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Opacity of the Universe to High-Energy Photons*

Robert J. Gould and Gérard P. Schréder
Department of Physics, University of California, San Diego, La Jolla, California

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Based on observational data, the spectra of cosmic radio, microwave, infrared, optical, and x-ray photons are estimated. The absorption probability per unit path length by the process of pair production in photon-photon collisions is then computed as a function of energy for high-energy photons traversing this photon gas, using the results of the previous paper. These calculations show that there should be a dip in the intensity of the high-energy cosmic photon spectrum by about a factor of 10 between 10^{12} and 10^{13} eV due to absorption by optical ($\sim$ a few eV) photons. Above 10^{14} eV, the high-energy cosmic photon spectrum should essentially cut off because of the strong absorption by the cosmic 3°K blackbody photons, and at higher energies by the cosmic radio photons.

I. INTRODUCTION

To calculate the probability of absorption by pair production in photon-photon collisions ($\gamma+\gamma\rightarrow e^{+}+e^{-}$) for high-energy photons traversing a cosmic (low-energy) photon gas one has to know the detailed spectrum of the ambient cosmic photons. Observations of the cosmic photon spectrum extend at least from about 4×10^{-9} eV in the low-frequency (1-MHz) end of the radio spectrum to about 1 MeV and possibly to 10^{15} eV at the high-energy end of the x- and γ-ray spectrum. Techniques for observing this spectrum vary considerably throughout this energy range and in fact there are many gaps where no observational information is available. For example, while we can observe part of the cosmic radio, microwave, and x-ray spectrum directly, with present techniques we cannot measure the infrared, optical, and ultraviolet components of the cosmic background radiation. Moreover, while future observational data may fill in some of the gaps, we shall never be able to measure directly the very low-energy part of the radio spectrum below 1 MHz. These low-energy photons are absorbed by the ionized interstellar gas surrounding us in the galactic disk by the process of inverse bremsstrahlung or "free-free" absorption. For this reason it would be desirable if there were some observable effect of the presence of the low-energy photons. As we shall show, one effect is the opacity they provide for very-high-energy ($\sim10^{20}$ eV) photons traversing cosmic distances; however, photon observations at these energies are very difficult, to say the least. Also, as has already been pointed out,[1] the presence of a 3°K cosmic blackbody radiation field has a similar effect. The cosmic photon spectrum in the optical region can only be *estimated* from our incomplete knowledge of the mean spectral emission per unit volume and of the red-shift effects of an expanding universe. Our procedures for dealing with these problems are given in Sec. II where we attempt to compute the complete spectrum of cosmic photons. In Sec. III we calculate the absorption probability per unit path length for high-energy cosmic photons by making use of the results of Sec. II and of the previous paper.

II. COSMIC PHOTON SPECTRUM

(a) Dependence on Cosmological Model

We consider a homogeneous, isotropic model of the universe with a local mean rate of production and emission of photons per unit volume and energy interval denoted by

$$\nu_e(\epsilon_e)=\langle dn/dtd\epsilon\rangle_e=\langle n_s dN_s/dtd\epsilon\rangle_e\,, \tag{1}$$

where n refers to the photon density, n_s the number density of sources, and N_s the number of photons emitted by each source, and the subscript e refers to *emission*; the average is over a volume containing many sources. In such an expanding universe photons emitted by sources at great distances which are moving away from us with a recession velocity approaching c are red-shifted from their emission energy; the observed emission *rate* is also reduced from the value at the source by the same factor (which is independent of photon energy). For this reason, in an expanding universe infinite in extent the local photon flux per steradian j (integrated over photon energy) and photon spectral density $n(\epsilon)=dn/d\epsilon$ due to emission from surrounding sources are finite and are given by

$$j=\frac{c}{4\pi}\int n(\epsilon)d\epsilon=\frac{R_c}{4\pi}\int \nu_e(\epsilon_e)d\epsilon_e; \tag{2}$$

here R_c is a cosmic cutoff radius or, roughly, the distance where the recession velocity approaches c. The appropriate value of R_c depends on the cosmological model; however, we can be within about a factor of two of most conventional cosmological models[2] by adopting $R_c=\frac{1}{2}R_H$ (half the Hubble radius). For a Hubble constant $H=75$ (km/sec)/megaparsec, we get $R_c=c/2H\approx6\times10^{27}$ cm.

