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INTERPRETATION OF THE COSMIC MICROWAVE BACKGROUND RADIATION ANISOTROPY DETECTED BY THE *COBE*[1] DIFFERENTIAL MICROWAVE RADIOMETER

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ABSTRACT

We compare the large-scale cosmic background anisotropy detected by the *COBE* Differential Microwave Radiometer (DMR) instrument to the sensitive previous measurements on various angular scales, and to the predictions of a wide variety of models of structure formation driven by gravitational instability. The observed anisotropy is consistent with all previously measured upper limits and with a number of dynamical models of structure formation. For example, the data agree with an unbiased cold dark matter (CDM) model with $H_0 = 50$ km s^{-1} Mpc^{-1} and $\Delta M/M = 1$ in a 16 Mpc radius sphere. Other models, such as CDM plus massive neutrinos [hot dark matter (HDM)], or CDM with a nonzero cosmological constant are also consistent with the *COBE* detection and can provide the extra power seen on 5–10,000 km s^{-1} scales.

Subject headings: cosmic microwave background — cosmology: observations — cosmology: theory — galaxies: clustering

1. INTRODUCTION

Anisotropy in the cosmic microwave background radiation (CMBR) is a predicted measurable effect of large-scale fluctuations in the early universe. The fluctuations are thought to be the seeds of structure in the present-day universe (Sachs & Wolfe 1967; Silk 1967; Peebles & Yu 1970; Bond & Efstathiou 1984, 1987; Holtzman 1989; Suto, Gouda, & Sugiyama 1990; Vittorio & Silk 1992). In contrast to many recent experiments, the 7° beam and full sky coverage of the *Cosmic Background Explorer* (*COBE*) Differential Microwave Radiometer (DMR) can measure the amplitude of spherical harmonics with $l < 20$, making it sensitive to large-scale fluctuations that have remained in the linear growth regime. While the detailed answers to the questions of galaxy formation probably lie at smaller angular scales where nonlinear growth is taking place, the large angular scale measurements can answer the very fundamental questions about the initial perturbation spectrum in a relatively model independent way.

The determination of ΔT on large angular scales from the first year of data taken by the DMR instrument on *COBE* (described in the accompanying *Letter* by Smoot et al. 1992) provides a detection of anisotropy that can be compared directly with the angular correlation functions derived from various models. We use several simple primordial density fluctuation spectra including power law and Gaussian spectra whose amplitudes are constrained by the galaxy-galaxy correlation function (Davis & Peebles 1983; the QDOT survey of Rowan-Robinson et al. 1990, and the APM survey of Maddox et al. 1990), and the large-scale flows seen by Bertschinger et al. (1990).

The *COBE* detection can also be compared with previously measured upper limits. Direct comparison can be made with experiments of similar angular resolution: Fixsen, Cheng, & Wilkinson (1983) at 24.5 GHz with a 7° beam, Lubin et al. (1985) at 90 GHz with a 7° beam, Davies et al. (1990) (Tenerife) at 10 GHz with an 8° beam, Watson et al. (1992) (14.9 GHz) with a 5°.6 beam, Meyer, Cheng, & Page (1991) (MIT) at 168 GHz with a 3°.8 beam and Boughn et al. (1991) (19 GHz) with a 3° beam. The *COBE* detection is consistent with the upper limits set by each of these experiments. Small- and intermediate-scale limits (Readhead et al. 1989 [OVRO] at 20 GHz with a 0°.03 beam, Timbie & Wilkinson 1990 [hereafter T & W] at 43 GHz with a 2° beam, Meinhold et al. 1991 [SP] at 90 GHz with a 0°.5 beam and Devlin et al. 1992 [MAX] at 180 GHz with a 0°.5 beam) can be combined with the *COBE* detection to provide stronger limits on models than would be possible with the *COBE* data alone.

2. COMPARISON WITH PREVIOUS MEASUREMENTS

The earlier large-scale anisotropy experiments from balloons and spacecraft have given upper limits on the quadrupole or on the amplitude of a scale-invariant primordial density fluctuation spectrum that are consistent with the *COBE* results. Fixsen et al. (1983) and Lubin et al. (1985) both give $Q_{\rm RMS} < 190\ \mu$K, while Klypin et al. (1987) give $Q_{\rm RMS} < 80\ \mu$K and the expected quadrupole for a Harrison (1970)–Zel'dovich (1972) spectrum as $\langle Q^2_{\rm RMS}\rangle^{0.5} < 56\ \mu$K. Page, Cheng, & Meyer

[1] The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the Cosmic Background Explorer (*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.

