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Spectral Distortions of the Relic Radiation from Pregalactic Dust and Decay of the Unstable Particles*

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Abstract

Results are presented of calculations of the cosmic background radiation spectral distortions due to the pregalactic dust being heated by the decay of unstable particles.

1. Introduction

Investigations of the relic electromagnetic radiation spectrum are traditionally one of the central items in the contemporary theory of the structure and evolution of the universe. Along with studies on the character of the quanta distribution in the Rayleigh–Jeans region ($\lambda \gg 1$ mm), greater emphasis has recently been given to experimental data in the Wien region ($\lambda \ll 1$ mm) where Matsumoto *et al.* (1988) have reported a significant distortion in the spectrum of the cosmic background radiation (CBR).

Obviously until other experiments provide confirmation the data of Matsumoto *et al.* (1988) should be regarded as indicating that the CBR spectrum may possibly have an anomaly, but how large is still to be finalised. However, it seems justified to examine the nature of possible energy release sources, and the mechanisms of energy conversion into the Wien region of the CBR spectrum.

This paper, as well as the earlier work by Negroponte *et al.* (1981), Bond *et al.* (1984, 1986) and Nasel'sky and Novikov (1989), relies on the assumption that spectral anomalies in the Wien region can be attributed to the re-emission of high-energy quanta from the pregalactic dust in the epoch with redshift $Z = 10$ to 100. This hypothesis supposes that first, at redshifts of $Z = 10$ to 100, a generation of primordial stars with $M \gg 1\,M_{\odot}$ already existed whose evolution had enriched its environment with heavy elements and dust, and that second, by that period in the system there already existed inhomogeneous electromagnetic radiation with energy quanta $E \gg kT_{\rm r}$ ($T_{\rm r}$ is the CBR temperature), and it is this radiation that converted into millimetre and submillimetre wavelength quanta. Below we try to follow the main typical features of this process by specifying the mechanism by which the high-energy component of the radiation spectrum is generated.

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The sources of quanta with energies $E \gg kT_r$ we consider here are the decay of hypothetical light massive particles involving the radiative branch $X \rightarrow X' + \gamma$; in their properties these particles are similar to those used by Doroshkevich and Khlopov (1985) and Doroshkevich *et al.* (1986) to explain typical features of large-structure formation in the universe. Here, however, we assume that the decay period of the X-particles corresponds to redshifts $Z_X = 10$ to 100, much less than in the work of Doroshkevich *et al.* Besides it is assumed here that these hypothetical particles decayed long before the moment (at redshift Z_d) of the pregalactic dust formation ($Z_X > Z_d$), and since the moment of decay t_X (redshift Z_X) to the moment t_d (redshift Z_d) the nonequilibrium radiation has been freely propagating. Here it is assumed that the effective quantum energy does not exceed 1 to 10 eV, and thus the effect of hydrogen re-ionisation can be neglected as well as the radiation spectrum change.

After the moment when the major fraction of primary stars forms and the medium is enriched with pregalactic dust this radiation will be mainly absorbed by dust specks and re-radiated into the near and far Wien spectrum sections of the CBR, thus causing anomalies therein. At the same time the primary non-equilibrium component will be partially preserved. Its intensity today is $\exp(-\tau)$ times weaker (where τ is the optical depth of dust), and also weaker due to the expansion of the universe, and its present characteristic quantum energy corresponds to either the infrared (IR) or optical regions of the background radiation in the universe. Along with the distortions in the mm and submm regions of the relic radiation, this IR background is an important observational test to get a better insight into the nature of early energy release and the density of pregalactic dust.

Our paper is arranged as follows: Section 2 introduces the major characteristics of the dust and unstable particles to determine the main modes of radiation propagation in the system; Section 3 calculates the spectrum of non-equilibrium high-energy quanta before the epoch of pregalactic dust formation, and presents a discussion on the basic properties of that spectrum; Section 4 is devoted to an investigation of the thermal balance of dust, taking into account that it is heated by CBR quanta and by the product of the decay of unstable X-particles. Further, Section 4 also discusses the character of the spectral distortions of the CBR and the properties of the IR radiation generated as a result of the primary high-energy component transformation. In closing the main conclusions of the paper are briefly summarised.

