THE ASTROPHYSICAL JOURNAL, 345: L9–L12, 1989 October 1

POSSIBLE INFRARED SIGNATURE OF DECAYING PARTICLES

BOQI WANG AND GEORGE B. FIELD
Harvard-Smithsonian Center for Astrophysics
Received 1989 May 24; accepted 1989 July 11

ABSTRACT

Previous discussions of massive decaying particles to explain the observed submillimeter background radiation are constrained by observations of the number of decay photons. In particular, to avoid exceeding the number of ionizing photons at redshifts between 1.7 and 3.8 inferred from the proximity effect in Lyman-α clouds, the current wavelength of the peak in the spectrum of decay photons must substantially exceed 1 μm. We propose that decay photons may account for the recently observed isotropic infrared background (IRB) between 1 and 5 μm. While maintaining consistency with the limits to the radiative decays of neutrinos from γ-rays observations of SN 1987A, we find that for decaying particle masses m_X in the range between 5 and 18 keV, the lifetime τ_d between 2 and 7×10^{10} s, and the photon branching ratio B_γ between 4 and 9×10^{-4}, the observed spectrum of decay photons is consistent with the observed spectrum of the IRB. The same parameters can explain the submillimeter background.

Subject headings: cosmic background radiation — early universe — elementary particles

I. INTRODUCTION

Since Matsumoto *et al.* (1988) found an isotropic radiation component at submillimeter wavelengths, interesting theoretical issues have arisen concerning the early thermal history of the universe. Because the energetics make it hard to produce the observed submillimeter background (SMB), which is roughly 10% of the cosmic microwave radiation background (CMB), via energy from normal stars (Lacey and Field 1988), and only marginally possible to produce with very massive objects (Bond, Carr, and Hogan 1986; Adams *et al.* 1989; Bond, Carr, and Hogan 1989), attention has also been turned to weakly interacting massive particles that decay into photons. Fukugita (1988) proposed that particles with mass $m_X = 1$–10 keV decay mainly into lighter weakly interacting particles, but also partly into photons with a small branching ratio B_γ. The keV photons keep the universe ionized and heat the resulting plasma, which subsequently distorts the CMB through Compton scattering.

In the original Fukugita model, it was postulated that the decay products have a density parameter $\Omega_X \sim 1$, in which case their masses are ~ 10 eV today. As the decay photons would also have energies ~ 10 eV, the model can be constrained by direct observations of decay photons (Fukugita 1988; Dar, Loeb, and Nussinov 1989; Field and Walker 1989). In particular, Field and Walker (1989) showed that the proximity effect in the numbers of Lyman-α clouds observed along the line of sight to quasars with redshifts between 1.7 and 3.8 (Bajtlik, Duncan, and Ostriker 1988) gives strong upper limits on the flux of photons with energies > 13.6 eV in the rest frame. According to Field and Walker, if $\Omega_X \sim 1$, so the photons would have energy ~ 50 eV at $z = 3.8$, the Fukugita model will work provided that the degradation in energy experienced by decay photons as they scatter off electrons is sufficient; such degradation is an inevitable consequence of the energy transfer to electrons which is the basis for Compton distortion of the microwave background. Field and Walker proposed model parameters such that the decay photons would appear at wavelengths $\gtrsim 1$ μm today ($z = 0$). This led us to examine the literature for evidence of features in the infrared background.

Matsumoto, Akiba, and Murakami (1988) recently observed diffuse celestial radiation at wavelengths between 1 and 5 μm with a rocket-borne infrared telescope. They found that after subtracting the foreground components, there still remains an appreciable amount of isotropic diffuse radiation, which may be attributed to an extragalactic origin. Boughn, Saulson, and Uson (1986) observed the smoothness of the K band (2.2 μm) diffuse radiation and found that the fluctuations in the background are very small. Their upper limits on brightness fluctuations on scales from 10″ to 30″ and 60″ to 300″ are roughly 10% of the radiation observed by Matsumoto, Akiba, and Murakami (1988), implying too large a surface number density of infrared sources and too small a K band luminosity of individual sources, if the observed isotropic radiation is to be explained by the standard scenario of galaxy formation. In the light of this newly detected infrared background (IRB), we consider a scenario in which the peak of the decay photon spectrum is at several microns. In the following we compare the observed spectrum of the IRB to that of decay photons with degraded energy, while constraining the calculations to ensure that the heat deposited in the electrons can explain the SMB. The results are further compared with other astrophysical limits on decaying particles, in particular those from γ-ray observations of SN 1987A.

