ANISOTROPY IN THE COSMIC MICROWAVE BACKGROUND: PRESENT STATUS-FUTURE DIRECTIONS

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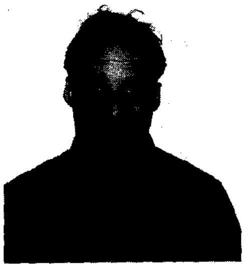

Measurments of the cosmic microwave background (CMB) stand as one of the experimental pillars of modern cosmology. In particular, anisotropy measurments of the CMB have been shown to be very powerful tests of theories which attempt to explain the origin, evolution, matter content, and geometry of the Universe. When anisotropy measurements are combined with maps of the galaxy distribution, they can also be used to gain information about the origin of large scale structure in the Universe. Since the detection of anisotropy by the Cosmic Background Explorer (COBE) satellite,[1] there has been a concerted effort to measure anisotropy at higher angular resolution with particular emphasis on medium/degree angular scales. In this talk, the scientific motivation behind these measurements is reviewed, a summary of the medium angular scale measurements is presented, and a description of some of the future experiments is given.

INTRODUCTION

Studies of the cosmic microwave background (CMB) form one of the three observational pillars of modern cosmology - the other two being the expansion of the Universe and the agreement between the predicted and observed primordial element abundances. The CMB offers a unique "snapshot" of the Universe at a very early age and can be studied by measuring its spectrum, polarization, and spatial distribution (anisotropy). This talk concentrates on anisotropy measurements with particular emphasis on degree-scale anisotropy measurements. The introduction presents the non-expert with some of the field-specific terminology and formalisms which are helpful in understanding why CMB measurements are interesting and how the results are quantified and compared. The main body of the talk focuses on the current status and future directions of CMB anisotropy measurements.

Why Measure CMB Anisotropy?

Measurements of CMB anisotropy give us information about the Universe when it was much younger and much simpler. In the standard Hot Big Bang model, photons and matter were in thermodynamic equilibrium until the Universe had expanded and cooled enough so that free electrons could "recombine" with protons to form atomic hydrogen. At this time (about 300,000 years after the Big Bang) the cross section for scattering photons changed from a Thomson cross section to Rayleigh cross section. Due to this transition in the photon scattering cross section, the mean free path of the photons increased to the horizon size and allowed the photons to "free stream" to us today. Any initial perturbations in the gravitational potential or subsequent variations in the energy density (adiabatic fluctuations) or the equation of state (isocurvature fluctuations) would leave an imprint on the CMB. The fluctuations are often characterized by their type (scalar or tensor) and the production mechanism (adiabatic, isocurvature). A general outcome of the inflationary model is that the initial density flucuations are Gaussian and they would produce CMB anisotropies which could be described by a 2D Gaussian random field. Several alternatives to this include cosmic string and texture models which would produce non-Gaussian signatures in the CMB. By measuring CMB anisotropy, we can begin to understand the type of fluctuations and the mechanisms that caused these fluctuations. Since these depend on the matter/energy content, the expansion rate, and the thermal history of the Universe, we can glean information about the cosmological parameters which describe the origin, evolution and geometry of the Universe. For a more complete description of the theoretical background, refer to the accompanying article by D. Spergel.

How Are CMB Anisotropy Results Quantified And Compared?

Since anisotropy measurements of the CMB temperature are taken on the celestial sphere, it is natural to expand the radiation temperature pattern in spherical harmonics for which,

$\frac{\Delta T(\widehat{n})}{T_0} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\widehat{n})$, where $T_0 = 2.726 \pm 0.01K$ is the temperature of the CMB monopole[2] and the $a_{\ell m}$'s are the multipole amplitudes. Assuming rotational invariance, the CMB radiation power spectrum, C_ℓ, is given in terms of the ensemble average of the product of the $a_{\ell m}$'s, $\langle a_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell\ell'}\delta_{mm'}C_\ell$. Any Gaussian model is completely specified in terms of the C_ℓ's. Power spectra can also be derived for non-gaussian models; however, unlike the Gaussian case, the power spectra do not contain all the information since the phase information is also required. The power spectrum can be extracted from the experimental two point correlation function which is given by

$$C_{exp}(\widehat{n}_i \cdot \widehat{n}_j) = \left\langle \frac{\Delta T(\widehat{n}_i)\Delta T(\widehat{n}_j)}{T_0^2} \right\rangle = \frac{1}{4\pi}\sum_{\ell=2}^{\infty}(2\ell+1)C_\ell W_\ell(\widehat{n}_i, \widehat{n}_j) \quad (1)$$