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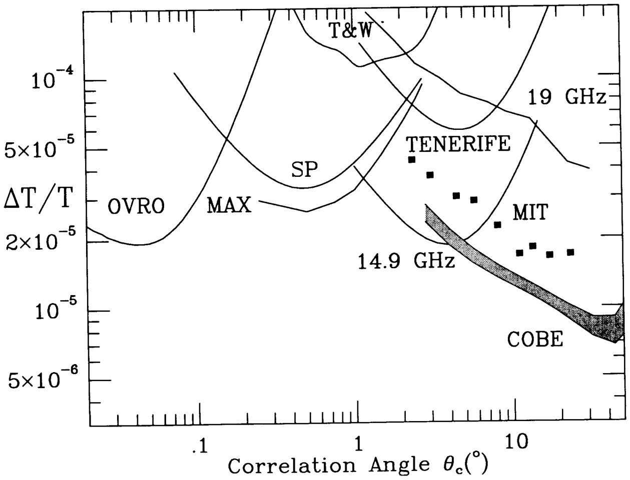

FIG. 1.—Limits on Gaussian correlation functions, $[C(0)]^{1/2}/T_0$ vs. θ_c. All are 95% confidence upper limits except for the *COBE* band which shows 2 σ upper and lower limits.

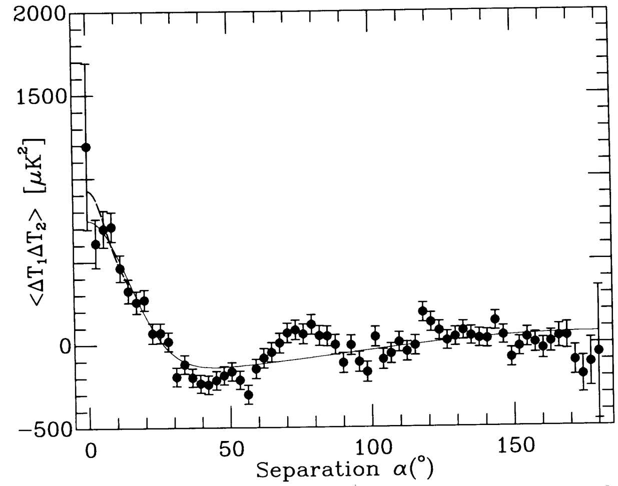

FIG. 2.—Correlation function from *COBE* data (*filled circles*) with a fit to a Gaussian model with $\theta_c = 13\overset{\circ}{.}5$ (*thin solid curve*) and a fit to Holtzman's correlation function convolved to the DMR beam (*dashed curve*).

(1991) give a limit $\langle Q_{\rm RMS}^2 \rangle^{0.5} < 22$ μK based on the MIT data. The corresponding numbers from *COBE* (Smoot et al. 1992) are that the actual measured quadrupole is $Q_{\rm RMS} = 13 \pm 4$ μK and the expected quadrupole for a Harrison–Zel'dovich spectrum is $\langle Q_{\rm rms}^2 \rangle^{0.5} = 17 \pm 5$ μk. The uncertainties on both numbers include estimated uncertainties in systematic error and galactic corrections, and the uncertainty on $\langle Q_{\rm RMS}^2 \rangle^{0.5}$ includes the "cosmic variance" due to the small number of degrees of freedom in the low-order multipoles that dominate the *COBE* signal. The *COBE* results are clearly consistent with these earlier works.

Both the MIT and 19 GHz experiment are survey experiments that produce maps. Meyer et al. (1991) and Boughn et al. (1991) quote their results in terms of Gaussian correlation functions, $C(\alpha) = (C(0) \exp(-\frac{1}{2}\alpha^2/\theta_c^2)$, with a variety of correlation angles θ_c. The comparison of *COBE* with these experiments may be done directly by computing the detected levels of the Gaussian correlation functions from the DMR map. Figure 1 gives 95% confidence upper limits on the amplitude of Gaussian correlation functions for various correlation angles from the OVRO, Timbie & Wilkinson, SP, MAX, Tenerife, 14.9 GHz, 19 GHz, and MIT experiments; and the upper and lower limits for *COBE* from the DMR 53 and 90 GHz maps. In all cases the DMR detection is below the upper limits of Meyer et al. and Boughn et al. Figure 2 shows the *COBE* correlation function using data from the two 53 GHz channels and the most sensitive 90 GHz channel, with $|b| > 30°$ and without subtracting any model of the galaxy. The accompanying *letter* by Bennett et al. (1992) shows that the effect of the Galaxy on the correlation function is small at these frequencies. The thin solid curve shows the best fit of the form

$$C_M(\alpha) = A + B \cos \alpha + C_M^0 \exp\left[\frac{-\alpha^2}{2(\theta_c^2 + 2\sigma^2)}\right] \quad (1)$$

with $\theta_c = 13\overset{\circ}{.}5$, where $C_M(\alpha) = \langle \Delta T(\theta) \Delta T(\theta + \alpha) \rangle$ is the measured correlation function which is the true correlation function convolved with the instrumental beam twice. The effective *COBE* beam, after allowing for binning the data into map pixels and binning the pixel-pair cross-products into the correlation function, is approximated by a Gaussian with $\sigma = \mathrm{FWHM}/2.36 = 3\overset{\circ}{.}2$. The coefficients A and B allow for the removal of the monopole and dipole terms before the correlation function was accumulated. Note that the y-axis in Figure 1 is $[C(0)]^{1/2}/T_0$, where

$$C_M^0 = \frac{C(0)\theta_c^2}{(\theta_c^2 + 2\sigma^2)} \quad (2)$$

Davies et al. gave their Tenerife result as C_M^0 which we have converted to $C(0)$ for Figure 1.

