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

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

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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 energy[1-3]. 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 Schréder[8]. 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

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

where

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

where $\alpha \simeq 1/137$ 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 $\simeq 1$ at $\xi \simeq 1$ and the asymptotic forms

$$f(\xi) \rightarrow \frac{\pi^2}{3}\, \xi\, \ell n \left(\frac{0.117}{\xi}\right) \qquad \text{for } \xi \ll 1 \tag{4}$$

and

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

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

$$T = T_0(1 + z) \tag{6}$$

and

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

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 range[2]

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

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

$$\tau(E_{\gamma 0}, z_{max}) = \int_0^{\ell_{max}(z_{max})} d\ell \; \kappa_{\gamma\gamma}[E_{\gamma 0}, \ell(z)]$$

$$= \int_0^{z_{max}} dz \; \kappa_{\gamma\gamma}(E_{\gamma 0}, z) \left(\frac{d\ell}{dz}\right) \tag{9}$$

where

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

Here H_0 is the Hubble constant so that $cH_0^{-1} \simeq 10^{28}$ 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 $n_0 \simeq 10^{-5}$ 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 to[2]

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

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

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

$$\tau(E_{\gamma 0}, z_{max}) \simeq 1.7 \times 10^2 \; E_{\gamma 0}^{1/2} (1 + z_{max})^{5/2} \exp\left[- \frac{1.12 \times 10^6}{(1 + z_{max})^2 \; E_{\gamma 0}} \right] \qquad (12)$$

A numerical solution found by setting equation (11) for $\tau(E_{\gamma 0}, z_{crit}) = 1$, which defines the critical redshift where the universe becomes opaque to γ-rays of energy $E_{\gamma 0}$, can be well approximated by the expression[2]

$$1 + z_{crit} \simeq 2.60 \times 10^2 \; E_{\gamma 0}^{-0.484} \qquad (13)$$

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

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

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

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

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

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

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, $\tau(E_{tr}, z_{max})$ again falls to unity. The expression for the optical depth when $\xi \ll 1$ is given for a flat universe by

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

$$\text{for } z_{max} \gg 1 \tag{17}$$

and for an open universe by

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

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

In both cases, we find $E_{tr} > 10^{13}$ 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 $\simeq 100$ 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 $E_c \simeq 7.1$ GeV.

Greisen[9] has suggested that pair-production interactions between γ-rays and optical photons occurring at redshifts $\simeq 10$ 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/cm^3 existing out to redshifts ~ 10.

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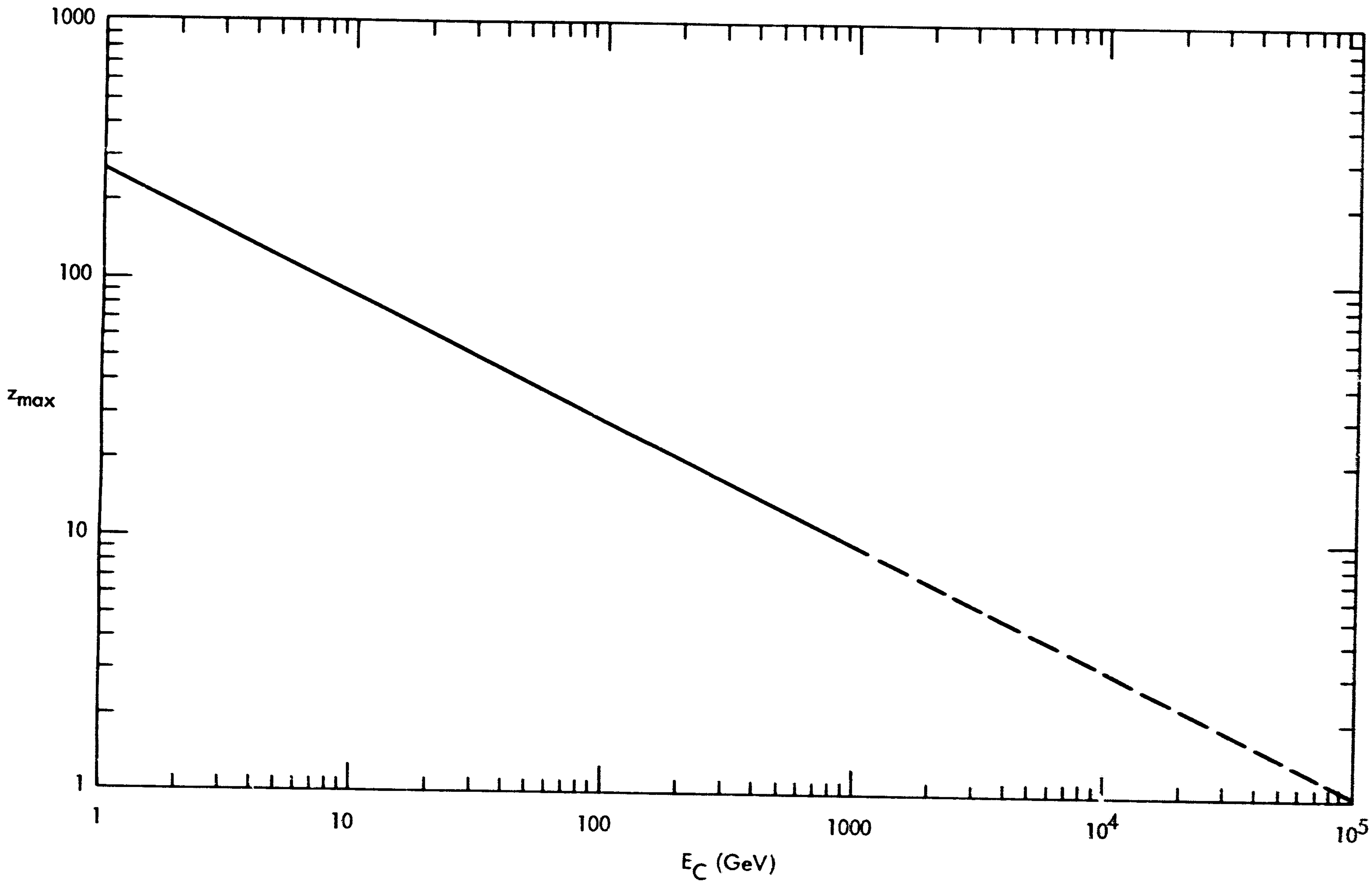

Figure 1. Cutoff Energy Versus Redshift for Cosmological Gamma-Rays