II. DECAY PHOTON SPECTRUM

It is easy to show that the energy ϵ of the decay photons in the Fukugita scenario is much larger than the temperature of the electrons (Dar, Loeb, and Nussinov 1989). In this case, the change in photon energy including both expansion and Compton scattering can be written as

$$d\epsilon = \frac{\epsilon}{1+z}\, d(1+z) - \frac{\epsilon^2}{m_e c^2}\, n_e \sigma_T c\, dt\,, \tag{1}$$

where n_e, m_e, and σ_T are the electron density, the electron mass, and the Thomson cross section, respectively. The solution of equation (1) depends on the relation between time t and redshift z. In the conditions considered here, the universe is almost entirely matter dominated (MD) by decaying particles before most of them decay into relativistic lighter particles, and almost entirely radiation dominated (RD) after. As we shall see below, the decay products of particles required to account for both the IRB and the SMB cannot give $\Omega_x = 1$. Thus there may be another MD regime after the RD era when some other nonrelativistic matter, e.g., the cold dark matter required by galaxy formation scenarios, becomes dynamically dominant. We will assume that the universe is MD before $t = \tau_d$ and RD after $t = \tau_d$, where τ_d is the lifetime of the decaying particle. The universe becomes MD later again by nonrelativistic matter at a time we denote by t_{eq}. The corresponding redshift z_{eq} at t_{eq} is given by $1 + z_{eq} = \Omega/\Omega_X$, where Ω is the density of all the matter (including baryons) in units of the critical density of the universe. We assume $\Omega = 1$ here. The approximation of instantaneous decay results in no more than 10% error in energy density calculations (Turner 1985). This approximation is not made, however, in computing the energy distribution of decay photons; rather, we calculate it exactly from the exponential decay law $\exp(-t/\tau_d)$ for the decaying particles.

If we express time t as

$$t = t_0 q(1+z)^{-\alpha}, \tag{2}$$

then $\alpha = 3/2$, $q = (\tau_d/t_{eq})^{1/4}$ for $t \le \tau_d$ (MD); $\alpha = 2$, $q = (t_0/t_{eq})^{1/3}$ for $\tau_d \le t \le t_{eq}$ (RD); and $\alpha = 3/2$, $q = 1$ for $t_{eq} \le t$ (MD). Here t_0 is the age of the universe; $t_0 \simeq 2/3H_0$ because most of the time is spent in the second MD phase. We take the Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1} throughout our calculations. Following from equation (2), in the limit $\tau_d \ll t_{eq}$, the density parameter is then $\Omega_X = 0.84 m_X n_{X0}/(1 + z_d)\rho_c$, where z_d is the decay redshift at which $t = \tau_d$, and ρ_c is the critical density. We will assume that the decaying particles are neutrino-like, i.e., their predecay comoving density $n_{X0} = 109$ cm $^{-3}$.

