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POLARIZATION OF THE BLACKBODY RADIATION AT 3.2 CENTIMETERS[1]

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ABSTRACT

Measurements of the linear polarization of the primeval fireball were made along a declination of 40°35 N, using a modified 3.2 cm Dicke radiometer. Harmonic analysis of the Stokes parameters of the radiation, Q and U, yields an upper limit of 1.61×10^{-3} K (90% confidence) on the large-scale polarization of the microwave background.

Subject headings: cosmic background radiation — polarization — radio sources: extended

I. INTRODUCTION

Many observations have been conducted to determine the large-scale isotropy of the microwave background (Partridge and Wilkinson 1967; Conklin 1969; Henry 1971; Boughn, Fram, and Partridge 1971; Corey and Wilkinson 1976; Smoot, Gorenstein, and Muller 1977). These constitute a sensitive test for nonuniformity in the Hubble expansion back to the epoch of last scattering, t_s. If recombination had occurred at a redshift of 1000, the limits inferred by power anisotropy measurements would point to a very uniform expansion since that time. In the event that t_s came much later, owing, for example, to a reheat phase associated with the formation of galaxies, a temperature asymmetry due to nonuniform expansion would have had much less time to grow. In this case the anisotropic expansion limit inferred from the power measurements of the background is not as stringent. Scattering would have thermalized the radiation and thus destroyed information from times earlier than t_s.

As pointed out by Rees (1968), a polarization measurement preserves information about the expansion produced before recombination. After the temperature in the expansion drops below about 10^9 K, an asymmetric expansion through the mechanism of Thomson scattering will produce a net linear polarization in the last few scatterings before recombination.

The work reported here was an attempt to detect linear polarization in the 2.7 K background at a wavelength of 3.2 cm. The null result can be interpreted, using Rees's axially symmetric model, as an upper limit on asymmetry in the Hubble expansion.

II. APPARATUS AND CALIBRATION

The Faraday-switched polarimeter used in this experiment is shown in Figure 1. A variation on a Dicke receiver, this device has a conical optimum gain horn with 15° beamwidth (FWHM), feeding into a cylindrical waveguide containing a thin ferrite rod (the switch). A coil surrounding the ferrite receives switching current from the audio oscillator used as the lock-in amplifier reference signal. The field produced rotates the polarization of the incoming radiation through 90° against the dual-mode transducer which acts as an analyzer, admitting radiation polarized in one direction to the receiver and dumping the other polarization to the sky. The receiver output at the lock-in frequency is proportional to either Q or U depending upon the orientation angle of the polarimeter. The system temperature was 830 K (double sideband), and total bandwidth was 96 MHz about the center frequency of 9.37 GHz.

Calibration was a two-step process. First, measuring the change in DC voltage at the second detector with the addition of a 300 K absorber over the antenna determined the gain of the microwave front end. Then, by inserting a known AC voltage at the lock-in frequency at the same point, the rest of the receiver was calibrated. The overall gain of the device was stable to within 5% over periods of several months.

The polarimeter was pointed to the zenith, where the Earth's rotation carried it through a circle of constant declination of 40°35 N. Mounted vertically on a rotating table, it was turned sequentially through eight positions, 45° apart, giving alternative measurements of the Stokes parameters Q and U and allowing removal of instrumental effects. Integration time at each position was 5 minutes, after which the integrator output, the time (EST), the polarimeter position, and the temperature of selected points about the apparatus were written on magnetic tape.

The largest source of possible systematic error in the measurements was the Faraday rotation switch. The voltage standing wave ratio of the device was a strong function of the magnetization of the ferrite. To prevent a modulated reflection of the local oscillator power in the receiver passband from appearing as signal, a circulator and isolator were inserted between the switch and the mixer. The absorption coefficient of the ferrite switch was

