COBE Observations and Results

George F. Smoot

Lawrence Berkeley National Laboratory
Space Sciences Laboratory
Center for Particle Astrophysics
Department of Physics
University of California, Berkeley CA 94720
e-mail: Smoot@cosmos.lbl.gov

Abstract. This paper summarizes the results from the COBE satellite mission. Nine years have passed since the launch of COBE and six years since the announcement of the discovery of cosmic microwave background anisotropies by the COBE DMR instrument. This is still a relatively short time to look back and understand the implications of COBE and the anisotropy discovery; however, this 3K Cosmology Conference provides some context. The Cosmic Background Explorer (COBE) satellite has made a major contribution to the field of cosmology and has help create the confidence and high level of interest that propels the field today. Two major CMB observations, the thermal spectrum of the CMB and the CMB anisotropies, plus a host of other observations and conclusions are the basis and a major but not exclusive portion of the legacy of COBE. The recent detection and observation of the cosmic infrared background (CIB) are also part of COBE's major contribution to cosmology.

Subject headings: cosmic microwave background – cosmology – – artificial satellites, space probes

INTRODUCTION

COBE (the Cosmic Background Explorer satellite) is NASA's first cosmological satellite. The spectacular results and success COBE provided stimulation to the field and to everyone's imagination which has resulted in the world's space agencies being open to future missions that promise to revolutionize and quantify our view of the Universe. COBE has also provided us with confidence in the Big Bang model of cosmology and our ability to test variants of the Big Bang models and determine their parameters with precision. COBE also determined two of those parameters remarkable well in a field characterized by uncertainty in these parameters at the 50 to 100% level.

The Cosmic Background Explorer (COBE) was NASA's first cosmological satellite and had a number of significant results:

- Full Sky Maps at 14 Frequencies
- Cosmic Microwave Background Spectrum – precision measurements
- CMB Anisotropies – detection, observation, measurement
- Diffuse Infrared Background – detection, measurement
- CMB Polarization – significant upper limits

COBE, additionally, proved to be a training ground for approaches, techniques, and people. These included those of the COBE team and the external community which had good and timely access to the data. This lead to much scientific interest and activity. Our current view of the data/signal flow and ultimate analysis and interpretation is very similar to that used on the COBE observations and analysis.

Boggess et al. [1] provide a COBE mission overview.

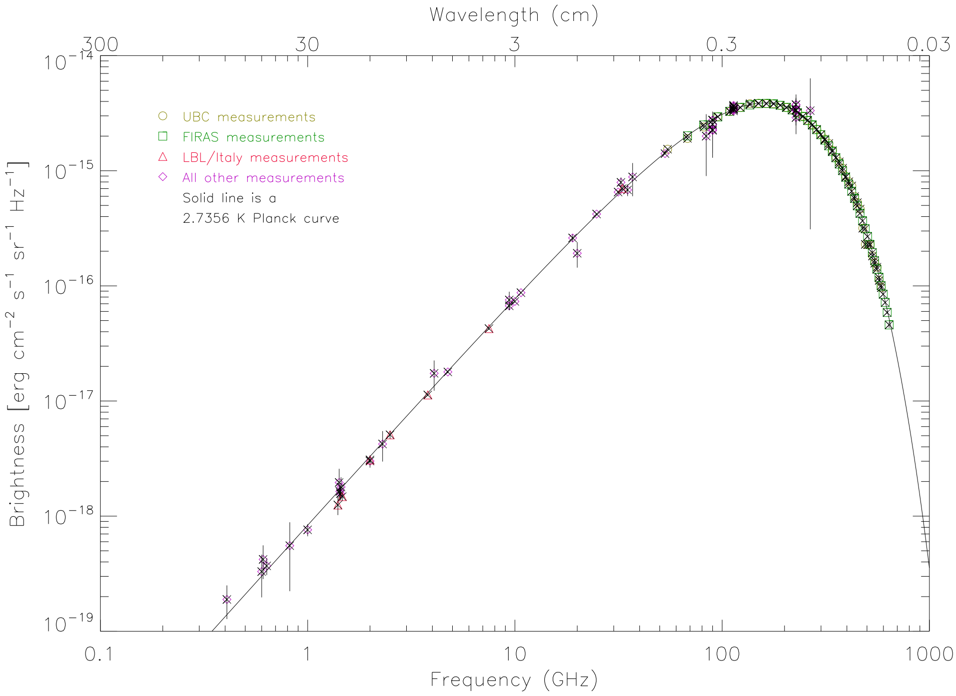

FIGURE 1. Brightness as a function of frequency of the CMB

I CMB THERMAL SPECTRUM

A Frequency Spectrum

The FIRAS (Far Infrared Absolute Spectrophotometer) instrument has made a high precision observation of the cosmic microwave background.

