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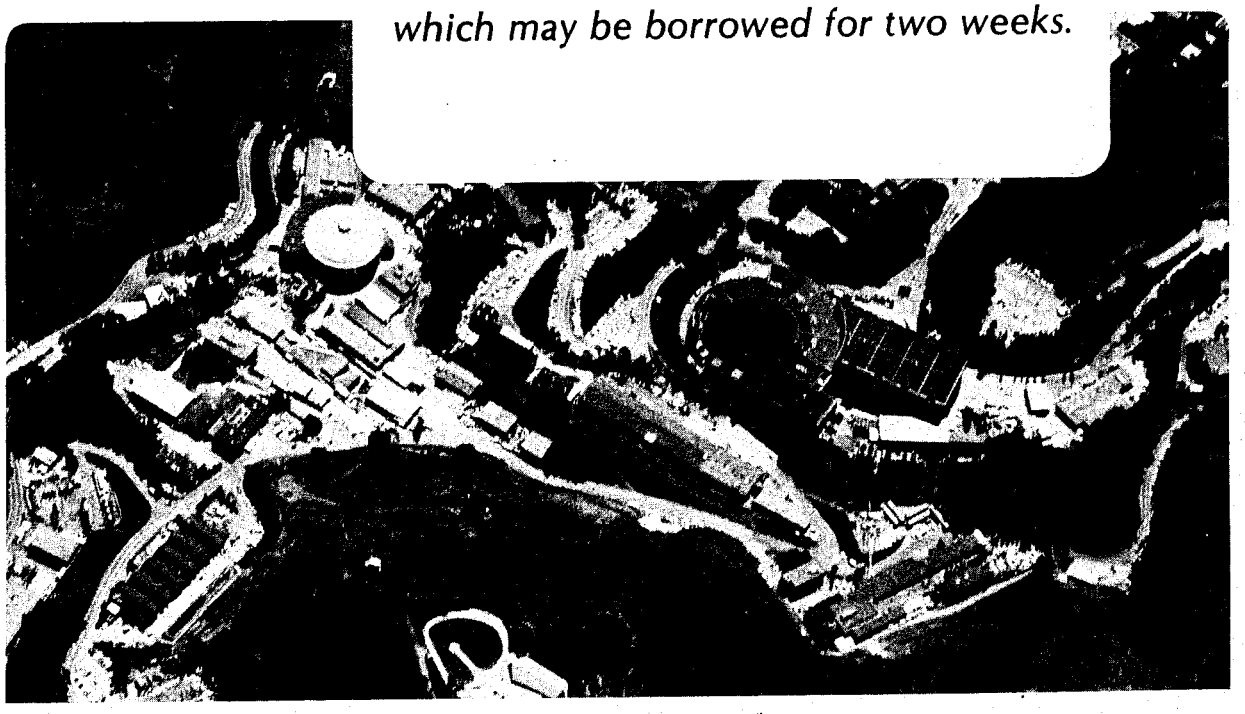

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An Analysis of Recent Measurements of the Temperature of the Cosmic Microwave Background Radiation

George Smoot, Steven M. Levin, Chris Witebsky, Giovanni De Amici
Space Sciences and Lawrence Berkeley Laboratories
University of California, Berkeley

Yoel Rephaeli
School of Physics and Astronomy, Tel Aviv University

ABSTRACT

This paper presents an analysis of the results of recent temperature measurements of the cosmic microwave background radiation (CMBR). The observations for wavelengths longer than 0.1 cm are well fit by a blackbody spectrum at 2.74 ± 0.02 K; however, including the new data of Matsumoto *et al.* (1987) the result is no longer consistent with a Planckian spectrum. The data are described by a Thomson-distortion parameter $u = 0.021 \pm 0.002$ and temperature 2.823 ± 0.010 K at the 68% confidence level. Fitting the low-frequency data to a Bose-Einstein spectral distortion yields a 95% confidence level upper limit of 1.4×10^{-2} on the chemical potential μ_0. These limits on spectral distortions place restrictions on a number of potentially interesting sources of energy release to the CMBR, including the hot intergalactic medium proposed as the source of the X-ray background.

Keywords: cosmic microwave background radiation, X-ray background, cosmology

I. Introduction

Recent measurements of the cosmic microwave background radiation (CMBR) temperature by Meyer and Jura (1985), Peterson, Richards, and Timusk (1985), Crane *et al.* (1986), Johnson and Wilkinson (1986), Sironi *et al.* (1987), Smoot *et al.* (1987), and Matsumoto *et al.* (1987) have greatly reduced the uncertainty in the spectrum of the radiation at wavelengths between 50 cm and 0.05 cm. Danese and De Zotti (1978, 1980) have analyzed previous CMBR temperature measurements for the presence of Thomson distortions; this paper updates their work. The results of the analysis are used to set limits on energy dissipation in the early universe.

Precise measurements of the CMBR spectrum are the most powerful probe available of the history of the universe in the period before galaxies and clusters of galaxies formed. The CMBR spectrum provides a record of the thermal history of the universe; in particular, the spectrum of the CMBR contains information about energy-releasing processes that may have distorted the CMBR spectrum from its initial blackbody distribution (Danese and De Zotti 1977, 1978, 1980, and 1982). Such distortions remain until the present, unless there is sufficient time for bremsstrahlung and Thomson scattering to relax the spectrum to a blackbody. A number of cosmologically revealing spectral distortions could remain today.

A Thomson distortion is the most likely spectral deviation from a Planckian (blackbody) spectrum. If an energy source heats the ionized intergalactic matter, the hot electrons scatter low energy photons to higher energy, making the CMBR cooler at frequencies below the peak and hotter above the peak (wavelength $\lambda < 0.1$ cm). This process must occur in X-ray emitting galactic clusters and is called the Sunyaev-Zel'dovich effect. A detection of this distortion measures the Thomsonization parameter y,

$$y = \int \frac{kT_e}{m_e c^2} n_e c \sigma_T dt$$

which is the number of Thomson scatterings times the dimensionless electron temperature.