The appropriate solutions of equation (1) can be written as

$$\epsilon = \epsilon_0 \left(\frac{t_i}{t}\right)^{1/\alpha} \left\{1 + \frac{2\alpha}{3(4-\alpha)} \eta_0 q^{3/\alpha} \left(\frac{t_0}{t_i}\right)^{(3-\alpha)/\alpha} \times \left[1 - \left(\frac{t_i}{t}\right)^{(4-\alpha)/\alpha}\right]\right\}^{-1} \tag{3}$$

for each MD or RD era in equation (2), where t_i is the time when the photon is injected with the initial energy $\epsilon_0 \simeq m_X/2$, and $\eta_0 = n_{e0}\sigma_T \epsilon_0/H_0 m_e c$ is the dimensionless efficiency parameter for Compton scattering. We take $\Omega_b = 0.09$ to be consistent with nucleosynthesis of light elements in standard big bang theories (Kawano, Schramm, and Steigman 1988). For t_i in the different epoch from t, equation (3) is subject to the boundary conditions at $t = \tau_d$ and $t = t_{eq}$.

From equation (3) we see that there exists an unique relation between ϵ (at time t) and t_i, for given values of m_X (or ϵ_0) and τ_d. Because the photon injection rate per unit comoving volume is $dn_{\gamma 0}/dt = B_\gamma n_{X0} \exp(-t/\tau_d)/\tau_d$, the comoving photon spectrum can be obtained as

$$\frac{dn_{\gamma 0}}{d\epsilon} = \alpha \frac{B_\gamma n_{X0}}{\epsilon_0} \frac{t}{\tau_d} \left(\frac{t_i}{t}\right)^{1/\alpha} \left(\frac{\epsilon_0}{\epsilon}\right)^2 \times \left[1 + \frac{2}{3}\alpha \eta_0 q^{3/\alpha} \left(\frac{t_0}{t_i}\right)^{(3-\alpha)/\alpha}\right]^{-1} \exp\left(-\frac{t_i}{\tau_d}\right), \tag{4}$$

where for given ϵ at t, t_i is to be obtained from equations (3). Using equation (4), one then can obtain the intensity per unit wavelength of decay photons, $I_\lambda \propto \epsilon^3 (dn_{\gamma 0}/d\epsilon)$. Some typical energy spectra with different values of $n_{\gamma 0} = B_\gamma n_{X0}$ are given in Figure 1. The small discontinuity to the right of the peak of each spectrum is due to the assumption of instantaneous transition from MD to RD at $t = \tau_d$. An exact dynamical solution for the universe would eliminate this small discontinuity.

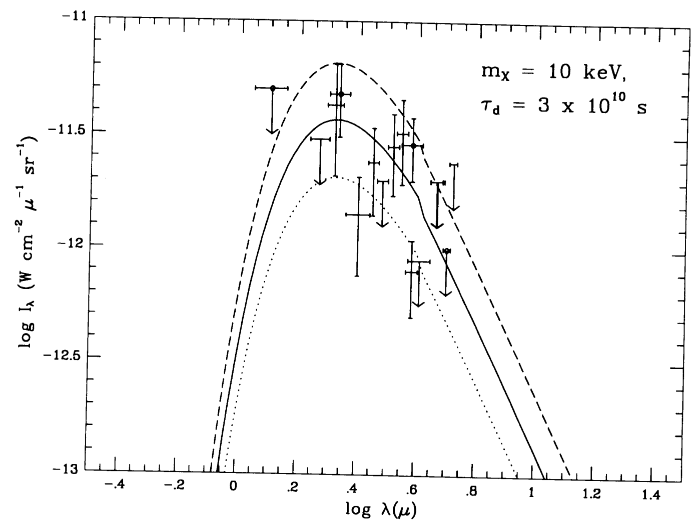

FIG. 1.—Calculated spectra I_λ of decay photons compared with observations. The curves correspond to spectra for $m_X = 10$ keV and $\tau_d = 3 \times 10^{10}$ s, with values of $n_{\gamma 0}$ (cm^{-3}) = 0.20 (*dashed*), and 0.06 (*dotted*), respectively. Their geometric mean $n_{\gamma 0}$ (cm^{-3}) = 0.11 (*solid*) is also plotted for comparison. The observed points are from Matsumoto, Akiba, and Murakami (1988); error bars represent 1 σ errors, with arrows indicating upper limits. Open circles and crosses represent the data of the wide-band (J, K, L, M band) and narrow-band (band 1–12, *left to right*) channels, respectively.

