# Results from the Cosmic Background Explorer[1]

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ABSTRACT - *COBE* has produced significant new scientific findings and results in the past year. The DMR instrument reported detections of temperature fluctuations in the cosmic microwave background (CMB) radiation. The DMR data are consistent with power law spectrum of Gaussian initial fluctuations with the quadrupole-normalized amplitude of $Q_{rms-PS} = 17\pm3$ $\mu$K and a power law index $n = 1.1 \pm 0.6$. These data are supportive of models of structure formation through gravitational instability.

The FIRAS instrument results improved indicating that the spectrum of the cosmic microwave background deviates from a Planckian spectrum by less than one part in 3000 of the peak intensity over the wavelength range 0.05 to 5 mm. These data rule out a number of alternative models of structure formation including explosive scenarios.

The initial *COBE* data products, in particular the first year DMR sky maps, were released to the scientific community in June 1993.

## 1 Introduction

The origin of large scale structure in the Universe is one of the most important issues in cosmology. Currently the leading models for structure formation postulate gravitational instability operating upon a primordial power spectrum of density fluctuations. The inflationary model of the early Universe [21] produces primordial density fluctuations [2],[22] [24],[39] with a nearly scale-invariant spectrum suggesting a viable mechanism for structure formation. Structure forms as the result of gravitational amplification of initially small perturbations in the primordial mass-energy distribution, and non-baryonic dark matter seems necessary to provide sufficient growth of these perturbations. The determination of the nature of the initial density fluctuations then becomes an important constraint to cosmological models [8]. The discovery of the anisotropy in the cosmic microwave background radiation by the COBE DMR instrument [36],[3],[25], [45] and the recent confirmation [18] mark a new era in cosmology and the beginning of investigations of these primordial fluctuations.

## 2 DMR and CMB Anisotropy

The Differential Microwave Radiometer (DMR) experiment is designed to map the microwave sky and find fluctuations of cosmological origin. For the 7° angular scales observed by the DMR, structure is superhorizon size so the spectral and statistical features of the primordial perturbations are preserved [32]. The DMR maps the sky at frequencies of 31.5, 53, and 90 GHz (wavelengths of 9, 5.7, and 3.3 mm). The frequency independence of the anisotropy is a strong argument that the anisotropy is in the cosmic microwave background radiation and not due to foreground Galactic emission or extragalactic sources. The confirming 'MIT' balloon-borne bolometer observations [18] have an effective frequency of about 170 GHz making the argument stronger. The typical fluctuation amplitude is roughly 30 $\mu$K or $\Delta T/T \sim 10^{-5}$ on a scale of 10°. The data appear consistent with a scale-invariant power spectrum with an uncertainty of $\pm 0.6$ in the exponent of the power law. The amplitude and spectrum are consistent with that expected for gravitational instability models involving nonbaryonic dark matter, and perhaps consistent with the measured large scale velocity flows. The angular power spectrum of the DMR maps is estimated by several methods, and is consistent with a near scale invariant power spectrum drawn from a Gaussian distribution. The horizon due to expansion of the universe limits the region over which we can observe these primordial fluctuations. For the very largest scales only a small number of fluctuations will be present inside our horizon creating error due to our cosmic sampling variance. If the fluctuations are drawn from a Gaussian distribution, the cosmic variance will limit the DMR's ability to determine the mean cosmic fluctuation amplitude to about 10%.

Since the DMR detection was announced several medium and smaller angular scale experiments have new results. These include: the UCSB South Pole experiment [17],[35], the Princeton Saskatoon experiment [44], the Tenerife collaboration [27],[42], the CARA South Pole experiments: Python [13], and 'White Dish' [33], the Center for Particle Astrophysics MAX balloon-borne experiment [12],[19],[30], the MSAM balloon-borne experiment [9], the Owens Valley Radio-astronomy Observatory (OVRO) [31], the Roma balloon-borne experiment ULISSE [11], and the Australia Telescope [41]. In general, these experiments report fluctuations at the $10^{-5}$ level. These measurements could in principle distinguish among models of structure formation, shed information on the nature of the dark matter, and probe the existence of cosmological gravity waves [10], [37]. However, the current results vary at the factor of two to three level which is just what is needed to make the distinctions. There is perhaps evidence that the data are not self-consistent. In part one can assume that some discrepancy is due to experimental error, to the limited region of the sky sampled by these experiments and to the potential confusion by galactic emission and extragalactic point sources. The community eagerly awaits refined observations of the power spectrum. In order to distinguish the various model one needs to measure the large angular scale power spectrum as accurately as possible given cosmic variance and utilize that as a normalization to the primordial spectrum against which to compare other observations and theoretical models.

