Recent results from COBE

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Abstract. The Cosmic Background Explorer (*COBE*[2]), NASA's first space mission devoted primarily to cosmology, carries three scientific instruments to make precise measurements of the spectrum and anisotropy of the cosmic microwave background (CMB) radiation on angular scales greater than 7° and to conduct a search for a diffuse cosmic infrared background (CIB) radiation with 0.7° angular resolution. The observing strategy is designed to minimize and allow determination of systematic errors that could result from spacecraft operations, the local environment of the spacecraft, and emissions from foreground astrophysical sources such as the Galaxy and the solar system. Data from the Far-InfraRed Absolute Spectrophotometer (FIRAS) show that the spectrum of the CMB is that of a blackbody of temperature T=2.73±0.06 K, with no deviation from a blackbody spectrum greater than 0.25% of the peak brightness. The first year of data from the Differential Microwave Radiometers (DMR) show statistically significant CMB anisotropy. The anisotropy is consistent with a scale invariant primordial density fluctuation spectrum and with the gravitational potential variations required to cause the observed present day structure. Infrared sky brightness measurements from the Diffuse InfraRed Background Experiment (DIRBE) provide new conservative upper limits to the CIB. Extensive modeling of solar system and galactic infrared foregrounds is required for further improvement in the CIB limits.

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[2] The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the *COBE*. Scientific guidance is provided by the *COBE* Science Working Group. GSFC is also responsible for the development of the analysis software and for the production of the mission data sets.

1. Introduction to the *COBE* and mission objectives

The observables of modern cosmology include the Hubble expansion of the universe; the ages of stars and clusters; the distribution and streaming motions of galaxies; the content of the universe (its mass density, composition, and the abundances of the light elements); the existence, spectrum and anisotropy of the cosmic microwave background radiation; and other potential backgrounds in the infrared, ultraviolet, x-ray, gamma-ray, etc. The purpose of the *COBE* mission is to make definitive measurements of two of these observable cosmological fossils: the cosmic microwave background (CMB) radiation and the cosmic infrared background (CIB) radiation. Since the discovery of the CMB in 1964 (Penzias & Wilson 1965), many experiments have been performed to measure the CMB spectrum and spatial anisotropies over a wide range of wavelengths and angular scales. Fewer attempts have been made to conduct a sensitive search for a CIB radiation, expected to result from the cumulative emissions of luminous objects formed after the universe cooled sufficiently to permit the first stars and galaxies to form.

In 1974 NASA issued Announcements of Opportunity (AO-6 and AO-7) for new Explorer class space missions. A proposal for a Cosmic Background Radiation Satellite was submitted by John Mather *et al.*(1974) from NASA/Goddard. The objectives of this mission were: (1) make "definitive measurement of the spectrum (of the 2.7 K CBR).. with precision of 10^{-4} around the peak... It will also look for the emission from cold dust clouds and from infrared galaxies"; (2) "measure the large scale isotropy of the background radiation... to a precision of 10^{-5}... Measurements at several wavelengths are required in order to distinguish anisotropy in the background radiation itself from anisotropy due to discrete sources"; and (3) "... search for diffuse radiation in the 5-30 micron wavelength range, expected to arise from interplanetary dust, interstellar dust, and, in particular, from the integrated luminosity of very early galaxies. The experiment is designed to separate these contributions by their spectral and directional properties." Additional proposals were also submitted for large angular scale microwave isotropy experiments by Sam Gulkis *et al.*(1974) from JPL and by Luis Alvarez *et al.*(1974) from UC Berkeley. NASA selected six investigators from these proposals and formed the core of what was to become the COBE Science Working Group, as shown in Table 1.

To achieve the full benefit of space observations, a goal of the mission and instrument design was that *COBE* measurements would be limited ultimately by our ability to identify and model the various components of the astrophysical foreground emission, and discriminate between them and the cosmological emission. This goal drove the design of the mission strategy, the spacecraft and operations, and the choice of instruments. Basic elements in the mission strategy were the requirements for highly redundant full sky coverage and for sufficient time in orbit to achieve necessary sensitivity and evaluate potential sources of systematic errors in the observations. The instruments were designed to measure specific attributes of the cosmological backgrounds and also, through their complementary spectral coverage, to enable the modeling and subtraction of foreground emissions. Early descriptions of the mission concept have been given by Mather (1982, 1987) and by Gulkis *et al.*(1990).

The three scientific instruments are the Far Infrared Absolute Spectrophotometer (FIRAS), the Differential Microwave Radiometers (DMR), and the Diffuse Infrared Background Experiment (DIRBE). The FIRAS objective is to make a precision mea-

Table 1. *COBE* Science Working Group

Bennett, C. L.	NASA-GSFC	DMR Deputy Principal Investigator
Boggess, N. W.	NASA-GSFC	*COBE* Deputy Project Scientist
Cheng, E. S.	NASA-GSFC	*COBE* Deputy Project Scientist
Dwek, E.	NASA-GSFC	
Gulkis, S.	NASA-JPL	
Hauser, M. G.	NASA-GSFC	DIRBE Principal Investigator
Janssen, M.	NASA-JPL	
Kelsall, T.	NASA-GSFC	DIRBE Deputy Principal Investigator
Lubin, P. M.	U.C.S.B.	
Mather, J. C.	NASA-GSFC	FIRAS Principal Investigator & COBE Project Scientist
Meyer, S. S.	M.I.T.	
Moseley, S. H.	NASA-GSFC	
Murdock, T. L.	Gen. Res. Corp.	
Shafer, R. A.	NASA-GSFC	FIRAS Deputy Principal Investigator
Silverberg, R. F.	NASA-GSFC	
Smoot, G. F.	LBL & UCB	DMR Principal Investigator
Weiss, R.	M.I.T.	*COBE* SWG Chairman
Wilkinson, D. T.	Princeton	
Wright, E. L.	U.C.L.A.	

surement of the spectrum of the CMB from 1 cm to 100 μm. The DMR objective is to search for CMB anisotropies on angular scales larger than 7° at frequencies of 31.5, 53, and 90 GHz. The DIRBE objective is to search for a CIB by making absolute brightness measurements of the diffuse infrared radiation in 10 photometric bands from 1 to 240 μm and polarimetric measurements from 1 to 3.5 μm. The FIRAS and DIRBE instruments are located inside a 650 liter superfluid liquid helium dewar.

2. *COBE* mission design & implementation

A full description of the *COBE* mission by Boggess *et al.*(1992) is summarized here. Many papers giving overviews, implications, and additional detailed information about the *COBE* have been presented by Mather *et al.*(1990b), Mather *et al.*(1991b), Mather (1991), Janssen & Gulkis (1992), Wright (1990), Wright (1991a), Hauser (1991a), Hauser (1991b), Smoot *et al.*(1991c), Smoot (1991), Bennett (1991), and Boggess (1991).

The need to control and measure potential systematic errors led to the requirements for an all-sky survey and a minimum time in orbit of six months. The instruments required temperature stability to maintain gain and offset stability, and a high level of cleanliness to reduce the entry of stray light and thermal emission from particulates. The control of systematic errors in the measurement of the CMB anisotropy and the need for measuring the interplanetary dust cloud at different solar elongation angles for subsequent modeling required that the satellite rotate.

In near-Earth orbit, the Sun and Earth are the primary continuous sources of thermal emission and it was necessary to ensure that neither the instruments nor the dewar were exposed to their radiation. A circular Sun-synchronous orbit satisfied these requirements. An inclination of 99° and an altitude of 900 km were chosen so that the orbital plane precesses 360° in one year due to the Earth's gravitational quadrupole moment. The 900 km altitude is a good compromise between contamination from the Earth's residual atmosphere, which increases at lower altitude, and interference due to charged particles in the Earth's radiation belts at higher altitudes. A 6 PM ascending node was chosen for the *COBE* orbital plane; this node follows the terminator (the boundary between sunlight and darkness on the Earth) throughout the year. By maintaining the spacecraft spin axis at about 94° from the Sun and close to the local zenith, it is possible to keep the Sun and Earth below the plane of the instrument apertures for most of the year. However, since the Earth's axis is tilted 23.5° from the ecliptic pole, the angle between the plane of the *COBE*'s orbit and the ecliptic plane varies through the seasons from -14.5° to +32.5°. As a consequence, the combination of the tilt of the Earth's axis, the orbit inclination, and the offset of the spacecraft spin axis from the Sun brings the Earth limb above the instrument aperture plane for up to 20 minutes per orbit near the June solstice. During this period the limb of the Earth rises a few degrees above the aperture plane for part of each orbit, while on the opposite side of the orbit the spacecraft goes into the Earth's shadow. In the nominal *COBE* orbit the spacecraft's central axis scans the full sky, though not with uniform coverage, every six months. The orbital period is 103 minutes, giving 14 orbits per day.