FIRAS [21] was built to measure the spectrum of diffuse emission from 1 to 100 cm^{-1}, with particular attention to possible differences between the spectrum of the cosmic microwave background radiation (CMBR) and a blackbody spectrum as small as 0.1% of the peak of the CMBR spectrum. The FIRAS has differential inputs and outputs, a full beam external calibrator, a controllable reference blackbody, and a polarizing Michelson interferometer with bolometer detectors. It operated at a temperature of 1.5 K inside a liquid helium cryostat to suppress instrument emission and improve detector sensitivities.

FIRAS improves upon previous measurements in reducing the potential contributions of the systematic errors by: 1) operating outside the atmosphere; 2) providing full aperture *in situ* calibration; 3) providing a continuous differential comparison with a reference blackbody adjusted to null the input signal; 4) operating the entire instrument, including the beam forming optics, in a shielded environment at cryogenic temperatures; and 5) using an improved horn antenna with a flared aperture to define the beam and reduce the contributions from objects outside the main beam. These were possible in the context of a satellite mission.

The ultimate result of the FIRAS observations and analysis was a remarkable precise measurement of the CMB spectrum and comparison [6] to that from a blackbody spectrum. The measured spectrum is shown in Figure 1 and 2.

The CMB spectrum would have a blackbody form if the simple, hot, Big Bang model is a correct description of the early universe, but will be distorted from that form by energy release for a redshift $z \lesssim 3 \times 10^6$ [31]. Such releases might arise from decay of unstable particles, dissipation of cosmic turbulence and gravitational waves, breakdown of