## 3 CMB Fluctuation Power Spectrum

The initial results of the DMR data analysis [36] showed that the two-point correlation function was well fitted by a power law power spectrum with the quadrupole-normalized amplitude of $Q_{rms-PS} = 17 \pm 3$ $\mu$K and a power law index $n = 1.1 \pm 0.6$. We have continued and extended the analysis taking more care in the analysis in anticipation of additional years' data and utilizing the existing data more fully. There are several corrections and foregrounds that must considered if one is to determine things to the 10% level.

One item that must be treated more carefully is the DMR beam filter function. For the first cut analyses we approximated the DMR antenna beam pattern as a Gaussian. An undergraduate, Ruediger Kneissl and I have done a more detailed treatment of the actual pattern and the resulting filter function. The correct filter function depends upon the particular data set being analyzed: antenna beam only, including 0.5-sec integration, including 2.6° pixel size, and 2.6° correlation function bins. The filter function for the beam is publised [47] and the others are available on request. The net effect of using the actual filter rather than the Gaussian approximation is to boost the intermediate, $(10 < l < 30)$, angular scale power and thus raise the spectral index by 0.2 to 0.3.

At a smaller level we are concerned with the effects of galactic cuts and uneven sky coverage. In this volume Tenorio et al. discuss the effect of these upon

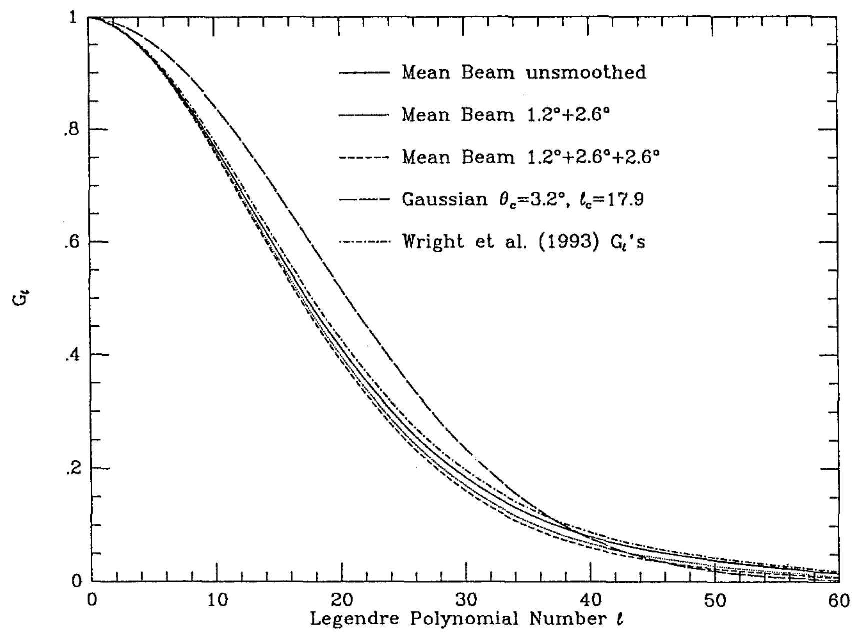


**Fig. 1.** Antenna Filter Function for various levels of data processing. These include the beam, the beam with 0.5-second integration time, plus 2.6° pixelization, and plus 2.6° correlation function binning. These curves from memo by Kneissl and Smoot.

the quadrupole amplitude. The effect on the full power spectrum is significantly less but still must be considered at the per cent level.

Because the DMR measures differences of all the pixels that are 60° apart on the sky, the instrument noise results in a slight correlation in the data at a 60° separation at the few per cent level. Because of cuts and uneven sky coverage this effect is mixed to other angles at the per cent or lower level. This angular correlation of noise shows up in the autocorrelation function but not in the cross-correlation of channels or maps with independent noise. These questions of the correlation of pixels noise and errors due to the differencing and map making procedure and the cuts,uneven sky coverage, and weighting are a major part of the thesis work of my graduate student, Charles Lineweaver. The broad strokes of these effects have been explored and we are at the tidying and writing stage.