If the matter of the universe is heated with extra energy before recombination ($z \gtrsim 10^3$), there will still be cooling below the peak and heating at high frequencies but bremsstrahlung will produce additional low-frequency (or long-wavelength) photons. Thus the brightness temperature will be higher at low and high frequencies but cooler in the middle frequency range. For energy release between redshifts of about 4×10^4 and 10^6 the number of Thomson scatterings is sufficient to bring the photons into thermal equilibrium with the primordial plasma but the bremsstrahlung and other radiative processes do not have sufficient time to add enough photons to recreate a Planckian distribution. The resulting distribution is a Bose-Einstein spectrum with a chemical potential, μ, that is exponentially attenuated at low frequencies, $\mu = \mu_o e^{-2\nu_o/\nu}$. The Planckian spectrum is the special case of the Bose-Einstein with zero chemical potential.

The energy injection discussed above causes cooling for the frequencies below the peak with the maximum decrease in the range from about 3 to 10 cm wavelength (10 to 3 GHz). This corresponds to a photon underpopulation (positive chemical potential) in that frequency region. If a process were to add photons in this range, one would observe a bump (negative chemical potential). There are a number of potential processes that could add photons to the CMBR. Through the 10 micron silicate and other emission features, the very early existence of dust could produce an apparent excess in the CMBR spectrum (Rees 1978). Another possible mechanism is the cosmological production of a weakly interacting particle, such as an unstable massive neutrino, that decayed into a photon and other daughters. The decay photons would add a bump to the spectrum. Even though the photons could have a sharply defined frequency, they would be smeared in frequency by the thermal energy of the parent, the varying redshifts at the times of the decays, and successive Thomson scatterings with the plasma.

At redshifts greater than a few times 10^6, the combined action of bremsstrahlung and radiative Compton scattering maintains a tight coupling between the matter and the radiation field. Photon production can take place on time scales short compared to the expansion time, and any non-blackbody spectral features are quickly erased. (Illarionov and Sunyaev 1975; Danese and De Zotti 1982; Lightman 1981).

At redshifts smaller than $\sim 10^5$, the electron density is no longer high enough for Thomson scattering to establish a Bose-Einstein spectrum. The spectrum assumes a mathematically more complex form, but its main characteristics are 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 Thomson scattering, and a high temperature in the Wien region, where the Thomson-scattered photons from long wavelengths have accumulated.

Neither Thomson scattering nor bremsstrahlung takes place in a neutral medium, so in simple cosmological models, the spectrum at recombination is more or less preserved until the present, though redshifted by a factor of a thousand or so. More complex cosmological models may call for substantial energy injection from galaxy or quasar formation which could reionize the intergalactic or intercluster medium, creating conditions somewhat like those at redshifts between 10^3 and 10^5 but with a lower electron density and a higher ratio of electron temperature to radiation temperature. The effect of these conditions on the CMBR spectrum would again be to raise the brightness temperature in the Wien region and at very long wavelengths.

It is convenient to express spectral distortions in terms of the Planckian brightness temperature T_B, defined as

$$T_B(x) = \frac{h\nu/k}{\ln[1 + 1/\eta(x)]} = \frac{xT_R}{\ln[1 + 1/\eta(x)]}$$

where T_R is the radiation temperature, $x \equiv h\nu/kT_R$ is the dimensionless, redshift-independent frequency, and $\eta(x)$ is the photon occupation number [e.g. for a blackbody spectrum, $\eta(x) = (e^x - 1)^{-1}$, $T_B(x) = T_R$].

Soon after the Big Bang the matter and radiation are in close thermal contact, and the CMBR spectrum is Planckian. At $z < z_T \approx 10^6$, Thomson scattering is the most effective mechanism of

interaction between the matter and the radiation field, transferring energy to and from existing photons rather than through photon production and absorption, so a net transfer of energy results in distortions in the radiation spectrum. The mean rate at which a photon can gain energy through Thomson scattering is given by the parameter $\alpha_0(z)$, defined as

$$\alpha_0(z) = \frac{kT_e(z)}{m_e c^2}\sigma_T n_e(z) c$$

where $T_e(z)$ is the electron temperature at redshift z, $n_e(z)$ is the electron density at z, and σ_T is the Thomson-scattering cross-section. Note that α_0 is simply the product of the ratio of electron kinetic energy to rest mass (which determines how efficiently Thomson scattering transfers energy) and the rate at which the photon undergoes Thomson scatterings; this quantity is proportional to the pressure of the medium ($n_e kT_e$).

The Thomsonization parameter discussed above is the integral of α_0 with respect to time, and is a measure of the fractional change in photon energy caused by Thomson scattering between some initial time t and the present. This integral is defined as

$$\begin{aligned} y(z) &= -\int_0^{t(z)} \alpha_0 dt \\ &= -\int_0^{z(t)} \alpha_0(z)\frac{dt}{dz}dz \end{aligned}$$

(Zel'dovich and Sunyaev 1969). The value of y is unity at a redshift $z_a \approx 3.8 \times 10^4 \hat{\Omega}_b^{-1/2}$ where $\hat{\Omega}_b = \Omega_b(H_0/50)^2$, Ω_b is the ratio of the baryon density to the critical density, and H_0 is the Hubble parameter in km/sec/Mpc (Danese and De Zotti 1980). If energy injection occurs at a redshift $z_h \gtrsim z_a$, Thomson scattering causes the spectrum to approach a Bose-Einstein distribution with a non-zero chemical potential μ.