III. COMPARISON WITH THE OBSERVATIONS

The background radiation at submillimeter wavelengths can be fitted by nonrelativistic Compton scattering with a Zel'dovich-Sunyaev parameter $y_c = 0.028 \pm 0.004$ (Hayakawa *et al.* 1987). This corresponds to an energy density $U_{SMB} = 4y_c a T_{CMB}^4 = (4.8 \pm 0.9) \times 10^{-14}$ ergs cm^{-3} at submillimeter wavelengths, where the temperature of the CMB, $T_{CMB} = 2.75 \pm 0.03$ K, is taken from the Compton scattering fit. A fit including observational data in the Rayleigh-Jeans part of the CMB would give somewhat smaller y_c but larger T_{CMB}; however, the values of U_{SMB} remain roughly the same (Adams *et al.* 1989).

Matsumoto, Akiba, and Murakami (1988) observed diffuse celestial light at various infrared wavelengths between 1 and 5 μm with a rocket-borne infrared telescope. The observed intensities after subtracting the foreground components are plotted in Figure 1. Here we tentatively assume that the new observation reveals the existence of a true IRB and propose that it is due to the photons emitted by decaying massive particles, while the SMB is caused by inverse Compton scattering of the CMB by electrons heated by the decay photons. Since the total present radiation density available from decay particles, $U_a = 0.84\epsilon_0 B_\gamma n_{X0}/(1 + z_d)$, is partitioned into either the SMB or the IRB for the conditions considered here (Field and Walker 1989), we have $U_{SMB} = U_a - U_{IRB}$.

In order to match both the SMB and the IRB, we calculated the spectrum of the IRB for pairs of values of m_X and τ_d. The shape of the spectrum, and hence the peak wavelength λ_p, depends only on m_X and τ_d, while the height of the spectrum depends on the multiplicative constant $n_{\gamma 0} = B_\gamma n_{X0}$. A spec-

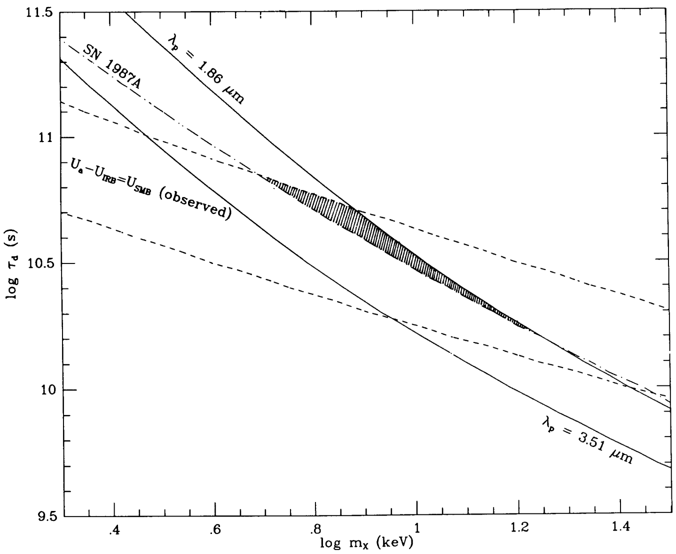

FIG. 2.—Curves (*solid*) in the m_X-τ_d plane along which the peak wavelength $\lambda_p = 1.86$ and 3.51 μm, respectively. Also drawn are curves (*dashed*) between which U_{SMB} equals the observed value, given the uncertainty in $n_{\gamma 0}$. The limit derived from γ-ray observations of SN 1987A is plotted as dash-dotted line, regions below which are excluded by the observations. The favored area, where the spectrum of the decay photon is consistent with the IRB, the SMB can be explained, and the limits from SN 1987A are satisfied, is shaded.