Another major area of concern is the question of galactic and extragalactic foregrounds. In the discovery papers [36],[3], [25],[45] we estimated that these galactic and extragalactic emissions were at the or less than 10% of the signal we observed. We have continued to work and gathered new data on the galactic emission. It appears that the galactic emission may be less anisotropic than feared and that the free-free emission in particular may be smoother and less intense than allowed. On the DMR's large angular scale extragalactic point-like sources are not significant. The cosmic nature of the measured fluctuations was tested [4] by correlating the DMR maps with maps of Galactic emission, the X-ray background, Abell clusters, and other foregrounds. No evidence for significant correlation was found. The "blamb" structure reported by the Relikt team [40] is not present in the DMR map. The net result is that except for the quadrupole the galactic emission effects are likely to be smaller than 10%.

The remaining question is what are the residual systematic errors? Have we found any new ones? And finally is there some left undiscovered? We have continued our data processing and analysis and have a new set of data processing software and have recently completed running the first two years of DMR data. We are now checking and verifying that the runs were done correctly and then will move into investigating the systematic errors. Our early and preliminary analysis indicate that the residual systematic errors are still not significant.

Our continuing analysis show the data are still consistent with a power law spectrum with previously quoted parameters: the quadrupole-normalized amplitude of $Q_{rms-PS} = 17 \pm 3$ $\mu$K and a power law index $n = 1.1 \pm 0.6$. We have used a number of approaches to determine the power spectrum directly including fitting spherical harmonics directly to the map, fitting the two-point correlation function to Legendre polynomials, and fitting the power spectrum to the map directly. We have also used topological measures and the sky-rms as a check of the statistics and mean power spectrum in the map. The results are all generally consistent. The DMR first year data power spectrum is shown along with the data from other recent CMB anisotropy experiments in Figure 2.

We have reason to hope that with four years of DMR data that the cosmic variance will be the dominant uncertainty in determining the CMB fluctuation power spectrum.

