the dipole and galactic emission there is no evidence for any other features in the sky maps. The observations place a limit of $\Delta T/T < 3 \times 10^{-5}$ (95% C.L.) on any rms quadrupole and $\Delta T/T < 2 - 4 \times 10^{-5}$ (95% C.L.) on any rms multipole, Y(l,m), with $\theta >$ 7 degrees (using T=2.73K). The limit on the corresponding correlation function $C(\alpha) < 0.01 mK^2$ (95% C.L.). For a more restricted range the correlation function is less than 0.005. The experiments continue to operate or be upgraded so that one can expect improved CMB anisotropy observations and thus cosmological limits.

2.2 Medium Angular Scale Observations:

On medium angular scale the best observations have been made from special ground-based sites and by balloon-borne instruments. Recent observations from

Antarctica (Meinhold and Lubin 1991) have currently published the best results ($\Delta T/T < 3.5 \times 10^{-5}$ 95% C.L. on about the 1/2 degree angular scale) and along with the measurements from Saskatchewan (Timbie and Wilkinson 1990) have shown that carefully selected sites in very low humidity locations make viable observing sites. The South Pole and the high antarctic plateau are particularly attractive possibilities (see The Development of Antarctic Astronomy this volume for site and observational information and CARA - The Center for Astrophysical Research in Antarctica). Davies is reporting the observations from Tenerife (Davies et al. 1987; Davies 1991).

Balloon-borne efforts have also progressed quite well in this angular scale. A Center for Particle Astrophysics collaboration (Alsop, et al. 1991, Fischer, et al. 1991), the Rome group (de Bernardis et al. 1988), and an MIT-Goddard Space Flight Center collaboration are all working in this range and are enlarging the wavelength range of observations and limits.

Nearly all these experiments report positive detections at the level of about $\Delta T/T \approx 2 \times 10^{-5}$. The experimenters are very careful to point out that the signal may be due to galactic or other foreground emission or due to systematic effects. The experimenters tend to lean away from claiming CMB anisotropy detection.

2.3 Small and Fine Angular Scale Observations:

Small angular scale observations are done with large to very large telescopes. The smallest telescope is roughly 5.5-m in diameter and the current largest telescope used is the VLA though we can expect observations to be made with the VLBI array when it is available. The CalTech-Owens Valley group (Readhead et al. 1989, Myers, et al. 1991) have used a 40-m dish to survey a set of 96 points on a ring with errors of about 100 μK. They have made a systematic set of observations of the Sunyaev-Zeldovich effect (Birkinshaw et al. 1991) and begun observations with a 5.5-m diameter dish. These significantly improve on previous SZ effect work and upon the previous best solid dish small angular scale CMB anisotropy observations (Uson and Wilkinson 1984).

Two groups have used the VLA for CMB anisotropy measurements (Fomalant et al. 1988, Partridge 1986, 1991). Both groups have gotten significant limits on the smallest angular scale as shown in Figure 1. Uson has continued his studies of the CMB into this area by testing Hat Creek VLB observatory as a possible instrument.

3. SIGNIFICANCE FOR THEORY

Through a large and systematic program by many groups, observers have searched for CMB anisotropies and set limits on the isotropy on angular scales from 0.1 arcmin (6 arcsec) to full sky maps with resolution of a few degrees. These limits are such that they severely constrain theory and paradigms of what has happened in the early to modern universe. The first and most obvious result has been the forcing of cosmologists to abandon the model of a simple universe evolving without new physics or non-baryonic matter. The CMB isotropy was the major driver for the adoption of the cold dark matter model and the inflationary paradigm.