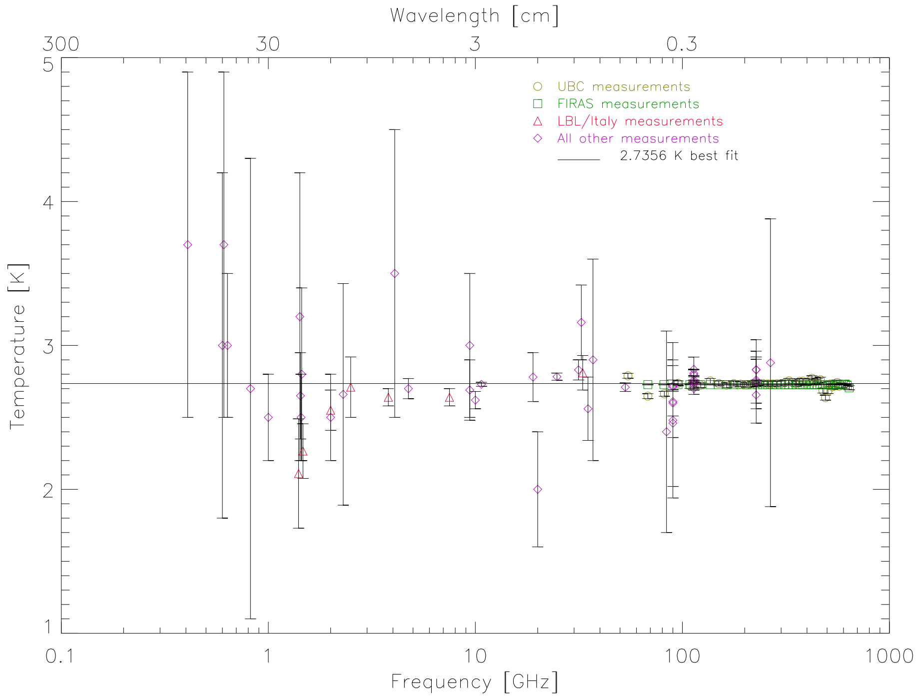

FIGURE 2. Thermodynamic temperature as a function of frequency of the CMB

cosmic strings and other more exotic transformations. The CMB was the dominant energy field after the annihilation of positrons and the decoupling of neutrinos until $z \gtrsim 3 \times 10^4$. For energy release into the electron-proton plasma, between redshift of a few times 10^4 and 10^6 [25] the number of Compton scatterings is sufficient to bring the photons into thermal equilibrium with the primordial plasma. During this time, bremsstrahlung and other radiative processes do not have enough time to add a sufficient amount of photons to create a Planckian distribution. The resulting distribution is a Bose-Einstein spectrum with a chemical potential, μ, that is exponentially attenuated at low frequencies, $\mu = \mu_0 e^{-2\nu_b/\nu}$ (where ν_b is the frequency at which Compton scattering of photons to higher frequencies is balanced by bremsstrahlung creation at lower frequencies [4]). At redshifts smaller than $\sim 10^5$, the Compton scattering rate is no longer high enough to produce a Bose-Einstein spectrum. The resulting spectrum has an increased brightness temperature in the far Rayleigh-Jeans region due to bremsstrahlung emission by relatively hot electrons, a reduced temperature in the middle Rayleigh-Jeans region where the photons are depleted by Compton scattering, and a high temperature in the Wien region where the Compton-scattered photons have accumulated.

These observations provide new limits on the following cosmological parameters:
T_0 – the thermodynamic temperature of the background radiation
Y_{ff} – a measure of the effects of Bremsstrahlung, unitless; a.k.a. J_{ff}
y – a measure of the effects of Compton scattering, unitless
μ_0 – describes the Bose-Einstein distortion, unitless.

The most complete fit is a nonlinear simultaneous fit of T_0, Y_{ff}, μ_0, y and β, as shown in Table 1, making use of all data published for the CMB monopole.

Big Bang only theory to give this precisely thermal (Planckian) spectrum.

TABLE 1. Non-linear fit with T_0, $Y_{\rm ff}$, μ_0 and y to CMB spectrum monopole.

T_0	=	2.7377	$\pm$	0.0038 K	(95% CL)
$Y_{\rm ff}$	=	-1.1×10^{-5}	$\pm$	2.3×10^{-5}	(95% CL)
μ_0	=	-3.0×10^{-5}	$\pm$	1.2×10^{-4}	(95% CL)
y	=	1.6×10^{-6}	$\pm$	9.6×10^{-6}	(95% CL)

$$\text{Correlation matrix} = \begin{array}{c} \\ T_0 \\ Y_{\rm ff} \\ \mu_0 \\ y \end{array} \begin{array}{c} \begin{array}{cccc} T_0 & Y_{\rm ff} & \mu_0 & y \end{array} \\ \begin{bmatrix} 1.00 & 0.01 & 0.06 & 0.09 \\ 0.01 & 1.00 & -0.27 & -0.18 \\ 0.06 & -0.27 & 1.00 & 0.82 \\ 0.09 & -0.18 & 0.82 & 1.00 \end{bmatrix} \end{array}$$

B Energy Limits

Energy released at different epochs probes different physical conditions in the early universe and creates different signatures in the CMB spectrum. Figure 1 shows the current spectrum observations and sample spectral distortion characteristic of each mechanism. Energy release at recent epochs ($z < 1000$) will re-ionize the intergalactic medium, which then cools through free-free emission. If the gas is hot enough or the release occurs before recombination ($z < 10^5$), Compton scattering of CMB photons from hot electrons provides the primary cooling mechanism. Early energy release ($10^5 < z < 10^7$) from relic decay reaches statistical equilibrium, characterized by a chemical potential distortion at long wavelengths.

In general the observational limits on potential spectral distortions in turn limit the energy release in the universe to roughly 10^{-4} of the energy of the cosmic background radiation for redshifts between $10^3 < z < 10^7$.