Smaller scale experiments often use chopping techniques that filter out the low-order multipoles. For a double-subtracted experiment like OVRO or Tenerife, the measured quantity is the temperature difference between the main beam and two reference beams:

$$S = T(\theta) - 0.5[T(\theta + \Delta\theta) + T(\theta - \Delta\theta)] \quad (3)$$

and the variance of S due to anisotropy is given by

$$\mathrm{var}(S) = 1.5C_M(0) - 2C_M(\Delta\theta) + 0.5C_M(2\Delta\theta) . \quad (4)$$

The 14.9 GHz experiment has $\Delta\theta = 8\overset{\circ}{.}1$, $\sigma = 2\overset{\circ}{.}4$, $[C(0)]^{1/2} < 51$ μK for $\theta_c = 4°$, and var $(S) < (35\ \mu\mathrm{K})^2$. A comparison of this medium-scale anisotropy limit with the large-scale anisotropy seen by Smoot et al. of $\langle Q_{\rm RMS}^2 \rangle^{0.5} = 17 \pm 5$ μK, which is determined at an effective scale $l_e \approx 4$, is a promising way to tighten the limits on the power-law index of the primordial density fluctuation spectrum. Smoot et al. find $n = 1.15^{0.45}_{-0.65}$ for a power spectrum $P(k) \propto k^n$, where $P(k) \propto |\int \Delta\rho(x) e^{ik \cdot x} d^3x|^2$. The index n is 1 for the Harrison-Zel'dovich spectrum predicted by the simple inflationary scenario for cosmology (Bardeen, Steinhardt, & Turner 1983). Taking the *COBE* $\langle Q_{\rm RMS}^2 \rangle^{0.5}$, we find that the expected variance of a double-subtracted experiment with $\sigma = 2\overset{\circ}{.}4$ and a throw of $8\overset{\circ}{.}1$ is var $(S) = 650$ $\mu\mathrm{K}^2$ for $n = 1$, and 1300 $\mu\mathrm{K}^2$ for $n = 1.5$. Given the uncertainty in the *COBE* $\langle Q_{\rm RMS}^2 \rangle^{0.5}$, this comparison of the *COBE* data at the largest scales to the ground-based data at the 8° scale, is just at the margin of having sufficient sensitivity to limit the range of n given by Smoot et al. (1992) to $n < 1.5$. Using the *COBE* correlation function in Figure 2, we can derive var $(S) = 500 \pm 769$ $\mu\mathrm{K}^2$ for a double-subtracted experiment with $\Delta\theta = 8\overset{\circ}{.}4$ and $\sigma = 3\overset{\circ}{.}2$, compared to an expected value of 420 $\mu\mathrm{K}^2$ for $n = 1$. Clearly it will be worthwhile to obtain more data on 8° scales, either with *COBE* or from the ground. We are in our third year of observation and have requested a fourth year of continued observations if the instrument and spacecraft continue to function well. The uncertainty on var (S) should be reduced by a factor of 4 with 4 times more data.

The experiments sensitive at scales from 0°.04 to 1°.5 cannot be directly compared to the DMR data because the 7° beam smooths over these scales. In particular, the fact that the lower limit on Gaussian correlation functions from *COBE* exceeds upper limits from small-scale experiments for $\theta_c < 4°$ does not indicate a problem—it merely indicates that the sky is not described by a Gaussian correlation function with $\theta_c < 4°$. The *COBE* maps are well described by a Gaussian correlation function with $\theta_c = 13.5 \pm 2°.5$, but a Gaussian correlation function is not consistent with models of structure formation.

However, using a power-law spectrum, $P(k) \propto k^n$, we can extrapolate to the smaller angular scales. For the MAX experiment, with $\Delta T/T < 2.6 \times 10^{-5}$ at $\theta_c = 0°.5$, the DMR detection would imply $\Delta T/T = (1.5 \pm 0.4) \times 10^{-5}$ for $n = 1$, or $\Delta T/T = (4.1 \pm 1.2) \times 10^{-5}$ for $n = 1.5$. Since the MAX scale is inside the horizon at recombination, the dynamical processes associated with structure formation will increase the predicted ΔT, so the limit $n < 1.5$ is secure unless late recombination or early reionization smooth out ΔT at 1° scale.

