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ON THE ORIGIN OF POSSIBLE DEVIATION FROM THE BLACKBODY SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND RADIATION: INVERSE COMPTON HYPOTHESIS BASED UPON THE EXPLOSION SCENARIO

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ABSTRACT

Possible deviation from the blackbody spectrum of the cosmic microwave background radiation at the Wien part is indicated by the rocket observation of Nagoya-Berkeley group. Here, the inverse Compton hypothesis is examined based upon the explosion scenario for galaxy formation. Allowed ranges of physical parameters for reproducing the observation are explored in relation to the isotropy of spectrum at the Rayleigh-Jeans part, the size of voids, and the X-ray background radiation.

Subject headings: cosmic background radiation — cosmology — galaxies: intergalactic medium

I. INTRODUCTION

The discovery of the cosmic microwave background radiation (MBR) in 1964 brought a brilliant victory to the big bang hypothesis over the steady state cosmology. After that, various observations of MBR have presented important constraints on galaxy formation theory. In particular, the Rayleigh-Jeans part at the wavelengths of 10 cm to 3 mm indicates the blackbody temperature to be $T_{RJ} = 2.756 \pm 0.016$ K (Johnson and Wilkinson 1987), and its surprising isotropy as $|\Delta T/T| < 2.1 \times 10^{-5}$ (Uson and Wilkinson 1984) places a severe constraint on the amplitude of density perturbations at the recombination epoch, if the MBR had not suffered scatterings after that.

On the other hand, it was very difficult to measure the temperature and fluctuation of the Wien part of MBR at 1 mm to 0.4 mm because of the atmospheric emission. Recently, the Nagoya-Berkeley group have succeeded in measuring the intensity of MBR at the Wien part and presented a beautiful result (Matsumoto *et al.* 1987). The equivalent blackbody temperature which they have estimated from their observed intensities are as follows:

$$\begin{aligned} \lambda &= 1.160 \text{ mm} & T &= 2.795 \pm 0.018 \text{ K}, \\ &0.709 \text{ mm} & &2.963 \pm 0.017 \text{ K}, \\ &0.481 \text{ mm} & &3.150 \pm 0.026 \text{ K}. \end{aligned} \tag{1}$$

The deviation from the blackbody spectrum is highly probable because their estimated temperature definitely increases with decreasing the wavelength even if the error is included.

What is the origin of this deviation? Two completely different mechanisms are supposed. One is the continuum emission from the dust with the temperature $T_d \approx 3$ K. The other is the inverse Compton scattering from the Rayleigh-Jeans part of the MBR by hot electrons. For both models, some energy sources are necessary, which heat dusts in the former model and electrons in the latter model. Total necessitated energies are same for both cases, and it is in the order of $\varepsilon_p(0) \approx n_\nu \times k\Delta T \approx 10^{-14}$ ergs cm^{-3} where n_ν, k and ΔT are the present number density of MBR photons, the Boltzmann constant and the deviation from the unique blackbody temperature. This seems enormously high. For comparison, the rest mass energy of baryons is $\varepsilon_b(0) \approx n_0 m_p c^2 \approx 3 \times 10^{-8} \Omega_{b,0} h_{100}^2$ ergs cm^{-3}. Here, n_0 is the present number density of baryons, m_p is the proton mass, c is the light velocity, $\Omega_{b,0}$ is the density parameter of baryons, and h_{100} is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. The energy density of photons changes as $\varepsilon_p(z) = \varepsilon_p(0)(1+z)^4$ and that of baryons as $\varepsilon_b(z) = \varepsilon_b(0)(1+z)^3$. Then, their ratio varies

$$\varepsilon_p(z)/\varepsilon_b(z) \approx 3 \times 10^{-7}(1+z)\Omega_{b,0}^{-1} h_{100}^{-2}. \tag{2}$$

Since the efficiency of energy ejection by nuclear reactions is at most in the order of 10^{-3} (Carr *et al.* 1984), the following condition must be satisfied

$$\Omega_{b,0} h_{100}^2/(1+z) \gtrsim 3 \times 10^{-4}, \tag{3}$$

if it is the nuclear energy.