The greatest significance of the non-detection of distortions in the CMB spectrum is the support it gives to the Hot Big Bang model of cosmology. A blackbody spectrum is the natural result of a system in thermal equilibrium; conversely, it is very difficult to superpose a set of non-thermal spectra or thermal spectra of different temperatures to mimic a blackbody to such tight tolerance over so broad a frequency range. Steady-state models generally create a microwave background by absorption and subsequent re-emission of starlight by dust. The re-emitted photons are then redshifted by the expansion of the universe, so that we observe a superposition of "shells" radiating at different epochs. If the dust opacity were independent of frequency, the microwave background would be a superposition of thermal spectra redshifted to different temperatures, equivalent to a Compton y distortion. The dust opacity can be tailored to bring the superposition closer to a blackbody, but the required (very high) opacities at millimeter wavelengths conflict with direct observations of high-redshift galaxies at these wavelengths ([23] p203-6).

The same basic arguments rule out "plasma universes" models.

The lack of spectral distortions has implications for structure formation. Explosive models of structure formation provide a simple way to sweep (baryonic) matter out of the observed voids. The resulting shocks, however, heat the baryons and distort the CMB spectrum. Upper limits on a Compton y distortion limit the maximum size of explosive voids to $R_{\rm void} < 2$ Mpc, much smaller than the observed voids [18].

C Dipole Anisotropy Spectrum

COBE FIRAS (& DMR) measured the spectrum of the CMB monopole and dipole with unprecedented accuracy. These observations have shown that the dipole frequency spectrum matches the differential to a Planckian to high precision. This is a cornerstone in our understanding of the expected frequency spectrum of the CMB anisotropies, which is less well measured by COBE, and thus the ability to relate measurements at different frequencies and to separate out potential foregrounds by their differing frequency spectra.

This provides:

- Support for Big Bang and Thermal Origin of the CMB
- T_{CMB}, n_γ, $v_{peculiar}$
- Spectral Shape for Anisotropies versus foregrounds
- Calibration for other experiments

- Limits on distortions and Energy Release in early universe

D Dipole as Check and Calibration (1%)

As observers we have been fortunate to have the dipole anisotropy as a reasonable signal on which to check and calibrate our anisotropy observations. COBE provides us with a sufficiently good observation and accurate measurement of the dipole both from its own calibration and the having observed the dipole and its annual modulation through four seasons. This provides a sufficiently accurate direction and amplitude [20] of the dipole to make it a reference standard for succeeding experiments.

II CMB ANISOTROPIES

COBE DMR detected and measured CMB anisotropies

- First detection of primordial CMB anisotropies
- Determination of Primordial Fluctuation Normalization at 10^{-5}
- Still best determination, cosmic variance limited, of large angular scale power spectrum
- With FIRAS good determination anisotropies have proper frequency spectrum
- Information on the Large Scale Structure of Space-Time
- Scientifically useful test-bed data set and procedures

A very major result from COBE was the DMR detection and reporting of CMB anisotropies. CMB anisotropies had long been sought and it is easy to forget how with year after year of improving upper limits on anisotropies people in the field had got to the mind set that there were no anisotropies and that quality of an experiment was in how low a limit it could set. A prime reason for the invention of cold dark matter was to avoid potential violation of CMB anisotropy limits. Things had gotten to the state that critics of the Big Bang cosmology were pointing to the lack of CMB anisotropies as a indicator of Big Bang model failure.

With the DMR announcement of the discovery of CMB anisotropies on all observed angular scales and with a near-scale invariant spectrum, the field was invigorated both by the results and by the great public interest. What soon became known as the COBE normalization was just a factor of two above the minimum required for gravitational instability formation of large scale structure. That plus the angular power spectrum was just what the theorists had ordered and gave the push to what turned out to be a rapid theoretical development of CMB anisotropy theory and related fields.

The response on the experimental/observational side was also quite impressive with new observations and instrumental developments occurring in rapid succession. Governmental agencies (e.g. NASA and NSF) gave high priority and significant funding support to CMB science. The most impressive long-term exploitation of the CMB were the development of proposed CMB anisotropy satellite by teams of scientists. These lead to NASA and ESA accepting the MAP and Planck missions.