trum for $m_X = 10$ keV and $r_d = 3 \times 10^{10}$ s, corresponding to $\lambda_p = 2.2$ μm, is shown in Figure 1. As can be seen there, curves with $n_{\gamma 0} = 0.06$ and 0.20 cm^{-3} pass below and above, respectively, most of the observational data, so we conclude that for this choice of m_X and τ_d, $\lambda_p = 2.2$ μm and $n_{\gamma 0}$ is between 0.06 and 0.20 cm^{-3}. We thus find a range of values for $n_{\gamma 0}$ for each (m_X, τ_d) pair. We then impose the additional requirement that $U_a - U_{IRB} = U_{SMB}$ (observed). In Figure 2 we plot the pairs (m_X, τ_d) which yield the observed U_{SMB}; it is a broad band because of the uncertainty in $n_{\gamma 0}$.

Taking into account the large uncertainties in the infrared data (see Fig. 1), λ_p could conceivably lie anywhere between 1.86 μm (band 1 of Masumoto, Akiba, and Murakami 1988), and 3.51 μm (band 7), both of which were observed with the narrow-band photometer. Since λ_p is readily calculated from m_X and τ_d, we conclude that the correct values of m_X and τ_d must lie in the band between the curve $\lambda_p = 1.86$ μm and curve $\lambda_p = 3.51$ μm, plotted in Figure 2.

As can be seen in Figure 2, there is a small region given by $m_X = 3$–26 keV and $\tau_d = 1$–10×10^{10} s which yields acceptable values for the spectrum of the IRB and for U_{SMB}. The corresponding values of $n_{\gamma 0}$ lie between 0.04 and 0.5 cm^{-3} [$B_\gamma = (4$–$46) \times 10^{-4}$].

IV. DISCUSSION

Bajtlik, Duncan, and Ostriker (1988) analyzed the distributions of Lyman-α absorption lines in quasar spectra, and showed that the proximity effect implies a constant intensity of radiation at Lyman limit at redshifts $1.7 < z < 3.8$. According to Field and Walker (1989) this implies a constant ionization rate for hydrogen, 3.4×10^{-12} s^{-1}. According to equation (4), the ionization rate caused by the decay photons discussed here reaches the value implied by the Lyman-α absorption lines only for $z \gtrsim 7$, so there is no contradiction between the present model and the proximity effect in quasars for redshift $\lesssim 3.8$, if, as Bajtlik, Duncan, and Ostriker (1988) assumed, the ionizing radiation in intergalactic space is due to quasars.

The Gamma Ray Spectrometer instrument on board the *Solar Maximum Mission* did not detect a signal above normal instrument background in the 4.1–6.4 MeV energy range during a 10 s time interval following the detection of the neutrinos from SN 1987A by the Kamiokande II detector. Based on this, Kolb and Turner (1989) showed that radiative decays of neutrinos of mass m_X are constrained by $\tau_d m_X/B_\gamma \gtrsim 8 \times 10^{14}$ s keV for 100 eV $\lesssim m_X \lesssim$ several MeV. This constraint, plotted in Figure 2, substantially reduces the ranges of the parameters to $m_X = 5$–18 keV, $\tau_d = (2$–$7) \times 10^{10}$ s and $n_{\gamma 0} = 0.04$–0.10 cm^{-3} (or $B_\gamma = 4$–9×10^{-4}). We notice, however, that both the peak wavelength λ_p and $n_{\gamma 0}$ are rather uncertain due to the uncertainty of the IRB spectrum. Thus once more accurate observations are available, the range of parameters may be changed. Also, the accuracy of the limit to the radiative decay of neutrinos from SN 1987A depends on the accuracy of calculations of the neutrino flux from SN 1987A. Stellar evolution models in general do not put constraints on particles with $m_X \gtrsim 10$ keV, and for $m_X \lesssim 10$ keV, constraints from stellar evolution models are less stringent than those from SN 1987A, unless $m_X \lesssim 60$ eV (Raffelt, Dearborn, and Silk 1988). Fukugita, Kawasaki, and Yanagida (1989) calculated spectra of decay photons and found a similar range for m_X ($\gtrsim 10$ keV) and τ_d[$\sim(7 \times 10^8)$–(2×10^{10}) s], but the B_γ they chose is too small to produce the IRB.