where $W_\ell(\widehat{n}_i, \widehat{n}_j)$ is the experimental window function[3] which quantifies an experiment's sensitivity to a given multipole moment. One measure of CMB anisotropy amplitude is the "band power estimate".[4] This effectively renormalizes the root mean square (rms) amplitude and allows for a straightforward comparison of experimental results which is independent of the experimental window function. Figure 1 shows a variety of COBE normalized theoretical power spectra compared to band power estimates (or limits) for many of the recent CMB anisotropy measurements. The only assumption that needs to be made for this estimate to be accurate is that the underlying power spectrum is relatively flat over the width of an experiment's window function. For a wide range of theoretical power spectra and for many of today's experiments, this is a good assumption. In order to calculate the band power estimate, a theoretical model which specifies the C_ℓ's must be assumed. Often a "flat" radiation power spectrum[5] given by $C_\ell = (24\pi/5)(Q_{flat}/T_0)^2/(\ell(\ell+1))$ (where $Q_{flat} = Q_{rms-PS}$ for an n=1 primordial density fluctuation index) is assumed. Q_{flat} is determined using a likelihood analysis to give the best band power estimate. For anisotropy measurements which have made maps of the CMB (such as COBE and the Far Infrared Survey(FIRS)), additional information such as the slope of the power spectrum can be determined. As the medium and small angular scale experiments broaden their window functions, specific features of the CMB power spectrum may well be extracted.

CURRENT STATUS

Since the announcement of detection of CMB anisotropy by the COBE team,[1] there has been an explosion of new results on all angular scales. At the largest angular scales, several groups have claimed to confirm the COBE results. A review of the COBE results is given in an accompanying article (C. Lineweaver) while the FIRS[6] and the Tenerife[7] (Ten) experiments have each presented data which is consistent with the basic COBE results. At the smallest angular scales, the majority of the results are claiming upper limits on CMB anisotropy. The results from the single dish experiments of the Owens Valley Radio Observatory[8,9] (OVRO)

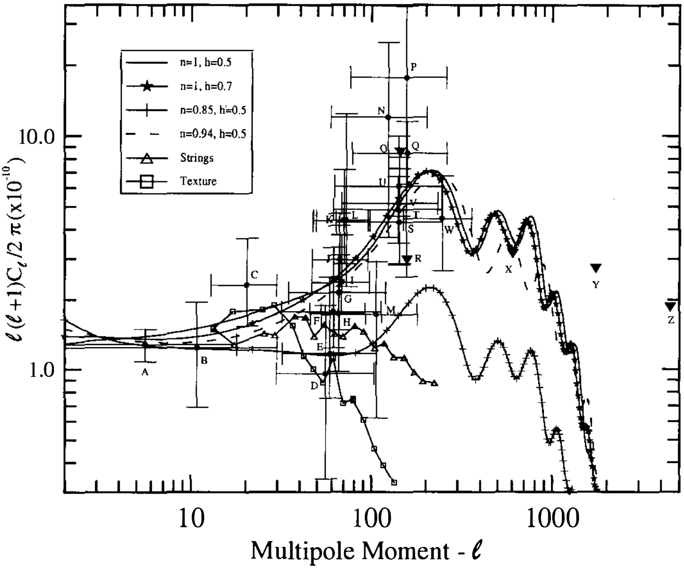

Figure 1: The current status of CMB anisotropy measurements given as band power estimates compared to a variety of COBE normalized theoretical power spectra. Vertical error bars are 1 σ errors on the band power, the horizontal bars delimit the half peak points of the experimental window function, and triangles are 95% confidence level upper limits. Abbreviations and references for each of the experiments are given in the text, and theoretical power spectra were provided by P. Steinhardt.[13] A)COBE, B)FIRS, C)Ten, D)SP91-Comb, E)SP94-Ka, F)SP94-Comb, G)SP94-Q, H)SK93-Ka, I)SK-Comb, J)SK94-Ka, K)SK94-Q, L)Python, M)ARGO, N)IAB, O)SP89, P)MAX2-GUM, Q)MAX3-GUM, R)MAX3-MP, S)MAX4-SH, T)MAX4-ID, U)MAX4-GUM, V)MSAM2, W)MSAM3, X)WD, Y)OVRO, Z)ATCA.

and the White Dish[10] (WD) experiments place limits on anisotropy at arcminute angular scales, and the interferometric measurements from the Australia Telescope Compact Array[11] (ATCA) and the Very Large Array[12] (VLA) place limits at the 10's of arc second scales. The majority of the recent results have come from the medium angular scales where there has been at least 10 seperate claims of detection of CMB anisotropy. In the following we present a compilation and brief description of the medium angular scale measurements in approximate order of decreasing full width at half maximum (FWHM) beam size. In addition, we have also tried to include preliminary announcements of results which have been presented at the Conference on Microwave Background Fluctuations held at the University of California, Santa Barbara on February 22-24, 1995.

