

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

X-641-70-26

PREPRINT

NASA TM X-63818

**PREDICTED HIGH-ENERGY BREAK IN THE
ISOTROPIC GAMMA-RAY SPECTRUM:
A TEST OF COSMOLOGICAL ORIGIN**

**G. G. FAZIO
F. W. STECKER**

JANUARY 1970

FACILITY FORM 602

N70-18890 (ACCESSION NUMBER)	10 (PAGES)	NASA-TM X-63818 (NASA CR OR TMX OR AD NUMBER)	29 (CATEGORY)
---------------------------------	---------------	--	------------------



**— GODDARD SPACE FLIGHT CENTER —
GREENBELT, MARYLAND**

29

X-641-70-26
PREPRINT

Predicted High-energy Break in the Isotropic Gamma-ray Spectrum:
A Test of Cosmological Origin

G. G. Fazio and F. W. Stecker

January 1970

Predicted High-energy Break in the Isotropic Gamma-ray Spectrum:
A Test of Cosmological Origin

G. G. FAZIO

Smithsonian Astrophysical Observatory, and Harvard College Observatory,
Cambridge, Massachusetts

and

F. W. STECKER

NASA Goddard Space Flight Center, Greenbelt, Maryland

Recent work by one of us (FWS) has emphasized the possible cosmological significance of the study of the isotropic component of cosmic γ radiation between 1 and 100 MeV energy¹⁻³. Vette et al.^{4,5} have presented evidence for a new component of isotropic γ radiation above 1 MeV energy being distinct in nature and origin from that at lower energies. At present, these data are consistent only with the hypothesis previously discussed^{6,7} that these γ -rays are the redshifted remnant of pion-producing cosmic-ray interactions at an earlier stage in the evolution of the universe corresponding to a redshift, $z \simeq 100$.

The purpose of this paper is to point out a critical test of the cosmological pion-decay hypothesis for the origin of the isotropic γ radiation above 1 MeV and to predict a high-energy break in this component. The test lies in the detection of a break in the γ -ray energy spectrum due to interactions of these γ -rays with the universal blackbody radiation at large redshifts, these interactions being of the form

$$\gamma + \gamma \rightarrow e^+ + e^- \tag{1}$$

Detailed calculations of the γ -ray absorption coefficient, $\kappa_{\gamma\gamma}(E_\gamma)$, for this process have been made by Gould and Schröder⁸. This absorption coefficient, which represents the probability per unit path length, l , that a γ -ray will be destroyed by the pair-production process (1), can be expressed, for γ -rays interacting with a blackbody radiation field of temperature, T , as

$$\kappa_{\gamma\gamma}(E_\gamma) = \frac{\alpha^2}{\pi\Lambda} \left(\frac{kT}{mc^2} \right)^3 f(\xi) \quad (2)$$

where

$$\xi \equiv \frac{(mc^2)^2}{kTE_\gamma} \quad (3)$$

where $\alpha \approx 1/137$ is the fine-structure constant ($e^2/\hbar c$), $\Lambda = \hbar/mc = 3.86 \times 10^{-11}$ cm, and k is the Boltzmann constant.

The function, $f(\xi)$, has a maximum value ≈ 1 at $\xi \approx 1$ and the asymptotic forms

$$f(\xi) \rightarrow \frac{\pi^2}{3} \xi \ln \left(\frac{0.117}{\xi} \right) \quad \text{for } \xi \ll 1 \quad (4)$$

and

$$f(\xi) \rightarrow \frac{\sqrt{\pi}}{2} \xi^{1/2} e^{-\xi} \quad \text{for } \xi \gg 1 \quad (5)$$

For cosmological applications, we must take into account the redshift dependences of T and E_γ in an expanding universe

$$T = T_0(1+z) \quad (6)$$

and

$$E_\gamma = E_{\gamma 0}(1+z) \quad (7)$$

where the subscript zero refers to currently observed ($z = 0$) quantities, so that $T_0 = 2.7$ K.

Taking the z -dependences into account, we find that equation (5) is applicable in the energy range²

$$E_{\gamma} \ll \frac{1.12 \times 10^6 \text{ GeV}}{(1+z)^2} \quad (8)$$

The optical depth of the universe to γ -rays is then given by

$$\begin{aligned} \tau(E_{\gamma 0}, z_{\text{max}}) &= \int_0^{\ell_{\text{max}}(z_{\text{max}})} d\ell \kappa_{\gamma\gamma}[E_{\gamma 0}, \ell(z)] \\ &= \int_0^{z_{\text{max}}} dz \kappa_{\gamma\gamma}(E_{\gamma 0}, z) \left(\frac{d\ell}{dz} \right) \end{aligned} \quad (9)$$

where

$$\frac{d\ell}{dz} = \frac{cH_0^{-1}}{(1+z)^2 (1+10^5 n_0 z)^{1/2}} \quad (10)$$

Here H_0 is the Hubble constant so that $cH_0^{-1} \approx 10^{28}$ cm and n_0 is the present mean atomic density of all the matter in the universe. We will consider here two types of model universes: 1) a "flat" or Einstein-de Sitter model with $n_0 \approx 10^{-5} \text{ cm}^3$; and 2) an "open" model with $n_0 \ll 10^{-5}/z$.