3. COMPARISON WITH MODELS

Many authors have computed predicted anisotropies of the CMB for different cosmological models. Sachs & Wolfe (1967) computed the effect of potential fluctuations that dominate the large angular scales observed by *COBE*. Peebles & Yu (1970) computed the interactions between baryonic matter and radiation for initial perturbations following the Harrison-Zel'dovich spectrum, which they independently derived. Peebles (1982) computed the anisotropy of the CMB in a cold dark matter (CDM)–dominated universe with primeval adiabatic fluctuations following a Harrison-Zel'dovich spectrum, normalized to the observed clustering of galaxies, which implies $\Delta M/M = 1$ in an $8/h$ Mpc radius sphere if the matter density is proportional to the number density of galaxies, where $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. Improved calculations for the small angular scale anisotropy in CDM–dominated universes were given by Vittorio & Silk (1984). Bond & Efstathiou (1984) give ΔT for a CDM–dominated model (which matches Peebles 1982) and for hot dark matter models.

In this section we compare the *COBE* results to papers that give predictions for a large range of models in a convenient form. For example, Suto et al. (1990) computed models with spectral indices on the primordial perturbation spectrum in the range $-1 \le n \le 1$, densities in the range $0 \le \Omega \le 1$, dominated by bayrons, hot dark matter (HDM) or CDM, and for adiabatic or isocurvature initial perturbations. Suto et al. computed predictions for several experiments including the Tenerife experiment. The 14.9 GHz upper limit on 8° scales can be used to rule out all of the isocurvature models computed by Suto et al., but their predictions for adiabatic models with $n = 1$ and $\Omega = 1$ are consistent with this limit.

Holtzman (1989) has published a grid of 94 different models for the formation of large-scale structure in the universe. Each model has a different composition, with varying densities of baryons, CDM, neutrinos, and vacuum energy. For each model, Holtzman gives the transfer function $T(k)$ relating the amplitude of the primordial perturbations to the current amplitude. While $T(k)$ can be applied to any initial spectrum, we have restricted our analysis to perturbations with scale-invariant spectra that always have the same amplitude for perturbations crossing the horizon. These scale invariant or Harrison-Zel'dovich spectra would be described by $P(k) \propto k^n$ with $n = 1$ in the analysis of Smoot et al. (1992).

For these initial spectra, Holtzman has computed the expected quadrupole anisotropy for all of his spatially flat models and provided a fitting function for the angular correlation function $C(0) - C(\alpha)$ that is accurate for $\alpha < 10°$–$15°$. We have used the predicted quadrupole anisotropy to compare Holtzman's spatially flat models to the *COBE* data, and for the open models with $\Omega = 0.2$ we have compared the *COBE* correlation function to the predicted correlation function over the range of angles from 0° to 14°.1, after convolving the predicted $C(0) - C(\alpha)$ with a Gaussian having $\sigma = 3.2(2°)^{1/2}$. The dashed curve in Figure 2 shows the match of the convolved Holtzman correlation function $C_H(\alpha)$ for $H_0 = 100$ km s^{-1} Mpc^{-1}, $\Omega_{\rm CDM} = 0.18$, and $\Omega_B = 0.02$ to the *COBE* data after adjusting a constant offset and the amplitude (or the convolved correlation bias $b_{\rm cc}$): $C_M(\alpha) = A + (1/b_{\rm cc}^2)C_H(\alpha)$. The predicted correlation function can also be used to compute the expected signals in the OVRO and SP experiments.

The Holtzman models are normalized to make the fractional fluctuation of the mass in a sphere of radius $8/h$ Mpc equal to unity. Thus $(\Delta M/M)_8 = 1$ for Holtzman's normalization. If galaxies are more strongly clustered than matter (Kaiser 1984; Davis et al. 1985), then the amplitude of the initial matter density perturbations necessary to make the observed galaxy density fluctuations should be reduced by a bias factor b_8, defined by the requirement that $(\Delta M/M)_8 = 1/b_8$. A value of $b_8 > 1$ reduces the amplitude of $\Delta T/T$ and the bulk flow velocity[11] by a factor b_8.

None of the isocurvature perturbation models given by Holtzman are compatible with the *COBE* data for a bias $b_8 < 4$.

Many of Holtzman's adiabatic perturbation models are acceptable. In general, dark matter models with large values of h predict smaller values of $\Delta T/T$, while higher baryon densities produce larger values of $\Delta T/T$. Baryon-dominated models produce quite large $\Delta T/T$ on small scales, so the comparison of the *COBE* correlation function with the model correlation function can be a more sensitive test than the quadrupole amplitude, and the small-scale ground-based experiments are even more definitive.