2. Main Characteristics of Pregalactic Dust and of its Heating Sources

We now consider a cosmological model with unstable particles [as done by Doroshkevich and Khlopov (1985), Doroshkerich *et al.* (1986) and Nasel'sky *et al.* (1986)] for which the characteristic time of decay appears to be much shorter than 5×10^{16} s. Along with these particles the cosmological substrate should also have stable gravitating relic particles which dominate the formation process of the contemporary large-scale structure of the universe (axions may be an example). As inflation models suggest, we assume that these stable particles ensure the equality of the present mass density of matter ρ_m with the critical density of matter ρ_{cr} ($\Omega \equiv \rho_m/\rho_{cr} = 1$).

If unstable X-particles have characteristics (residual concentration, rest mass, etc.) similar to those of neutrinos, then at the rest mass $m = 1$ to 5 eV (if there were no decay) their present density would be $\Omega_X \equiv \rho_X/\rho_{cr} \lesssim 0 \cdot 2$. The instability of X-particles leads to their rest mass being pumped into radiation which, prior to the epoch of dust formation, is propagating practically without any interation with the matter ($Z_d < Z_X < 1000$).

The assumption that there are 'cold' gravitating relic particles (CDM model) immediately leads to the conclusion that at cosmic scales corresponding to the mass scale $M = (10^5\text{–}10^6)M_\odot$, the formation of gravitational structures should already be expected at redshifts $Z = 30$ to 60 (Silk 1985). Since the mass of the first stars there should be much higher than $M_\odot$, it is evident that their evolutionary time should be much lower than the age of the universe in the same epoch.

It is natural that primary massive stars ending their evolution in a burst will increase the intensity of high-energy quanta in the range $E \gg kT_r$. However, for realistic values of the coefficients of the matter rest-mass transformation into radiation [see Lacey and Field (1988) for this purpose], the contribution of this component to the integral non-equilibrium background is negligible.

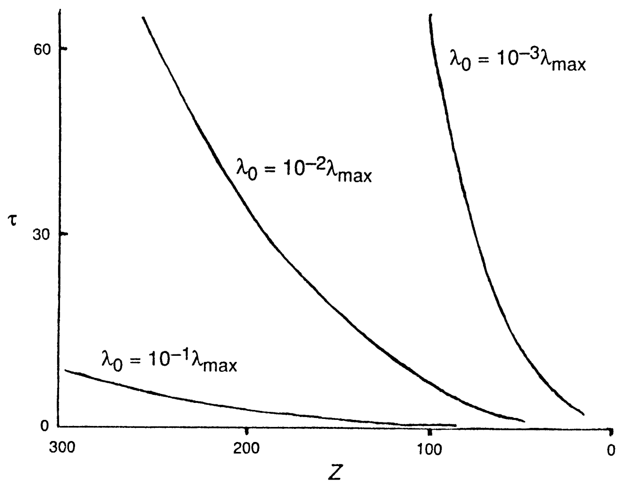

Fig. 1. Optical depth of dust τ versus the redshift Z. The value $\lambda_{max} = 1 \cdot 4$ corresponds to the maximum of the CBR spectrum, with $\Omega_d = 2 \times 10^{-5}$.

We now consider what conditions should be imposed on the characteristics of the pregalactic dust to ensure absorption of the nonequilibrium component of the radiation. To do this we assume that the dust particles are spheres with radius $r_d = 10^{-5}$ cm and with proper density $\rho_d^* = 2\ \mathrm{g\,cm^{-3}}$, while their mass density in the universe is a fraction ($\Omega_d = 10^{-4}\text{–}10^{-5}$) of the hydrogen and helium density. Then, the optical absorption depth of dust at frequency ν will be

$$\tau = c\pi r_d^2 n_d H_0^{-1} \int_0^Z (1+Z)^{1/2} Q(\nu, Z)\, dZ, \tag{1}$$

where $Q = (1 + \nu_d/\nu)^{-m}$ is an absorption coefficient, n_d is the dust number density (at $Z = 0$), H_0 is the Hubble constant [$h = H_0/(50\ \mathrm{km\,s^{-1}\,Mpc^{-1}})$] and $\nu_d = c/2\pi r_d$. In calculations that follow a value for the exponent of $m = 1$ is assumed, after which the optical depth dependence on ν or on the contemporary value of the radiation wavelength λ is easily derived. Fig. 1 illustrates this dependence. As shown, already at $\Omega_d = 2\times10^{-5}$–$10^{-4}$ the radiation from X-particles with energy 1 to 5 eV is in fact fully absorbed, that is, $\tau \gg 1$.