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[1] R. J. Gould and G. P. Schréder, Phys. Rev. Letters **16**, 252 (1966); see also J. V. Jelley, *ibid.* **16**, 479 (1966).

[2] G. J. Whitrow and B. D. Yallop, Monthly Notices Roy. Astron. Soc. **127**, 301 (1964); **130**, 31 (1965); also R. N. Giere, M.S. thesis, Cornell University, 1963 (unpublished).

The effect of a choice of cosmological model on the shape of a cosmic photon spectrum from distant sources, smeared by the differential red shift, is quite strong. Here, again attempting to "average" over conventional cosmological models[2] and for simplicity and convenience we *assume* that, for

$$\nu_e(\epsilon_e)=A\delta(\epsilon_e-\epsilon_{ei}), \tag{3}$$

$$\begin{aligned} n(\epsilon)=B\epsilon&=(2AR_c/c\epsilon_{ei}^2)\epsilon, && \epsilon<\epsilon_{ei} \\ &=0, && \epsilon>\epsilon_{ei}. \end{aligned} \tag{4}$$

Equations (2), (3), and (4) define for our purposes, the cosmological model[3] adopted for purposes of calculation. One can readily show that this model gives for the general case where the emission spectrum $\nu_e(\epsilon_e)$ is a continuum instead of a δ function:

$$n(\epsilon)=\frac{2R_c}{c}\epsilon\int_\epsilon^\infty \epsilon_e^{-2}\nu_e(\epsilon_e)d\epsilon_e. \tag{5}$$

We shall make use of these relations shortly.

(b) Cosmic Radio Spectrum

Based on the work of Turtle *et al.*[4] we take a spectrum of extra-galactic radio photons of the form

$$(dn/d\epsilon)_R=n_R(\epsilon)=K\epsilon^{-2}; \tag{6}$$

for a "brightness temperature" of the extragalactic component of 15°K at 178 MHz one finds $K=1.09\times10^{-20}$ erg/cm^3. As we have mentioned earlier, we have no direct knowledge of the extent of the cosmic radio spectrum at the low-frequency end; however, there is one theoretical argument which can be used here. It is well known that if there exists a photon-*production* rate $[\nu_e(\epsilon_e)]$ throughout the universe which is of the form of a power law, the *equilibrium* photon-density spectrum $[n(\epsilon)]$ will also be a power law with the same index. This would also follow from our special result (5). The result holds if absorption of the photons produced is negligible. On the other hand, if the path length from which we are receiving photons is determined by absorption instead of by the cosmic expansion and red-shift effect, the observed photon density would be proportional to the production rate and the absorption mean free path. The principal absorption process at low radio frequencies would be inverse bremsstrahlung or "free-free" absorption by the intergalactic plasma, for which the associated absorption mean free path λ_{abs} is proportional to[5] ϵ^2. For definiteness, we assume that there exists a production spectrum $\nu_e(\epsilon_e)\propto\epsilon_e^{-2}$ for $0<\epsilon_e<\infty$ and throughout the universe. In the part of the spectrum where the universe is optically thick to radio emission the spectral density of photons would be proportional to $\lambda_{\text{abs}}(\epsilon)\nu_e(\epsilon)=\text{constant}$. We find that for an ionized intergalactic gas composed mostly of hydrogen of density 10^{-5} cm^{-3} and temperature[6] $\sim3\times10^4$ °K, $\lambda_{\text{abs}}<R_c$, the cosmic cutoff distance, for frequencies less than about 100 kHz. Thus, above this frequency we assume a cosmic radio spectrum given by (6) and below we take $n_R(\epsilon)$ equal to a constant, the value from (6) corresponding to 100 kHz. In Fig. 1 we have plotted the associated spectral energy density $\epsilon n_R(\epsilon)$.