Thus, flat baryon plus CDM models with $\Omega_B + \Omega_{\rm CDM} = 1$ and $h = 1$ produce a quadrupole that is too small for $\Omega_B \le 0.3$, while higher values of Ω_B require bias factors $b_8 > 3$ to match the *COBE* correlation function over 0°–14°, and $b_8 > 5$ to match the MAX upper limit at 1° scales. Flat baryon plus CDM models with $h = 0.5$ are consistent with the *COBE* quadrupole and correlation function for $\Omega_B \le 0.3$, but the small-scale experiments rule out $\Omega_B = 0.3$. Thus the flat $b_8 = 1$ CDM plus baryon model with $\Omega_B = 0.1$ and $h = 0.5$ is consistent with big bang nucleosynthesis, the *COBE*- and ground-based anisotropy data, and the bulk flow in a 6000 km s^{-1} radius sphere. Bond & Efstathiou (1987) also analyzed this model and gave identical predictions for the large-scale ΔT.

The large N-body calculations performed by Couchman & Carlberg (1992) show that a low bias CDM model can be

[11] The bulk flow computed from Holtzman's eq. (19) must be multiplied by $d \ln D/dt = fH_0$, where D is the growing mode and $f \approx \Omega^{0.6}$ is given by Peebles (1984).

consistent with the two-point correlation function for separations smaller than $13/h$ Mpc while Davis et al. (1985) required large biases. The Couchman & Carlberg calculation used a pure CDM model with $\Omega = 1$, $\Omega_B = 0$, $h = 0.5$, and $b_8 = 0.86$. This model gives $\langle Q_{\rm RMS}^2 \rangle^{0.5} = 15$ μK, consistent with the *COBE* result. Furthermore, this model produces some of the excess power at large scales seen in the APM galaxy correlation function.

Open CDM plus baryon models with $\Omega = 0.2$ and $h = 1$ can fit the *COBE* data with bias factors $b_8 < 2$, as long as the baryons contribute ≤ 0.1 of the total density. The model at this limit, with $\Omega_B = 0.02$, is also consistent with big bang nucleosynthesis. However, this model violates the OVRO limit by a factor of 1.1 ± 0.4 and the MAX limit by a factor of 1.2 ± 0.4 for the bias factor of 1.7 that is needed to match the *COBE* correlation function. With this bias the bulk flow in a 6000 km s^{-1} radius top-hat window is only 137 km s^{-1} which is too small to be consistent with the bulk flow of 327 ± 82 km s^{-1} observed by Bertschinger et al. (1990). Models with $h = 0.5$ and $\Omega = 0.2$ require large bias factors ($b_8 > 4$) to match the *COBE* data for any baryon fraction and are thus ruled out.

Models dominated by a nonzero cosmological constant have an increased ΔT compared to flat matter dominated models with the same Hubble constant, so the models with $h = 0.5$ and $\Omega_{\rm vac} = 0.8$ computed by Holtzman all require unacceptably large bias factors ($b_8 > 4$) to be consistent with *COBE*. Raising h to 1 lowers the predicted ΔT, and a model with $\Omega_B = 0.02$, $h = 1$, $\Omega_{\rm CDM} = 0.18$, and $\Omega_{\rm vac} = 0.8$ is consistent with the *COBE* data, the small-scale ΔT data, the bulk flow, and the APM excess power (Efstathiou, Sutherland, & Maddox 1990). Gorski, Vittorio, & Silk (1992) have computed spatially flat models with CDM plus nonzero cosmological constants and give predicted quadrupoles that are consistent with Holtzman's models. Gorski et al. also give predicted amplitudes of $\Delta T/T$ multipoles from $l = 2$ to $l = 30$ which vary like $\langle |a_{lm}|^2 \rangle \propto [l(l+1)]^{-1.12}$. As a result, the predicted correlation function for this model corresponds to $n = 0.76$ in the analysis by Smoot et al., and analysis of more *COBE* data may be able to test this model.

Models with massive neutrinos, (HDM), CDM, and baryons were also calculated by Holtzman. If there is one neutrino type with a mass much greater than the others, then all models with $h = 1$ give ΔT's that are too small. However, models with $h = 0.5$ and $\Omega_B = 0.01$ or 0.1 give acceptable ΔT's for all values of Ω_ν. The model that best fits the excess power, bulk flow and ΔT constraints has $h = 0.5$, $\Omega_B = 0.1$, $\Omega_{\rm CDM} = 0.6$, and $\Omega_\nu = 0.3$. This model (with a neutrino mass of ~ 7 eV) gives an excellent fit to the observed bulk flow and the CMB anisotropy at large and small scales, provided that the bias $b_8 = 1.5$, which is a very reasonable value. With this bias the model predicts a bulk flow of 320 km s^{-1}, and $\Delta T/T = 1.6 \times 10^{-5}$ for the OVRO experiment, which satisfies their upper limit, and 3.6×10^{-5} for the MAX experiment, which violates the upper limit by a factor of 1.4 ± 0.4.