The explosion scenario for galaxy formation by Ostriker and Cowie (1981) and Ikeuchi (1981) presumes the energy injection by exploding stars or quasars, which are assumed to be Population III objects. According to this scenario, the condition (3) is not absurd. In this *Letter*, we examine the inverse Compton hypothesis for the origin of probable deviation from the blackbody spectrum of MBR based upon the explosion hypothesis.

II. DETERMINATION OF y-PARAMETER

Inverse Compton scattering process with nonrelativistic electrons is described by the Kompaneets equation. Its solution can be determined only by one parameter, the Compton

y-parameter, which is defined as

$$y = \int_0^\tau (kT_e/m_e c^2)\, d\tau_T, \qquad (4)$$

where T_e is the electron temperature and m_e is the electron mass. The increment of opacity of the Thomson scattering is

$$d\tau_T = \sigma_T n_e\, dl \qquad (5)$$

where σ_T is the Thomson cross section and n_e is the number density of electrons. This Kompaneets equation is valid when $h\nu \ll m_e c^2$ and $kT_e \ll m_e c^2$. The former is safely satisfied for any case, but the latter is dangerous in the present model. We briefly discuss the effect of special relativity in § V.

When initial photon spectrum is Planckian and $T_e \gg T_r$ (temperature of radiation), which is easily satisfied in the present case, the Kompaneets equation has a following analytic solution in the Rayleigh-Jeans part of MBR (Zeldovich and Sunyaev 1969):

$$T_0 = T_1 e^{-2y}, \qquad (6)$$

where T_0 and T_1 are, respectively, the effective blackbody temperature at the Rayleigh-Jeans part before and after the inverse Compton scattering. We take the observed Rayleigh-Jeans part $T_1 = T_{RJ} = 2.70$ K. Using the blackbody spectrum with T_0, the spectrum at the Wien part is compared with the Planck spectrum for a fixed y and we finally obtain the effective blackbody temperature $T_B(\nu; y)$. Comparing $T_B(\nu; y)$ with equation (1) we determine the best value for y as $y = 0.02$.

III. EXPLOSION SCENARIO

Basing their work upon the explosion scenario for galaxy formation, Yoshioka and Ikeuchi (1987) have examined the formation process of large voids. At the same time they have studied thermal process in association with explosions. Here, we utilize their results without going to details.

a) Models

For the density parameters we tentatively assume the following baryon-dominated universe: (1) $\Omega_0 = \Omega_{b,0} = 1.0$, (2) $\Omega_0 = \Omega_{b,0} = 0.1$, where Ω_0 and $\Omega_{b,0}$ are the present density parameter of the universe and that of baryons. We suppose that the seed objects with mass M_i explosively release energy E_i at the redshift z_i with the efficiency ε. Then we have (Carr, Bond, and Arnett 1984)

$$E_i = 1.8 \times 10^{61} (\varepsilon/10^{-4})(M_i/10^{11}\, M_\odot) \text{ ergs}. \qquad (7)$$

The shock waves generated by explosions propagate in the universe and heat up the general intergalactic gas (IGG). Electrons heated up to $T_e = 10^{\sim 8-9}$ K transform the photons at the Rayleigh-Jeans part to the Wien part by inverse Compton scatterings.