3. Non-equilibrium Radiation Spectrum before the Dust Formation Epoch

To calculate the spectrum of radiation that results from the decay of unstable particles we assume that the quanta generation spectrum has a δ-shape, and that one γ-quantum carries away half the rest energy of an X-particle. If a fraction α of the X-particle energy density transforms into radiation, and $1-\alpha$ to the other decay products respectively, then the transformation dynamics for unstable particles and their decay products is described by the equations

$$\frac{\partial \epsilon_X}{\partial t} + 3H(t)\epsilon_X = -\frac{\epsilon_X}{\tau_X}, \tag{2}$$

$$\frac{\partial \epsilon_*}{\partial t} + 4H(t)\epsilon_* = \frac{\epsilon_X}{\tau_X}(1-\alpha), \tag{3}$$

where $H(t) = (\mathrm{d}a/\mathrm{d}t)/a$ is the current value of the Hubble constant, ϵ_X is the energy density of unstable particles X, ϵ_* is the energy density of relativistic decay products, and τ_X is the X-particle decay period.

The equations (2) and (3) should be complemented with the radiation equation. For that purpose we introduce the spectral energy density $I(\nu)$ which obeys the equation

$$\frac{\partial I(\nu)}{\partial t} + 4H(t)\,I(\nu) - H(t)\,\frac{\partial}{\partial \nu}(\nu I(\nu)) = \frac{\alpha\epsilon_X}{\tau_X}\delta(\nu-\nu_0) - c\pi r_d^2\, n_d(t)\, Q(\nu)\, \theta(t-t_d)\, I(\nu), \tag{4}$$

where ν_0 is the quantum frequency corresponding to $m_X/2$, t_d is the dust formation time corresponding to the redshift Z_d and $\Theta(X)$ is the Heaviside theta-function.

Let us consider the behaviour of the system (2)–(4) at times $t < t_d$ when the pregalactic dust contribution can be neglected in (4). In this case, at $\tau_X < t < t_d$, the spectral density of the quanta energy $I(\nu)$ behaves as

$$I(\nu) = \frac{3\alpha\epsilon_X(\tau_X)}{2\nu_0}\left(\frac{a(\tau_X)}{a(t)}\right)^3 \left(\frac{\nu a(t)}{\nu_0\, a(\tau_X)}\right)^{3/2} \times \exp\left\{-\left(\frac{\nu a(t)}{\nu_0\, a(\tau_X)}\right)^{3/2}\right\}\Theta(\nu_0-\nu). \tag{5}$$

As is evident from (5) taking into account the quanta redshift in the process of the cosmological expansion of the universe will smear the decay line. A power spectrum forms in the low-frequency region ($\nu \ll \nu_0$) which is proportional to $\nu^{3/2}$, while in the high-frequency region the spectral density of the quanta energy cuts off exponentially. This spectrum may exist only until the moment of time t_d when the dust was produced. It should be taken into consideration at $t > t_d$ that, in the frequency range for which the optical absorption depth of dust meets the condition $\tau(\nu) \gg 1$, the behaviour of $I(\nu)$ will differ considerably. This effect can be followed most easily for the range of frequencies higher than ν_c, corresponding to the present position of the maximum point of the relic radiation spectrum:

$$\begin{aligned} I_i(\nu, t_{\text{now}}) &= \frac{3a\epsilon_X(\tau_X)}{2\nu_0}\left(\frac{a(\tau_X)}{a(t_{\text{now}})}\right)^3\left(\frac{\nu a(t_{\text{now}})}{\nu_0\, a(\tau_X)}\right)^{3/2} \\ &\quad \times \exp\left\{-\left(\frac{\nu a(t_{\text{now}})}{\nu_0\, a(\tau_X)}\right)^{3/2} - \beta\left(-\frac{1}{3} - \frac{\nu a(t_d)}{\nu_0\, a(t_{\text{now}})}\right.\right. \\ &\quad \left.\left. + \operatorname{artan}\left(\frac{\nu a_{\text{now}}}{\nu_d\, a_d}\right)^{1/2}\right)\right\}\theta(\nu_0 - \nu), \end{aligned} \tag{6}$$

where $a_{\text{now}} \equiv a(t_{\text{now}})$ and $\nu_d \equiv \nu(Z_d)$, while the β coefficient is related to the parameters of our problem as

$$\beta = 3\cdot 6 \times 10^{-2}\,\frac{\Omega_m}{0\cdot 1}\,\frac{\Omega_d}{10^{-4}}\left(\frac{r_d}{10^{-5}}\right)^{-1} Z_d^{3/2}. \tag{7}$$

