INVERSE COMPTON RADIATION FROM INTERGALACTIC ELECTRONS AND COSMIC BLACKBODY PHOTONS*

James E. Felten†

Department of Astronomy and Center for Radiophysics and Space Research, Cornell University, Ithaca, New York
(Received 12 November 1965)

The cosmic microwave radiation observed by Penzias and Wilson[1] has recently been discussed by Hoyle[2] and Gould[3] as a possible source of the "isotropic" component of cosmic x rays, via the inverse Compton interaction of the microwave photons with fast electrons in our galaxy. Sanguine estimates[2] of the relevant galactic parameters, however, still leave the theoretical x-ray flux below the experimental results[4] by about a factor of four, and a more conservative approach[3] yields a factor of discrepancy closer to 200. We wish to show that a more natural explanation of the x radiation may be given in terms of intergalactic rather than galactic electrons, and also that in this model the presence of the microwave photons may provide an explanation for an otherwise puzzling feature in the cosmic gamma-ray spectrum.

For the purposes of this argument we assume that the theoretical interpretation given by Dicke et al.[5] to the microwave result is correct: namely, that this radiation ($T_{\rm eff} \approx 3.5°K$ at $\lambda \approx 7.3$ cm) is representative of a universal equilibrium blackbody radiation distribution at that temperature, perhaps surviving from an earlier stage of the universe. (It is worth emphasizing that such hypothesis is by no means firmly established by the measurements to date, far from the peak of the purported distribution at $\lambda \sim 1$ mm.) The associated photon-energy density in space is

$$\rho \approx 7.6\times 10^{-15} T^4 \sim 10^{-12} \text{ erg cm}^{-3}, \quad (1)$$

or ~1 eV cm^{-3}, 100 times larger than the intergalactic starlight density.[6]

Such a large photon density must generate hard radiation through inverse Compton collisions of the soft photons with any fast electrons which may be present. These electrons might enter the intergalactic medium from various sources, notably by escape from the strong radio galaxies,[7] a process whose importance is difficult to estimate. Eliding details,[8,9] we will assume here that electrons are injected into space by radio galaxies in a power-law energy spectrum

$$N(E)dE \approx N_0 E^{-m} dE, \quad (2)$$

with $m \approx 2.4$ as suggested by the observed radio spectral indexes,[10] and that the mean source strength over all space for electrons above ~1 GeV is

$$\sigma \sim 3\times 10^{-34} \text{ erg cm}^{-3} \text{ sec}^{-1}. \quad (3)$$

(3) normalizes (2) and is obtained from radio source counts and from the assumption that B fields in strong sources are not much stronger, say, than those in the halo of our galaxy, $\sim 10^{-6}$ G; i.e., that these sources shine brightly in synchrotron radiation because of large concentrations of fast electrons rather than strong fields. It is also assumed that such sources expand and dissipate in times $\sim 10^6$ yr, and not longer. This means that their electron energy is released rapidly. Therefore (3) has the nature of an upper limit on the electron source strength due to strong radio galaxies, and apparently to all known sources.

Now in the absence of other losses these electrons, free in the universe, would be adiabatically cooled by the Hubble expansion in a time $t_h \sim 10^{10}$ yr; the equilibrium energy spectrum would then preserve the power-law character of (2), and we could normalize (roughly) by setting the energy density above 1 GeV $\sim \sigma t_h$. The intergalactic electron spectrum would then be like the dashed line in Fig. 1. But since other losses are operative a somewhat more careful treatment is called for. If the energy loss of an individual electron is of the form

$$-dE/dt \approx A + BE + CE^2 \quad (4)$$

and the injection is given by (2), it is easily shown[11] that the equilibrium energy spectrum is of the form

$$n(E)dE \approx KE^{-m}[(A/E)+B+CE]^{-1}dE. \quad (5)$$

In the intergalactic medium, ionization loss contributes to the A term, but is probably not important above a few MeV, and will not con-