A 3-axis attitude control system was implemented by using a pair of inertia wheels (yaw angular momentum wheels), with their axes oriented along the spacecraft spin axis. These wheels carry an angular momentum opposite that due to the spacecraft rotation to create a nearly zero net angular momentum system. The spacecraft orientation is controlled by three reaction wheels with spin axes 120° apart in the plane perpendicular to the spacecraft spin axis and by electromagnetic coils (torquer bars) that interact with the Earth's magnetic field. Earth and Sun sensors (one of each on each of the three transverse control axes) provide control signals to point the spin axis away from the Earth and at least 90° from the Sun. Rate damping and fine resolution attitude sensing are provided by six gyros, one on each transverse control axis and three on the spin axis. Coarse attitude parameters are calculated by using telemetered data from the attitude control sensors to produce attitude solutions good to 4 arcmin (1 σ). A fine aspect is determined by using gyro data to interpolate between the positions of known stars detected in the short wavelength bands of the DIRBE instrument. The fine aspect solution has an accuracy of 1.5 arcmin (1 σ) and is now used in the analysis of data from all three instruments (Kumar *et al.*1991).

The FIRAS instrument, located inside the dewar, points along the spin axis with its 7° field of view. The three pairs of DMR receivers are spaced 120° apart around the aperture plane of the dewar. Each radiometer channel measures the difference in sky signal from a pair of horn antennas defining 7° fields of view separated by 60°, each beam being 30° from the spin axis. The spin causes a short-term interchange of the two beams associated with a single differential radiometer and thereby gives a modulation of the differential sky signal at the spin rate. The 0.8 rpm spin rate was chosen to be fast enough to reduce the noise and systematic errors that could otherwise arise from radiometer gain and offset instabilities. The DIRBE, also located inside the dewar, views 30° from the spin axis. The spin allows DIRBE to measure the emission and scattering by the interplanetary dust cloud over a range of solar elongation angles for each celestial direction, which aids in the discrimination and subsequent modelling of zodiacal radiation. DMR and DIRBE trace out a pattern of epicycles that enable them to scan half of the sky every day and obtain multiple measurements for each pixel of the sky.

The dewar is a 650 liter superfluid helium cryostat that kept the FIRAS and DIRBE instruments cooled to ~1.6 K. A deployable dewar aperture cover protected the cryogen and permitted calibration and performance testing of the cryogenic instruments prior to launch. A contamination shield attached to the inside of the dewar cover protected the DIRBE primary mirror from particulate or gaseous contamination until ejection of the dewar cover in orbit. It also protected DIRBE from emission from warm parts of the cryostat during ground testing. The deployed conical Sun-Earth shield protects the scientific instruments from direct solar and terrestrial radiation and provides thermal isolation for the dewar. The shield also provides the instruments isolation from Earth-based radio frequency interference (RFI) and from the spacecraft transmitting antenna. The shield was designed to be flexible and was folded to fit within the Delta rocket fairing for launch. Contamination covers attached to the Sun-Earth shield were placed over the DMR horn antennas and were pulled away in orbit by the deployment of the shield. The deployed solar arrays provide the nominal spacecraft and instrument power load of 542 Watts.

The *COBE* has two omnidirectional antennas, one to communicate with the Tracking and Data Relay Satellite System (TDRSS), and the other to transmit data stored on tape recorders directly to the ground. The antennas are located on a mast at the bottom of the spacecraft deployed after launch. The *COBE* has a command and data handling system that stores and decodes the commands received from the ground, collects data from the instruments and spacecraft at the rate of 4 kbps, and prepares data for transmission to the ground. The on-board tape recorders and data system allow 24 hours of data to be transmitted to the Wallops Flight Facility in a single 9 minute pass. The data rate allocations for DIRBE, FIRAS, and DMR are 1716, 1362 and 250 bps, respectively. The remainder of the telemetry is assigned to spacecraft subsystems.

The *COBE*, as initially proposed, was to have been launched by a Delta rocket. However, once the design was underway, the Shuttle was adopted as the NASA standard launch vehicle. After the Challenger accident occurred in 1986, ending plans for Shuttle launches from the West Coast, the spacecraft was redesigned to fit within the weight and size constraints of the Delta. The final *COBE* satellite had a total mass of 2,270 kg, a length of 5.49 m, and a diameter of 2.44 m with Sun-Earth shield and solar panels folded (8.53 m with the solar panels deployed).

Ground testing of the *COBE* was necessary to demonstrate that the individual subsystems, and ultimately the entire spacecraft and instrument assembly in its flight configuration, could satisfy both the sensitivity and systematic error requirements. System level tests were performed: to simulate the space environments, including vacuum and temperature; to determine susceptibility to vibration, acoustic excitation, and acoustic shock; to quantify electromagnetic interference (EMI) self-compatibility and RFI susceptibility; to determine the interaction between instruments and spacecraft; to simulate the thermal and power conditions that would occur during eclipse periods; to test the deployables and moving parts (Sun-Earth shield, antenna boom, solar panels, dewar cover, FIRAS external calibrator and moving mirror transport, and DIRBE shutter and chopper); and characterize and calibrate the instruments.

Technical papers on various aspects of the *COBE* have been published. These include papers on contamination control (Barney 1991); test facility requirements for thermal balance tests (Milam 1991); design of the dewar (Hopkins & Castles 1985); optical alignments (Sampler 1990); thermal performance of the dewar prior to launch and in orbit (Hopkins & Payne 1987, Volz & Ryschkewitsch 1990a, Volz *et al.*1990, Volz *et al.*1991a & 1991b, Volz & Dipirro 1992); thermal design of the cryogenic optical assembly (Mosier 1991a, 1991b); cryogenic cool-down tests (Coladonato *et al.*1990), and attitude control (Bromberg & Croft 1985).

3. *COBE* operations in orbit

The *COBE* was launched aboard Delta rocket No. 189 at 1434 UT on November 18, 1989 from the Western Space and Missile Center at Vandenberg Air Force Base, California. The DMR receivers began operating the day after launch. The dewar cover was ejected three days after launch, and the FIRAS and DIRBE instruments began obtaining data on the same day. During the first month in orbit, various tests were undertaken to evaluate the performance of the instruments and spacecraft, and to optimize instrument parameters.

The *COBE* operated in a routine survey mode. The three instruments completed their first full sky coverage by mid-June 1990, and returned high quality data until the depletion of the liquid helium at 0936 UT September 21, 1990. The FIRAS, which had surveyed the sky 1.6 times, ceased operating when the helium ran out, but the DMR is still operating normally in all of its six channels. By November 1991 (over one year after helium depletion) the dewar temperature at the DIRBE detectors was about 50 K. The six longest wavelength bands were turned off in September 1990, but the four short wavelength bands of the DIRBE continue to acquire data at reduced sensitivity. The detector system responsivity in the short wavelength bands decreased about an order of magnitude following cryogen depletion (largely due to the change in load resistance). However, sky maps of the large scale interplanetary dust signals are of adequate quality to permit searching for evidence of temporal changes on annual time scales.

In flight, the helium temperature inside the main cryogen tank was 1.40 K and the temperature of the inner surface of the Sun-Earth shield was 180 K. As expected, the Earth limb rose a few degrees above the Sun-Earth shield for a part of every orbit during a three month period starting in May. At these times, the Earth's radiation produced thermal transients in the instruments and adversely affected data for a portion of each orbit. Some of these data are still usable after careful calibration. One of the gyros for a transverse control axis failed electrically on the fourth day after launch. On September

7, 1991, one of the three gyros on the spin axis failed, but no data were lost and satellite operations continue in the nominal orbit.

4. Spectral results from FIRAS

4.1. The spectrum of the primeval radiation

The discovery of the cosmic microwave background radiation by Penzias & Wilson (1965) provided strong evidence for Big Bang cosmology. Radiation produced in the very early universe was frequently scattered until about 300,000 years after the Big Bang. At this point, the "recombination", the characteristic energy in the universe fell to the point where previously free electrons could combine with nuclei to form neutral atoms. The 2.7 K radiation we see today has been traveling to us unimpeded since that time. The rapid production and destruction of photons within the first year after the Big Bang forced the radiation to have a Planck (blackbody) spectrum. Any mechanism that injected energy into the Universe (e.g. a particle decay) between a year after the Big Bang and $\sim$ 2000 years after the Big Bang would give rise to a radiation spectrum characterized by a non-zero chemical potential. Thus there would be a Bose-Einstein spectral distortion with the photon occupation number

$$N(\epsilon) \sim \frac{1}{e^{(\epsilon-\mu)/kT} - 1} \tag{1}$$

where μ is the chemical potential and ϵ is the photon energy. A Compton distortion is usually parameterized in terms of a Compton y-parameter,

$$y = \frac{\sigma_T}{m_e c^2} \int n_e k(T_e - T_{CMB}) c dt \tag{2}$$

where σ_T is the Thomson scattering cross-section and the integral is the electron pressure along the line of sight. A Compton distortion of the spectrum can become important when $(1+z)dy/dz > 1$, which occurs $\sim$ 2000 years after the Big Bang. The thermodynamic temperature distortion observed at a frequency ν is

$$\frac{\delta T}{T} \approx y \left(x \frac{e^x + 1}{e^x - 1} - 4 \right) \tag{3}$$

where $x = h\nu/kT_{CMB}$, h is the Planck constant, and k is the Boltzmann constant (Sunyaev & Zeldovich 1980). After recombination it becomes nearly impossible to distort the CMB spectrum short of reionizing the universe. Thus a perfect Planck CMB spectrum would support the prediction of the simplest Big Bang model of the universe, while spectral distortions would indicate the existence of more complicated releases of energy.