The CMB power spectrum can readily be interpreted for what it tells us about the primordial power spectrum of fluctuations and then applied either backwards to tell us about early-universe, high-energy physics or viewed forward in its relation to large scale structure. The field, especially theoretically and rightly so, is focused on these issues. However, there are other things that we can learn about the universe using these data. We can learn a lot about the geometry and dynamics of the universe and set very tight limits on anisotropic Hubble expansion and on shear and rotation (vorticity) in the universe. We also know that the geometry of the universe is very near to the idealized Robertson-Walker metric with only small perturbations which must be on the same scale as the CMB anisotropies. In 1968 Ehlers, Geren, and Sachs proved the theorem: If a family of freely-falling observers measure self-gravitating background radiation to be *exactly* isotropic, then the Universe is *exactly* Friedmann-Lemaitre-Robertson-Walker. This has been interpreted/extrapolated by me and others that the observed high degree of observed CMB isotropy and the assumption that our location is not special imply that the Universe's metric is nearly Robertson-Walker with perturbations of the order of 10^{-5}. After COBE Stoeger, Maartens, and Ellis have shown that if all fundamental observers measure the cosmic microwave background radiation to be almost isotropic in an expanding Universe, or that one observer observing over all time sees a nearly isotropic CMB, then that Universe is almost spatially homogeneous and isotropic. This puts us on firmer footing and allows us to use the CMB isotropy observations to set limits on the anisotropy, homogeneity, and dynamics of the Universe.

The fact that the CMB anisotropies show that we can treat the Universe as if it has a Robertson-Walker metric with small perturbations, justifies the assumption that large scale structure theory had been built upon as it simplifies and makes the mathematics tractable.

The DMR consists of 6 differential microwave radiometers: 2 nearly independent channels, labeled A and B, at frequencies 31.5, 53, and 90 GHz (wavelength 9.5, 5.7, and 3.3 mm respectively). Each radiometer measures the difference in power between two 7° fields of view separated by 60°, 30° to either side of the spacecraft spin axis [26]. *COBE* was launched from Vandenberg Air Force Base on 18 November 1989 into a 900 km, 99° inclination circular orbit, which precesses to follow the terminator (light dark line on the Earth) as the Earth orbits the Sun. Attitude control keeps the spacecraft pointed away from the Earth and nearly perpendicular to the Sun with a slight backward tilt so that solar radiation never directly illuminates the aperture plane. The combined motions of the spacecraft spin (75 s period), orbit (103 m period), and orbital precession ($\sim 1°$ per day) allow each sky position to be compared to all others through a highly redundant set of temperature difference measurements spaced 60° apart. The on-board processor box-car integrates the differential signal from each channel for 0.5 s, and records the digitized differences for daily playback to a ground station.

A COBE DMR 4-year Maps

The COBE Differential Microwave Radiometers (DMR) instrument has mapped the full microwave sky to sensitivity 17 μK per 7° field of view.

The maps are of high quality and provide redundancy of observations. For example the 53 GHz 4-year A+B map has signal-to-noise ratio is larger than two.

The observation of anisotropies opens one new cosmological test: probing topology of the Universe. The most straightforward topology that we can imagine is an essentially isotropic and homogeneous Universe that is simply connected However, we know of no constraints that actually require that the Universe be simply connected. It might in fact have the topology of a donut or many other possible objects.

Over time there have been reports of periodicity in the Universe both in terms of large scale structure of galaxies ($\sim$128 Mpc) and quasars (much larger scale). This has led a number of people to suggest that the Universe is small with opposite faces identified (or some other combination). Such universes would be periodic on the identified axes and thus could not have anisotropies with wavelengths longer than their symmetry axes. The existence of very large angular scale anisotropies, i.e. the quadrupole, octupole, and hexadecapole, put stringent limits on the size of the universe. Various analyses of the DMR data set a limit on the smallness of the universe at about 0.5 of the Hubble diameter (e.g. [12], [2]). This is an illustration of the power of the CMB as a cosmological probe.

B Ability to Make Observations with Sufficiently Low Systematics

A key issue in making observations at such low signal levels is whether systematic errors are likely to provide fundamental limits. A a detailed treatment of the upper limits on residual systematic errors ([14], [15]) by the DMR team showed convincingly that one could reduce the systematic errors to well below the 10% level in the temperature maps and the 1% level in the power spectrum. This was further enhanced by the cross-correlation of the DMR maps with other results as additional new observations were made. In particular the positive cross-correlation between the *COBE* data and data from balloon-borne observations at a shorter wavelength [8] and later by comparison of the *COBE* data and data from the ground-based Tenerife experiment [19] at longer wavelengths showed that the anisotropy features were real and had the expected spectral dependence. This conclusion was based upon the long lever arm and the realization that the COBE DMR observation frequencies were essentially centered in a low valley between Galactic and extra-galactic foreground signals.