Energy injection at redshifts between z_a and z_T gives rise to a blackbody spectrum at long wavelengths (due to bremsstrahlung), a Bose-Einstein spectrum at short wavelengths (due to Thomson scattering), and a transition region in between. At the redshift z_a, the photon occupation number η_a and the brightness temperature $T_B(x)$ are

$$\eta_a(x) = \frac{1}{\exp[x + \mu(x)] - 1} \tag{1}$$

and

$$T_B(x) = T_R \frac{x}{x + \mu(x)} \, .$$

The frequency-dependent chemical potential $\mu(x)$ is approximated by the equation

$$\mu(x) = \mu_0 \exp(-2x_1/x) \, ,$$

$$x_1 \approx 5.3 \times 10^{-3} g(x)^{1/2} \Omega_b [(z + z_{eq})^{1/2} - (z_{eq} + z_{rec})^{1/2}]^{1/2} \, ,$$

where μ_0 is the chemical potential in the Bose-Einstein regime, x_1 is the frequency characterizing the transition from a blackbody to a Bose-Einstein spectrum (Sunyaev and Zel'dovich 1970; Danese and De Zotti 1980), z_{eq} is the redshift at which the matter and radiation energy density are equal, z_{rec} is the redshift at which recombination occurs, and $g(x)$ is the Gaunt factor. The Bose-Einstein chemical potential μ_0 is proportional to the ratio of the injected energy to the energy previously present in the radiation field:

$$\mu_0 \approx 1.4 \frac{\delta U}{U_0} \tag{2}$$

where U_0 is the energy density of the unperturbed radiation field and δU is the energy added to the radiation field (Chan and Jones 1975). The transition frequency x_1 is the minimum frequency

at which Thomson scattering can efficiently shift bremsstrahlung photons to higher frequencies, computed at the redshift z_a (Jones 1980). The brightness temperature $T_B(x)$ goes through a minimum at $x = 2x_1$. At $x << x_1$ and $x >> \mu_0$, T_B asymptotically approaches T_R.

The spectrum continues to evolve after z_a, even though Thomson scattering can no longer alter it substantially. Danese and De Zotti (1980) have pointed out that bremsstrahlung produces photons in the transition region which partially fill in the hole created by Thomson scattering. The expression they derive to account for alterations in η is

$$\eta(x) = e^{-y_B(x)}\eta_a + \frac{1 - e^{-y_B(x)}}{e^x - 1} , \tag{3}$$

where η_a is the photon occupation number at z_a, derived in equation (1), and $y_B(x)$ is the optical depth for free-free absorption looking back to the redshift z_B ($\approx 1.2 \times 10^4 \hat{\Omega}_b^{-1/2}$), the latest epoch when Thomson scattering could effectively remove photons from the transition region. The two terms in equation (3) represent the attenuation of the initial spectrum by free-free absorption and the production of bremsstrahlung photons; their main effects are to increase the frequency of the minimum in T_B by a factor of about 2.5 and to reduce the maximum distortion by about a factor of 1.5 (Danese and De Zotti 1978).

If energy injection occurs at a redshift z_h smaller than z_a, Thomson scattering may still affect the radiation spectrum even though it cannot establish a Bose-Einstein distribution. The Thomson-distorted spectrum is given by the equation (Danese and De Zotti 1978)

$$\eta_c(x, u) \approx (e^x - 1)^{-1} \left[1 + u\frac{xe^x}{e^x - 1}\left(\frac{x}{\tanh(x/2)} - 4\right)\right] , \tag{4}$$

where u is defined by the equation:

$$u = -\int_0^{z_h} \alpha_0(z)\frac{T_e - T_R}{T_e}\frac{dt}{dz}dz = -\int_0^{z_h} \frac{k(T_e - T_R)}{m_e c^2}\sigma_T n_e(z) c\frac{dt}{dz}dz ,$$

T_e and T_R being respectively the electron and radiation temperatures (Illarionov and Sunyaev 1974). Note that for $T_e >> T_R$, $u \approx y$. The value of u is determined by $\delta U/U_0$, the fractional energy added to the CMBR:

$$\begin{aligned} \frac{\delta U}{U_0} &= e^{4u} - 1 \\ &\approx 4u \qquad (u << 1) \end{aligned} \tag{5}$$

(Sunyaev and Zel'dovich 1980). Thomson scattering has the effect of depressing T_B by an amount $2uT_R$ at frequencies $x < 1$ and sharply enhancing it beyond.

Equation (4) does not include the effects of bremsstrahlung. At frequencies less than x_B ($5 \times 10^{-4} < x_B < 5 \times 10^{-2}$, depending upon z_h and $\hat{\Omega}_b$) the universe becomes opaque to free-free absorption and T_B rises from $T_R(1 - 2u)$ to T_e. Zel'dovich *et al.* (1972) have shown that the amount of the temperature rise is

$$\Delta T = 7.4\, T_R u .$$

When bremsstrahlung is included in the calculation of η, the resulting equation has a form similar to that of equation (3):

$$\eta = e^{-y_B(x_e)}\eta_c + \frac{1 - e^{-y_B(x_e)}}{e^{x_e} - 1} , \tag{6}$$

but η_c now comes from equation (4) rather than equation (1), and the electron temperature T_e is explicitly used to calculate x_e.

II. Fits to Observations

The combined results of recent measurements at wavelengths longer than 0.1 cm (Table 1) yield a CMBR temperature of 2.74 ± 0.02 K and fit a blackbody spectrum with a χ^2 of 24.0 for 17 degrees of freedom. Including the new data of Matsumoto *et al.* (1987), the data set is inconsistent with a blackbody spectrum. A significant part of the χ^2 comes from the disagreement of Matsumoto *et al.* (1987) and Peterson *et al.* (1985), and we have used the small rather than conservative errors of Peterson *et al.* (1985), but leaving the Peterson *et al.* (1985) data out entirely does not alter our conclusions.