4.2. The FIRAS instrument

The FIRAS instrument is a polarizing Michelson interferometer (Mather 1982, Mather *et al.*1991a) with two separate spectral channels. The low frequency channel, extending from 0.5 mm to 1 cm, was designed to obtain a precision comparison between the CMB spectrum and a Planckian calibration spectrum. The objective was to attain, in each

5% wide spectral element and each 7° pixel, an accuracy and sensitivity of $\nu I_\nu \cong 10^{-9}$ W m^{-2} sr^{-1}, which is 0.1% of the peak brightness of a 2.7 K blackbody. The high frequency channel, with a useful spectral range from 0.12 mm to 0.5 mm, was designed to measure the emission from dust and gas in our galaxy and to remove the effect of galactic radiation on the measurements of the CMB made in the low frequency channel.

The FIRAS uses a multimode flared horn (Mather, Toral, & Hemmati 1986) with a 7° beam. The instrument directly measures the difference between the sky signal in its beam and that from a temperature-controlled internal reference body. The best apodized spectral resolution is 0.2 cm^{-1} (6 GHz). The in-orbit absolute calibration of FIRAS was accomplished by inserting an external blackbody calibrator periodically into the mouth of the horn. The calibrator is a precision temperature-controlled blackbody, with an emissivity greater than 0.999. The FIRAS uses bolometric detectors (Mather 1981, 1984a,b) in both bands.

In ten months of cryogenic operation the FIRAS obtained over two million interferograms. This complete data set is now undergoing careful analysis.

4.3. FIRAS results

Analysis of the FIRAS data to date confirm the prediction of the simplest Big Bang model that the CMB must have a thermal spectrum. Initial results based on only nine minutes of data showed that there is no deviation from a blackbody spectrum $B_\nu(T)$ as large as 1% of the peak brightness (Mather *et al.*1990a, 1991a) over the spectral range from 500 μm to 1 cm. The temperature of the CMB in the direction of the north galactic pole is 2.735 ± 0.060 K, where 60 mK is the initial conservative uncertainty in the calibration of the thermometry of the absolute calibrator. These data also ruled out the existence of a hot smooth intergalactic medium that could emit more than 3% of the observed x-ray background. The thermal character of the CMB spectrum was subsequently confirmed by Gush, Halpern, & Wishnow (1990), who obtained virtually the same temperature over the spectral range 2-30 cm^{-1}. Neither mean CMB temperature quoted above are corrected for the dipole distortion. These experiments found no submillimeter excess as previously reported by Matsumoto *et al.*(1988b).

More recently, Shafer *et al.*(1991) and Cheng *et al.*(1991a) have examined FIRAS spectra in a direction known previously to be very low in interstellar material ($l = 142°$, $b = 55°$). In this direction, known as Baade's Hole, the temperature is 2.730 ± 0.060 K and there is no deviation from a blackbody spectrum greater than 0.25 % of the peak brightness. The lack of deviations from a Planck spectrum translate to a limit on a chemical potential (see eqn 1) of $|\mu/kT| < 0.005$ (95% CL) and a limit on the Compton y-parameter (eqn 2) of $y < 0.0004$ (95% CL). These results rule out a hot smooth intergalactic medium that could emit more than 1% of the observed x-ray background.

The dipole anisotropy of the CMB, presumed due to our peculiar motion relative to the Hubble flow, can be seen clearly in the FIRAS data, and is consistent with previous results (Cheng *et al.*1990). The FIRAS data show for the first time that the difference in spectra between the poles of the dipole is that expected from two Doppler-shifted blackbody curves. This result also indicates that the stability of the FIRAS instrument is better than one part in 5000 over long time scales. The dipole amplitude measured by FIRAS is 3.31 ± 0.05 mK in the direction (l,b)=($266° \pm 1°$, $47.5° \pm 0.5°$).

FIRAS results also include the first nearly all-sky, unbiased, far infrared survey of the galactic emission at wavelengths greater than 120 μm (Wright *et al.*1991). Wright *et al.*present a map of the dust emission across the sky from the *COBE* FIRAS experiment. They write the absolute Galactic emission intensity in the form $I(\nu,l,b) = g(\nu)G(l,b)$, where $g(\nu)$ is the mean spectrum of the emission and $G(l,b)$ is a dimensionless map. The dust component of the mean spectrum is given as

$$g_d(\nu) = 0.00016 \left(\bar{\nu}/30\mathrm{cm}^{-1}\right)^{1.65} B_\nu(23.3\ \mathrm{K}), \tag{4}$$

or,

$$g_d(\nu) = 0.00022 \left(\bar{\nu}/30\mathrm{cm}^{-1}\right)^{2} [B_\nu(20.4\ \mathrm{K}) + 6.7 B_\nu(4.77\ \mathrm{K})] \tag{5}$$

where $\bar{\nu}$ is the frequency in units of cm^{-1}, and $B_\nu(T)$ is the Planck function. The total far infrared luminosity of the Galaxy is inferred to be $(1.8 \pm 0.6) \times 10^{10} \mathrm{L}_\odot$ (Wright *et al.*1991).

Wright *et al.*report that spectral lines from interstellar [C I], [C II], [N II], and CO are detected in the mean galactic spectrum, $g(\nu)$. The lines of [C II] at 158 μm and [N II] at 205.3 μm were sufficiently strong to be mapped. This is the first observation of the 205.3 μm line. Wright *et al.*interpret the [C II] line as coming from photodissociation regions and the [N II] lines as partially arising from a diffuse warm ionized medium and partially arising from dense H II regions. Petuchowski & Bennett (1992) agree with this conclusion and further elaborate on it by apportioning the [C II] and [N II] transition line intensities among various morphologies of the interstellar medium. Petuchowski & Bennett (in preparation) have conducted observations on NASA's Kuiper Airborne Observatory to measure the scale height of the 205.3 μm [N II] line with a much higher angular resolution (~1 arcmin) than FIRAS.

5. DMR: microwave anisotropy measurements and interpretations

Primordial gravitational potential fluctuations at the surface of last scattering give rise to the distribution and motions of galaxies and to large angular scale fluctuations in the CMB (Sachs & Wolfe 1967). In inflationary models of cosmology (Guth 1981, Linde 1982, Albrecht & Steinhardt 1982) the gravitational energy fluctuations arise from quantum mechanical fluctuations from 10^{-35} seconds after the Big Bang that inflate to become classical fluctuations with a nearly scale invariant power spectrum (Bardeen, Steinhardt, & Turner 1983, Guth & Pi 1982, Hawking 1982, Starobinskii 1982). Inflation theories are not yet sufficiently constrained to be able to make accurate predictions of the amplitude of current energy fluctuations. Rather, estimates of the energy fluctuations inferred from observations are a constraint on the theories.

The large angular scale CMB temperature anisotropy ΔT and gravitational potential fluctuations at the surface of last scattering $\Delta\Phi$ are simply related by $3\Delta T/T = \Delta\Phi/c^2$ for adiabatic fluctuations in a universe with no cosmological constant ($\Lambda_0 = 0$). On much smaller scales than the DMR measures ($\theta < 4°$), i.e. on scales in causal contact with one another after the universe became matter dominated, the gravitational potential fluctuations are affected by the growth of structures through gravitational instability (e.g. Bond & Efstathiou 1987). Usually the mass density is written as

$$\rho(\vec{x},t) = \overline{\rho}(1 + \delta(\vec{x},t)), \tag{6}$$

where $\delta(\vec{x},t)$ describes the spatial density fluctuations. Density fluctuations are often considered in terms of their spectrum by comoving wavenumber, k. The Fourier relations are

$$\delta(\vec{k}) = \int \frac{d\vec{x}}{(2\pi)^3} e^{-i\vec{k}\cdot\vec{x}} \delta(\vec{x}), \qquad \delta(\vec{x}) = \int d\vec{k} e^{i\vec{k}\cdot\vec{x}} \delta(\vec{k}). \tag{7}$$

Newtonian gravitational potential fluctuations are related to density fluctuations through the Poisson equation, $\nabla^2\Phi = 4\pi G\rho$, and its Fourier transform $\Phi_k = -4\pi G\bar{\rho}a^2\delta_k/k^2$, where a is the cosmological scale factor relating the physical scale size r to the comoving scale size x, $r = a(t)x$.