Thus, the expressions (5)–(7) permit us to try to calculate the distortions of the relic radiation spectrum in the epoch of dust formation.

4. Thermal Mode of Dust and Distortions in the Relic Radiation (CBR) Spectrum

As in Bond *et al.* (1984, 1986), we examine the thermal balance of dust wherein the loss of the thermal energy of particles due to radiation is compensated by their heating by relic radiation quanta and by the nonequilibrium electromagnetic background resulting from X-particle decay:

$$\int d\nu\, B(\nu, T_d) Q(\nu) = \int d\nu\, I_{\text{tot}}(\nu)\, Q(\nu), \tag{8}$$

where $B(\nu, T_d)$ is the spectral density of dust radiation at the temperature T_d and $I_{\text{tot}}(\nu)$ is the total spectral density of the relic radiation energy and of the nonequilibrium electromagnetic (EM) background:

$$\frac{\partial I_{\text{tot}}}{\partial t} + 3H(t)\, I_{\text{tot}} - H(t)\nu\,\frac{\partial I_{\text{tot}}}{\partial \nu} = c\pi r_d^2\, n_d\, Q(\nu)\{B(\nu, T_d) - I_{\text{tot}}(\nu)\}. \tag{9}$$

Further on we make the assumption that the dust temperatue T_d differs but only slightly from the nonperturbed temperature of the relic radiation T_c, thus appreciably simplifying the analysis of the system (8) and (9).

Of greatest interest is the frequency range near the peak of the relic radiation spectrum. This range (the parameter Ω_d being fixed) may first evolve in the mode $\tau(\nu) \gg 1$, gradually transforming into the $\tau(\nu) \ll 1$ mode. To study the radiation spectrum in this range we write (9) in the integral form

$$J(\nu) = \exp\{-\tau(\nu, t_d)\}\left(J(\nu, t_d) - \int_{t_d}^{t} d\tau \exp\tau(t, \nu) x Q(\nu) b(\nu, T_d)\right), \tag{10}$$

where

$$\begin{aligned} b(\nu, T_d) &= B(\nu, T_d)a^3, \\ \tau(\nu, t) &= \int_t^{t_d} dt\, Q(\nu) c\pi x_d^2 n_d, \end{aligned}$$

and the first term in the large parentheses corresponds to the spectral density of the radiation energy at the moment t_d of dust formation. With (10) in view, we calculate the dust temperature $T_d(t_d)$ needed to determine the character of relic radiation spectrum distortions near the spectrum peak. In these calculations we use (10) at $t = t_d$ and substitute $I_{tot}(\nu, t_d)$ in the integral equation (8). Some simple transformations yield

$$T_d(t_d) = T_c(t_d)\left(1 + 0\cdot 55\alpha\omega \frac{h\nu_0}{kT_c}\frac{Z_d}{Z_X}\right)^{1/5}, \tag{11}$$

where $\omega = \epsilon_X/\epsilon_c$ $(t = t_d)$ is the ratio of the energy densities of the X-particles to relic radiation, h is Planck's constant and k is the Boltzmann constant.

As Fig. 1 shows at the dust formation moment $t = t_d$ $(Z_d = 10\text{–}10^2)$, the range of frequencies close to the relic radiation spectrum peak is evolving in the optical transparency mode $\tau(\nu) < 1$. This circumstance makes it possible to employ the approximate solution of the quanta transfer equation (9) in the form (Bond *et al.* 1986; Nasel'sky and Novikov 1989)

$$f_{tot}(\nu, Z = 0) = f_c(T_c, Z = 0) + \tau(\nu, Z_d)\{f_{eq}(T_d(Z_d)) - f_c(T_c(Z_d))\}, \tag{12}$$

where

$$f_{tot} = I_{tot}/\nu^3, \qquad f_c(T_c, Z = 0) = \left\{\exp\left(-\frac{h}{k}\frac{\nu}{T_c}\right) - 1\right\}^{-1},$$

$T_c = 2\cdot 74$ K, $\tau(\nu, Z_d)$ is the optical depth of dust in the epoch with the redshift Z_d, f_{eq} $(T_d(Z_d)) = B(\nu, T_d)/\nu^3$, and $T_c(Z_d) = T_c(1+Z_d)$ is the relic radiation temperature at $Z = Z_d$.