As well as checking the results for overall consistency with a blackbody spectrum, one can also analyze the measurements for possible distortions. When only the CMBR measurements in Table 1 at wavelengths longer than 0.1 cm are fitted to equation (3), the resulting values are:

$$\begin{array}{llll} \hat{\Omega}_b = 1.0 & T = 2.76 \pm 0.02 \text{ K} & \mu_0 = (4.2 \pm 4.9) \times 10^{-3} & \chi^2 = 23.14 \\ \hat{\Omega}_b = 0.1 & T = 2.76 \pm 0.02 \text{ K} & \mu_0 = (2.4 \pm 3.5) \times 10^{-3} & \chi^2 = 21.98 \\ \hat{\Omega}_b = 0.01 & T = 2.76 \pm 0.02 \text{ K} & \mu_0 = (2.0 \pm 1.5) \times 10^{-3} & \chi^2 = 21.76 \end{array}$$

for 19 degrees of freedom and the errors are for the 68% confidence level.

Equations (4) and (6) can be used to derive best-fit values of T_R and u. Because the value of z_h affects the contribution of bremsstrahlung to the low-frequency portion of the spectrum, z_h and $\hat{\Omega}_b$ must both be specified for the model fit. Table 2 lists the best-fitted values of T_R and u over a range of redshifts and densities. The values are derived from all the measurements in Table 1. The best-fit values of u indicate a Thomsonization distortion at the 12-σ level with the entire significance due to the data of Matsumoto *et al.* (1987); without their data the best-fitted value is negative but consistent with zero.

III. Impact on CMBR-Production Models

The measured values of μ_0, which are all consistent with zero, can be used in conjunction with equation (2) to set upper limits on the energy transferred to the radiation field at redshifts between z_a and z_T. The complete data set yields the 95% confidence level limits:

$$\begin{array}{ll} \hat{\Omega}_b = 1.0 & \frac{\delta U}{U_0} \leq 10.0 \times 10^{-3} \\ \hat{\Omega}_b = 0.1 & \frac{\delta U}{U_0} \leq 6.7 \times 10^{-3} \\ \hat{\Omega}_b = 0.01 & \frac{\delta U}{U_0} \leq 3.6 \times 10^{-3} \, . \end{array}$$

Similarly, equation (5) and the measured values for u restrict the energy release that could have occurred at more recent times. Depending on the density parameter and the redshift of energy release, these results indicate an energy transfer to the CMBR of approximately 8%.

One can do a whole series of parameter fits using various assumptions about the density of the universe, the baryon (electrons for Thomson scattering) density, and the epoch and nature of the energy release. These families of parameter limits can then be converted into limits on energy release in those situations. One can then make a series of curves showing maximum allowable fractional energy release, $\delta E/E_R$, as a function of redshift for various densities.

The fractional energy release limits can then be used to set limits on processes of cosmological interest. Examples of these are: (1) The spectrum of adiabatic density perturbations (Sunyaev and Zel'dovich 1970) (2) The spectrum of primordial turbulence and vorticity (Illarionov and Sunyaev 1974; Chan and Jones 1976) (3) Annihilation of matter and antimatter in the early universe (Stecker and Puget 1972; Sunyaev and Zel'dovich 1980) (4) Energy release by evaporating primordial black holes or unstable (decaying) particles (Dolgov and Zel'dovich 1981; Silk and Stebbins 1983) (5) an improved estimate of the average photon density of the Universe.

From the constraints on the chemical potential, the energy in turbulence on scales which are currently 30 kpc to 4 Mpc is less than one per cent of that in the CMBR. This limit is sufficient

References	Wavelength (cm)	ν (GHz)	T_{CBR} (K)
Sironi *et al.* 1987	50.0	0.6	2.45 ± 0.7
Levin *et al.* 1987	21.2	1.41	2.22 ± 0.38
Sironi (Smoot *et al.* 1985*b*)	12.0	2.5	2.79 ± 0.15
De Amici *et al.* 1987	8.1	3.7	2.58 ± 0.13
Mandolesi *et al.* 1986	6.3	4.75	2.70 ± 0.07
Kogut (Smoot *et al.* 1987)	3.0	10.0	2.61 ± 0.06
Johnson and Wilkinson 1986	1.2	24.8	2.783 ± 0.025
De Amici (Smoot *et al.* 1985*b*)	0.909	33.0	2.81 ± 0.12
Bersanelli (Smoot *et al.* 1987)	0.333	90.0	2.60 ± 0.10
Meyer and Jura 1985	0.264	113.6	2.70 ± 0.04
	0.132	227.3	2.76 ± 0.20
Crane *et al.* 1986	0.264	113.6	2.74 ± 0.05
	0.132	227.3	$2.75^{+0.24}_{-0.29}$
Peterson,	0.351	85.5	2.80 ± 0.16
Richards, and	0.198	151	$2.95^{+0.11}_{-0.12}$
Timusk 1985	0.148	203	2.92 ± 0.10
	0.114	264	$2.65^{+0.09}_{-0.10}$
	0.100	299	$2.55^{+0.14}_{-0.18}$
Matsumoto *et al.* 1987	0.116	259	2.795 ± 0.018
	0.0709	423	2.963 ± 0.017
	0.0481	624	3.146 ± 0.022

Table 1: Recent Measurements of the Cosmic Background Radiation Temperature.

$\hat{\Omega}_b$	z_h	T_R (K)	u	Maximun T_R (K)	Maximum u	χ^2_{best}
1.0	4×10^4 (z_a)	2.814	1.89×10^{-2}	2.836	2.21×10^{-2}	98.56
	1×10^4	2.816	2.08×10^{-2}	2.838	2.41×10^{-2}	70.79
	4×10^3	2.819	2.14×10^{-2}	2.840	2.49×10^{-2}	58.69
	1×10^3	2.823	2.15×10^{-2}	2.844	2.49×10^{-2}	50.49
0.1	1×10^5 (z_a)	2.822	2.15×10^{-2}	2.843	2.49×10^{-2}	52.67
	4×10^4	2.822	2.15×10^{-2}	2.843	2.49×10^{-2}	51.90
	1×10^4	2.823	2.15×10^{-2}	2.844	2.49×10^{-2}	51.08
	4×10^3	2.823	2.16×10^{-2}	2.844	2.49×10^{-2}	50.74
	1×10^3	2.823	2.15×10^{-2}	2.844	2.49×10^{-2}	50.49

Table 2: Best-fitted values of T_R and u from all measurements. The maximum T_R and u are the maximum values of these parameters on the $\chi^2_{best} + 4$ ellipse. This ellipse corresponds to about the 95% confidence level. The χ^2 is computed with 19 degrees of freedom.

to rule out turbulence and vorticity as the drivers of galactic formation. Similar arguments can be made regarding adiabatic perturbations and the limits are borderline. However, the small scale anisotropy measurements place an even more restrictive limit, providing re-ionization of the universe did not happen sufficiently early to scatter the CMBR and erase the distortions. Theorists now indicate that they need dark matter to generate galaxy formation within those limits.