COBE DMR provided a crucial test of how well an experiment could control the systematics as the circumstances, frequency and hardware redundancy, and careful analysis of the observations were provided under the aegis of a satellite mission.

C Treatment and Level of Foregrounds

The correlation between "free-free" and dust emissions was demonstrated with the DMR data. This was a rediscovery of the known partial correlation between HII regions and dust but also lead to the realization that there might be other forms of emission such as that from rotating dust grains.

As COBE was able to separate foregrounds and CMB signals reasonably well, and thus was also able to measure the power spectrum of anisotropies versus foregrounds (e.g. [9]). This lead to the possibility that the CMB and foregrounds might also be distinguished by their power spectra as well as frequency spectra.

This also lead to a set of programs to understand the possible confusing foregrounds and find methods to separate them. Key examples include the Galactic Emission Mapping (GEM) project (URL http://aether.lbl.gov/www/projects/gem) discussed in this talk, the WOMBAT challenge (URL http://astro.berkeley.edu/wombat/), and the MAP and Planck efforts.

D Gaussian versus non-Gaussian

The COBE DMR was the first experiment to offer up data and analysis to show that the CMB anisotropies are consistent with Gaussian fluctuations and show that there was little evidence of non-Gaussianity (Only two papers by any one analyzing the data claim any evidence of non-gaussianity and that evidence is very restricted.) Gaussianity is a standard assumption of many analysis techniques and most models.

E Summary of 4-Year COBE-DMR CMB Measurements

- Consistent with results from first- and two-year data
- Signal-to-noise ratio in a 10° smoothed map is 2, enough to provide a clear visual impression of the data.
- CMB monopole temperature is $T_0 = 2.725 \pm 0.020$ K
- CMB dipole amplitude is 3.353 ± 0.024 mK
  toward 11 h 12.2 ± 0.8 m, -7.06° $\pm$ 0.16°
- CMB quadruple rms amplitude is $4 < Q_{rms} < 28 \mu K$ at the 95% confidence level
- CMB quadrupole amplitude fitted to a power-law spectrum is $Q_{rms-PS} = 15.3^{+3.8}_{-2.8}\ \mu K$
  and to a sCDM model 17.5 ± 2.
- The best-fitted power-law spectral index is 1.2 ± 0.3 Which is very close to what is expected from a scale-invariant power spectrum of primordial fluctuations.
- The DMR anisotropy data are consistent with Gaussian statistics.
  Statistical tests prefer Gaussian to other models tested.

F 4-Year COBE-DMR CMB Polarization Measurements

Using the COBE DMR data we have been able to produce high quality linear (53 & 90 GHz) and circular polarization (31.5 GHz) maps of the full sky.

These maps show

- The degree of polarization is small. $\frac{\Delta P}{T} < \frac{\Delta T}{T}$
- Fits to global patterns show only upper limits:
  - RMS polarization less than 10^{-5}
  - Temperature-polarization cross-correlation << temperature correlations
  - Quadrupole-type polarization less than 10^{-5}.
  - Combined polarization and temperature fit shows strong limit on anisotropic expansion.
- Polarized signal from Galactic plane is small

TABLE 2. List of COBE team papers on CIB

Author	Topic	Reference	astro-ph number
Hauser et al. (1998)	DIRBE Results Summary	Ap. J. 508, 25-43	astro-ph/9806167
Kelsall et al. (1998)	Zodiacal Light	Ap. J. 508, 44-73	astro-ph/9806250
Arendt et al. (1998)	Galactic Contribution	Ap. J. 508, 74-105	astro-ph/9805323
Dwek et al. (1998)	Cosmological Implications	Ap. J. 508, 106-122	astro-ph/9806129
Fixsen et al. (1998)	FIRAS: Spectrum of CIB	Ap. J. 508, 123-128	astro-ph/9803021
Dwek & Arendt (1998)	3.5 μm CIB	Ap. J. 508, L9-L12	astro-ph/9809239

The data are all consistent with no polarization at the 30% of the temperature anisotropy levels measured by the DMR and thus with all standard models. The 95% C.L. limits on linear polarization amplitude is $P/T_{CMB} < 10^{-5}$ and on circular polarization are $V/T_{CMB} < 6 \times 10^{-5}$ on 7° and larger angular scales. A combined fit to polarization and anisotropy limits anisotropic axi-symmetric expansion to $\Delta H/H < 2 \times 10^{-6}$.