Introducing then the effective radiation temperature (Bond *et al.* 1986)

$$T_{eff}(\nu) = f_{tot}(\nu)\nu,$$

and taking into consideration (12), yields the following expression for its present value ($Z = 0$):

$$T_{\mathrm{eff}}(\nu, Z=0) = T_{\mathrm{c}}\left(1 + y\frac{\nu}{\nu_*}\right), \tag{13}$$

where

$$y = 17\alpha\omega\frac{\Omega_{\mathrm{m}}}{0\cdot 1}\frac{\Omega_{\mathrm{d}}}{10^{-4}}\left(\frac{m_{\mathrm{X}}}{1\ \mathrm{eV}}\right)^2\left(\frac{Z_{\mathrm{d}}}{10^2}\right)^{5/2}\left(\frac{Z_{\mathrm{X}}}{10^2}\right)^{-2},$$

$$\nu_* = \frac{\nu_0}{1+Z_{\mathrm{X}}} = 2\cdot 4\times 10^{12}\frac{m_{\mathrm{X}}}{1\ \mathrm{eV}}\frac{Z_{\mathrm{X}}}{10^2}.$$

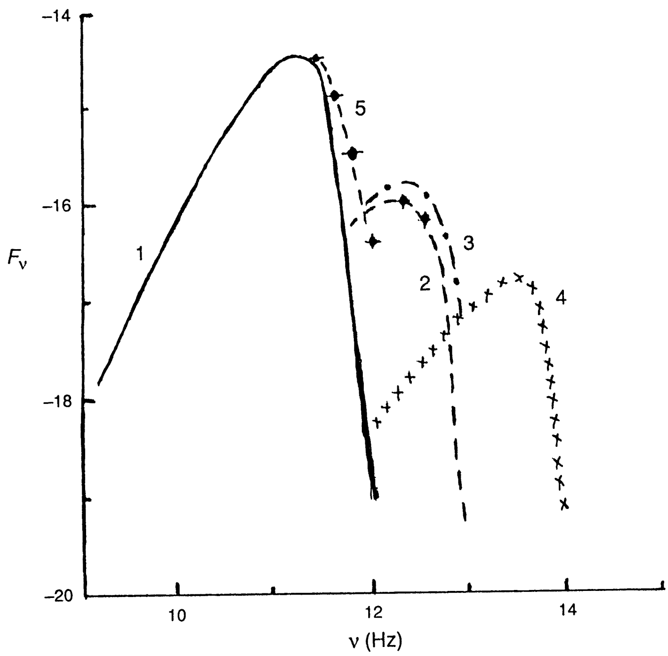

Fig. 2. Spectral distribution of radiation energy flux in the frequency region 10^9 to 10^{14} Hz. The solid circles are the data observed by Matsumoto *et al.* (1988).
Curve 1 — cosmic background radiation, $T = 2\cdot 74$ K.
Curve 2 — model with $m_{\mathrm{X}} = 1$ eV, $Z_{\mathrm{X}} = 100$, $Z_{\mathrm{d}} = 60$, $\alpha = \omega = 1$, $\Omega_{\mathrm{m}} = 0\cdot 1$ and $\Omega_{\mathrm{d}} = 2\times 10^{-5}$.
Curve 3 — same as curve 2 except $Z_{\mathrm{d}} = 100$.
Curve 4 — model with $m_{\mathrm{X}} = 10$ eV, $Z_{\mathrm{X}} = 100$, $Z_{\mathrm{d}} = 30$, $\alpha = \omega = 1$, $\Omega_{\mathrm{m}} = 0\cdot 1$ and $\Omega_{\mathrm{d}} = 2\times 10^{-5}$.
Curve 5 — model with T_{d} $(Z = 0) = 3\cdot 6$ K and τ_{d} (7000 μm) $\approx 0\cdot 12$.