We assume the initial space density of seeds to be $N_{s,i}$, which is conserved in the comoving coordinate $N_s(z) = N_{s,i}(1+z)^3/(1+z_i)^3$, and the expanding shock waves would overlap at $z = z_{\rm over}$. A simple overlapping condition

$$\frac{4\pi}{3} R_s^3(z_{\rm over}) N_s(z_{\rm over}) = 1 \qquad (8)$$

gives the initial seed number

$$N_{s,i} = \frac{3}{4\pi}\left[R_s(z_{\rm over})\left(\frac{1+z_i}{1+z_{\rm over}}\right)\right]^{-3}, \qquad (9)$$

where $R_s(z_{\rm over})$ is the shell radius at $z_{\rm over}$. Then, independent parameters, which characterize the present model, are E_i, z_i, and $z_{\rm over}$ except for the cosmological parameter Ω_0 and $\Omega_{b,0}$.

b) Basic Equations

By using the thin shell approximation, the equation of motion of the shell is written as (Ostriker and McKee 1984)

$$\frac{d}{dt}(M_s V_s) = 4\pi R_s^2 [P + \rho_b V_H (V_s - V_H)] - \frac{GM_s}{2R_s^2}, \qquad (10)$$

where V_s and V_H are the expanding velocity of the shell and the unperturbed Hubble velocity, ρ_b and P are the average gas (baryon) density and pressure inside the shell, and $M_s = 4\pi R_s^3 \rho_b/3$ is the mass swept to the shell.

The total energy E of the shell is the sum of kinetic $E_{\rm kin} = M_s V_s^2/2$, and thermal $E_{\rm th} = 4\pi R_s^3(3P/2)/3$ energy, and it decreases by the energy loss

$$\frac{dE}{dt} = -\int_v \Lambda\, dV, \qquad (11)$$

where Λ is the cooling rate per unit volume (Umemura and Ikeuchi 1984) and the integral is taken over the volume of thin shell. The enhanced density behind the shock front is taken as $\rho = D\rho_b$, where the enhancing factor D is assumed to be 10 (Ikeuchi, Tomisaka, and Ostriker 1983). The electron temperature at the shell T_e is easily calculated $T_e = (E_{\rm th}/M_s)(2\mu/3k)$, μ being the mean particle mass. The above equations (10) and (11) are integrated for a given set of parameters $(E_i, z_i, z_{\rm over})$.

The y-parameter is defined by

$$y = \int_{z_i}^{0} \frac{kT_e(z) f_h(z)}{m_e c^2} \sigma_T n_e(z) c\left(\frac{dt}{dz}\right) dz$$
$$= 9.98 \times 10^{-12} h_{100} \Omega_{b,0} \int_0^{z_i} T_e(z) f_h(z)(1+z) \times (1+\Omega_0 z)^{-1/2}\, dz. \qquad (12)$$

Since the hot gas regions are clumpy the filling factor $f_h(z)$ of them is multiplied. It is defined as

$$f_h(z) = [R_s(z)(1+z)/R_s(z_{\rm over})(1+z_{\rm over})]^3 \quad \text{at } z > z_{\rm over},$$
$$= 1 \quad \text{at } z < z_{\rm over}. \qquad (13)$$

TABLE 1

CALCULATED MODELS

Model	Ω_0	$\Omega_{b,0}$	$z_{\rm over}$	Minimum E_i	$\varepsilon\Omega^B_{b,0}/10^{-3}$	$R_s(0)$ (Mpc)
A.......	1.0	1.0	3.0	10^{64-65} ergs	~ 0.04	> 10
B.......	1.0	1.0	10.0	10^{63-64}	~ 0.04–0.05	> 5
C.......	0.1	0.1	3.0	10^{66}	~ 0.04	> 20
D	0.1	0.1	10.0	10^{65-66}	~ 0.04	> 15