These are significant results on the polarization in and by themselves; however, it is also instructive to compare them to theoretical predictions. Nearly all theoretical calculations (e.g. [22], [13]) indicate that the expected level of the polarized component is of order 10% of the temperature anisotopy for small angular scales ($> 1°$) and significantly less for larger angular scales. In general reionization results in a relatively larger ratio but in no case would the polarized signal be larger than the level of anisotropy and in most cases remains at the 10% or lower level. Thus the DMR is consistent with the current theoretical predictions but does not have the sensitivity to confirm them in a convincing manner.

III DIFFUSE INFRARED BACKGROUND

A primary objective of the COBE mission has been the detection and measurement of the diffuse cosmic infrared background (CIB). The DIRBE (Diffuse Infrared Background Experiment) was designed primarily to conduct a systematic search for an isotropic infrared background in ten photometric bands from 1.25 to 240 μm.

The search for the cosmic infrared background was an unfulfilled field of observational cosmology. The search for the CIB is impeded by two fundamental challenges: no unique spectral signature was predicted for such a background and there are many contributors locally and Galactically to the infrared sky brightness at all wavelengths. Some of these sources, such as the interplanetary dust, are quite bright. The lack of unique spectral signature arises in part because of the very many different sources of such signals. Possible existence of infrared backgrounds had been reported by previous experiments but the community as a whole remained far from convinced by the results.

The apparent attenuation of TeV gamma rays provided indirect evidence for an infrared background [29].

Both the COBE DIRBE and FIRAS Instruments provide information about the diffuse infrared background, which at this point is primarily detected at long wavelengths. Because of this the earliest reports came from the FIRAS data (see e.g. Puget et al. 1996).

The relevant papers by the COBE team are shown in Table 2.

The extragalactic background light consists of the cumulative emissions from various pregalactic objects, protogalaxies, galaxies, and clusters of galaxies summed over the evolution of the Universe. Much of the extragalactic background light is predicted to be manifested as the cosmic infrared background due to the process of absorption and reradiation by dust particles and by the general redshifting due to the expansion of the Universe.

Theorists have anticipated that there are two major energy sources that contribute to the extragalactic background light: nuclear and gravitational. Nuclear energy released in stellar nucleosynthesis is radiated predominantly in the ultraviolet to visible wavelengths and is either redshifted or absorbed and reradiated into the infrared ($\lambda \simeq 1\mu$m) wavelength region. Similarly, released gravitational energy is shifted toward longer wavelengths. The infrared is thus expected to contain a significant fraction of all the energy released in the Universe since the recombination epoch. Its observation then constrains the relative contribution of all potential energy sources.

The integrated CIB intensity detected by COBE in the 140-1000 μm wavelength range is about 16 nW m^{-2} sr^{-1}. This intensity is consisentwith the energy release expected from nuclear energy sources and xonstitutes about 20% - 50% of the total energy released in the formation of He and metals throughout the history of the Universe. Galaxy number counts provide a lower limit of 12 nW m^{-2} sr^{-1} in the 0.36 to 2.2. μm wavelength interval. The explored regions then account for a total intensity of 28 nW m^{-2} sr^{-1}. If attributed to nuclear sources only, this intensity implies more than about 10% of the baryonic mass density implied by big bang nucleosynthesis analysis has been processed in stars to He and heavier elements. This leaves little room for strong and exotic other sources of energy release through this epoch.

IV SUMMARY/PERSPECTIVE

CONCLUSIONS: What We Learned from COBE?

COBE demonstrated

- A Cosmology Satellite can be wildly Successful
- A Development of Techniques and Personnel
- CMB spectrum very close to Planckian
- There are primordial perturbations / temperature anisotropies
- Gravitational Instability is proper paradigm - normalization
- The Hot Big Bang Model is strongly supported
- The CMB polarization is small
- The large-scale structure of space-time is simple
- Constraints on non-standard physics to early times
- CIB exists at an appropriate level

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