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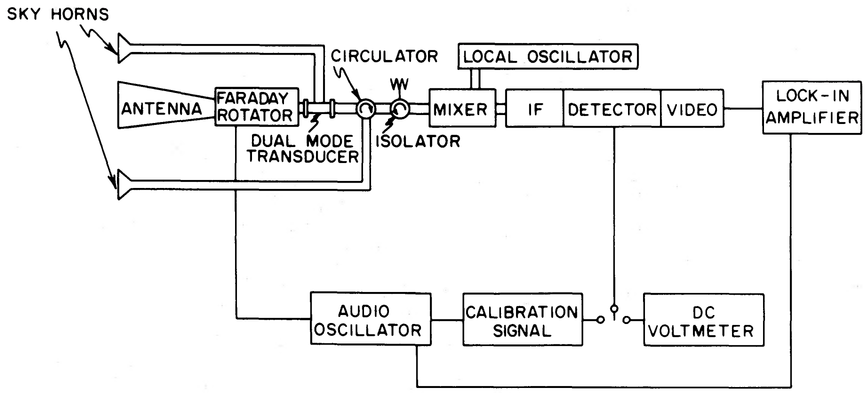

FIG. 1.—The 3.2 cm Faraday-switched polarimeter. The sky horns are used as convenient cold loads.

also a factor in that it was a nonlinear function of both temperature and magnetization. Control of the environment in the equipment shed reduced the temperature problem to acceptable levels. Because of the nonlinearity of the ferrite absorption curve, any change in the average magnetization due to changes in the component of Earth's magnetic field along the axis of the polarimeter caused a change in the absorption-produced offset in the switch. To prevent this from causing a position-dependent signal as the device was rotated, the entire microwave front end of the polarimeter was encased in magnetic shielding, which reduced the effect of the Earth's magnetic field by two orders of magnitude.

III. ANALYSIS OF DATA

As a first step the data were edited to remove portions which for one reason or another were not acceptable. Data which were excluded fell into the following categories:

1. Contamination by precipitation and thunderstorm activity. Rain collecting on the antenna window caused spurious readings, while electrical storm activity in the area produced unacceptable levels of radio-frequency interference. Because of a stormy spring and summer in the Princeton area, this was a major cause of lost data.
2. Solar contamination. The antenna was surrounded by an axially symmetric ground shield to prevent terrain features from radiating into the asymmetric antenna beam. When the Sun rose above this shield, its radiation produced a false polarization signal.
3. Errors due to malfunction of the apparatus.
4. Any isolated reading which was more than 3 standard deviations above the local mean. A total of 387 points were eliminated in this way, most of which occurred near periods of heavy thunderstorm activity, during which the data were known to be bad.

Out of roughly 94,000 points collected between 1972 August 9 and 1973 August 10, 40.4% (38,029) were suitable for use.

When making Q and U Stokes parameter measurements, positions of the polarimeter which differ by 180° are equivalent while those 90° apart are opposite in sign. By subtracting readings 90° apart and dividing by 2, the position-independent offset of the polarimeter is eliminated and the portion of the signal corresponding to the desired parameter is averaged. A time for the average is computed from the times of the individual readings and is converted to the right ascension of the point of observation. The above process is equivalent to synchronous detection. The rotating polarimeter chops incoming radiation at twice its rotation frequency, while the averaged Q and U parameters are the two phases extracted in a manner similar to that of a vector lock-in amplifier. The double lock-in technique gave good immunity against gain fluctuations and changes in the polarimeter offset which occur on time scales longer than half the polarimeter rotation period.

Figures 2 and 3 show the data folded into sidereal and solar time bins 1 hour wide. Q is the difference in antenna temperatures with north-south polarization (T_{NS}) and east-west polarization (T_{EW}). U is measured by rotating the device 45°.

The errors for each bin are computed from the data folded into the bin in the following way. Because of the 90° subtraction process, the variances of the folded data must be corrected. When the subtraction was performed, a new set of data was formed by averaging adjacent points in the original set. By propagation of errors, one can show that the variance of the new data set is half that of the old. Thus, estimating the variance of the averaged points constitutes estimating the variance of the original data and dividing by 2.