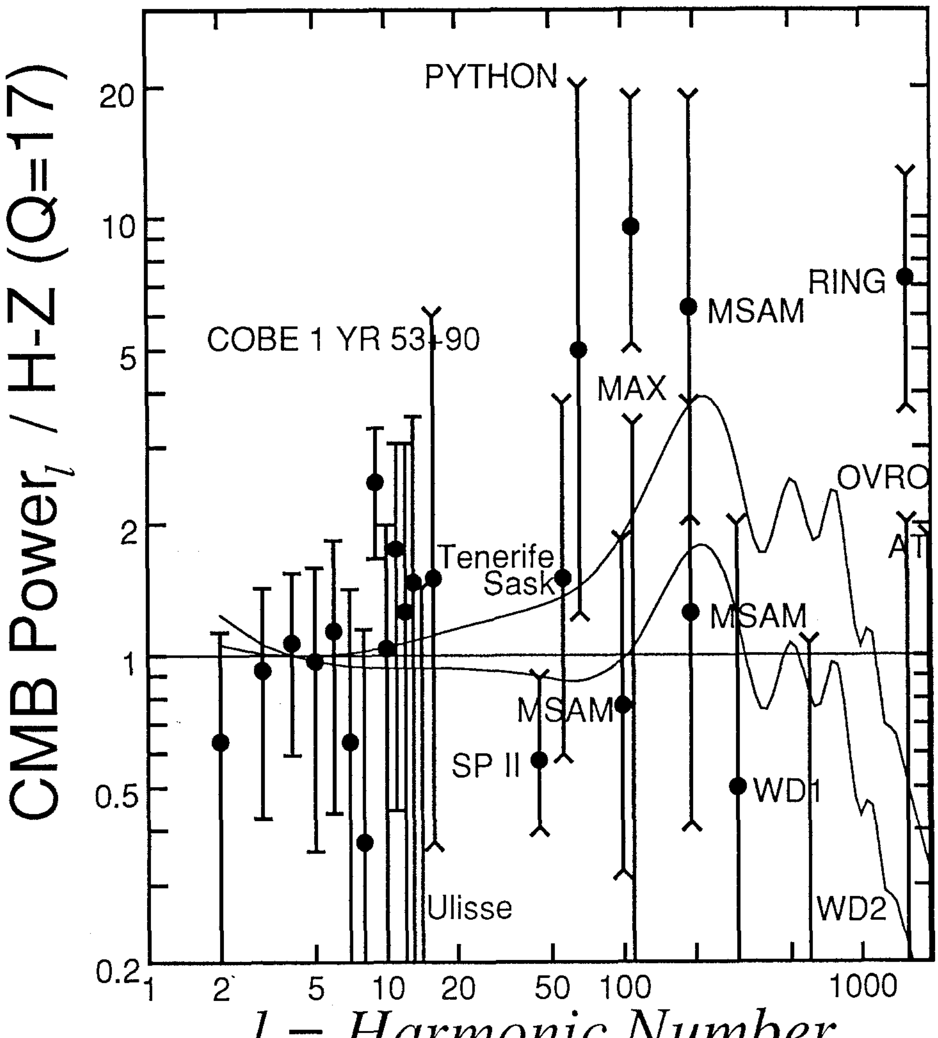


**Fig. 2.** Power Spectrum from COBE DMR and other Anisotropy Experiments. The data points refer to the experiments mentioned in ssection 1 and the two curves are from Crittendon et al. 1993 representing the predicted spectrum for inflation generated (upper) pure density fluctuations (essentially a flat inflaton potential) and (lower) equal density and gravitational wave contributions to the quadrupole.

# 4 FIRAS and CMB Spectrum Observations

The Far Infrared Absolute Spectrophotometer (FIRAS) instrument compared the spectrum of the CMBR to that of a precise blackbody for the first time. It has a 7° diameter beamwidth, and covers two frequency ranges, a low frequency channel from 1 to 20 $cm^{-1}$ and a high frequency channel from 20 to 100 $cm^{-1}$. Preliminary results [28] showed that the CMBR is consistent with a blackbody at $2.735 \pm 0.06$ K, and that deviations are less than 1% of the peak brightness. The UBC rocket result [20] nearly immediately confirmed the FIRAS results. New FIRAS results show that deviations from a blackbody are 30 times smaller: less than one part in 3000 of the peak intensity [14],[15],[28],[47].

The absolute temperature of the cosmic background, $T_o$, was determined in two ways. The first uses the thermometers in the external calibrator and gives $T_o = 2.730$ K. The second calibrates the temperature scale from the wavelength scale, and gives 2.722 K for $T_o$. The adopted value is $2.726 \pm 0.010$ K (95% confidence [29]), which averages these two methods. Three additional determinations of $T_o$ depend on the dipole anisotropy. The spectrum of the dipole anisotropy is sensitive to the assumed blackbody temperature. Since the velocity of the solar system with respect to the CMB is not known a priori, only the shape and not the amplitude of the dipole spectrum can be used. For FIRAS, this analysis [14] gives $T_o = 2.714 \pm 0.022$ K, while for DMR [26] it gives $T_o = 2.76 \pm 0.18$ K. The DMR data analysis keeps track of the changes in the dipole caused by the variation of the Earth's velocity around the Sun during the year. In this case the velocity is known, so $T_o$ can be determined from the amplitude of the change in the dipole, giving $T_o = 2.75 \pm 0.05$ K.

The spectrum observations imply a tight limit on energy release in the early universe and strong support for the hot Big Bang model. From a redshift of about $10^6$ to $10^3$ no process can release electromagnetic energy at a level exceeding about $10^{-4}$ of that in the cosmic background radiation. Limits on the distortion parameters are $|y| < 2.5 \times 10^{-5}$ and $|\mu/kT| < 3.3 \times 10^{-4}$ with 95% confidence. The Comptonization parameter $y$ restricts the possible thermal history of the intergalactic medium, which must not be very dense or very hot (less than $\approx 10^4$ KeV). In addition, the FIRAS results limit energy release into the far infrared from Population III stars or evolving IRAS galaxies. In both cases, less than 1% of the hydrogen could have burned [47] after a redshift of 80, assuming $\Omega_{baryon} h^2 = 0.015$.

The FIRAS results can be combined and compared with other observations of the cosmic background spectrum. At this time the spectrum of the cosmic background is well described by a single temperature blackbody over four decades in frequency (or wavelength), without significant deviations. However, more precise measurements at long wavelengths could improve the COBE limits on $\mu$ by a factor of 10.

Non-cosmological results of the FIRAS include the determination of the mean far infrared spectrum of the Galaxy, and its decomposition into two components of dust emission and 9 spectrum lines [45]. The lines of [N II] and [C II] have been further interpreted [5], [34].