The annihilation of matter and antimatter is constrained similarly by the limits on energy release provided by the limits on y and the chemical potential μ. If the Grand Unification and Inflation theories were well established, then the excess of matter over antimatter and the possibility of residual antimatter might be of no concern. For redshifts between 10^6 and 4×10^4 the amount of energy released in annihilation is less than 1% of that in the CMBR. After a redshift of about 4×10^4 the limit is about 10%.

The decay of massive particles can also produce a non-Planckian spectrum. Silk and Stebbins (1983) have shown that one can use the limits on CMBR spectral distortions to rule out weakly interacting particles which have lifetime, τ, between about 0.1 years and the Hubble time (10^{10} years) and masses, m, between about 10^{-6} and 10^6 eV, with the exception of a small range along $m^2\tau = 10^{10}(\mathrm{eV})^2$ years which is hidden in the interstellar background.

Upper limits on $\delta U/U_0$ derived from μ_0 and u are summarized in Figure 1. Some care must be taken in applying these limits to astrophysical processes, since the energy generated by these processes may not be readily transferred to the CMBR. Figure 2 shows the data in Table 1, along with five sample distortions.

The situation after recombination is not so simple. Because the neutral matter interacts only very weakly with the radiation, the kinetic energy of its bulk motion does not cause distortions in the CMBR spectrum. On the other hand, any significant release of thermal energy by the matter would ionize some fraction of it once again. If the ionized matter is not strongly clumped, the reionized medium interacts with the radiation as before. At redshifts greater than ~ 8, the time scale on which the matter is cooled by Thomson scattering is shorter than the expansion time of the universe (Sunyaev and Zel'dovich 1980), so most of the excess thermal energy in the reionized medium is taken up by CMBR photons, causing a distortion. In this case, the observational bounds

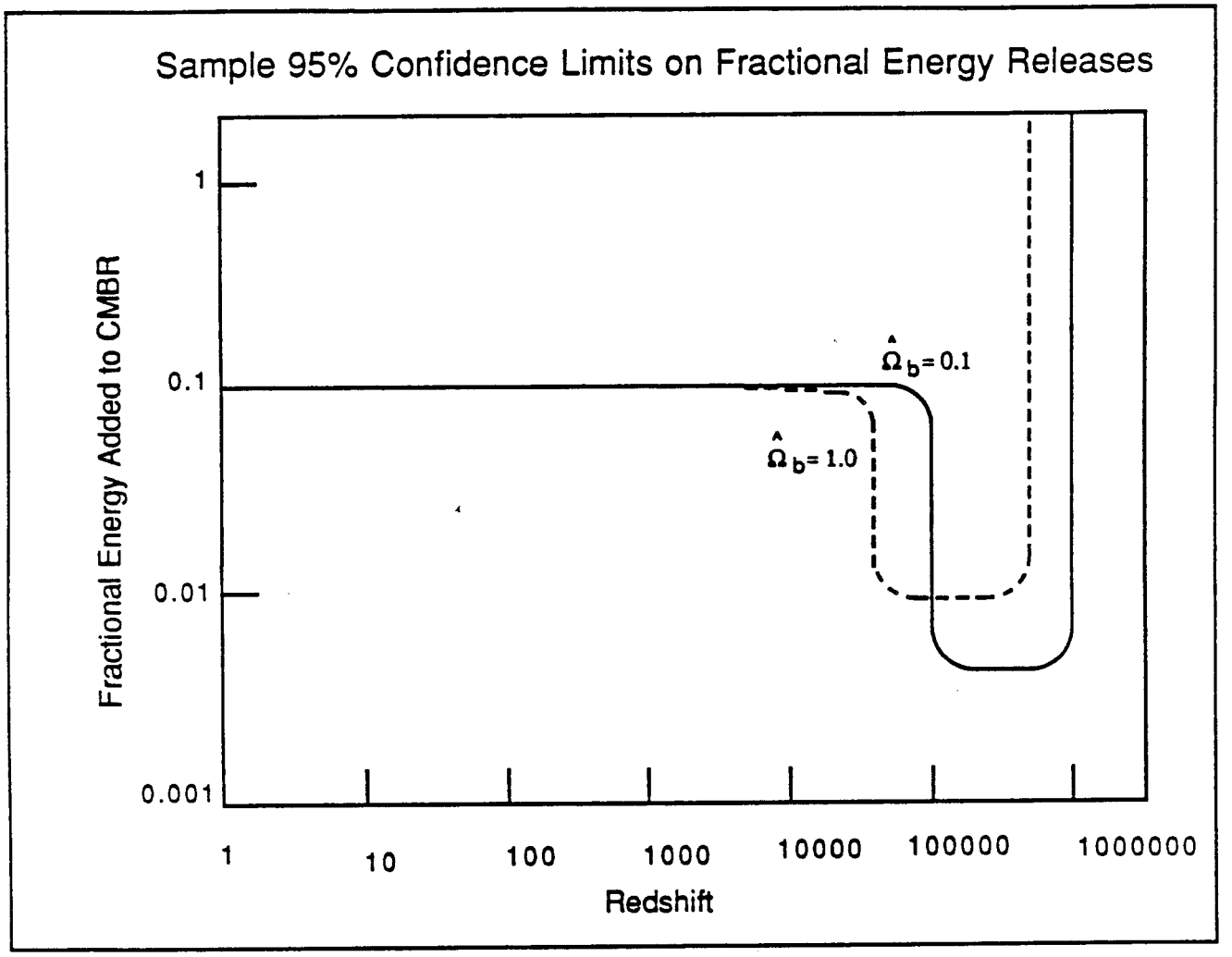

Figure 1: Limits on the fractional energy added to the CMBR as a function of z_h.