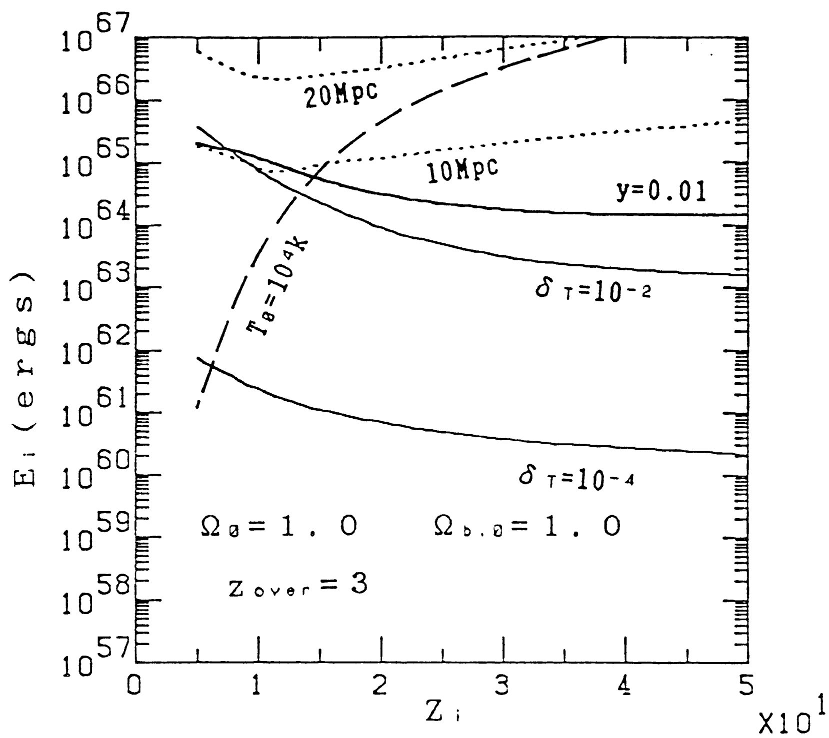

FIG. 1.—Contour maps of y (*heavy solid lines*), $R_s(0)$ (*dotted line*), $T_I(0)$ (*dashed line*), and $|\Delta T/T|$ (*solid line*) in the $E_i - z_i$ plane for case A

c) *Results*

In Table 1, we tabulated parameters Ω_0, $\Omega_{b,0}$ and $z_{\rm over}$ of examined models.

In Figure 1, we illustrate in the $E_i - z_i$ plane the contour maps of the y-parameter (*heavy solid lines*), the present radius of a shell $R_s(0)$ (*dotted lines*), and the present temperature of *IGG* $T_I(0)$ (*dashed lines*) for case A in Table 1. After the overlapping, we suppose the shell expands with cosmic expansion, $R_s(0) = R_s(z_{\rm over})(1 + z_{\rm over})$. The necessitated value of $y \approx 0.02$ is obtained almost independent of z_i at $E_i \approx 10^{64-65}$ ergs. However, if we constrain the size of the shell $R_s(0) > 10$ Mpc as usual voids (de Lapparent, Geller, and Huchra 1986) it leads to $z_i \lesssim 20$.

For case B with $z_{\rm over} = 10$, the energy injection occurs at $z > 10$ and the blackbody spectrum is easily deformed by efficient Compton scatterings. This can be seen from a relatively high value of y. On the other hand, as the results of the early overlapping and the efficient Compton cooling the shell can not expand much. With decreasing $z_{\rm over}$ two competitive effects work comparatively.

In Figure 2, we show the results of case D for comparison. In such a low-density universe, the shell can expand easily so large as $R_s(0) \approx 20$ Mpc, but the Compton scatterings are not so efficient because of low number density of hot electrons. In order to save the latter point it must be $E_i \gtrsim 10^{65.5}$ ergs.

In Table 1, we summarize the minimum energy for reproducing condition $y \gtrsim 10^{-2}$ and the present shell radius $R_s(0)$. The resultant ejection energy density is obtained as $\varepsilon_{\rm ej} = E_i N_{s,i}$, which is transformed to the condition for the equivalent burnt-out mass at the present epoch using the efficiency of energy release ε,

$$\varepsilon\Omega^B_{b,0} \geq E_i N_{s,i} \Big/ \left[c^2 \rho_{{\rm cr},0} (1 + z_i)^3 \right], \tag{14}$$

where $\rho_{{\rm cr},0}$ is the critical density at the present epoch. For each model, $\varepsilon\Omega^B_{b,0}$ is also tabulated. As is seen, $\varepsilon\Omega^B_{b,0} \approx (0.4\text{–}0.5) \times 10^{-4}$. If the energy source is the nuclear energy, $\varepsilon \lesssim 10^{-3}$. Therefore, $\Omega^B_{b,0}$ must be larger than 0.04–0.05.