The above ranges of parameters, consistent with other astrophysical constraints, implies that $z_d = (6$–$10) \times 10^3$, and that $\Omega_X = 0.07$–0.14. The photon decay branching ratio $B_\gamma = (4$–$9) \times 10^{-4}$ is much larger than in previous calculations. This is because $m_X/(1 + z_d) \sim 1$ eV rather ~ 20 eV as in models in which the universe is closed by the products of X decay particles, so that B_γ must be larger to explain the SMB. The ratio of energy density at submillimeter wavelengths to that at infrared wavelengths is $U_{SMB}/U_{IRB} = 0.4$–1.3. Since $U_{SMB} \simeq 0.1 U_{CMB}$, this implies that $U_{IRB} = 0.1$–0.3 times U_{CMB}.

V. CONCLUSIONS

Consistent with other astrophysical constraints on the decaying particles, we find that for decay particle masses $m_X = 5$–18 keV, lifetimes $\tau_d = (2$–$7) \times 10^{10}$ s, and photon branching ratios $B_\gamma = (4$–$9) \times 10^{-4}$, the SMB can be explained by inverse Compton scattering of the cosmic microwave background radiation by electrons heated by decay photons, and that the resulting spectrum of decay photons is consistent with its being the observed IRB. We stress, however, that the infrared data may be contaminated by rocket engine exhaust, and there may exist foreground components as yet unknown. More accurate, contamination-free observations, will be needed to test the present proposal.

We are grateful to Terry Walker for helpful discussions. We also would like to thank Fred Adams and Lawrence Krauss for useful comments and Ned Ladd for assistance with the graphics. This work is supported in part by the NASA grant NAGW931.

REFERENCES

Adams, F. C., Freese, K., Levin, J., and McDowell, J. C. 1989, *Ap. J.*, **344**, 24.
Bajtlik, S., Duncan, R. C., and Ostriker, J. P. 1988, *Ap. J.*, **327**, 570.
Bond, J. R., Carr, B. J., and Hogan, C. J. 1986, *Ap. J.*, **306**, 428.
———. 1989, *Ap. J.*, submitted.
Boughn, S. P., Saulson, P. T., and Uson, J. M. 1986, *Ap. J.*, **301**, 17.
Dar, A., Leob, A., and Nussinov, S. 1989, *Ap. J.*, **338**, L41.
Field, G. B., and Walker, T. P. 1989, *Phys. Rev. Letters*, **63**, 117.
Fukugita, M. 1988, *Phys. Rev. Letters*, **61**, 1046.
Fukugita, M., Kawasaki, M., and Yanagida, T. 1989, *Ap. J.* (*Letters*), **342**, L1.
Hayakawa, S., Matsumoto, T., Matsuo, H., Murakami, H., Sato, S., Lange, A. E., and Richards, P. L. 1987, *Pub. Astr. Soc. Japan*, **39**, 941.
Kawano, L., Schramm, D., and Steigman, G. 1988, *Ap. J.*, **327**, 750.
Kolb, E. W., and Turner, M. S. 1989, *Phys. Rev. Letters*, **62**, 509.
Lacey, C. G., and Field, G. B. 1988, *Ap. J.*, **330**, L1.
Matsumoto, T., Akiba, M., and Murakami, H. 1988, *Ap. J.*, **332**, 575.
Matsumoto, T., Hayakawa, S., Matsuo, H., Murakami, H., Sato, S., Lange, A. E., and Richards, P. L. 1988, *Ap. J.*, **329**, 567.
Raffelt, B., Dearborn, D., and Silk, J. 1988, *Ap. J.*, **336**, 61.
Turner, M. S. 1985, *Phys. Rev.*, **D31**, 1212.

George B. Field and Boqi Wang: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138