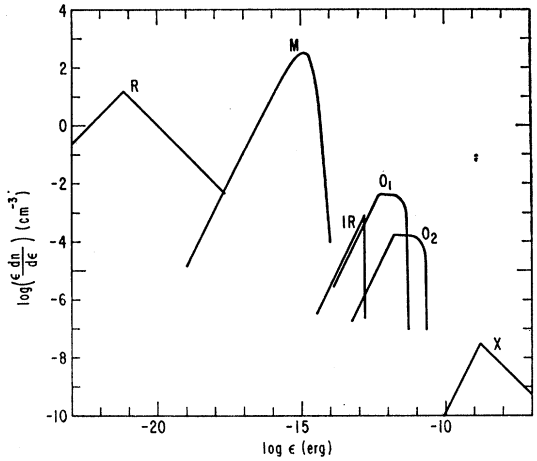

FIG. 1. The general cosmic-photon spectrum. Shown are the derived spectra of the radio (R) photons, microwave (M) 3°K blackbody radiation, infrared (IR) radiation from differential expansion smeared 12.8-μ line emission from galaxies, similarly smeared optical radiation from cool stars in galaxies (O_1) and from hot stars in galaxies (O_2), and the cosmic x-ray (X) photons

We should emphasize that our adopted cosmic radio spectrum is based on many assumptions and/or speculations, and our result may seem extreme. Nevertheless, there is no observational evidence against it and, as we shall see, it has some interesting consequences.

(c) Microwave Spectrum

Much has been written lately about the recently discovered cosmic microwave (assumed) blackbody radiation. We assume that this radiation is truly cosmic and fills the whole universe, giving a spectral density

$$n_M(\epsilon)=(hc)^{-3}(\epsilon/\pi)^2(e^{\epsilon/kT}-1)^{-1}. \tag{7}$$

We have plotted $\epsilon n_M(\epsilon)$ for $T=3$°K, which is the latest average measured value.[7]

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[3] Actually, the model assumed may be described as homogeneous, isotropic, having intrinsic source strength independent of time, and having expansion scale factor $R(t)\propto t^{1/2}$.

[4] A. J. Turtle, J. F. Pugh, S. Kenderdine, and I. I. K. Pauliny-Toth, Monthly Notices Roy. Astron. Soc. **124**, 297 (1962); see also F. G. Smith, *ibid.* **131**, 145 (1965).

[5] Cf. L. Oster, Rev. Mod. Phys. **33**, 525 (1961).

[6] Cf. R. J. Gould and W. Ramsay, Astrophys. J. **144**, 587 (1966); V. L. Ginzburg and L. M. Ozernoi, Astron. Zh. **42**, 943 (1965) [English transl.: *Soviet Astronomy*—AJ **9**, 726 (1966)].

[7] A. A. Penzias and R. W. Wilson, Astrophys. J. **142**, 419 (1965); P. G. Roll and D. T. Wilkinson, Phys. Rev. Letters **16**, 405 (1966); G. B. Field and J. L. Hitchcock, *ibid.* **16**, 817 (1966); P. Thaddeus and J. F. Clauser, *ibid.* **16**, 819 (1966).

(d) Infrared Spectrum

Recently it has been emphasized[8] that the cosmic infrared spectrum should be dominated by the magnetic-dipole radiation from the transition between the fine-structure levels $^2P_{3/2}$ and $^2P_{1/2}$ of Ne^+ which exists in the ionized interestellar gas in galaxies. The line is excited by inelastic electron collisions and its wavelength is $12.8\,\mu$, that is, in the far infrared. Because of the differential red shift from the cosmic expansion, the cosmic radiation due to this line emission from galaxies would be smeared into a continuum of the form (4). The luminosity of our galaxy in this line is related to the total number of hydrogenic-radiative recombinations per second and also to the rate of thermal-bremsstrahlung-radio emission which is an observable quantity. In this manner one estimates[9] 2.4×10^{41} erg/sec for the galactic luminosity in 12.8-μ radiation. Taking this value for the *mean* 12.8-μ luminosity per galaxy in the universe and a number density of sources (galaxies) of[10] $n_s=1\times10^{-75}$ cm^{-3} we calculate the infrared spectrum $\epsilon n_{IR}(\epsilon)$ shown in Fig. 1.