A "transfer function", $T(k)$, relates the initial primordial density fluctuations at the epoch t_i to those observed at the present epoch, t_o: $\delta(k,t_o) \propto T(k)\delta(k,t_i)$. By convention, on large angular scales (small k) $T(k) = 1$ for Λ_0=0 and $\Omega_0 = 1$ cosmologies. That is, the fluctuations on the largest angular scales are primordial and unaffected by any physical evolution since there was never sufficient time for causal contact on this scale. The statistics of the primordial density fluctuations, $\delta(k,t_i)$, are described by a primordial power spectrum, the Peebles-Harrison-Zeldovich (Peebles & Yu 1970, Harrison 1970, Zeldovich 1972) spectrum,

$$P(k,t_i) = \left\langle |\delta(k,t_i)|^2 \right\rangle = Ak^n \tag{8}$$

where the angle brackets represent a spatial average over a large volume of the universe. For this spectrum the rms Sachs-Wolfe potential fluctuations (and the resulting CMB temperature anisotropies) as a function of angle θ are $\Delta\Phi_{rms}/c^2 = 3\Delta T_{rms}/T \propto \theta^{(1-n)/2}$ for $\Omega_0 = 1$ and $\theta \gtrsim 4°$ (Sachs & Wolfe 1967). Note that $P(k,t_o) = T^2(k)P(k,t_i) = Ak^nT^2(k)$. The scale invariant value $n = 1$ gives gravitational potential fluctuations with an rms amplitude that is independent of scale size and a large angular scale CMB temperature fluctuation spectrum that is approximately independent of the separation angle. For $\Omega_0 < 1$ and $\Lambda_0 = 0$ the above expression is still approximately true for angles $\theta < \Omega_0/(1-\Omega_0)^{1/2}$.

Measurements of the abundances of the light elements together with nucleosynthesis calculations imply that $0.011 \leq \Omega_B h^2 \leq 0.037$ (Walker *et al.*1991, Olive *et al.*1990), where Ω_B is the fraction of the critical mass density ($\rho_c = 3H_o^2/8\pi G = 1.88h^2 \times 10^{-29}$ gm cm^{-3}) in baryons and $h = H_0/100$ km s^{-1} Mpc^{-1}. Inflation requires that $\Omega_0 + \Lambda_0/3H_0^2 = 1$ so that either $\Lambda_0 \neq 0$, or inflation theory is incorrect, or most of the mass in the universe is yet to be detected nonbaryonic material. It is useful to assume that this nonbaryonic material does not interact with light. This simultaneously explains why it is not seen, and allows it to begin clustering while the universe was radiation dominated, earlier than is possible for the baryonic matter. The nonbaryonic material is broadly categorized as "hot" or "cold" dark matter, depending on whether it was or was not relativistic when the universe became matter-dominated. A neutrino with mass is a favorite hot dark matter candidate.

Bond & Efstathiou (1984) calculated the transfer function of the "standard cold dark matter model" assuming $T_{0,CMB} = 2.7$ K, $\Omega_B \ll \Omega_{CDM}$, and three massless neutrinos with $T_{0,\nu} = 1.9$ K, giving

$$T(k) = \frac{1}{[1 + (ak + (bk)^{3/2} + (ck)^2)^\nu]^{1/\nu}} \tag{9}$$

where $a = 6.4/(\Omega_0 h^2)$ Mpc, $b = 3.0/(\Omega_0 h^2)$ Mpc, $c = 1.7/(\Omega_0 h^2)$ Mpc, and $\nu = 1.13$. The scale size corresponding to the time when CDM and radiation have equal energy densities is $10/(\Omega_0 h^2)$ Mpc. Holtzman (1989) presents the results of calculations of $T(k)$ for 94 cosmological models.

A successful model of cosmology and the evolution of structure must match the amplitude and spectrum of density fluctuations from the galaxy scale to the horizon scale. Several observables have been derived from galaxy surveys, including the two-point correlation function, the amplitude of its integral, the rms mass fluctuation in a fixed radius sphere, and rms galaxy streaming velocities. The two point correlation function is defined by $\xi(x) = \langle \delta\rho(\vec{x}' + \vec{x})\delta\rho(\vec{x}')/\overline{\rho}^2 \rangle$. $\xi(x)$ is simply the Fourier conjugate of the power spectral density

$$P(k) = \int \frac{d\vec{x}}{(2\pi)^3} e^{-i\vec{k}\cdot\vec{x}} \xi(|\vec{x}|). \tag{10}$$

The integral of the two point correlation function is $J_3(R) \equiv \int_0^R \xi(x) x^2 dx$ (Peebles 1981). Based on the CfA redshift survey Davis & Peebles (1983) find $J_3(10/h\ \ \text{Mpc}) \approx 277h^{-3}$ Mpc^3 and $J_3(25/h\ \ \text{Mpc}) \approx 780h^{-3}\text{Mpc}^3$. J_3 relates directly to the power spectral density of fluctuations according to

$$J_3(R) = 4\pi \int \frac{P(k)}{k} [\sin kR - kr\cos kR]\, dk \tag{11}$$

where the J_3 definition assumed a spatial top-hat sampling or window function that results in the k-space weighting function $3(kR)^{-3}(\sin kR - kR\cos kR)$. Galaxies are not necessarily distributed in the same way as the mass density fluctuations. In general a linear proportionality is assumed, $(\delta\rho/\rho)_g = b(\delta\rho/\rho)_\rho$ where the constant b is the "biasing factor". The two point correlation function then scales as $\xi_g = b^2\xi_\rho$. The rms density fluctuation in a sphere of radius 8/h Mpc is $\sigma_8 \approx 1/b$ (Peebles 1982). The radius 8/h Mpc is chosen because the rms fluctuation of the galaxy distribution is unity at this radius. Note that, if the biasing factor is a constant (independent of angular scale), ratios of the rms density fluctuations over different scale sizes, such as σ_8/σ_{25} are independent of b. Kaiser *et al.*(1990) find that $b/\Omega_0^{0.6} = 1.16 \pm 0.21$ based on redshift surveys of IRAS galaxies so it is likely that $b < 2$. The rms of the peculiar velocities of galaxies averaged over a sphere of radius R is another observable that relates directly to the presently observed spectral power density by

$$\left\langle v^2(R) \right\rangle \approx 36\pi H_0^2 \Omega_0^{8/7} \int P(k) \frac{(\sin kR - kR\cos kR)^2}{(kR)^6} dk. \tag{12}$$

Bertschinger *et al.*(1990) derive average galaxy velocities in a sphere of given radii centered on the local group of $v(\text{R}{=}4000\ \text{km s}^{-1}) = 388 \pm 67\ \text{km s}^{-1}$ and $v(\text{R}{=}6000\ \text{km s}^{-1}) = 327 \pm 82\ \text{km s}^{-1}$ Thus measurements of ξ, J_3, σ_8, and $\langle v^2 \rangle$ help to determine $P(k)$ today.

Peacock (1991) finds that the power spectrum that is a best-fit to several independent observations of galaxy clustering is

$$P(k) = \frac{1}{4\pi k^3} \frac{(k/k_0)^\alpha}{1 + (k/k_c)^{-\beta}} \tag{13}$$

where $\alpha = 1.6$, $\beta = 2.4$, $k_0 = 0.19$ h Mpc^{-1}, and $k_c \approx 0.025$ h Mpc^{-1}. More recently, in light of the new *COBE* results summarized below, Peacock prefers $k_c \approx 0.033$ h Mpc^{-1} (private communication).

Hence, measurements of large scale (i.e. primordial) CMB anisotropies can provide the observational link between the production of gravitational potential fluctuations in the early universe and the observed galaxy distributions and velocities today. Large scale CMB anisotropy measurements provide both the amplitude and the power spectrum of the primordial fluctuations . Large scale anisotropy measurements are usually expressed in terms of a multipole expansion and a correlation function. The multipole expansion of the CMB temperature as a function of sky location is

$$T(\theta,\phi) = \sum_{l}\sum_{m=-l}^{l} a_{lm}Y_{lm}(\theta,\phi). \tag{14}$$

where $Y_{lm}(\theta,\phi)$ are the spherical harmonic functions. Since DMR is a differential experiment, as are almost all anisotropy experiments, the $l = 0$ monopole term is not observed. (It is observed by FIRAS.) The $l = 1$ dipole term is also dropped since it is dominated by the Doppler effect due to our local peculiar velocity and not by cosmic perturbations. Thus the $l = 2$ quadrupole term is the first term of interest. We are at liberty to select any coordinate system we choose. Since galactic emission dominates the sky signal, we choose galactic coordinates, with the usual galactic coordinate angles angles l and b. We define $Q(l,b)$ to be the $l = 2$ term of equation (14) and rewrite the five $Y_{l=2,m}$ components:

$$\begin{aligned} Q(l,b) &= Q_1(3\sin^2 b - 1)/2 + Q_2 \sin 2b \cos l + Q_3 \sin 2b \sin l + \\ &\quad Q_4 \cos^2 b \cos 2l + Q_5 \cos^2 b \sin 2l \end{aligned} \tag{15}$$

where the rms quadrupole amplitude is

$$Q^2_{rms} = \frac{1}{4\pi}\int_{4\pi} Q^2(l,b)d\Omega \;=\; \frac{4}{15}\left(\frac{3}{4}Q_1^2 + Q_2^2 + Q_3^2 + Q_4^2 + Q_5^2\right). \tag{16}$$

There is a small kinematic quadrupole, $Q_{rms} = 1.2$ μK, from the second order terms in the relativistic Doppler expansion (Peebles & Wilkinson 1968), for which $(Q_1, Q_2, Q_3, Q_4, Q_5)$=(0.9, -0.2, -2.0, -0.9, 0.2) μK.