The above results permit a comparison of the level of distortions in the relic radiation spectrum near the peak and in the Wien region with the observational data (Matsumoto *et al.* 1988). We give the results of this comparison in Figs 2 and 3. Fig. 2 illustrates the spectral distribution of the radiation energy flux in the frequency region $\nu = 10^9$ to 10^{14} Hz, which covers the region of the relic background spectrum peak and the infrared region. As is seen, along with a growing intensity of quanta flux (compared with the blackbody spectrum) in the $\nu = 10^{11}$ to 10^{12} Hz range, due to dust emission, an IR background inevitably forms whose origin is attributed to the weakening intensity of X-particle decay radiation as a result of dust absorption and of the expansion of the universe. It follows from Fig. 2 that with a growing rest mass for the X-particles (their initial number density is fixed), not only does the quanta flux near the relic radiation spectrum peak become more intense, but also the secondary peak shifts toward the far IR. It should be stressed in this connection that, for the identification of the nature of sources of spectral distortions in the relic radiation, there is undoubted interest not only in the detailed measurement of the flux at frequencies 10^{11} to 3×10^{11} Hz (near Wien region), but also in the transition region $\nu = 10^{12}$ Hz where the effect of the galactic dust background already manifests itself.

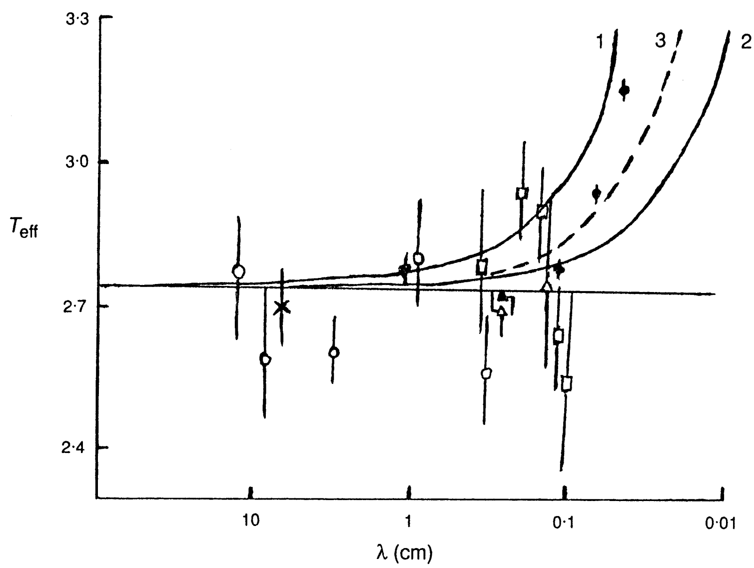

Fig. 3. Equivalent blackbody temperature versus wavelength. For sources of the observational data see Matsumoto *et al.* (1988). The horizontal line is for $T_r = 2 \cdot 74$ K.
Curve 1 — model with $m_X = 1$ eV, $\alpha = \omega = 1$, $\Omega_m = 0 \cdot 1$, $\Omega_d = 2\times10^{-5}$, $Z_X = 100$ and $Z_d = 60$.
Curve 2 — same as curve 2 except $Z_d = 30$.
Curve 3 — model with $m_X = 10$ eV, $\alpha = \omega = 0 \cdot 2$, $\Omega_m = 0 \cdot 1$, $\Omega_d = 2\times10^{-5}$, $Z_X = 100$ and $Z_d = 30$.

5. Conclusions

The results of this work demonstrate that the intensity excess in the Wien spectral region can be attributed to the re-emission of high-energy quanta from the pregalactic dust, and that the source of these quanta could be the decay of unstable relic particles.

In our previous paper Nasel'sky and Norikov (1989) the correlation between the spectral and angular fluctuations was discussed.

We would like to mention also that according to Berezhiani *et al.* (1989) the distortion in the CBR spectrum in the submillimetre waveband 400–700 μm

(Matsumoto *et al.* 1988) could be the result of the photon flux decays of relic particles without any dust.

When this paper was prepared for publication we received the preprints by Adams *et al.* (1989) and Bond *et al.* (1989) where the same problem has been discussed.

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