(e) Optical Spectrum

It is much more difficult to estimate the spectrum of optical photons than for the infrared region. This is because we have only limited information on the emission spectrum of galaxies which extends from the infrared (photon energies $\epsilon_e\sim0.3$ eV) to the ultraviolet ($\epsilon_e\sim10$ eV). Moreover, there are variations among the spectra of individual galaxies[11] which contribute further to smearing out the over-all cosmic spectrum. We have adopted the following viewpoint in calculating the cosmic spectrum of optical photons. We consider the spectrum to consist of two parts: (1) a part O_1 resulting from emission from the cool stars in nuclei of galaxies and (2) a part O_2 resulting from emission from hot, young stars in the outer, spiral arm regions of galaxies. For O_1 we take a mean total luminosity per galaxy of $L_1=10^{44}$ erg/sec. On the basis of observations of external galaxies which show a range of about 4000 to 6000°K in "color" temperature, we adopt a spectral range of emission for L_1 of $\epsilon_{\mathrm{ea}}=0.3$ to $\epsilon_{\mathrm{eb}}=3$ eV over which we take $dL_1/d\epsilon_e=\mathrm{constant}$; outside this range we set $dL_1/d\epsilon_e=0$. We take a density of sources $n_s=1\times10^{-75}$ and thus for ν_e:

$$\begin{aligned}\nu_e(\epsilon_e)&=\frac{n_sL_1}{(\epsilon_{\mathrm{eb}}-\epsilon_{\mathrm{ea}})\epsilon_e}=C/\epsilon_e,\quad \epsilon_{\mathrm{ea}}<\epsilon_e<\epsilon_{\mathrm{eb}}\\&=0\qquad\text{otherwise.}\end{aligned}\tag{8}$$

Then by (5) we have

$$n_0(\epsilon)=(R_cC/c)\times\begin{cases}[\epsilon(\epsilon_{\mathrm{ea}}^{-2}-\epsilon_{\mathrm{eb}}^{-2})], & \epsilon<\epsilon_{\mathrm{ea}}\\ [\epsilon^{-1}-\epsilon\epsilon_{\mathrm{eb}}^{-2}], & \epsilon_{\mathrm{ea}}<\epsilon<\epsilon_{\mathrm{ab}}\\ 0, & \epsilon>\epsilon_{\mathrm{eb}}.\end{cases}\tag{9}$$

The associated *energy density* for this spectrum is

$$\begin{aligned}\int\epsilon n_O(\epsilon)d\epsilon=\frac{2n_sL_1R_c}{3c}=\tfrac{2}{3}n_sL_1H^{-1}\\ \approx8\times10^{-3}\ \mathrm{eV/cm^3},\end{aligned}\tag{10}$$

which is close to Felten's estimate.[12] The spectrum $\epsilon n_O(\epsilon)$ is plotted (as O_1) in Fig. 1.

We estimate the contribution from O_2 by computing the associated luminosity from the hot stars in the disk of our own galaxy. Here the emission spectrum extends to higher energies but not beyond 13.6 eV since these photons are absorbed within galaxies in ionizing atomic hydrogen. Taking a spatial distribution of hot main sequence stars and associated "luminosity function" as employed by Gould,[9] we have estimated a *total* luminosity from hot stars in the galactic disk of 2.3×10^{43} erg/sec and a luminosity for $\epsilon_e<13.6$ eV of 1.8×10^{43} erg/sec. It is this latter value which we adopt to calculate the intergalactic spectrum O_2, for which we take $dL_2/d\epsilon_e=\mathrm{constant}$ over $\epsilon_e=\epsilon_{\mathrm{ea}}=1$ eV to $\epsilon_{\mathrm{eb}}=13.6$ eV and $dL_2/d\epsilon_e=0$ otherwise. The cosmic spectrum is then given by an expression similar to (9). The energy-density spectrum $\epsilon n_O(\epsilon)$ is plotted in Fig. 1.