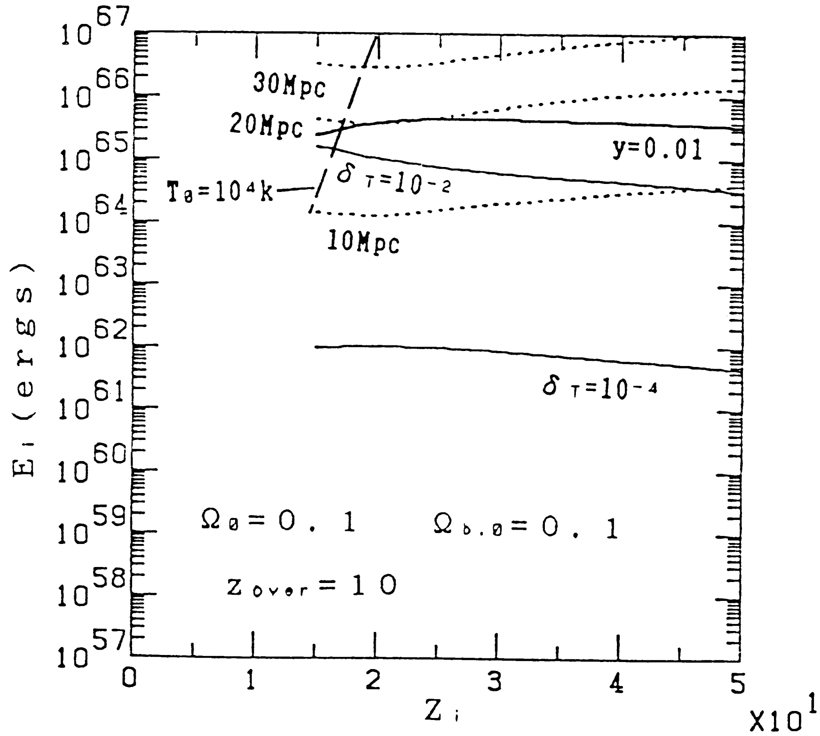

FIG. 2.—Same as Fig. 1 but for case D

For any case, the temperature of IGG becomes much lower than 10^4 K for the model of $z_i > 15$ and is higher than 10^4 K for $z_i < 15$. Then, the Gunn-Peterson test demands the reheating and reionization in the former case.

On the other hand, the contribution of hot gas to the X-ray background radiation at $E_x = \sim$ 2–10 keV should not exceed the observed one (Marshall *et al.* 1980). This gives the upper limit to the explosion redshift as $z_i \gtrsim 10$ for case A.

IV. DISCUSSION

a) *Fluctuation of MBR*

In the preceding section we discarded the induced anisotropy of MBR. Generally speaking, the explosions might occur randomly in space, so that the number of explosions contained in the observed beam should fluctuate (Hogan 1984; Vishniac and Ostriker 1986). Yoshioka and Ikeuchi (1987) have carefully examined the anisotropy of MBR due to the random explosions in consideration of relative sizes between the beam width of telescope and the shell size. The cross sections of beam and shell are, respectively, given by $A_b = \pi(B/2)^2$ and $A_s = \pi R_s^2(z)$, B being related to the beam width. The interpolation formula for the anisotropy of MBR is