The time-averaged values of the polarization in sidereal bins are

$$\langle Q \rangle = (-0.67 \pm 0.14) \times 10^{-3}\ \mathrm{K}\,,$$
$$\langle U \rangle = (-0.88 \pm 0.14) \times 10^{-3}\ \mathrm{K}\,. \qquad (1)$$

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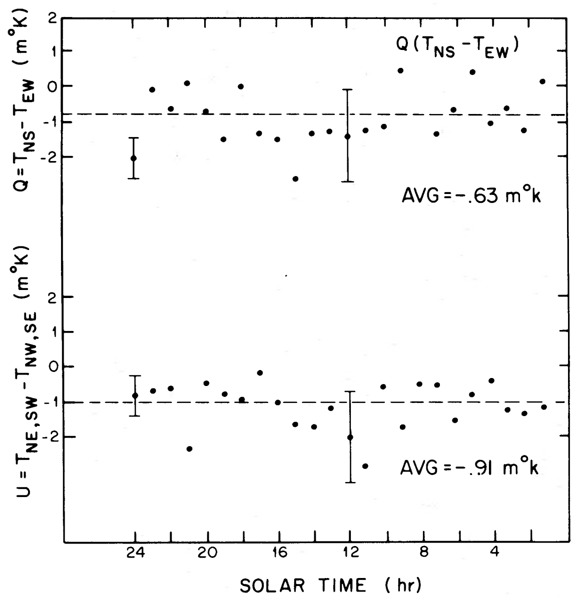

FIG. 2.—The 3.2 cm polarization data folded into solar bins. The nonuniform errors are caused by the discarding of measurements contaminated by the Sun during the summer months.

Large-scale celestial sources of the type sought here should have $\langle U \rangle = 0$ (see eq. [10]). The nonzero experimental value for $\langle U \rangle$ indicates that perhaps much of the constant contribution is from other than cosmological sources. When combined into a polarization vector, the experimental values appear to align with the largest horizon feature—an elevator tower only just geometrically shielded by the ground screens. Calculations using sidelobe gain measurements indicate order-of-magnitude agreement but are not reliable enough to allow separating out the ground effect. Thus the possibility of a nonzero contribution from the Galaxy or cosmological effects cannot be ruled out, and equation (1) indicates

$$|\langle Q \rangle| < 0.90 \times 10^{-3}\ \text{K, with } 90\%\ \text{confidence}, \qquad (2)$$

as an upper limit on the constant component of the N-S-E-W polarization of the 2.7 K background radiation.

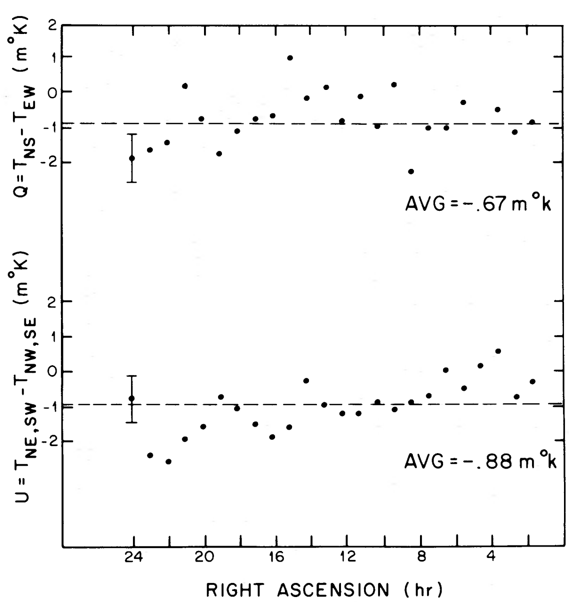

FIG. 3.—The 3.2 cm polarization data folded into sidereal bins

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Next, Figures 2 and 3 were analyzed for harmonic structure; this should not be contaminated by stationary ground effects. Table 1 shows the results of fitting the data to a constant level (DCL) and the lowest eight sinusoidal harmonics. Note that the values of χ^2 for the fits to a constant level are large in three out of four cases, indicating a poor fit. Although an attempt was made to remove all data with false solar signal, some contamination is still possible; therefore, some structure is not totally unexpected when the data are folded in solar time. On the other hand, high values of χ^2 in the sidereal case indicate real structure of a nonterrestrial nature in the data.

Unless the data are spread uniformly over a year, residual solar-contamination sidebands can get into the sidereal time results. This effect was calculated using Figure 2 and the known data nonuniformity; the effect is negligible. In the worst case, that of the 24 hour amplitudes, where the length of the data string is just capable of distinguishing between solar and sidereal contributions, the solar amplitudes are smaller than the corresponding sidereal ones.