(f) X-Ray Spectrum

In the high-energy photon region we take, based on observations of a number of groups[13] a spectrum of the form

$$n_X(\epsilon)=K'\epsilon^{-2},\quad \epsilon>1\ \mathrm{keV},\tag{11}$$

with $K'=5\times10^{-17}$ erg/cm^3. As shown by Felten and Gould,[14] because of intergalactic photoelectric absorption one expects (and there is some slight indication of this) that the x-ray spectrum may turn over at 1 keV and be of the form

$$n_x(\epsilon)=K''\epsilon,\quad \epsilon<1\ \mathrm{keV}.\tag{12}$$

We match the two distributions at $\epsilon=1$ keV to determine K''. The resulting spectrum $\epsilon n_X(\epsilon)$ is plotted in Fig. 1.

III. ABSORPTION PROBABILITY

Employing the calculations of the previous paper to the computation of the absorption probability for high-energy photons traversing the photon spectra of Sec. II we get the results presented in Fig. 2. The universe

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[8] R. J. Gould and D. W. Sciama, Astrophys. J. **140**, 1634 (1964).

[9] R. J. Gould, Astrophys. J. **146**, 944 (1966).

[10] A. Sandage, Astrophys. J. **141**, 1560 (1965).

[11] A general reference for information on the optical spectra of external galaxies is *Problems of Extragalactic Research* (IAU Symposium No. 15), edited by G. C. McVittie (The Macmillan Company, New York, 1962).

[12] J. E. Felten, Astrophys. J. 144, 241 (1966).

[13] For a recent summary of cosmic x-ray data see J. E. Felten and P. Morrison, Astrophys. J. 146, 686 (1966).

[14] J. E. Felten and R. J. Gould, Phys. Rev. Letters **17**, 401 (1966).

can be considered opaque to high-energy photons if the absorption probability per unit path length $d\tau_{\text{abs}}/dx > R_H^{-1} \sim 10^{-28}$ cm^{-1}. We see that this is so for essentially all photon energies greater than 10^{14} eV, because of the presence of the microwave[15] and radio photons. Also, it appears that absorption by the optical photons makes the universe opaque to photons of energy between 10^{12} and 10^{13} eV. Thus, we expect the universe to have high-energy photon "windows" between 10^{13} and 10^{14} eV as well as below 10^{12} eV down to ~1 keV where photoelectric absorption dominates.[14] Thus, if there exists a production spectrum (per unit volume) throughout the universe of, say, the form $\nu(E) \propto E^{-\Gamma}$, we would observe a spectrum of the same form, except that there would be a dip of about a factor of 10 in intensity in the region around 10^{12} to 10^{13} eV and essentially a cutoff or end to the spectrum at about 10^{14} eV.

We have already discussed[1] the observational evidence that such a cutoff exists. The fraction of extensive air showers having an abnormally low number of muons (these showers are thought to be initiated by primary photons) is about 1 in 10^3 at shower energies around 10^{14} eV, while no showers out of 13 000 at 10^{16} eV have been found to be muon poor.[16] It should be noted, as was done also by Jelley,[1] that at the peak of the microwave absorption around 10^{15} to 10^{16} eV the mean free path for photon absorption ($\sim 10^{22}$ cm) is even small compared with the radius of the galaxy (3×10^{22} cm). Thus, if there were high-energy photon production in the galactic disk, the directional anisotropy effects would be less than if the Galaxy were transparent at these energies. There would still be a strong concentration toward the galactic plane, however.