A panoramic comparison of Holtzman's models with the *COBE* data and the excess power is shown in Figures 3 and 4. The y-axis on these plots is a measure of the excess power at large scales, defined as $3.4(\Delta M/M)_{25}/(\Delta M/M)_8$ so that its value for the CDM plus baryon model with $h = 0.5$, $\Omega_B = 0.1$, and $\Omega_{\rm CDM} = 0.9$ is unity. The range of acceptable excess powers outlined by height of the box in these figures is based on galaxy survey data, not *COBE* data. We have centered the box on the vacuum-dominated model with $h = 1$, $\Omega_B = 0.02$, $\Omega_{\rm CDM} = 0.18$,

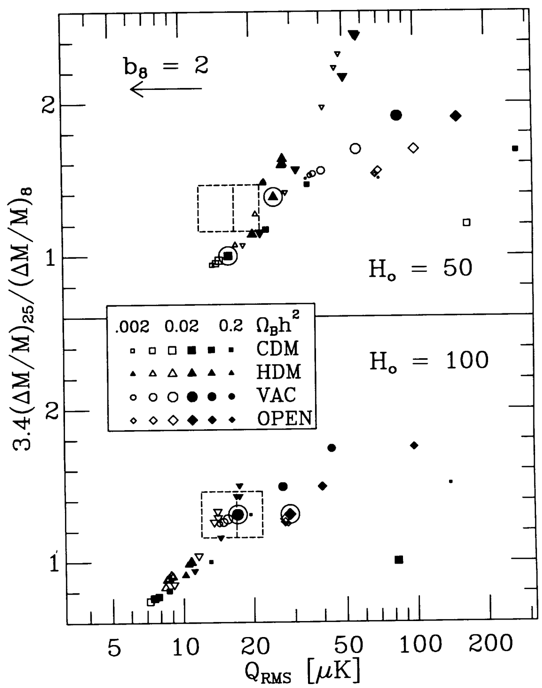

FIG. 3.—Excess power at 25 Mpc scale vs. quadrupole amplitude for Holtzman models. Models falling within the box are consistent with the amplitude of a Harrison-Zel'dovich spectrum determined from *COBE* data with $b_8 = 1$. The arrow shows the effect of $b_8 = 2$ on the models. Circled symbols are models specifically discussed in the text. Point-down triangles have 3 equally massive neutrino types, while point-up triangles have only 1 massive neutrino type.

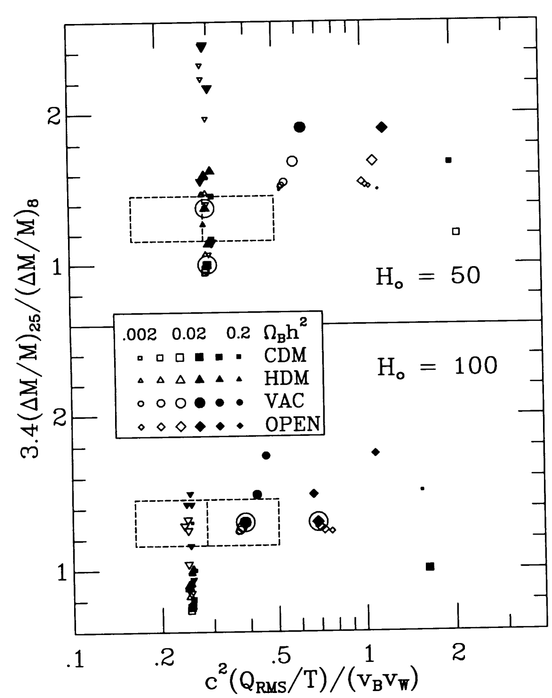

FIG. 4.—Excess power vs. ratio of the quadrupole to the bulk flow measured in a 6000 km s^{-1} radius top-hat window. Changes in b_8 do not affect this plot.

and $\Omega_{vac} = 0.8$ recommended by Efstathiou et al. (1990). The height of the box is set so that CDM is "2 σ" from the desired excess power. The shape of the symbols in these plots show what has been added to CDM plus baryons: diamonds and squares are purely CDM plus baryons, triangles have HDM added, and circles have vacuum energy added. All the models except for the diamonds are spatially flat: the diamonds are open universes with $\Omega = 0.2$. The comparison to the *COBE* data for open models is based on the correlation function fit because of the theoretical difficulty in calculating the quadrupole in open universes. For these models the x-axis variable is computed using $Q_{RMS}(\text{model}) = b_{cc}\langle Q^2_{RMS}\rangle^{0.5}(COBE)$ so for all models, points to the right of the box require initial fluctuations that are larger than those seen by *COBE*. The size of the symbols indicates how close the baryon density is to the density given by nucleosynthesis models, which we take to be $\Omega_B h^2 = 0.02$ (Boesgaard & Steigman 1985; see also Walker et al. 1991). Open symbols have baryon densities lower, and filled symbols higher, than the nucleosynthetic value. Four models have been emphasized in these figures by drawing circles around their symbols. These are the CDM model with $h = 0.5$, $\Omega_B = 0.1$, and $\Omega_{CDM} = 0.9$ at unit excess power; the open CDM model with $h = 1$, $\Omega_B = 0.02$, and $\Omega_{CDM} = 0.18$; the vacuum-dominated CDM model with $h = 1$, $\Omega_B = 0.02$, $\Omega_{CDM} = 0.18$, and $\Omega_{vac} = 0.8$; and the one heavy neutrino model with $h = 0.5$, $\Omega_B = 0.1$, $\Omega_{CDM} = 0.6$, and $\Omega_\nu = 0.3$.