Standard cold dark matter models estimate the amplitude of temperature fluctuations to be $\approx 10^{-5}$ on medium to large angular scales (Bond & Efstathiou 1984). Likewise analysis of large scale velocity flows (Gorski 1991; Bertschinger et al. 1991) show that the fluctuations must be on the same approximate scale. New measurements of the galaxy correlation function extending into this angular scale are interpreted as requiring a somewhat greater amplitude (Efstathiou, Sutherland, & Maddox 1990; Maddox, Efstathiou, Sutherland, & Loveday 1990). The anisotropy observations show the amplitude to be $\Delta T/T < 3 \times 10^{-5}$ at 95% C.L. and do not see the extra power expected in the 1 degree angular scale. The measurements are nearing the minimal level predicted, thus while not in direct contradiction, these results indicate that the primordial fluctuations are small and that future measurements will directly confront current models.

The quadrupole CMB anisotropy limits mean the current energy density of long-wavelength (λ_{GW}) gravity waves relative to the critical energy density of the universe to $\Omega_{GW}<5\times10^{-3}(h\lambda_{GW}/1\ Mpc)^{-2}$. The anisotropy limits rule out significant rotation of the universe (Collins & Hawking 1973). A typical limit on the rotation rate ω_o divided by the expansion rate is $\omega_o/H_o<10^{-6}$.

The smoothness of the sky maps restricts the possible range of topological defects such as cosmic strings, domain walls, and textures that might be the non-linear seeds for galaxy and cluster formation to the point that the latter two are effectively ruled out.

The limits on anisotropy on all scales is strong support for the inflationary paradigm or some mechanism in quantum cosmology which homogenizes and isotropizes the early universe. The universe very well described by the Robertson-Walker metric with a very uniform rate of expansion in all directions. We have yet to discover the primal seeds that lead to galaxy formation. The generally accepted picture of structure formation is gravitational instability: "There are small initial perturbations which first grow linearly and then non-linearly to collapsed objects such as stars, galaxies, clusters of galaxies and quasars, and perhaps great walls." How will we reconcile this picture with a universe which on the largest scales is so stable against gravity, while astronomers discover larger and larger structures?

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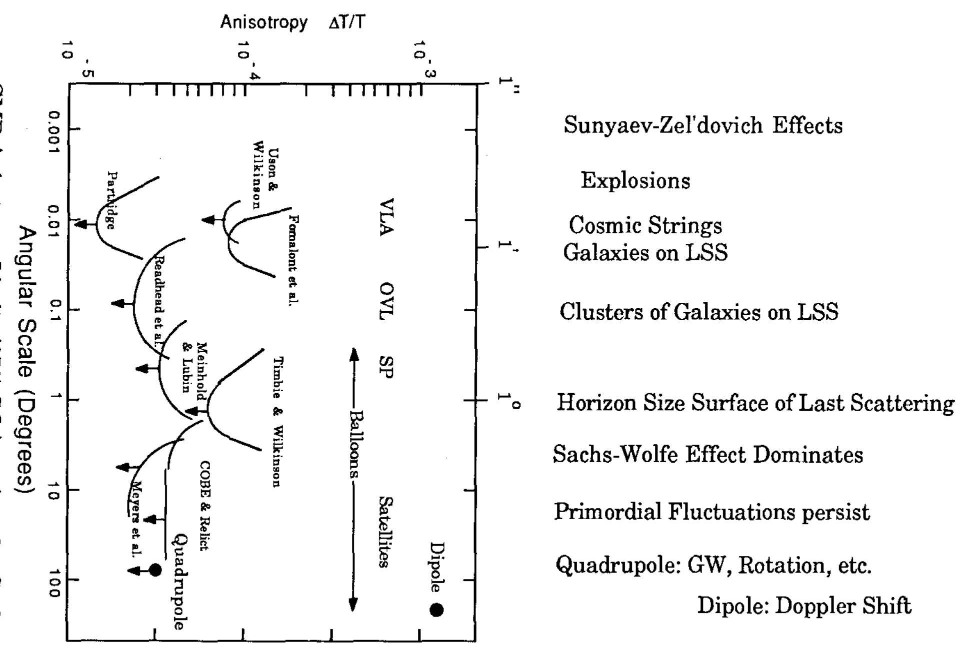

CMB Anisotropy Limits (95% C.L.) vs. Angular Scale

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