The measured correlation function determines the parameters of the fluctuation power spectrum. The correlation function is

$$C(\alpha) = \sum_{l>1} \Delta T_l^2 W(l)^2 P_l(cos(\alpha)), \tag{17}$$

where P_l are Legendre polynomials, and a 3.2° rms Gaussian beam gives a weighting $W(l) = \exp[-\frac{1}{2}(l(l+1)/17.8^2)]$ and

$$\Delta T_l^2 = \frac{1}{4\pi}\sum_{m} |a_{lm}|^2 \tag{18}$$

are the rotationally-invariant rms multipole moments. As with the spherical harmonic expansion, the $l = 0$ is excluded from the correlation function since it is not measured by differential instruments, and the $l = 1$ term is excluded because it is contaminated by the kinematic dipole. The $l = 2$ quadrupole term is sometimes excluded since the quadrupole has only $2l + 1 = 5$ degrees of freedom, and thus has an intrinsically high statistical, or "cosmic" variance, independent of the measurement. For a power law primordial fluctuation spectrum the predicted moments, as a function of spectral index $n < 3$, are given by Bond & Efstathiou (1987):

$$< \Delta T_l^2 >= (Q_{rms})^2 \frac{(2l+1)}{5} \frac{\Gamma(l + (n-1)/2)\Gamma((9-n)/2)}{\Gamma(l + (5-n)/2)\Gamma((3+n)/2)}. \tag{19}$$

For $n = 1$ this simplifies to

$$< \Delta T_l^2 >= (Q_{rms})^2 \frac{6}{5} \frac{2l+1}{l(l+1)}. \tag{20}$$

Smoot *et al.*(1991b) presented preliminary DMR results based on six months of data. Smoot *et al.*(1992) describe results based upon the first year of DMR data, Bennett *et al.*(1992a) describe the calibration procedures, Kogut *et al.*(1992) discuss the treatment of systematic errors, and Bennett *et al.*(1992b) discuss the separation of cosmic and Galactic signals. Wright *et al.*(1992) compare these data to other measurements and to models of structure formation through gravitational instability. Previously published large-angular-scale anisotropy measurements include Fixsen *et al.*(1983), Lubin *et al.*(1985), Klypin *et al.*(1987), and Meyer *et al.*(1991). Some excellent reviews of CMB anisotropy and cosmological perturbation theory include Bertschinger (1992), Efstathiou (1990), Kolb & Turner (1990), Peebles (1971, 1980), and Wilkinson (1986).

5.1. The DMR instrument and data processing

The *COBE* DMR instrument is described by Smoot *et al.* (1990). DMR operates at three frequencies: 31.5, 53 and 90 GHz (wavelengths 9.5, 5.7, and 3.3 mm), chosen to be near the minimum in Galactic emission and near the CMB maximum. Wright et al. (1990) have used the FIRAS and DMR data to show that the ratio of the galactic emission to that of the CMB reaches a minimum between 60 and 90 GHz. There are two nearly independent channels, A and B, at each frequency. The orbit and pointing of the *COBE* result in a complete survey of the sky every six months while shielding the DMR from terrestrial and solar radiation (Boggess *et al.*1992).

The DMR measures the difference in power received between regions of the sky separated by 60°. For each radiometer channel a baseline is subtracted and the data are calibrated. Data are rejected when the limb of the Earth is higher than 1° below the Sun/Earth shield plane, when the Moon is within 25° of a beam center, when any datum deviates from the daily mean by more than 5σ, or when the spacecraft telemetry or attitude solution is of poor quality. Small corrections are applied to remove the estimated emission from the Moon and Jupiter in the remaining data. Corrections are also applied to remove the Doppler effects from the spacecraft's velocity about the Earth and the Earth's velocity about the solar system barycenter. A least-squares minimization is used to fit the data to spherical harmonic expansions and to make sky maps with 6144 nearly equal area pixels using a sparse matrix technique (Torres *et al.* 1989, Janssen & Gulkis 1992). The DMR instrument is sensitive to external magnetic fields. Extra equations are included in the sparse matrix to allow these magnetic susceptibilities to be fit separately as a linear function of the Earth's field and the radiometer orientation. The magnetic corrections are on the scale of 10 to 100 μK in the time-ordered data. Residual uncertainties in the individual radiometer channel maps, after correction, are typically 2 μK and never more than 8.5 μK.

Kogut *et al.*(1992) have searched the DMR data for evidence of residual systematic effects. The largest such effect is the instrument response to an external magnetic field. Data binned by the position of the Earth relative to the spacecraft show no evidence for contamination by the Earth's emission at the noise limit (47 μK at 95% CL). The contribution of the Earth's emission to the maps is estimated to be less than 2 μK. The time-ordered data with antenna beam centers more than 25° away from the Moon are corrected to an estimated accuracy of 10% (4 μK) of the lunar flux. The estimated residual effect on the maps is less than 1 μK. Kogut *et al.*list upper limits for the effects of variations in calibration and instrument baselines, solar and solar system emissions, RFI, and data analysis errors. The quadrature sum of all systematic uncertainties in a typical map, after corrections, is < 8.5 μK for rms sky fluctuations, < 3 μK for the quadrupole and higher-order multipole moments, and < 30 μK^2 for the correlation function (all limits 95% CL).

5.2. The DMR anisotropy

The DMR maps are dominated by the dipole anisotropy and the emission from the Galactic plane. The dipole anisotropy ($\Delta T/T \approx 10^{-3}$) is seen consistently in all channels with a thermodynamic temperature amplitude 3.36±0.1 mK in the direction $l = 264.7° \pm 0.8°$, $b = 48.2° \pm 0.5°$, consistent with the FIRAS results, above. Our motion with respect to the CMB (a blackbody radiation field) is assumed to produce the dipole anisotropy, so the dipole and associated ≈ 1.2 μK rms kinematic quadrupole are removed from the maps.

The DMR instrument noise and the intrinsic fluctuations on the sky are independent and thus add in quadrature to give the total observed signal variance

$$\sigma^2_{obs} = \sigma^2_{DMR} + \sigma^2_{Sky}. \tag{21}$$

The σ_{obs} is estimated from the two channel (A+B)/2 sum maps, and the (A-B)/2 difference maps provide an estimate of σ_{DMR}, yielding the sky variance $\sigma_{Sky}(10°) = 30 \pm 5$ μK for $|b| > 20°$. The observations are made with a 7° beam, and the resulting maps are smoothed with an additional 7° Gaussian function, resulting in the effective 10° angular resolution.

The correlation function, C(α), is the average product of temperatures separated by angle α. It is calculated for each map by rejecting all pixels within the Galactic latitude band $|b| < 20°$, removing the mean, dipole, and quadrupole from the remaining pixels by a least squares fit, multiplying all possible pixel pair temperatures, and averaging the results into 2.6° bins. Bennett *et al.*(1992b) conclude that the galactic contribution to the correlation signal is small for $|b| > 15°$. This is consistent with the fact that the correlation function and rms sky fluctuation are insensitive to the Galactic latitude cut angles so long as $|b| < 15°$ is excluded. The DMR correlation functions exhibit temperature anisotropy on all angular scales greater than the beam size (7°) and differ significantly ($> 7\sigma$) from the flat correlation function due to receiver noise alone.

All six channels show a statistically significant quadrupole signal. A comparison of the fitted quadrupoles between channels and frequencies, and between the first and second six months of data, shows that individual quadrupole components, Q_i, typically differ from map to map by $\approx 10\ \mu$K with comparable uncertainty. Determination of the cosmic quadrupole is linked to its separation from Galactic emission (Bennett *et al.*1992b), summarized below. Discrete extragalactic sources individually contribute less than 2 μK in the DMR beam and the expected temperature variations are less than 1 μK (Franceschini *et al.* 1989).