TABLE 1

HARMONIC ANALYSIS OF DATA[a]

P	T	σ_T	Φ	σ_Φ	ν	χ^2	$\frac{T - \langle T \rangle}{\sigma_T}$
			Q in Solar Bins				
DCL	−0.63	0.14	...	...	23	30.60	−4.50
24	+0.33	0.21	+97.36	34.35	21	26.94	+0.19
12	+0.19	0.20	−123.61	62.45	19	25.59	−0.50
8	+0.28	0.20	−42.31	42.08	17	24.21	−0.05
6	+0.22	0.20	−100.89	53.08	15	23.25	+0.35
4.8	+0.09	0.20	+182.42	129.61	13	23.22	−1.00
4	+0.60	0.20	+73.14	19.40	11	14.95	+1.55
3.4	+0.23	0.20	+30.88	51.09	9	14.96	−0.30
3	+0.15	0.20	−89.83	78.45	7	14.64	−0.70
			U in Solar Bins				
DCL	−0.91	0.14	...	...	23	17.93	−6.50
24	+0.10	0.21	+123.20	109.79	21	16.99	−0.90
12	+0.23	0.20	−40.31	49.17	19	15.35	−0.30
8	+0.14	0.20	+139.94	84.06	17	14.45	−0.75
6	+0.19	0.20	−163.76	60.61	15	13.92	−0.50
4.8	+0.31	0.20	−102.86	37.02	13	11.79	−0.10
4	+0.24	0.20	−133.50	48.93	11	10.96	−0.25
3.4	+0.08	0.20	−124.28	143.00	9	10.92	−1.05
3	+0.47	0.20	+52.36	24.81	7	5.61	+0.90
			Q in Sidereal Bins				
DCL	−0.67	0.14	...	...	23	32.98	−4.79
24	+0.52	0.21	−80.52	21.79	21	25.65	+1.10
12	+0.20	0.20	+89.61	58.59	19	24.35	−0.45
8	+0.19	0.20	−83.75	61.66	17	23.10	−0.50
6	+0.31	0.20	−16.64	37.81	15	20.89	+0.10
4.8	+0.41	0.20	+84.80	28.58	13	17.11	+0.60
4	+0.36	0.20	+62.64	31.95	11	13.68	+0.35
3.4	+0.10	0.20	−59.81	116.81	9	13.63	−0.95
3	+0.39	0.20	−105.69	30.12	7	10.42	+0.50
			U in Sidereal Bins				
DCL	−0.88	0.20	...	...	23	27.07	−6.29
24	+0.58	0.20	+39.24	20.53	21	17.30	+1.45
12	+0.45	0.21	+22.62	25.30	19	12.78	+0.76
8	+0.33	0.20	−1.32	35.01	17	9.63	+0.20
6	+0.30	0.20	+79.77	38.67	15	7.14	+0.05
4.8	+0.17	0.20	+187.52	67.42	13	6.46	−0.60
4	+0.08	0.20	+40.47	136.89	11	6.28	−1.05
3.4	+0.29	0.20	+183.51	40.62	9	3.85	0.00
3	+0.25	0.20	−163.63	46.74	7	2.61	−0.20

[a] P = period in hours of solar or sidereal time. T = amplitude of harmonic component in mK. σ_T = error in amplitude. Φ = phase of component in degrees from bin 0 (bin 24). σ_Φ = error in phase. ν = degrees of freedom in fit. χ^2 = chi-square for the fit. $\langle T \rangle$ = expected value of T based on experimental errors and random numbers = 0.29 K. $(T - \langle T \rangle)/\sigma_T$ = number of sigma of amplitude above expected value.

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There is a good possibility that some of the structure indicated in Figure 3 is due to polarized galactic radiation; the plane passes through the beam near R.A. = 5^h and 20^h. Using polarization surveys at lower frequency, I tried to calculate the effect (Nanos 1973). The large gap in frequency between the available surveys (21, 50, and 75 cm) and the present data (3.2 cm), their nonuniform coverage of the regions of interest, and the complex nature of the galactic magnetic fields and electron concentrations (which gives rise to nonuniform Faraday rotation and depolarization) precluded any definitive subtraction of the galactic effect. Qualitatively, the application of a reasonable spectral index to, for example, the 21 cm data (Bingham 1966) indicates that a galactic contribution could be expected at the 1 mK level.