Advanced Cosmic Microwave Explorer (ACME)/South Pole - SP

Our group at UCSB has had 3 successful seasons of degree scale measurements from the ground based site at the Amundsen-Scott South Pole station. The initial 1988-89 austral summer measurements[14,15] (SP89) used a 90 GHz SIS receiver on the ACME telescope. A more sensitive Ka-band (25-35 GHz) receiver using a high electron mobility transistor (HEMT) amplifier was used on ACME for our second set of observations[16,17] (SP91). Our most recent set of measurements[18] (SP94) extend on our previous observations with the use of a 3 channel Q-band (38-45 GHz) receiver to add to the 4 channel Ka-band (26-36 GHz) receiver. This additional receiver has allowed better discrimination against many of the possible foreground contaminants. The SP94 data show significant correlated structure between the separate Ka and Q-band observations that has a spectrum which is consistent with a CMB spectrum. The SP94 analysis also presents a reanalysis of the SP91 data which accounts for the correlated noise between the channels.

Big Plate/Saskatoon - SK

Big Plate is a ground based experiment which operates from Saskatoon, Canada. This experiment was first run in 1993[19], and used a HEMT receiver operating at 3 bands between 26 and 36 GHz (Ka-band) in two orthogonal polarizations and had a 1.44° FWHM beam. This initial observation detected significant structure which has a spectrum consistent with a CMB spectrum. This observation was repeated in 1994 with the original Ka-band receiver in addition to a Q-band receiver which observed at 3 additional bands between 36 and 46 GHz[20] with a FWHM of 1.04°. The original structure was confirmed with these observations and better constraints were placed on the radiometric spectral index of the observed structure. Additional measurements are now underway with a smaller beamsize and an 8° throw which should allow for a good measurement of the band power in addition to the slope of the CMB power spectrum at medium angular scales.

ARGO

ARGO is a balloon borne, bolometric experiment[21] which has flown once from Italy to Spain. This experiment has a 52' beam and has 4 frequency bands centered at 150, 250, 375, and 600 GHz. ARGO observed significant structure in a relatively low foreground region in the Hercules constellation which had a spectrum consistent with a CMB spectrum. Unfortunately, ARGO crashed upon landing in Spain and will not fly again.

Italian Antarctic Base - IAB

The IAB experiment[22] operated for 17 days during the 1991-92 austral summer from the IAB site at Terra Nova Bay. This is a ^{3}He cooled bolometer system which has a 50' FWHM beam and operates at a single frequency band centered at 140 GHz. This experiment measured significant strucure which could not be correlated with IRAS dust; however, because it is a single frequency measurement, this experiment cannot discriminate against astrophysical foregrounds using spectral arguments.

Python

Python is a ground based, bolometric system which is operated from the Amundsen-Scott South Pole station. This experiment utilizes a 4 element focal plane array of single mode corrugated scalar feeds which each operate at a center frequency of 90 GHz and each have a 45' FWHM beam. This experiment first claimed a detection after the 1992-93 austral summer of observations[23)] and has since confirmed the observation with additional measurements during the 1993-94 austral summer. Much more sky coverage has been obtained during the 1994-95 season and increased frequency coverage will be available with the use of a lower frequency HEMT based receiver. A large amount of data may soon be available with a successful completion of South Pole winter over measurement using a HEMT receiver.

Millimeter-wave Anisotropy Experiment - MAX

MAX is a collaboration between UCSB and UC Berkeley which uses the ACME telescope in a balloon borne, bolometric experiment.[24)] We have had 5 successful flights between 1989 and 1994. In its various incarnations, MAX has had either 3 or 4 different frequency channels operating at center frequencies ranging from 90 to 450 GHz with FWHM beam sizes of 0.5° to 0.75°. MAX has observed anisotropy near the star Gamma Ursa Minor (GUM) in 3 different flights[25,26,27)] and in 2 other low foreground regions[28)] near the stars Iota Draconis (ID) and Sigma Herculis (SH). In the third flight a moderate dust region near the star Mu Pegasi (MP) was also observed[29)] and the observed structure corrlated well with the IRAS 100 micron map. Since the residual CMB component of the MP scan was low compared to other MAX observations, this region was observed a second time during the fifth flight of MAX in addition to two other low foreground regions[30,31)].