For the flat model with $\xi \gg 1$, equation (9) reduces to²

$$\tau(E_{\gamma 0}, z) = 3.9 \times 10^8 E_{\gamma 0}^{-1/2} \int_0^{z_{\text{max}}} dz (1+z)^{-1/2} \exp \left[- \frac{1.12 \times 10^6}{(1+z)^2 E_{\gamma 0}} \right] \quad (11)$$

with $E_{\gamma 0}$ in GeV.

For $z_{\max} \gg 1$, equation (11) can be further simplified to yield

$$\tau(E_{\gamma 0}, z_{\max}) \approx 1.7 \times 10^2 E_{\gamma 0}^{1/2} (1 + z_{\max})^{\xi/2} \exp \left[- \frac{1.12 \times 10^6}{(1 + z_{\max})^2 E_{\gamma 0}} \right] \quad (12)$$

A numerical solution found by setting equation (11) for $\tau(E_{\gamma 0}, z_{\text{crit}}) = 1$, which defines the critical redshift where the universe becomes opaque to γ -rays of energy $E_{\gamma 0}$, can be well approximated by the expression²

$$1 + z_{\text{crit}} \approx 2.60 \times 10^2 E_{\gamma 0}^{-0.484} \quad (13)$$

For the open model with $\xi \gg 1$, we find

$$\tau(E_{\gamma 0}, z_{\max}) = 3.9 \times 10^8 E_{\gamma 0}^{-1/2} \int_0^{z_{\max}} dz \exp \left[- \frac{1.12 \times 10^6}{(1 + z)^2 E_{\gamma 0}} \right] \quad (14)$$

For $z_{\max} \gg 1$, equation (14) can be approximated by

$$\tau(E_{\gamma 0}, z_{\max}) \approx 1.7 \times 10^2 E_{\gamma 0}^{1/2} (1 + z_{\max})^3 \exp \left[- \frac{1.12 \times 10^6}{(1 + z_{\max})^2 E_{\gamma 0}} \right] \quad (15)$$

Thus, there is no significant difference between the opacities of the open and the flat universes. This being the case, we can invert equation (13) to obtain an expression for the predicted cutoff energy, E_c , above which γ -rays originating at a redshift, z_{\max} , cannot reach us. This relation is given by

$$E_c \simeq \left[\frac{2.60 \times 10^2}{(1 + z_{\max})} \right]^{2.06} \quad (16)$$

and is graphed in Fig. 1.

In the other extreme, $\xi \ll 1$, we find that as the energy increases, the universe will not become transparent to γ -rays again until we reach an energy, E_{tr} , where the optical depth, $\tau(E_{\text{tr}}, z_{\max})$ again falls to unity. The expression for the optical depth when $\xi \ll 1$ is given for a fiat universe by

$$\tau(E_{\gamma 0}, z_{\max}) \simeq 4.4 \times 10^{13} E_{\gamma 0}^{-1} \int_0^{z_{\max}} dz (1+z)^{-3/2} \simeq 8.8 \times 10^{13} E_{\gamma 0}^{-1}$$

for $z_{\max} \gg 1$ (17)

and for an open universe by

$$\tau(E_{\gamma 0}, z_{\max}) \simeq 4.4 \times 10^{13} E_{\gamma 0}^{-1} \int_0^{z_{\max}} dz (1+z)^{-1}$$

$$\simeq 4.4 \times 10^{13} E_{\gamma 0}^{-1} \ln(1 + z_{\max}) \quad (18)$$

In both cases, we find $E_{\text{tr}} > 10^{13}$ GeV, so that we can safely assume that the universe, owing to the blackbody radiation field, is essentially opaque to γ -rays of all energies greater than $E_c(z_{\max})$ as given by equation (16).

It follows that if the cosmological hypothesis for the origin of the isotropic component of cosmic γ -rays above 1 MeV is valid and if, indeed, most of these γ -rays originated at a redshift ≈ 100 as the cosmological interpretation of the measurements of Vette *et al.* would indicate, then we would expect to find a high-energy break in the isotropic γ -ray spectrum at $E_c \approx 7.1$ GeV.

Greisen⁹ has suggested that pair-production interactions between γ -rays and optical photons occurring at redshifts ≈ 10 might also produce a high-energy break at ~ 10 GeV. However, the metagalactic optical photon density even at present ($z = 0$) is only theoretically estimated and can only be hypothesized at large redshifts. It must thus be kept in mind that the alternative prediction of a γ -ray break proposed by Greisen would occur only with the currently proposed starlight radiation density of 10^{-2} eV/cm³ existing out to redshifts ~ 10 .

We should like to thank Dr. Frank C. Jones for some valuable discussion of this paper.