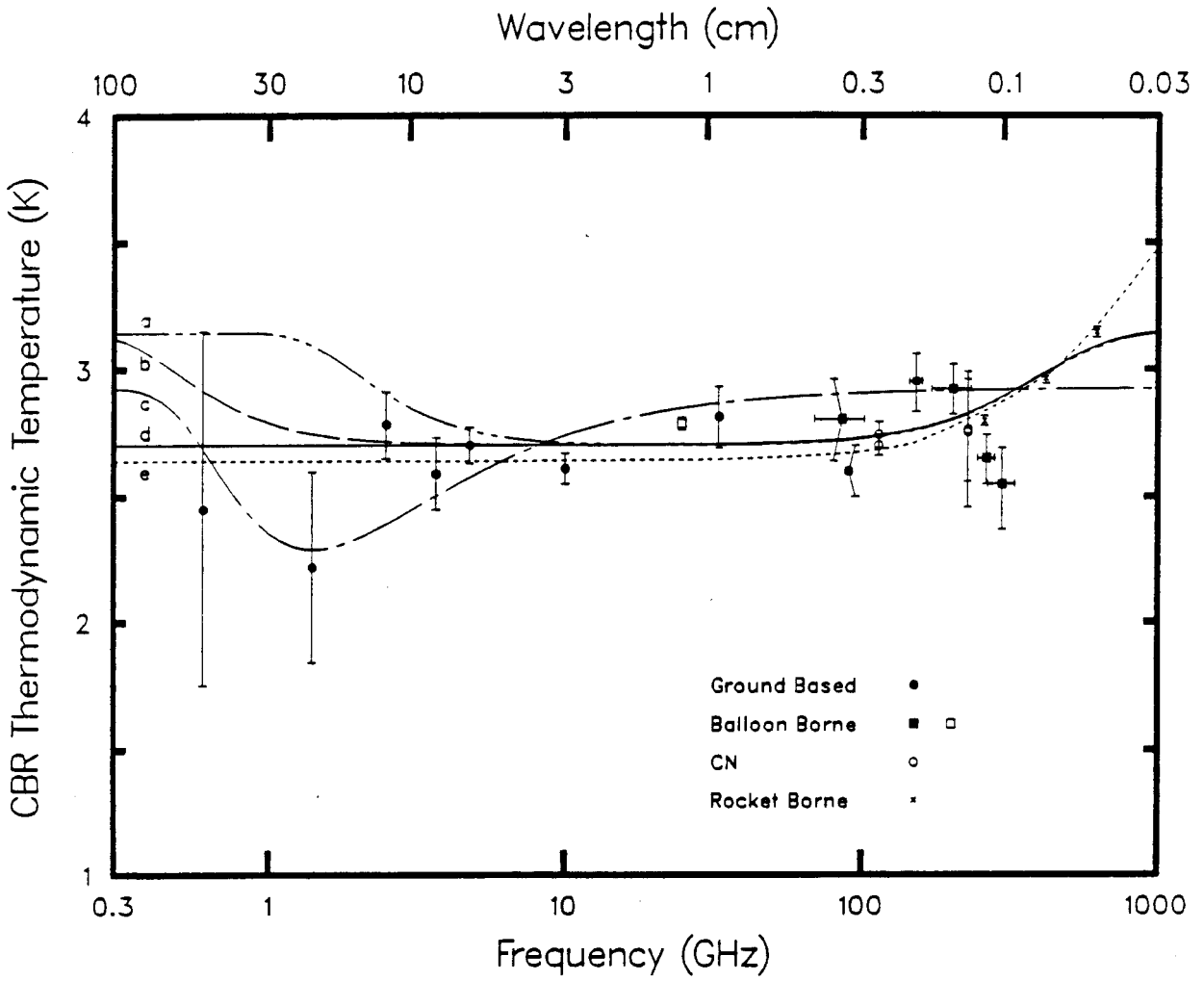

Figure 2: Spectrum of the CMBR. The model distortions shown have parameters:
(a) $\hat{\Omega}_b = 1.0$, $T_R = 2.819$ K, U = 0.02143, $z_h = 4000$;
(b) $\hat{\Omega}_b = 0.1$, $T_R = 2.823$ K, U = 0.02154, $z_h = 10000$;
(c) $\hat{\Omega}_b = 0.1$, $T_R = 2.925$ K, $\mu_0 = 0.01166$.
(d) $\hat{\Omega}_b = 0.1$, $T_R = 2.823$ K, U = 0.02152, $z_h = 1000$;
(e) Semi-relativistic calculation of the CMBR spectrum, taken from Wright (1979). This model corresponds approximately to U = 0.03 and $T_R = 2.82$ K with an electron temperature of 1.5×10^9 K.

on u limit the thermal energy released to reionized matter between $z \approx 8$ and $z \approx 1500$ to less than 10% of the energy in the CMBR. For energy release after $z \approx 8$, the same 10% limit applies, but in this case it refers to the energy actually transferred to the CMBR, which will, in general, be less than the energy released to the matter. Similarly, if the electrons in the reionized medium are relativistic, Equation (4) is no longer correct, and the distorted spectrum will have a steeper slope at high frequencies, rather than leveling off as shown in curves a, b, and d of Figure 2.