Because of the high probability that the data was contaminated by polarized radiation from the Galaxy, it was decided to use the fitted amplitudes from Table 1 to derive an upper limit on a possible cosmological effect. No correction for galactic radiation was attempted.

The quantity $(T/\langle T \rangle)^2$, where T is a 12 or 24 hour amplitude and $\langle T \rangle$ is its expected value (0.29×10^{-3} K) based on random statistics, is just the signal power divided by the noise power, a quantity which is distributed as a noncentral χ^2 distribution with 2 degrees of freedom. From the appropriate probability curves (Groth 1975), the desired upper limits for the 12 and 24 hour sidereal amplitudes of the polarized radiation from all sources are

$$\begin{aligned} \text{for } Q \text{ 24 hr: } & T < 0.75 \times 10^{-3}\,\mathrm{K}\,, \\ \text{12 hr: } & T < 0.38 \times 10^{-3}\,\mathrm{K}\,, \\ \text{for } U \text{ 24 hr: } & T < 0.81 \times 10^{-3}\,\mathrm{K}\,, \\ \text{12 hr: } & T < 0.67 \times 10^{-3}\,\mathrm{K}, \text{ with } 90\% \text{ confidence}\,. \end{aligned} \tag{3}$$

IV. MODEL

The experimental upper limits in equations (2) and (3) can be used to impose limits on the parameters of the anisotropic model studied by Rees (1968). For an axially symmetric Euclidean model with metric given by $ds^2 = dt^2 - A^2(dx^2 + dy^2) - W^2dz^2$ (Thorne 1967; Jacobs 1968), Rees has shown that the temperature of radiation polarized perpendicular to and coplanar with the plane formed by the symmetry axis and the line of sight to the observer are given by

$$\begin{aligned} T_a &= T_{\mathrm{avg}}(1 + \epsilon_a \sin^2\theta)\,, \\ T_w &= T_{\mathrm{avg}}(1 + \epsilon_w \sin^2\theta)\,, \end{aligned} \tag{4}$$

where θ is the angle between the line of sight and the symmetry axis. Using this notation, one has all the information on the polarization expressed in the asymmetry parameters and, by solving a differential equation, can determine their evolution.

The growth of the parameters between scatterings is given by

$$\frac{d}{dt}\begin{pmatrix}\epsilon_a\\ \epsilon_w\end{pmatrix} = \Delta h\begin{pmatrix}1\\1\end{pmatrix}, \tag{5}$$

where, for any time,

$$\Delta h = dW/Wdt - dA/Adt \tag{6}$$

is a differential Hubble's constant (Rees 1968). To compute the effect of Thomson scattering (cross section σ_{T}), it is easiest to express the radiation temperature in terms of its Stokes parameters in the manner of Chandrasekhar (1960) and, using his phase matrix, integrate over one scattering to get

$$\frac{d}{dt}\begin{pmatrix}T_w\\ T_a\\ 0\\ 0\end{pmatrix} = T'_{\mathrm{avg}}\begin{pmatrix}1 + \frac{1}{2}\epsilon_a + \frac{1}{10}\epsilon_w + (\frac{7}{10}\epsilon_w - \frac{1}{2}\epsilon_a)\sin^2\theta\\ 1 + \frac{1}{2}\epsilon_a + \frac{1}{10}\epsilon_w\\ 0\\ 0\end{pmatrix}, \tag{7}$$

where those terms which integrate to zero owing to azimuthal symmetry have been deleted from the matrix and $T'_{\mathrm{avg}} = T_{\mathrm{avg}}\sigma_{\mathrm{T}}$. The resultant change in the asymmetry parameters over one scattering time is

$$\frac{d}{dt}\begin{pmatrix}\epsilon_a\\ \epsilon_w\end{pmatrix} = \begin{pmatrix}-1 & 0\\ -\frac{1}{2} & -\frac{3}{10}\end{pmatrix}\begin{pmatrix}\epsilon_a\\ \epsilon_w\end{pmatrix} nI(t)\sigma_{\mathrm{T}}c + \Delta h\begin{pmatrix}1\\1\end{pmatrix}, \tag{8}$$

where $I(t)$ is the ionized fraction of the electron density n. The coefficients differ from those given previously by Rees (1968). A simplification of the equation leading to a straightforward solution is to set $I(t) = 1$ for all time t.