References

- ¹Stecker, F. W., Nature, 220, 675 (1968).
- ²Stecker, F. W., Astrophys. J., 157, 507 (1969).
- ³Stecker, F. W., and Silk, J., Nature, 221, 1229 (1969).
- ⁴Vette, J. I., Gruber, D., Matteson, J. L., and Peterson, L. E.,
Proc. I.A.U. Symp. No. 37, Rome (edit. by Gratton, L.) (in the press).
- ⁵Vette, J. I., Gruber, D., Matteson, J. L. and Peterson, L. E., to be published.
- ⁶Stecker, F. W., Proc. I.A.U. Symp. No. 37, Rome (edit. by Gratton, L.) (in the press).
- ⁷Stecker, F. W., Nature, 224, 870 (1969).
- ⁸Gould, R. J., and Schröder, G. P., Phys. Rev., 155, 1404 (1967).
- ⁹Greisen, K., From a lecture given at the Brandeis Summer Institute in Physics, 1968, Cornell Laboratory for Nuclear Science Report (CLNS-77).

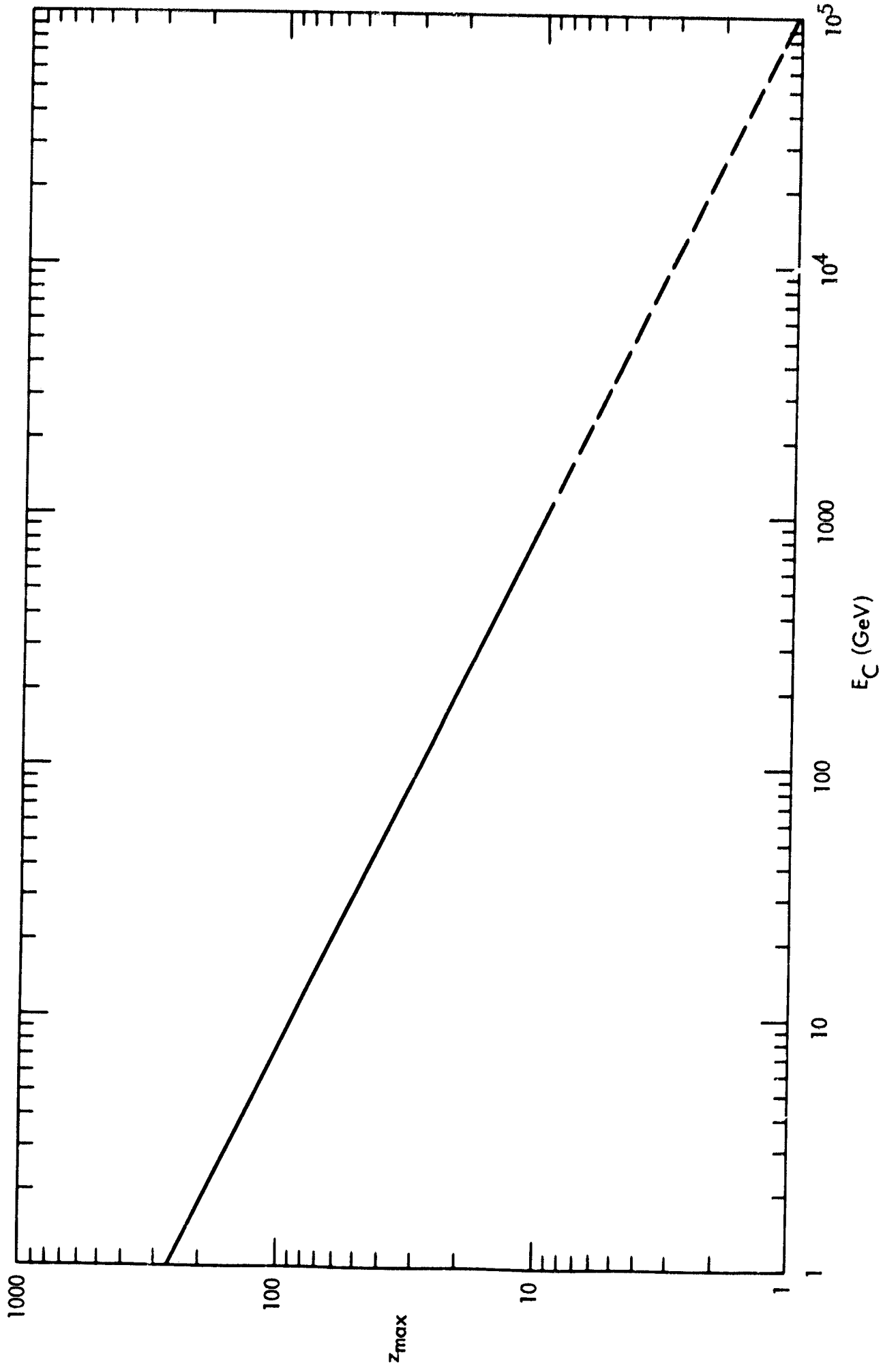


Figure 1. Cutoff Energy Versus Redshift for Cosmological Gamma-Rays