Much of this analysis breaks down if a large fraction of the matter in the universe is highly clumped or bound up in an early generation of stars. In that case, Thomson scattering may not be able to transfer the heat efficiently from the matter to the CMBR. The form and extent of the resulting distortions depend on the details of the model. One such class of models—the hypothesis that some or all of the CMBR is thermal radiation from warm dust produced by Population III stars at $z \gtrsim 10$—has been suggested by Rees (1978), Negroponte *et al.* (1981), Wright (1982), and others to explain the spectral distortion reported by Woody and Richards (1979, 1981) Although the details of such models have to some extent been tailored to fit the Woody-Richards distortion, significant departures from a blackbody curve are almost inevitable because of the spectral characteristics of the carbon or silicate materials that make up the grains. The absence of significant distortions in recent measurements of the CMBR spectrum is a heavy blow against such theories. To devise a plausible dust-emission model that gives a Planckian spectrum over a hundredfold range in wavelength may well prove an impossible task. Hawkins and Wright (1987) and Wright (1987) have attempted this using long thin needles and fractal dust grains.

An important implication of this limit is the constraint it places on the amount a hot intergalactic medium (IGM) can contribute to the diffuse X-ray background (XRB). Such a hypothesis has been contemplated (Cowsik and Kobetich 1972) and found to be consistent with the x-ray data (Field and Perrenod 1977; Sherman 1980; Marshall *et al.* 1980), although a test of this hypothesis requires a careful (and somewhat uncertain) subtraction of the contribution from discrete X-ray sources. The residual spectrum may be too flat to be simply explained as having thermal bremsstrahlung origin (Zamorani and Giacconi 1986). In the most recent analysis Guilbert and Fabian (1986) restate that one can obtain an accurate fit to the X-ray observations, but that the energy required to heat the IGM is a severe problem. Nonetheless, if the presumed IGM were to contribute significantly to the XRB, it must have $\hat{\Omega}_b \gtrsim 0.22$ and must have been heated within the redshift interval $3 \lesssim z_h \lesssim 6$ to an electron energy $kT_e \approx 36(1+z_h)$keV. A hot IGM would distort the CMBR spectrum by Thomson scattering. Guilbert and Fabian predict that the expected Rayleigh-Jeans temperature change, $\Delta T = 2uT_R$, should be about 0.07 K so that $u \sim 0.013$ is implied. Our corresponding value for $3 \lesssim z_h \lesssim 6$ is $u = 0.022 \pm 0.002$ at the 95% confidence level.

The potential implications of this distortion call for confirmation of the Matsumoto *et al.* (1987) results and determination of the epoch at which the distortion occurred. For example
(1) Did the Compton/Thomson distortion occur before recombination? – If so, we should see the bremsstrahlung photons as excess low frequency (long wavelength) photons in the CMBR spectrum.
(2) Did the distortion occur in the range $7 \lesssim z_h \lesssim 1000$? – If so, the bremsstrahlung photons should contribute to the X-ray background.
(3) Did the distortion occur in the range $3 \lesssim z_h \lesssim 6$ and produce the diffuse XRB? – If so, what happened, what was the source of the energy, and how much baryonic matter is out there?

In all cases there are questions about how much energy it took and how smooth was the distribution of hot IGM. How much are small angular scale anisotropies washed out? The recent measurements present an exciting prospect in that we may have moved from an era of setting limits on distortions in the CMBR to measuring a distortion's parameters in order to learn about a process occurring in the early universe.

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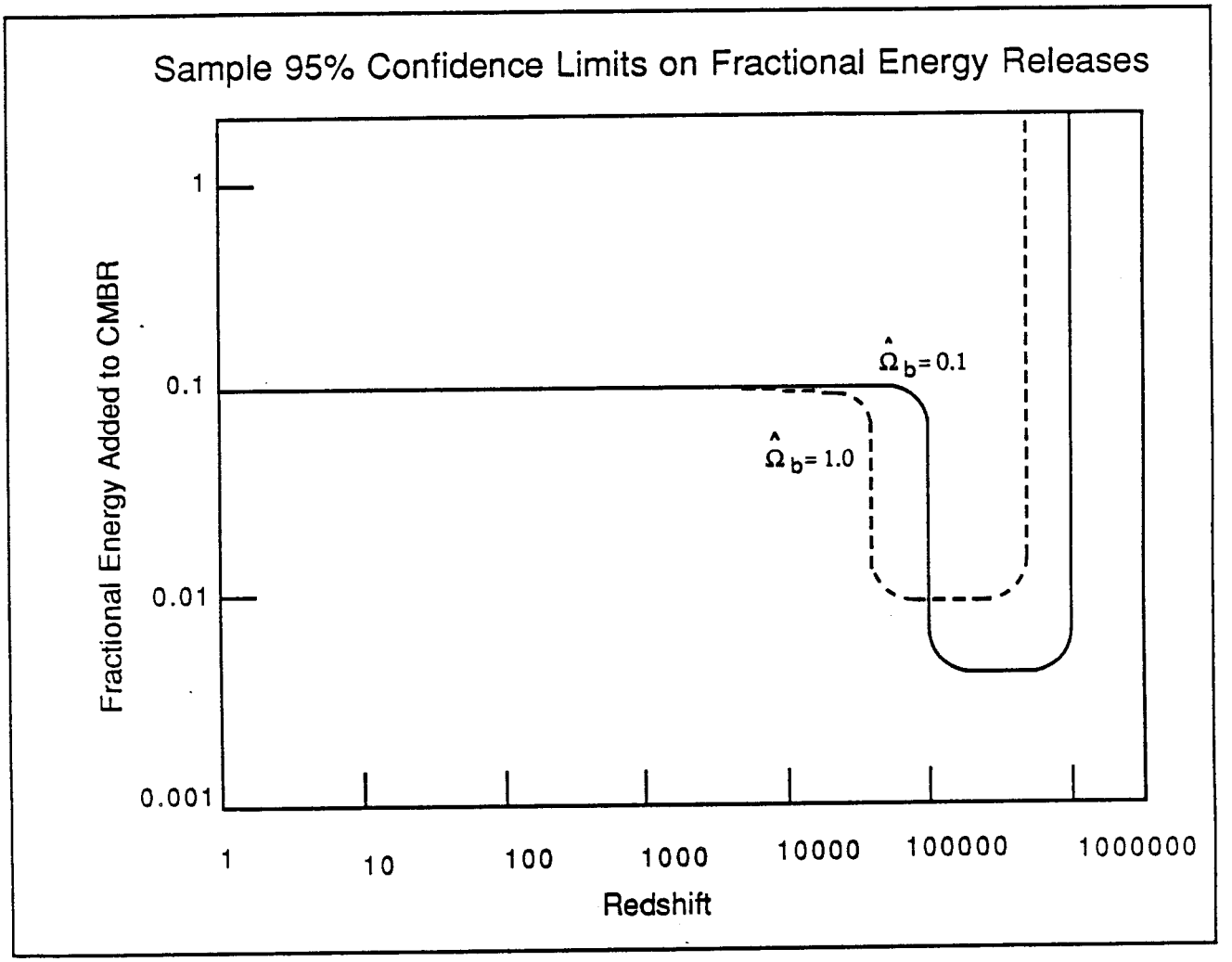