5.3. Separation of galactic signals & the cosmic quadrupole

The DMR anisotropy maps are sufficiently sensitive and free from systematic errors that our knowledge of Galactic emission is a limiting factor in interpreting the measurements of the 1-year DMR maps. The detected signals expressed in thermodynamic temperature are nearly constant amplitude: the rms fluctuations on a 10° scale are proportional to $\nu^{-0.3\pm1}$ and the quadrupole and correlation functions $\propto \nu^{-0.2\pm1}$. The flat spectral index of the DMR anisotropy, without correction for Galactic emissions, is consistent with a cosmic origin and inconsistent with an origin from a single Galactic component. However, from this fact alone we are unable to rule out a correlated superposition of dust, synchrotron, and free-free emission and thus more detailed galactic emission models are required. Bennett *et al.*(1992b) constructed preliminary models of microwave emission from our Galaxy based on *COBE* and other data for the purpose of distinguishing cosmic and Galactic signals.

Four emission components are important at microwave wavelengths. CMB anisotropies are assumed to produce differences in the measured antenna temperature according to $\Delta T_A = \Delta T\ x^2 e^x/(e^x-1)^2$, where $x = h\nu/kT$, T is thermodynamic temperature. Synchrotron emission arises from relativistic electrons accelerated by magnetic fields. Free-free emission occurs when free electrons are accelerated by interactions with ions. Thermal emission from dust is also important at microwave wavelengths.

The brightest pixels in the DMR maps are T_A=5.9 ± 0.4 mK at 31.5 GHz, 1.9 ± 0.2 mK at 53 GHz, both at (l,b)=(337°, -1°), and 1.3±0.2 mK (348°,+1°) at 90 GHz. Galactic plane emission would have to be removed to better than 1% to reveal cosmologically interesting fluctuations in the CMB at low Galactic latitudes, so our preliminary models concentrate on $|b|>10°$.

The intensity of synchrotron radiation is given by the integral $I(\nu) = \iint P(\nu,\vec{B},E)\,N(E,\vec{l})\,dE\,dl$ where $P(\nu,\vec{B},E)$ is the power emitted at a frequency ν by a single electron of energy E in a magnetic field $\vec{B}$, and $N(E,\vec{l})dE$ is the number of relativistic electrons of energy E per unit volume at the position $\vec{l}$ along the line of sight. Since $N(E,\vec{l})$ and $\vec{B}(\vec{l})$ are not known for every position in the Galaxy, approximations must be made to model synchrotron emission. Bennett *et al.*(1992b) use the local electron spectrum in conjunction with radio data to approximate the synchrotron integral.

Free-free emission is characterized by an antenna temperature that depends only on the emission measure and electron temperature along the line of sight for each frequency, with a spectral index $\beta_{ff} = 2 + [10.48 + 1.5\ln(T_e/8000\text{ K}) - \ln\nu_{\text{GHz}}]^{-1}$. β is the spectral index of the antenna temperature, $T_A \propto \nu^{-\beta}$, which relates to the flux density, $S(\nu)$, by $S(\nu) \propto 2kT_A(\nu)\nu^2/c^2$. With $T_e = 8000$ K (Reynolds 1985), the ratio of the 53 GHz free-free antenna temperature to Hα intensity can be expressed as $T_A(\mu\mathrm{K})/I(\mathrm{Rayleigh}) = 0.83\ \mu\mathrm{K}/0.44$ Rayleigh $= 2\ \mu$K/Rayleigh, almost independent of the electron temperature. Reynolds (1984, 1992) has observed several high-latitude lines of sight with a 0.8° beam and reports that the high latitude Hα diffuse Galactic distribution is $I(\mathrm{R}) \approx 1.2 \csc|\mathrm{b}|$ for $|b| > 15°$. Deviations from a cosecant-law are larger than the ≈15% Hα measurement uncertainties (Reynolds 1992).

Another estimate of the high latitude emission measure comes from the *COBE* FIRAS measurement of the N^+ ground state transition at 205 μm (Wright *et al.*1991). The observed intensity of this line is $I(\mathrm{N}^+) \approx (7 \pm 2) \times 10^{-8} \csc|\mathrm{b}|$ erg s^{-1} cm^{-2}sr^{-1} for $|b| > 15°$ compared with $I(\mathrm{N}^+) \approx 2.4\times10^{-8}\csc|\mathrm{b}|$ erg s^{-1} cm^{-2}sr^{-1} predicted by Reynolds (1992) for the diffuse component. In doing Hα background measurements, Reynolds picks locations that are free from discrete sources, while the *COBE* observations do not exclude sources. The *COBE* observations may also include emission with velocities outside of Reynolds' Hα passband. If we assume that the excess observed N^+ arises from the full sky (unbiased) sampling by FIRAS and any Hα bandwidth exclusions by Reynolds, then we can use the ratio of measured-to-predicted N^+ to correct the diffuse free-free predictions for these effects. We deduce from the above that a correction factor of ~3 is required; the free-free emission is then approximately $T_A(\mu\mathrm{K}) \approx 7 \csc|b|$ for $|b| > 15°$ at 53 GHz. This prediction is only approximate since it depends on assumptions of the chemical abundance of nitrogen and its fractional population in the N^+ state. Our factor of ~3 to convert from diffuse to full sky-averaged Hα intensity is consistent with the Reynolds (1992) a priori estimate of a factor of ~2. Unfortunately, there exists no full sky survey of free-free emission to the sensitivity required by the *COBE* DMR, so the DMR 31.5 GHz map must serve this purpose. We compare this with the cosecant-law predictions discussed above and find good agreement.

Along each line of sight the observed dust emission is the sum over the emission from each dust grain. Since the grain temperatures, emissivities, and spatial distributions are not known, it is not possible to make *a priori* full sky dust emission models. We must rely, instead, on full sky measurements of the dust intensity at higher frequencies and extrapolate these with empirical spectral fits. The dust antenna temperature is $T_A = 33\ G(l,b)\ R^d_\nu\ \mu\mathrm{K}$, where R^d_ν=(0.43, 1.0, 2.3) at (31.5, 53, 90 GHz) and $G(l,b)$ is the dimensionless map of the dust distribution from FIRAS, discussed earlier. $G(l,b) \approx 1$ in the plane of the Galaxy and ranges from 0.03 to 0.1 at high Galactic latitudes.

Bennett *et al.*(1992b) present three approaches to modeling the Galactic emission signal in the DMR maps. A "subtraction technique" makes use of external data to *subtract* Galactic emission maps from the DMR maps. The dust and synchrotron emission models, described above, were subtracted from the DMR maps. Since no map exists of the ionized component of our Galaxy, the 31 GHz residual map is used to subtract the free-free emission from the 53 and 90 GHz DMR maps. The angular autocorrelation functions of the individual emission components show that the Galactic components have different angular correlations than the residual cosmic signal. In fact, the cosmic correlation function is largely unaffected by the Galactic model subtraction. A "fitting technique" directly *fits* the DMR maps pixel-by-pixel. The results of the fit are maps of free-free and Planckian emission. A "combination technique" uses a linear *combina-*

tion of the DMR 31.5, 53, and 90 GHz maps to minimize the Galactic emission without recourse to Galactic models or other data. The subtraction, fitting, and combination techniques produce consistent results. The combination technique is independent of the fitting and subtraction techniques, aside from the use of DMR data and the assumed free-free spectral index. Bennett *et al.*conclude that no known Galactic emission component or superposition of components can account for most of the observed anisotropy signal. In the absence of significant extragalactic source signals or systematic errors, as argued above, this signal must be intrinsic to the CMB radiation.

DMR maps, with the modeled Galactic emission removed, are fit for a quadrupole distribution. Bennett *et al.*derive a cosmic quadrupole, corrected for the expected kinematic quadrupole, of $Q_{rms} = 13 \pm 4\ \mu$K, $(\Delta T/T)_Q = (4.8 \pm 1.5) \times 10^{-6}$, for $|b| > 10°$. When Galactic emission is removed from the DMR data, the residual fluctuations are virtually unaffected and therefore they are not dominated by any known Galactic emission component(s).

5.4. Interpretation of the DMR anisotropy

The anisotropy detected by the DMR is interpreted as being a direct result of primordial fluctuations in the gravitational potential. Assuming a power spectral density of density fluctuations of the form $P(k) = Ak^n$, the best-fit results are $n = 1.1 \pm 0.5$ with $Q_{rms-PS} = 16 \pm 4\ \mu$K. Q_{rms-PS} is the rms quadrupole amplitude resulting from this power spectrum fit, i.e. making use of fluctuation information from all observed angular scales, as opposed to the Q_{rms} derived from a direct quadrupole fit. Forcing the spectral index to $n = 1$ gives $Q_{rms-PS} = 16.7 \pm 4\ \mu$K and increases the χ^2 from 79 to 81 for 68 degrees of freedom. Interpreted as a power-law spectrum of primordial fluctuations with a Gaussian distribution, the ΔT_l^2 in each horizon have a χ^2 distribution of $2l + 1$ degrees of freedom, giving a cosmic variance for observations within a single horizon volume in the universe of $2 < \Delta T_l^2 >^2 /(2l + 1)$. Best fit values are $n = 1.15^{+0.45}_{-0.65}$ and $Q_{rms-PS} = 16.3 \pm 4.6\ \mu$K including the cosmic variance, with a χ^2 of 53. Cross-correlation of the 53 GHz and 90 GHz maps are consistent with a power law spectra with index $n = 1 \pm 0.6$ and amplitude $Q_{rms-PS} = 17 \pm 5\mu$K, including cosmic variance.