In Figure 3, the excess power is plotted versus the anisotropy seen by *COBE*. The position and width of the box in the quadrupole direction are set using $\langle Q^2_{RMS}\rangle^{0.5} = 17 \pm 5$ μK. Thus model predictions should lie within the box, but only with a "1 σ" confidence. A bias factor $b_8 = 2$ shifts the models to the left as shown by the arrow. Clearly many models have acceptable quadrupoles, excess powers, and baryon densities.

In Figure 4, the predicted anisotropies have been divided by the predicted bulk flow velocity and the radius of the window used to compute the bulk flow, normalized by the speed of light. This combination should be independent of the window size use to determine the bulk flow for a Harrison-Zel'dovich spectrum at sufficiently large scales. The box denoting the observations is centered on the ratio of the DMR amplitude from Smoot et al. (1992) and the bulk flow observed by Bertschinger et al. (1990) in a 6000 km s^{-1} radius window. The width of the box is derived using the 29% uncertainty of the DMR result, the 25% uncertainty in the measured bulk flow, and the 41% uncertainty in the bulk flow due to the fact that the bulk flow squared follows the χ^2 distribution with 3 degrees of freedom.

4. DISCUSSION

The anisotropies we have detected are all at scales that are very large compared to the scales of the inhomogeneities studied by angular correlation and redshift surveys of galaxies. The maps have a beam size of 7°, which corresponds to 80,000 km s^{-1} for $\Omega = 1$. To compare the observed anisotropy with galaxy surveys, we assume a primordial spectrum with the Harrison-Zel'dovich form, as predicted by the inflationary scenario. Models from Holtzman (1989) with baryon densities fixed by standard hot big bang nucleosynthesis, and the rest of the closure density supplied by cold dark matter, have predicted quadrupoles $Q \approx 8/(b_8 h)$ μK. Thus unbiased CDM with $H_0 = 50$ km s^{-1} Mpc^{-1} is consistent with the anisotropy reported by Smoot et al. (1992).

The APM galaxy survey by Maddox et al. (1990) has suggested the existence of a perturbation spectrum with more power on large scales (10,000 km s^{-1}) than that provided by CDM alone. Clearly the *COBE* DMR results do not require this excess power, and Couchman & Carlberg (1992) show that nonlinear effects can produce a variable bias factor that enhances the large-scale power in CDM models. However, the observed anisotropy is close to the largest anisotropy predicted by reasonable dark matter–dominated models, so a spectrum with modestly enhanced power at large scales, combined with $b_8 H_0$ somewhat larger than 50 km s^{-1} Mpc^{-1} could also fit the DMR data. For example, models with $\Omega = 0.2$, $H_0 = 100$ km s^{-1} Mpc^{-1} that are either open or flat and vacuum-dominated are consistent with the observed anisotropy while providing the excess power on large scales. Models with massive neutrinos, CDM and baryons can also produce the observed ΔT, large-scale structure, and bulk flows.

By determining the potential fluctuations at very large scales, the measurement reported by Smoot et al. (1992) will lead to much more definite models of the formation of galaxies, clusters of galaxies and superclusters. With the primordial density fluctuation spectrum specified by an assumed Harrison-Zel'dovich form and the *COBE* determined amplitude, the small-scale anisotropy experiments allow one to measure the transfer function that maps primordial perturbations into current structure. Features in the transfer function can be used to identify the nature of dark matter: for example, the mass of a neutrino corresponds to the wavenumber of a break in the transfer function. With the large-scale amplitude seen by *COBE*, and the transfer functions predicted by dark matter models of structure formation, small-scale anisotropy should be detected at levels only slightly below the current OVRO and MAX upper limits.