Medium Scale Anisotropy Measurement - MSAM

The MSAM experiment is also a balloon borne, bolometric experiment which has had two successful flights since 1992. This experiment uses the same 4 channel radiometer as was used in the FIRS experiment (with modified internal optics) and has a 0.5° beam. The first flight of this experiment[32)] observed significant structure with a spectrum consistent with a CMB spectrum. Two unresolved sources which contributed much of the observed signal were left out of the initial analysis for fear of foreground contamination. Since the initial measurement, a high resolution measurement[33)] has ruled out the possiblity of a source smaller than 2' in one of the fields and simulations[34)] have shown that the MSAM features are in agreement with a standard CDM model. Thus, the initial removal of sources is considered incorrect and the subsequent CMB signal is higher than initially reported. The analysis of the second flight is underway and shows structure which is very similar to the structure observed during the first flight. A third flight of the system will occur during the 1995 summer, and a fourth flight will occur during the summer of 1996 using a receiver with lower frequency bolometers.

FUTURE DIRECTIONS

Over the last 10 years, there has been a rapid increase in detector sensitivity. If a comparison is made between today's space qualified detectors and those which are aboard COBE, there has been an increase of 40-100 in detector sensitivity. This has given the CMB community a realizable goal of mapping large regions (or the full sky) at much smaller angular scales than COBE. A wide variety of factors such as receiver sensitivity, frequency coverage, foreground contamination, minimization of systematic effects, beam size, observation strategy and sky coverage affect the direction of future experiments. With this many considerations, it has become quite clear that no single experiment will be able to extract all the information which is presumably imbedded in the CMB radiation power spectrum. Rather, a variety of experiments using both HEMT-based and bolometric receivers operating over a wide range of frequencies and angulars scales will be needed to accurately characterize the shape of the CMB radiation power spectrum. In the following, a summary of some of the future experiments which are being developed (or proposed) is given. For clarity, these are divided into ground based, balloon borne and space based experiments.

Ground Based Measurements

Ground based measurements have a unique advantage over balloon borne or satellite measurments in that large single dishes or interferometric arrays can be used to study small scale CMB anisotropies. The size and cost constraints restrict balloon and space based experiments to angular scales greater than 10' corresponding to $\ell's < 1000$. Smaller scales have been under study for quite some time by the OVRO, ATCA, and VLA groups and are expected to continue into the future. The medium angular scale, ground-based measurements from Saskatoon and the South Pole are also expected to continue over the next several years. If the South Pole experiments can be made to run continuously through large fractions of the year, much larger regions of the sky could soon be measured. The challenge of medium scale ground based measurements is to make maps over large regions in which the large angular scale and small angular scale information is retained. This may prove to be difficult if not impossible due to the atmosphere. One possible solution to this is the development of medium angular scale interferometric systems which are less susceptible to atmosphere. Several of these are either operating, such as the Cosmic Anisotropy Telescope(CAT), or are in the process of being built (33 GHz Interferometer)[35]. The Very Small Array (VSA) and the Cosmic Background Imager

(CBI) are two more ambitious projects which have been proposed to map anisotropies from 10'-2° (for the VSA) and 2'-20' (for CBI)[36]. In addition to being less susceptible to atmosphere, interferometric measurements also afford the luxury of a straightforward method of removing point source contamination, they allow contemporaneous measurements of the more variable flat spectrum radio sources, and any clusters in the field that cause a Sunyaev-Zeldovich decrement could be characterized. The obvious drawback of interferometric measurements is that their sky coverage is rather limited.