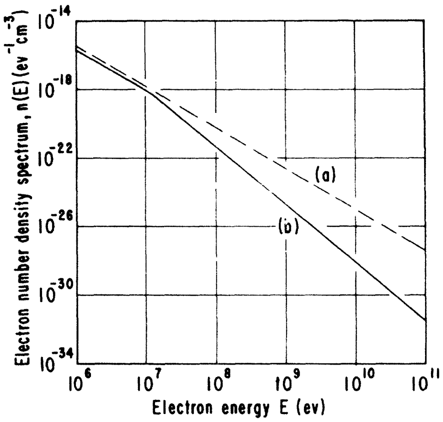

FIG. 1. Equilibrium energy spectrum for intergalactic electrons (a) before and (b) after correction for effect of inverse Compton losses to ambient blackbody photons.

cern us here. The B term arises mainly from loss by adiabatic expansion. Synchrotron loss and inverse Compton loss both contribute to C, but in the presence of the photon density (1) the latter must dominate the former in weak intergalactic magnetic fields. The energy spectrum (5) then steepens by one power, due to Compton loss, above an energy E_1 given roughly by setting $B \sim CE_1$, or equivalently by equating the expansion time to the lifetime against Compton loss[9]:

$$10^{10}\ \text{yr} \approx 3\times 10^{17}\ \text{sec} \sim (10^7/\rho\gamma_1)\ \text{sec}. \qquad (6)$$

Here $\gamma_1 \equiv E_1/m_0c^2$. Using (1) we find $\gamma_1 \sim 30$, $E_1 \sim 15$ MeV. The electron spectrum looks roughly like the solid line of Fig. 1, with spectral index ≈3.4 above 15 MeV.

The inverse Compton radiation generated by a fast electron immersed in a thermal photon flux is peaked at a recoil photon energy $\epsilon_C \approx 3.6\gamma^2kT$. For $T \sim 3.5$°K, $3.6kT \approx 10^{-3}$ eV; therefore, the observable cosmic x rays (above the cosmic absorption cutoff at a few keV) come from electrons of high energy on the steepened part of the spectrum. In this region we may write the spectrum as a power law, $n(\gamma)d\gamma \approx n_0\gamma^{-p}d\gamma$, with $p \approx 3.4$. We have shown elsewhere[7,9] that the Compton specific intensity received from a source region of radius R centered on the earth and filled uniformly with such an electron density is

$$I_C(\epsilon) \approx 1.0\times 10^3 (57)^{3-p} n_0 R \rho T^{(p-3)/2} \epsilon^{(1-p)/2}; \qquad (7)$$

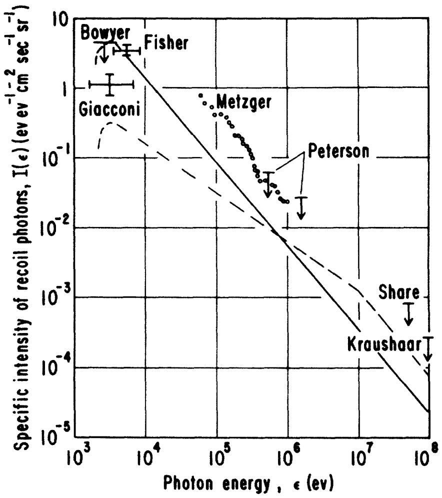

FIG. 2. Theoretical spectra of inverse Compton radiation from intergalactic electrons, compared with data.[4,12] Solid line: radiation expected from interaction of electrons with cosmic blackbody flux at 3.5°K. Dashed line: radiation expected from interaction with starlight in the absence of the blackbody flux. The onset of cosmic x-ray absorption at a few keV is shown schematically. The solid line is steepened to spectral index 1.2 throughout by the effect of the large Compton loss upon the energy spectrum of intergalactic electrons.

here I_C is in $\text{eV}^{-1}\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{sr}^{-1}$, n_0 in cm^{-3}, R in light yr, ρ in eV cm^{-3}, and ϵ in eV. With $R \approx 10^{10}$ light yr, coresponding roughly to the integrated contribution from all of space, we obtain the Compton intensity shown by the solid line in Fig. 2. The spectral index is $(p-1)/2 \approx 1.2$. Also shown (by a dashed line) is the cosmic Compton spectrum which would be expected in the absence of the soft photon flux (1), the Compton radiation arising in this case from the interaction of ordinary starlight with the electrons injected by (2). In the latter case the break in the equilibrium spectrum comes at a higher energy and manifests itself as a break from spectral index 0.7 to 1.2 in the hard gamma-ray spectrum. Both curves must fall off below a few keV due to cosmic absorption.