The case for the Harrison-Zel'dovich perturbation spectrum predicted by inflation, and dark matter-dominated scenarios for structure formation, is supported by the *COBE*–DMR results. The initial perturbations on scales of 800 km s^{-1} needed to make clusters of galaxies in the CDM model can be connected to the perturbations on scales of 10^5–10^6 km s^{-1} needed to make the anisotropy seen by *COBE*, and the slope of this connection matches the slope of the Harrison-Zel'dovich spectrum predicted by the standard inflationary scenario. Allowing for factor of 2 errors from uncertainty in b_8, one still finds that the mean slope of the primordial perturbation spectrum is $n = 1 \pm 0.23$ over three decades in scale. But the results of this paper have an even greater significance, since the ΔT observed by the DMR experiment is a direct measure of the fluctuations produced during the inflationary epoch, giving $\epsilon_H = (5.4 \pm 1.6) \times 10^{-6}$ (Abbott & Wise 1984) for $\langle Q^2_{RMS}\rangle^{0.5} = 17 \pm 5$ μK, and thus provide the earliest observational information about the origin of the universe, going back to 10^{-35} s after the big bang.

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REFERENCES

Abbott, L. F., & Wise, M. B. 1984, ApJ, 282, L47
Bardeen, J. M., Steinhardt, P. J., & Turner, M. S. 1983, Phys. Rev. D, 28, 679
Bennett, C. L., et al. 1992, ApJ, 396, L7
Bertschinger, E., Dekel, A., Faber, S. M., Dressler, A., & Burstein, D. 1990, ApJ, 364, 370
Boesgaard, A. M., & Steigman, G. 1985, ARA&A, 23, 319
Bond, J. R., & Efstathiou, G. 1984, ApJ, 285, L45
———. 1987, MNRAS, 226, 655
Boughn, S. P., Cheng, E. S., Cottingham, D. A., & Fixsen, D. J. 1991, in AIP Conf. Proc. 222, After the First Three Minutes, ed. S. S. Holt, C. L. Bennett, & V. L. Trimble (New York: AIP), 107
Couchman, H. M. P., & Carlberg, R. G. 1992, ApJ, 389, 453
Davies, R. D., Lasenby, A. N., Watson, R. A., Daintree, E. J., Hopkins, J., Beckman, J., Sanchez-Almeida, J., & Rebolo, R. 1987, Nature, 326, 462
Davis, M., Efstathiou, G., Frenk, C. S., & White, S. D. M. 1985, ApJ, 292, 371
Davis, M., & Peebles, P. J. E. 1983, ApJ, 267, 465
Devlin, M., et al. 1992, in Proc. NAS Colloq. on Physical Cosmology (Irvine, CA), in press
Efstathiou, G., Sutherland, W. J., & Maddox, S. J. 1990, Nature, 348, 705
Fixsen, D. J., Cheng, E. S., & Wilkinson, D. T. 1983, Phys. Rev. Lett., 50, 620
Gorski, K. M., Silk, J. & Vittorio, N. 1992, Phys. Rev. Lett., 68, 733
Harrison, E. R. 1970, Phys. Rev. D, 1, 2726
Holtzman, J. A. 1989, ApJS, 71, 1
Kaiser, N. 1984, ApJ, 284, L9
Klypin, A. A., Sazhin, M. V., Strukov, I. A., & Skulachev, D. P. 1987, Soviet Astron. Lett., 13, 104
Lubin, P., Villela, T., Epstein, G., & Smoot, G. 1985, ApJ, 298, L1
Maddox, S. J., Efstathiou, G., Sutherland, W. J., & Loveday, J. 1990, MNRAS, 242, 43P
Meinhold, P., & Lubin, P. 1991, ApJ, 370, L11
Meyer, S. S., Cheng, E. S., & Page, L. A. 1991, ApJ, 371, L7
Page, L. A., Cheng, E. S., & Meyer, S. S. 1991, BAAS, 23, 1399
Peebles, P. J. E. 1982, ApJ, 263, L1
———. 1984, ApJ, 284, 439
Peebles, P. J. E., & Yu, J. T. 1970, ApJ, 162, 815
Readhead, A. C. S., Lawrence, C. R., Myers, S. T., Sargent, W. L. W., Hardebeck, H. E. & Moffet, A. T. 1989, ApJ, 346, 566
Rowan-Robinson, M., et al. 1990, MNRAS, 247, 1
Sachs, R. K., & Wolfe, A. M. 1967, ApJ, 147, 73
Silk, J. 1967, Nature, 215, 1155–1156
Smoot, G. F., et al. 1992, ApJ, 396, L1
Suto, Y., Gouda, N., & Sugiyama, N. 1990, ApJS, 74, 665
Timbie, P. T., & Wilkinson, D. T. 1990, ApJ, 353, 140
Vittorio, N., & Silk, J. 1984, ApJ, 285, L39
Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H.-S. 1991, ApJ, 376, 51
Watson, R. A., Gutierrez de la Cruz, C. M., Davies, R. D., Lasenby, A. N., Rebolo, R., Beckman, J. E., & Hancock, S. 1992, Nature, in press
Zel'dovich, Ya. B. 1972, MNRAS, 160, 1P