Figure 1: Limits on the fractional energy added to the CMBR as a function of z_h.

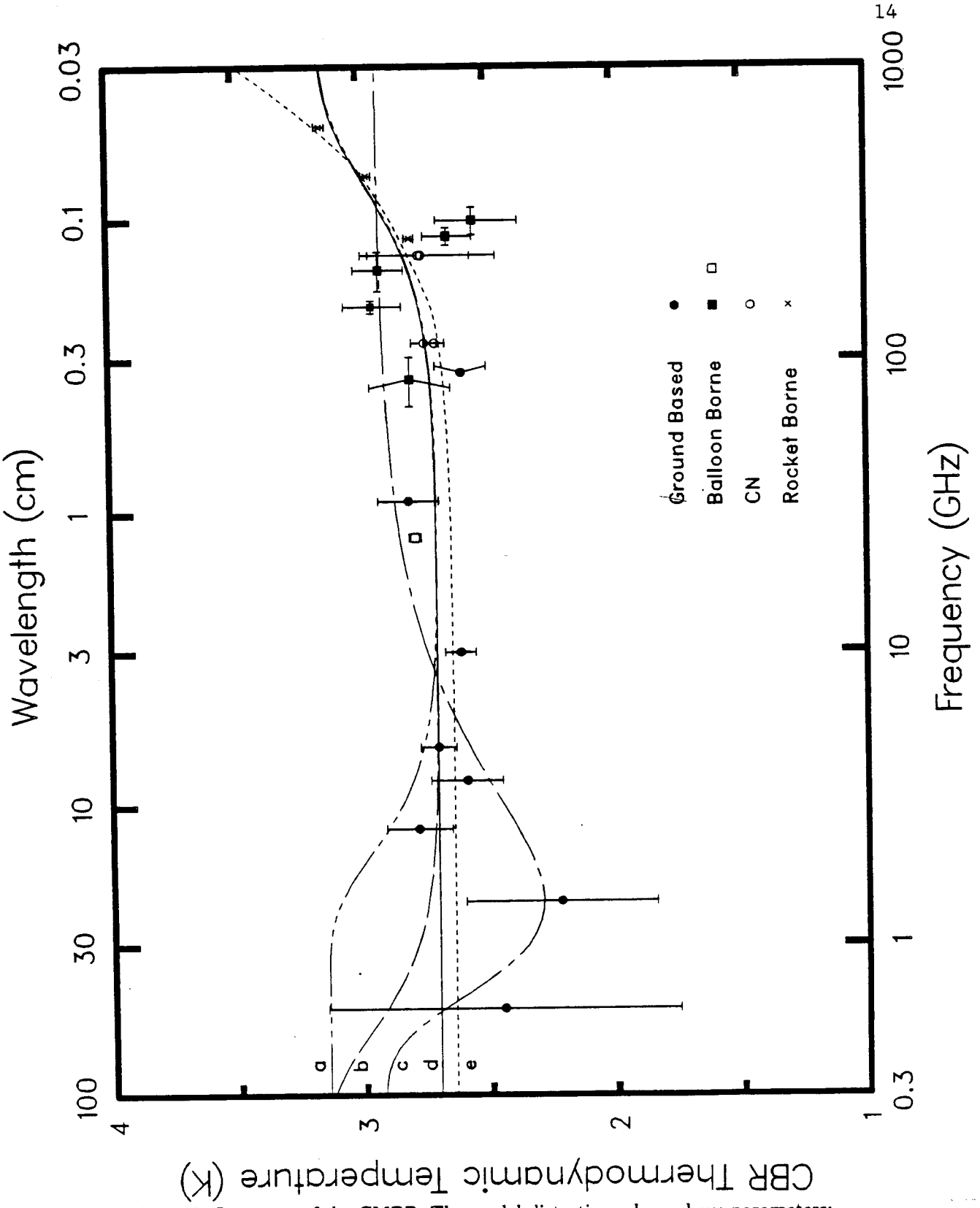

Figure 2: Spectrum of the CMBR. The model distortions shown have parameters:
(a) $\hat{\Omega}_b = 1.0$, $T_R = 2.819$ K, U = 0.02143, $z_h = 4000$;
(b) $\hat{\Omega}_b = 0.1$, $T_R = 2.823$ K, U = 0.02154, $z_h = 10000$;
(c) $\hat{\Omega}_b = 0.1$, $T_R = 2.925$ K, $\mu_0 = 0.01166$.
(d) $\hat{\Omega}_b = 0.1$, $T_R = 2.823$ K, U = 0.02152, $z_h = 1000$;
(e) Semi-relativistic calculation of the CMBR spectrum, taken from Wright (1979). This model corresponds approximately to U = 0.03 and $T_R = 2.82$ K with an electron temperature of 1.5×10^9 K.