The observed cosmic quadrupole from the maps [$Q_{rms} = 13 \pm 4\mu$K from Bennett *et al.*1992b (see above)] is slightly below the mean value predicted by the higher-order moments deduced from the correlation function ($Q_{rms-PS} = 16 \pm 4\mu$K). This is a likely consequence of cosmic variance: the mode of the χ^2 distribution is lower than the mean. A map quadrupole value of 13 μK or lower would be expected to occur 35% of the time for an $n = 1$ universe with $Q_{rms-PS} = 16\ \mu$K. The results above exclude the quadrupole before computing C(α). Including the quadrupole in computing C(α) increases the χ^2, raises n to 1.5, and decreases Q_{rms-PS} to 14μK.

The measured parameters [$\sigma_{Sky}(10°)$, Q_{rms}, Q_{rms-PS}, $C(\alpha)$, and n] are consistent with a Peebles-Harrison-Zeldovich (scale invariant) spectrum of perturbations, which predicts $Q_{rms} = (1^{+0.3}_{-0.4})Q_{rms-PS}$ and $\sigma_{Sky}(10°) = (2.0 \pm 0.2)Q_{rms-PS}$. The theoretical 68% CL errors take into account the cosmic variance due to the statistical fluctuations in perturbations for our observable portion of the Universe. The minimum Q_{rms} for models with an initial Peebles-Harrison-Zel'dovich perturbations, normalized to the local large-scale galaxy streaming velocities, is predicted to be 12 μK, independent of the Hubble constant and the nature of dark matter (Gorski 1991, Schaefer 1991).

These observations are consistent with inflationary cosmology models. The natural interpretation of the DMR signal is the observation of very large (presently >>100 Mpc) structures in the Universe which are little changed from their primordial state (t << 1 sec). These structures are part of a power law spectrum of small amplitude gravitational potential fluctuations that on smaller length scales are sources of the large scale structure observed in the Universe today. The DMR data provide strong support for gravitational instability theories (Wright *et al.*1992). Wright *et al.*compare the 94 cosmological models for which Holtzman (1989) has computed a transfer function, $T(k)$, with the DMR anisotropy results. None of the Holtzman isocurvature models are compatible with the DMR anisotropy amplitude for a biasing factor $b < 4$. Wright *et al.*find that three Holtzman models fit the observational data (galaxy clustering, galaxy streaming velocity, and CMB quadrupole amplitude) reasonably well. These models are described below.

A model with vacuum energy density with $\Omega_{vac} = \Lambda_0/3H_0^2 = 0.8$, $H_0 = 100$ km s^{-1} Mpc^{-1}, $\Omega_B = 0.02$, $\Omega_{CDM} = 0.18$ is an excellent fit to the observational data (see, e.g. Gorski, Silk & Vittorio 1992; Efstathiou, Bond & White 1992, and Peebles 1984, 1991).

A "mixed dark matter" (MDM) model that fits the data uses both hot dark matter (a massive neutrino with $\Omega_{HDM} = 0.3$) and cold dark matter ($\Omega_{CDM} = 0.6$) with baryonic dark matter $\Omega_B = 0.1$ and $H_0 = 50$ km s^{-1} Mpc^{-1}. See, for example, Efstathiou, Bond & White (1992), Davis, Summers & Schlegel (1992), and van Dalen & Schaefer (1992) for further recent discussions of mixed dark matter models.

An open universe model with $\Omega_0 = 0.2$, $\Omega_B = 0.02$, and $\Omega_{CDM} = 0.18$ for $H_0 = 100$ km s^{-1} Mpc^{-1} satisfies the observations, except perhaps for the galaxy rms peculiar velocities, but is in conflict with the inflation model and theoretical prejudices for $\Omega_0 = 1$ (see Gouda & Sugiyama 1992, Peebles 1984, 1991).

The unbiased standard cold dark matter is in conflict with galaxy clustering data, even without the constraint of the COBE data (e.g. Vogeley *et al.*1992, Loveday *et al.*1992). Hogan (1991, 1992, 1993) and Hoyle & Burbidge (1992) interpret the *COBE*-DMR results in terms of models where the temperature anisotropies do not arise from gravitational potential fluctuations on the surface of last scattering. Bennett & Rhie (1992) interpret the DMR data in terms of global monopoles and textures.

In summary, the *COBE* detection of CMB temperature anisotropy has added another important observational piece of knowledge to the cosmic puzzle. There is not yet a clear favorite among the models that attempt to account for all of the pieces, nor is there likely to be one without further observational information.

6. The DIRBE experiment

6.1. The cosmic infrared background radiation

The Diffuse Infrared Background Experiment (DIRBE) is the first space experiment designed primarily to measure the CIB radiation. The aim of the DIRBE is to conduct a definitive search for an isotropic CIB radiation, within the constraints imposed by the local astrophysical foregrounds.

Cosmological motivations for searching for an extragalactic infrared background have been discussed in the literature for several decades (early papers include Partridge & Peebles 1967; Low & Tucker 1968; Peebles 1969; Harwit 1970; Kaufman 1976). Both the cosmic redshift and 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. Hence, the wide spectral range from 1 to 1000 μm is expected to contain much of the energy released since the formation of luminous objects, and could potentially contain a total radiant energy density comparable to that of the CMB.

The CIB radiation has received relatively little attention in the theoretical literature compared to that devoted to the CMB (Negroponte 1986), which has a central significance to Big Bang cosmology and quite distinctive and definite predictions as to its character. However, advances in infrared instrumentation, and especially the introduction of cryogenically cooled infrared instruments on space missions, have stimulated increasing attention to prediction of the character of the CIB radiation (Fabbri and Melchiorri 1979; Bond, Carr, and Hogan 1986; McDowell 1986; Fabbri *et al.*1987; Fabbri 1988; Bond, Carr, and Hogan 1991). Measurement of the spectral intensity and anisotropy of the CIB radiation would provide important new insights into intriguing 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.

Observing the CIB radiation is a formidable task. Bright foregrounds from the atmosphere of the Earth, from interplanetary dust scattering of sunlight and emission of absorbed sunlight, and from stellar and interstellar emissions of our own Galaxy dominate the diffuse sky brightness in the infrared. Even when measurements are made from space with cryogenically cooled instruments, the local astrophysical foregrounds strongly constrain our ability to measure and discriminate an extragalactic infrared background. Furthermore, since the absolute brightness of the CIB radiation is of paramount interest for cosmology, such measurements must be done relative to a well established absolute flux reference, with instruments which strongly exclude or permit discrimination of all stray sources of radiation or offset signals which could mimic a cosmic signal.

Hauser (1991b) lists recent experiments capable of making absolute sky brightness measurements in the infrared (for a compilation including some earlier measurements, see Negroponte 1986). Instruments or detector channels designed specifically to measure that part of the spectrum dominated by the CMB radiation have been excluded. Murdock & Price (1985) flew an absolute radiometer with strong stray light rejection on a sounding rocket in 1980 and 1981. Their primary objective was measuring scattering and emission from interplanetary dust, and no attempt was made to extract an extragalactic component. Matsumoto *et al.*(1988a) flew a near-infrared experiment on a rocket in 1984. They have reported possible evidence for an isotropic residual near 2 μm, perhaps in a line feature, for which they cannot account in their models of emission from the interplanetary medium and the Galaxy. This group has flown a modified instrument early in 1990 to investigate further this result (Noda *et al.*1992). The IRAS sky survey instrument, though not specifically designed for absolute background measurements, was, within the limits of long term stability, capable of good relative total sky brightness measurements, and so is included in this list. Uncertainties in the IRAS absolute calibration have impeded efforts to extract an estimate of the CIB radiation (Rowan- Robinson 1986). The FIRAS high frequency channel (100 to 500 μm), with its all-sky coverage, excellent stray light rejection, absolute calibration, and high sensitivity, also promises to be an important instrument for CIB radiation studies. Quantitative comparison of the measurements from the experiments discussed above, and a summary of current CIB radiation limits are discussed further below.

6.2. The DIRBE instrument

The experimental approach is to obtain absolute brightness maps of the full sky in 10 photometric bands (J[1.2], K[2.3], L[3.4], and M[4.9]; the four IRAS bands at 12, 25, 60, and 100 μm; and 140 and 240 μm bands). To facilitate discrimination of the bright foreground contribution from interplanetary dust, linear polarization is also measured in the J, K, and L bands, and all celestial directions are observed hundreds of times at all accessible angles from the Sun in the range 64° to 124°. 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 both estimated CIB radiation contributions (e.g., Bond, Carr, Hogan 1986) and the total infrared sky brightness.