# 5 DIRBE and the Cosmic Infrared Background

The primary objective of the Diffuse Infrared Background Experiment (DIRBE) is to conduct a definitive search for an isotropic cosmic infrared background (CIB), within the constraints imposed by the local astrophysical foregrounds, from 1 to 240 $\mu$m . Additional objectives include studies of the interplanetary dust cloud and the stellar and interstellar components of the Galaxy. Both the cosmic redshift and the reprocessing of short-wavelength radiation to longer wavelengths by dust act to shift the short-wavelength emissions of cosmic sources toward or into the infrared, and the CIB may contain much of the energy released since the formation of luminous objects. Measurement of the CIB would provide important new insights into issues such as the amount of matter undergoing luminous episodes in the pregalactic Universe, the nature and evolution of such luminosity sources, the nature and distribution of cosmic dust, and the density and luminosity evolution of infrared-bright galaxies.

The DIRBE has obtained absolute brightness maps of the full sky in 10 photometric bands (1.2, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140 and 240 $\mu$m ). To facilitate discrimination and study of the bright foreground contribution from interplanetary dust, linear polarization is measured at 1.2, 2.2, and 3.5 $\mu$m , using a combination of orthogonal polarizers and spacecraft rotation. All celestial directions are observed hundreds of times at all accessible angles from the Sun in the range 64 - 124°. The instrument has a large field of view, 0.7°square, and the sky signal is continuously chopped against a zero-flux internal surface. A cold shutter allows measurement of instrumental offsets and internal stimulation of the detectors.

The photometric quality of the DIRBE data is excellent; when the full reduction of the cryogenic-era data is complete, photometric consistency over the sky and over the 10 month period is expected to be near 1% or better. The instrument rms sensitivity per field of view in 10 months is $\lambda I_\lambda$ = (1.0, 0.9, 0.6, 0.5, 0.3, 0.4, 0.4, 0.1, 11.0, 4.0) $\times 10^{-9}$ W $m^{-2}$ $sr^{-1}$, respectively for the ten wavelength bands listed above. These levels are generally well below estimated CIB radiation contributions and foregrounds.

Papers on the foregrounds have been submitted to the Astrophysical Journal and presented [1],[6],[16], [23],[38],[43] at the Back to the Galaxy Conference. Preliminary full sky maps at wavelengths from 1.2 to 240 $\mu$m have provided dramatic new views of the stellar and interstellar components of the Milky Way. The zodiacal dust bands discovered in the IRAS data are confirmed, and scattered near-infrared light from the same particles has also been detected. Starlight from the galactic bulge region, after correction for extinction, has been shown to have an asymmetric distribution consistent with a non-tilted stellar bar. The warp of the near and far infrared emission near the galactic plane is similar to that expected from previous studies of the stellar and interstellar components of the Galaxy. New upper limits have been set on the CIB all across the infrared spectrum, conservatively based upon the minimum observed sky brightness [23].

## 6 COBE Data Products Release

An initial set of COBE data products from all three instruments was released in June 1993, and a new data release in June 1994 will include all-sky DIRBE and FIRAS coverage, DIRBE polarimetry, FIRAS data from the low-frequency band, and the first two years' worth of DMR data. Additional data will be released in June 1995. Documentation and initial data products are available by anonymous FTP from nssdca.gsfc.nasa.gov with the username "anonymous" and your e-mail address as password. Change to directory [000000.cobe] and get the file aareadme.doc. Data and documentation may also be obtained on tape by request to the Coordinated Request and User Support Office (CRUSO), NASA/GSFC, Code 633.4, Greenbelt, MD 20771, phone: 301-286-6695, e-mail: request@nssdca.gsfc.nasa.gov.

## 7 Discussion and Summary

The COBE has been a remarkably successful space experiment with dramatic observational consequences for cosmology, and the DIRBE determination of the cosmic infrared background is yet to come. The very tight limits on deviations of the spectrum from a blackbody rule out many non-gravitational models for structure formation, while the amplitude of the $\Delta T$ discovered by the COBE DMR implies a magnitude of gravitational forces in the Universe sufficient to produce the observed clustering of galaxies, but perhaps only if the Universe is dominated by dark matter. The DMR $\Delta T$ provides measurement of the 'initial conditions' for the gravitational instability modes.

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