Balloon Borne Measurements

The next generation of balloon borne experiments will be quite different than the present generation. The primary motivation behind this change is that the design of the experiments is centered on characterizing the CMB anisotropy rather than just detecting the CMB anisotropy. This has driven the experimenters to consider focal plane array receivers, long duration balloon (LDB) flights lasting 2 weeks and other novel ballooning technologies such as flying on top of balloons and using pressurized balloons for super long duration balloon (SLDB) flights lasting as long as 3 months. All of the proposed next generation balloon payloads can be classified as medium angular scale measurements. At this time, there are at least 5 different groups who are in various stages of developing a new generation of medium scale balloon borne experiments. MAXIMA is a Berkeley-Rome experiment which is designed to be a standard duration (12-48 hrs) payload which incorporates a multi-pixel (4 frequencies/pixel) array of bolometers which are cooled to 100 mK in an adibatic demagnetization refrigerator. BOOMERANG is a Caltech-Berkeley-Rome experiment which will also incorporate a bolometric array for use in a LDB payload. TOPHAT is a Goddard-Chicago-Princeton-Brown LDB experiment which will fly a ^{3}He-cooled, 5 channel bolometric receiver mounted in an optical platform on top of a balloon. QMAP is a Princeton balloon borne experiment which will incorporate a small array operating between 26-90 GHz using an optical configuration similar to the Saskatoon measurements. In the near term, our UCSB group is developing a focal plane array of HEMT amplifiers for use in an LDB flight. In the longer term a lower weight (200 kg) version of our LDB payload (ACE) is intended to fly as an SLDB experiment. Each of these new experiments will use technologies which could be directly applied to a spacecraft. Some of these technologies include the use of focal plane array optics, novel cryogenic systems, new types of bolometric detectors and HEMT amplifiers as well as the use of solar power. The various engineering aspects (such as low weight, low power consumption, and continuous unaided operation) of LDB and SLDB payloads make these experiments a very important proving gound for future space-based experiments.

Satellite Measurements

A satellite mission dedicated to measuring CMB anisotropy at medium angular scales would greatly benefit cosmology and our understanding of the Universe. There are various approaches to designing such a satellite which depend on the cost constraints, size limitations and favored receiver technology. This has given rise to at least three different US groups (Far Infrared Explorer-FIRE, Microwave Anisotropy Project-MAP, and Primordial Structure Investigator-PSI), a large European collaboration (Cosmic Background Anisotropy Satellite/Satellite for Measurements of Background Anisotropies-COBRAS/SAMBA or CO/SA), and the Russian's RELICT-2, each of whom are pursuing satellite missions to measure medium scale anisotropy.

The various US missions are in the proposal writing process, so the details of each of the individual missions have not been publicized. Only broad descriptions are available based on the monetary restrictions (~\$70 million) and the size limitations of the proposed MIDEX launch vehicle. The size limitations of the launch vehicle restrict the diameter of the primary to be less than 2 m. The corresponding smallest acheivable angular scales are at the 10'-15' FWHM level. Each of these missions is expected to propose to place the satellite at Lagrangian Point 2 (L2) where the contaminating Earth shine and thermal considerations are much more favorable than a low Earth orbit. Each of these experiments are expected to reach per pixel sensitivities which are much better than COBE's (with much higher angular resolution) and will cover a large fraction of the sky.

The CO/SA experiment combines the low frequency advantages of HEMTs with the high frequency advantages of bolometers. The low frequency portion of the experiment will consist of a 28 element array of corrugated scalar feed horns which will allow for dual polarization measurements of the CMB at 4 frequencies between 30 and 125 GHz. The HEMTs will be ambiently cooled to 100 K and will surround the bolometric array in the focal plane. The bolometric array will operate at 100 mK and have 4 frequencies between 100 and 800 GHz. The bolometric array will be thermally isolated from the ambiently cooled HEMTs. The FWHM beamsizes of the various frequency bands will range from 3' at the highest frequencies to 30' at the lowest frequencies. The highest frequency channel is not sensitive to the CMB and is used as a dust monitor, so the smallest beamsize which will be sensitive to the CMB will have a FWHM closer to 10'. This will allow for accurate measurements of the multipoles of the CMB from the dipole ($\ell = 1$) to an $\ell \sim 1000$.

The RELICT2 satellite will measure anistropy at degree angulars scales and will operate at 4 frequencies between 20 and 200 GHz. Although this satellite is furthur along than any of the others in it's development, it does not have a firm launch date.

The start of the Student Explorer Development Initiative (STEDI) program has also opened another opportunity for a possible CMB satellite mission. Given the weight constraint ($<$ 140 kgs), the power consumption ($<$ 75 W), limited size ($<$ 76 cm diameter, $<$ 178 cm height), and \$4 million budget this would be a considerably scaled back version of the satellites described above. Our initial proposal (called the Cosmic Fluctuations Instrument-COFI) offered this as an approach which could provide a useful complement to the ballooning and ground-based efforts.

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