$$|\Delta T/T| = \left[\left[\int_{z_i}^{0}\left\{\left(\frac{2}{3}\right)\left[\frac{\sigma T}{A_c(z)}\right]\left[\frac{E_{\rm th}(z)}{m_e c^2}\right]\right\}^2 \times N_s(z) A_c(z) c\left(\frac{dt}{dz}\right) dz\right]\right], \qquad (15)$$

where we utilize the effective cross section $A_c = \pi[B/2 + R_s(z)]^2$. Since the explosion scenario gives $A_c(z)$, $E_{\rm th}(z)$ and $N_s(z)$, we can calculate $|\Delta T/T|$ by using equation (15). We take the angular beam width as $\Delta\theta = 1\overset{'}{.}5$.

In Figures 1 and 2, we also plot the contours $|\Delta T/T| = 10^{-2}$ and 10^{-4} by solid lines. This indicates that if the deviation from the blackbody spectrum of MBR at the Wien part is originated in the inverse Compton effects of $y \approx 10^{-2}$, they inevitably produce the anisotropy of MBR in the order of $|\Delta T/T| \approx 10^{-2}$. Since the upper limit of the anisotropy at the Rayleigh-Jeans part is so small as $\sim 2 \times 10^{-5}$ (Uson and Wilkinson 1984), the anisotropy of MBR due to the inverse Compton effects should be erased by the Thomson scattering by the electrons in ionized IGG. A rough criterion of this erasing effect will be that the optical depth exceeds about ln ($\sim$ [2–3] $\times 10^2$)

$$\tau_{\rm T} = \int_{z_i}^{0} \sigma_{\rm T} n_e(z) c\left(\frac{dt}{dz}\right) dz \gtrsim 5. \qquad (16)$$

This condition is rewritten as

$$\Omega_{b,0} h_{100}(1 + z_i)^{3/2} \gtrsim 130 \qquad \Omega_0 = 1,$$

$$\Omega_{b,0} h_{100}(1 + z_i)^2 \gtrsim 160 \qquad \Omega_0 \ll 1.0, \qquad (17)$$

where we assume $1 + z_i \gg 1$. This result indicates that the explosions and inverse Compton effects had to occur at $z_i \gtrsim 40$ for consistent value of $\Omega_{b,0}$.

b) *Effects of Special Relativity*

From the condition that the y-parameter should be in the order of 10^{-2}, the initial temperature of IGG might be

$$T_i = 3.5 \times 10^9 (y/10^{-2}) h^{-1} \Omega_{b,0}^{-1} (1 + z_i)^{-3/2} \; (\Omega_0 = 1). \tag{18}$$

Therefore, the hot electrons may be considered to be relativistic, $kT_e \approx m_e c^2$. In this case, although we must abandon the Kompaneets equation, which is valid only for $kT_e \ll m_e c$, we examine only the relativistic effect of scatterings in the present *Letter*. We calculate the photon spectrum which suffers the Compton scatterings with optically thin relativistic electron gas following Wright (1979).

The relativistic effect considerably increases the increment of effective temperature at the Wien part in the result of scatterings with large energy shifts. The consistent set of parameters T_e, T_0, and y with observations would be

$$T_e \approx (0.5\text{–}1) \times 10^9 \text{ K}, \quad T_0 \approx 2.8 \text{ K}, \quad y \approx 0.01\text{–}0.02,$$
$$\tau \approx 0.1\text{–}0.2.$$

V. CONCLUSION

Summing up the results in § III and the above, the following time sequence in the explosion scenario would be probable:

$z_i \approx 50$:	explosions of $E_0 \approx 10^{65}$ ergs and $\Omega_{b,0}^B \gtrsim 0.04$; inverse Compton scattering of MBR;
$z \approx 50$–10:	smearing out of anisotropy of MBR by the Thomson scattering;
$z \approx 10$:	overlapping of shells;
$z \approx 5$:	fragmentation of shells and formation of quasars and galaxies;
$z \approx 4$:	reheating and reionization of IGG by diffuse UV flux.

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