For comparison we have plotted roughly some experimental results,[4,12] still tentative in this difficult field. Discrepancies with the x-ray data in the keV range should not be taken too seriously because of the lack of spectral information in the data and the uncertain position of the cosmic absorption limit. The magnitudes of the other measured fluxes are adequately matched by either curve, to within the accuracy of the cosmic normalization; however, the steep slope of the data, particularly as shown in the spectrum of Metzger et al., strongly suggests that the blackbody radiation is present and has steepened the cosmic electron spectrum. The solid curve is then the relevant one.

We have seen that this steepening of the x-ray spectrum follows naturally from the assumptions that the universal blackbody radiation is present and that the fast electrons are intergalactic. Whether this steepening could occur for radiation originating in the galactic halo, under the very different conditions prevailing there, is uncertain. This question, together with further details of the research reported here, will be discussed in forthcoming papers.

P. Morrison provided valuable advice at the inception of this work and suggested at an early date the possible importance of cosmic blackbody radiation to the problem. I have enjoyed informative conversations with G. B. Field and R. J. Gould.

---

*Based on portions of a thesis submitted to the Graduate School of Cornell University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Work supported by the U. S. Air Force Office of Scientific Research under Contract No. AF49(638)-1527.

†Present address: Department of Physics, University of California, San Diego, La Jolla, California

[1]A. A. Penzias and R. W. Wilson, Astrophys. J. 142, 419 (1965).

[2]F. Hoyle, Phys. Rev. Letters 15, 131 (1965); and private communication to R. J. Gould.

[3]R. J. Gould, Phys. Rev. Letters 15, 511 (1965).

[4]E.g., R. Giacconi, H. Gursky, F. R. Paolini, and B. B. Rossi, Phys. Rev. Letters 9, 439 (1962).

[5]R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson, Astrophys. J. 142, 414 (1965).

[6]J. E. Felten, to be published.

[7]J. E. Felten and P. Morrison, Phys. Rev. Letters 10, 453 (1963).

[8]G. R. Burbidge, Progr. Theoret. Phys. (Kyoto) 27, 999 (1962).

[9]J. E. Felten, thesis, Cornell University, 1965 (unpublished).

[10]K. I. Kellermann, Astrophys. J. 140, 969 (1964).

[11]H. Tunmer, Monthly Notices Roy. Astron. Soc. 119, 184 (1959).

[12]S. Bowyer, E. T. Byram, T. A. Chubb, and H. Friedman, Nature 201, 1307 (1964); P. C. Fisher, H. M. Johnson, W. C. Jordan, A. J. Meyerott, and L. W. Acton, to be published; W. Kraushaar, G. W. Clark, G. Garmire, H. Helmken, P. Higbie, and M. Agogino, Astrophys. J. 141, 845 (1965); A. E. Metzger, E. C. Anderson, M. A. Van Dilla, and J. R. Arnold, Nature 204, 766 (1964); L. E. Peterson, to be published; G. H. Share, Bull. Am. Phys. Soc. 10, 14 (1965).

SELF-FOCUSING OF OPTICAL BEAMS

P. L. Kelley

Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts
(Received 21 October 1965)

The possibility has been noted of the self-trapping of optical-frequency electromagnetic beams due to a nonlinear increase in index of refraction, and various physical mechanisms which could give rise to the nonlinearity have been discussed.[1-3] Trapped modes have been found.[3-5]

In this note we study a situation not examined previously: the situation where the self-focusing effect due to the nonlinear index increase is not compensated for by diffraction. In this case there will be a build-up in intensity of part of the beam as a function of distance in the direction of propagation. We will define a self-focusing length, and show that this definition is reasonable by numerically solving the nonlinear wave equation. This self-focusing length is the distance in which the intensity of the self-focused region tends to become anomalously large. Other optical nonlinearities are likely to limit the focusing process in intense beams and may stabilize the intense region into filaments.

The importance of the effect in stimulated Raman emission as well as in other nonlinear effects should be considerable.[3] In a self-focused region the Raman gain should be anomalously large. The anomalous Raman gain has been the subject of some controversy and a number of communications have appeared.[6] One of the important observed features is that the anomalous gain in liquids occurs only after the beam has traveled some distance through the liquid. It is proposed here that this distance is the self-focusing length described in the present note and that the calculation report-