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Though unrealistic, the result does have application to the situation before recombination and is of particular interest in a reheat phase. For this case the relationships between the parameters of the expansion and the degree of polarization are

$$\epsilon = \tfrac{1}{2}(\epsilon_a + \epsilon_w) = \frac{6}{7}\frac{\Delta h_0}{n_0 \sigma_T c}\,,$$

$$(T_a - T_w)/2T = \tfrac{1}{6}|\epsilon| \sin^2\theta\,. \tag{9}$$

The subscript zero indicates quantities evaluated at the current epoch. For $I(t) = 1$ an asymptotic solution is reached after a few scatterings and $\Delta h_0/h_0 = \Delta h/h$. The net result of the scattering is to produce a polarization which is a function of the angle between the line of sight and the axis of the universe. If ϕ is the angle between the rotation axis of the Earth and this symmetry axis, the linear Stokes parameters of the radiation incident from a declination δ and a right ascension α would be

$$Q = (T_w - T_a)_{\max}[\sin 2\phi \sin\delta \cos\delta \sin(\alpha - \alpha_0 - \pi/2)$$
$$+ \sin^2\phi(1 - \tfrac{1}{2}\cos^2\delta)\sin 2(\alpha - \alpha_0 + \tfrac{1}{4}\pi) + \cos^2\delta(1 - \tfrac{3}{2}\sin^2\phi)]\,,$$
$$U = (T_w - T_a)_{\max}[\sin 2\phi \cos\delta \sin(\alpha - \alpha_0 + \pi) + \sin^2\phi \sin\delta \sin 2(\alpha - \alpha_0)]\,. \tag{10}$$

V. RESULTS

Attempting to fit the 12 and 24 hour sidereal results from Table 1 to equations (10) does not meet with great success. The phases of the four periodic components do not agree with the predicted phase relationships. Between some components the phases differ by more than 2 σ. This is another reason to use only amplitude limits (eqs. [3]) to interpret the results.

When inserted into equations (10) with the declination 40°35 N, the upper limits of equations (3) give

$$Q\colon |(T_w - T_a)|_{\max} < 1.61 \times 10^{-3}\ \mathrm{K}\,,$$
$$U\colon |(T_w - T_a)|_{\max} < 1.31 \times 10^{-3}\ \mathrm{K},\ \text{with } 90\%\ \text{confidence}\,. \tag{11}$$

The possibility that the angle between the Earth's rotation axis and the axis of the universe, ϕ, might be very small must be considered. In this case the 12 and 24 hour amplitudes would also be very small and the cosmological contribution would show up primarily in the constant level, equation (2). To generate an upper limit for this case, ϕ is assumed to be zero in equations (10), giving

$$|(T_w - T_a)|_{\max} < 1.55 \times 10^{-3}\ \mathrm{K},\ \text{with } 90\%\ \text{confidence}\,. \tag{12}$$

The data contain known contributions from the ground and the Galaxy which cannot be removed. The harmonic components are small ($\sim$1–2 σ), with phases which do not agree well with the model. For that reason the largest of the three values for $|(T_w - T_k)|_{\max}$, 1.61×10^{-3} K, is taken as the upper limit and amounts to 0.06% polarization for a 2.7 K blackbody. With this result in equations (9), the asymmetry parameter and $\Delta h_0/h_0$ are found to be

$$|\epsilon| \lesssim 1.79 \times 10^{-3}\,,$$
$$\Delta h_0/h_0 \lesssim 2.57 \times 10^{-4}\,, \tag{13}$$

where the nominal values $n_0 = 10^{-5}\ \mathrm{cm^{-3}}$ and $h_0 = 50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ were used. It should be remembered that equations (9) were derived assuming that $I(t) = 1$. This model is surely too simple, but as discussed by Rees, it does have application, particularly in the event of a reheat phase at $z \gtrsim 7$ due perhaps to galaxy formation.

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