The DIRBE instrument is an absolute radiometer, utilizing an off-axis Gregorian telescope with a 19-cm diameter primary mirror. Since the DIRBE was designed to make an absolute measurement of the spectrum and angular distribution of the diffuse infrared background it must have extremely strong rejection of stray light. The optical configuration (Magner 1987) has strong rejection of stray light from the Sun, Earth limb, Moon or other off-axis celestial radiation, or parts of the COBE payload (Evans, 1983; Evans and Breault 1983). Stray light rejection features include both a secondary field stop and a Lyot stop, super-polished primary and secondary mirrors, a reflective fore-baffle, extensive internal baffling, and a complete light-tight enclosure of the instrument within the COBE dewar. Additional protection is provided by the Sun and Earth shade surrounding the COBE dewar, which prevents direct illumination of the DIRBE aperture by these strong local sources. The DIRBE instrument, which was maintained at a temperature below 2 K within the dewar as long as the helium was present, measures absolute brightness by chopping between the sky signal and a zero flux internal reference at 32 Hz using a tuning fork chopper. The synchronously demodulated signal is averaged for 0.125 second before transmission to the ground. Instrumental offsets are measured by closing a cold shutter located at the prime focus. All spectral bands view the same instantaneous field-of-view, 0.7° x 0.7°, oriented at 30° from the spacecraft spin axis. This allows the DIRBE to modulate the angle from the Sun by 60° during each rotation, and to sample fully 50% of the celestial sphere each day. Four highly-reproducible internal radiative reference sources can be used to stimulate all detectors when the shutter is closed to monitor the stability and linearity of the instrument response. The highly redundant sky sampling and frequent response checks provide precise photometric closure over the sky for the duration of the mission. Calibration of the photometric scale is obtained from observations of isolated bright celestial sources. Careful measurements of the beam shape in pre-flight system testing and during the mission using scans across bright point sources allow conversion of point-source calibrations to surface brightness calibrations.

The data obtained during the helium temperature phase of the mission are of excellent photometric quality, showing good sensitivity, stability, linearity, and stray light immunity. Few artifacts are apparent other than those induced by energetic particles in the South Atlantic Anomaly and variations in instrument temperature. Both of these effects will be removed in final data processing. Strong rejection of off-axis radiation sources is confirmed by the absence of response to the Moon (which saturates the response in all detectors when in the field of view) until it comes within about 3° of the field of view. The sensitivity per field of view, listed above, is based on noise measured with the shutter closed and response determined from measurements of known celestial sources. The noise when the shutter was open is somewhat above the shutter-closed values due to discrete source confusion. The nuclear radiation environment in orbit caused very little response change (<1%) in all detectors except the Ge:Ga photoconductors used at 60 and 100 μm. Thermal and radiative annealing procedures applied to these detectors following passages through the South Atlantic Anomaly will allow response correction to about 1% at these wavelengths. It is expected that fully reduced DIRBE sky maps will have photometric consistency over the sky better than 2% at each wavelength, nearest neighbor band-to-band (color) brightness accuracy of 3% or better, and absolute intensity scale accuracy better than 20%.

6.3. DIRBE results

Preliminary results of the DIRBE experiment have been described by Hauser *et al.*(1991), Hauser (1991a, 1991b). Qualitatively, the initial DIRBE sky maps show the expected character of the infrared sky. For example, at 1.2 μm stellar emission from the galactic plane and from isolated high latitude stars is prominent. Zodiacal scattered light from interplanetary dust is also prominent. These two components continue to dominate out to 3.4 μm, though both become fainter as wavelength increases. A composite of the 1.2, 2.3, and 3.4 μm images was presented by Mather et al. (1990b). Because extinction at these wavelengths is far less than in visible light, the disk and bulge stellar populations of the Milky Way are dramatically apparent in this image. At 12 and 25 μm, emission from the interplanetary dust dominates the sky brightness. As with the scattered zodiacal light, the sky brightness is strongly dependent upon ecliptic latitude and solar elongation angle. At wavelengths of 60 μm and longer, emission from the interstellar medium dominates the galactic brightness, and the interplanetary dust emission becomes progressively less apparent. The patchy infrared cirrus noted in IRAS data (Low *et al.*1984) is evident at all wavelengths longer than 25 μm. Weiland *et al.*(1991) gave a preliminary description of the emission from the interplanetary dust bands, and Murdock *et al.*(1991) have used the DIRBE data to carry out a preliminary examination of the ecliptic pole emission.

The DIRBE data will clearly be a valuable new resource for studies of the interplanetary medium and Galaxy as well as the search for the CIB radiation.

In searching for the extragalactic infrared background, the most favorable conditions are directions and wavelengths of least foreground brightness. In general, because of the strong interplanetary dust foreground and the relatively modest gradient of that foreground over the sky, the infrared sky is faintest at high ecliptic latitude. A preliminary DIRBE spectrum of the sky brightness toward the south ecliptic pole was presented by Hauser *et al.*(1991), and is reproduced in Table 2.

Table 2. Cosmic Infrared Background Limits

Reference	λ (μm)	λI_λ (10^{-7} W m^{-2} sr^{-1})
DIRBE	1.2	8.3 ± 3.3
(South Ecliptic Pole)	2.3	3.5 ± 1.4
	3.4	1.5 ± 0.6
	4.9	3.7 ± 1.5
	12.	29. ± 12
	22.	21. ± 8
	55.	2.3 ± 1
	96.	1.2 ± 0.5
	151.	1.3 ± 0.7
	241.	0.7 ± 0.4

This table shows the strong foreground from starlight and scattered sunlight at the shortest wavelengths, a relative minimum at 3.4 μm, emission dominated by interplanetary dust peaking around 12 μm, and generally falling brightness from there out to submillimeter wavelengths.

To meet the cosmological objective of measuring the CIB radiation, the foreground light from interplanetary and galactic sources must be discriminated from the total observed infrared sky brightness. This task requires extensive careful correlation studies and modelling, which in the case of the DIRBE investigation is in progress. A conservative upper limit on extragalactic light is the total observed brightness in a relatively dark direction. The sky brightness at the south ecliptic pole is a fair representation of the best current limits from the DIRBE. The faintest foregrounds occur at 3.4 μm, in the minimum between interplanetary dust scattering of sunlight and re-emission of absorbed sunlight by the same dust, and longward of 100 μm, where interstellar dust emission begins to decrease. Through careful modelling, we hope to be able to discriminate isotropic residuals at a level as small as 1 percent of the foregrounds. These near-infrared and submillimeter windows will allow the most sensitive search for, or limits upon, the elusive cosmic infrared background.

These data are to be compared with the theoretical estimates of contributions to the CIB radiation from pregalactic and protogalactic sources in a dust free universe (Bond, Carr, and Hogan 1986, Carr 1988). The present conservative observational limits are beginning to constrain some of the theoretical models at short infrared wavelengths, though in a dusty universe energy from these sources can be redistributed farther into the infrared. If the foreground components of emission can confidently be identified, the current *COBE* measurements will seriously constrain (or identify) the CIB radiation across the infrared spectrum. However, the spectral decade from about 6 to 60 μm will have relatively weak limits until measurements are made from outside the interplanetary dust cloud.

The CIB radiation promises to enhance our understanding of the epoch between decoupling and galaxy formation. The high quality and extensive new measurements of the absolute infrared sky brightness obtained with the DIRBE and FIRAS experiments on the *COBE* mission promise to allow a definitive search for this elusive background, limited primarily by the difficulty of distinguishing it from bright astrophysical foregrounds.

7. *COBE* data products and plans

Extensive data products from the *COBE* mission consisting of calibrated maps and spectra with associated documentation are planned. The *COBE* databases have been described by White & Mather (1991). An overview of the *COBE* software system has been given by Cheng (1991). All *COBE* data processing and software development for analysis take place at the Cosmology Data Analysis Center (CDAC) in Greenbelt, MD, a facility developed by the *COBE* project for that purpose. This facility, and the software tools developed there, will become available to the scientific community when the data products are released.

Initial data products are planned for release in mid 1993. Galactic plane maps, including the nuclear bulge, will be available at all 10 DIRBE wavelengths and the high frequency FIRAS band. Full sky maps from all six DMR radiometers will also be available.

Full sky maps from all three *COBE* instruments, spanning four decades of wavelength, are planned for release in mid-1994. These data gathered by the *COBE*'s three instruments will constitute a comprehensive data set unprecedented in scope and sensitivity for studies of cosmology, and large scale galactic and solar system science.

Acknowledgments

The authors gratefully acknowledge the contributions to this report by their colleagues on the *COBE* Science Working Group and the other participants in the *COBE* Project. Many people have made essential contributions to the success of *COBE* in all its stages, from conception and approval through hardware and software development, launch, flight operations, and data processing. To all these people, in government, universities, and industry, we extend our thanks and gratitude. In particular, we thank the large number of people at the GSFC who brought this challenging in-house project to fruition.

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