Observations of cosmic photons in the region 10^{12} to 10^{13} eV would be of great value, since in this region absorption due to the cosmic optical photons is important. In fact, this may provide a means of determining the optical photon density and of testing cosmological models. The technique of observing shower Čerenkov radiation[17] would probably be most useful here; however, apparently it can only be used to determine high-energy photon fluxes from discrete sources. Some slight indication that quasars may be such sources has come from observations of this type by the Harwell group.[18]

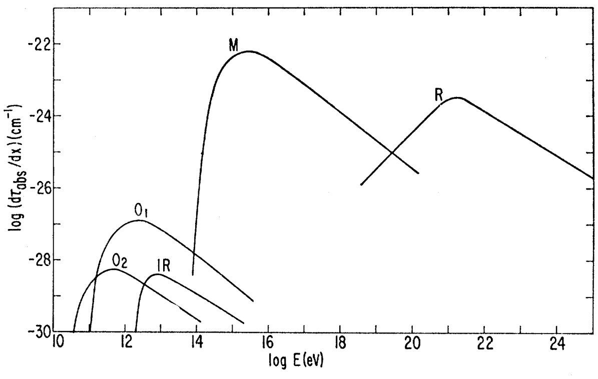

FIG. 2. Absorption probability per unit distance by $\gamma + \gamma' \rightarrow e^{+} + e^{-}$ as a function of photon energy for high-energy photons traversing the cosmic-photon gas. The contributions from the optical (O_1 and O_2), infrared (IR), microwave (M), and radio-(R) cosmic-photon gas are shown. Absorption at lower energies by x-ray photons is negligible.

Finally, we should like to comment briefly on the comparison of the results of our calculations with those of previous workers. Absorption by cosmic optical photons was first considered by Nikishov.[19] Here, our result should definitely be more accurate, both regarding the assumed spectral shape and total photon density. In particular Nikishov's spectral shape (blackbody at 6000°K) is much too peaked; no effect of smearing by differential red shift was considered by him. Our calculations of the absorption by cosmic radio photons should be compared with that of Goldreich and Morrison.[20] They assumed a much narrower spectrum extending only from 10 to about 1000 MHz. The observational situation on this point of especially the low-frequency extension of the cosmic-radio sepctrum is, in our opinion, inconclusive. In both cases the calculated photon absorption is strong at the very high energies. However, cosmic photon observations at these energies are probably too difficult with present techniques because of the very small expected fluxes, so it does not seem likely that the problem will be clarified by these means in the near future.

ACKNOWLEDGMENTS

We have benefited from conversations with J. E. Felten. We should also like to thank P. Hoffrichter for valuable help with the computational procedures.

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[15] Our graph previously published (Ref. 1) for the microwave absorption is in error quantitatively (the absorption probability as previously given is too small by a factor ~6).

[16] M. H. La Pointe, I. Escobar, H. Bradt, K. Kamata, J. Gaebler, V. Domingo, K. Suga, Y. Toyoda, and K. Murakami, Bull. Am. Phys. Soc. **11**, 384 (1966). *Note added in proof.* Dr. K. I. Greisen, who has reviewed the data on high-energy muless extensive air showers very recently, informs us that the apparent high-energy cutoff for these showers seems to be around 10^{16} eV rather than 10^{14} eV. As we had mentioned earlier (Ref. 1), a cutoff at 10^{14} eV could be interpreted as an effect of absorption by 3°K blackbody photons if the showers are due to high-energy photons traversing cosmic distances.

[17] J. V. Jelley and N. A. Porter, Quart. J. Roy. Astron. Soc. **4**, 275 (1963).

[18] C. D. Long, N. A. Porter, T. C. Weeks, J. H. Fruin, and J. V. Jelley, Ann. Astrophys. **28**, 263 (1965); Phys. Letters **10**, 176 (1964).

[19] A. I. Nikishov, Zh. Eksperim. i Teor. Fiz. **41**, 549 (1961) [English transl.: Soviet Phys.—JETP **14**, 393 (1962)].

[20] P. Goldreich and P. Morrison, Zh. Eksperim. i Teor. Fiz. **45**, 344 (1963) [English transl.: Soviet Phys.—JETP **18**, 239 (1964)].