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ABSTRACT

The only practical way of determining the existence of cosmological antimatter is by the detection of gamma-radiation produced by the mutual annihilation of matter and antimatter in the universe. It is shown here that annihilation gamma-radiation has a characteristic spectrum which distinguishes it from other types of cosmic gamma-radiation. Such spectra are presented here, based on the results of recent accelerator experiments on antiproton annihilation and also including cosmological distortions of local annihilation-gamma-ray spectra. Using the "baryon inhomogeneity" cosmology of Harrison, it may be possible to account for both the observed cosmic isotropic X-rays and gamma-rays as due to redshifted annihilation-gamma-radiation where the mean value of the product of interacting matter and antimatter densities is of the order of 10^{-18} cm^{-6}.

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F. W. Stecker*

1. INTRODUCTION

The existence or nonexistence of antimatter in the universe is a question of importance in the fields of cosmology and particle physics (Alfvén 1965).[1] Recently, Harrison has proposed the existence of large amounts of antimatter in the universe in order to account for the condensation of matter into galaxies (Harrison 1967).[2] The only practical way of determining the existence of such antimatter is by the detection of the gamma-radiation produced when antimatter and matter annihilate into mesons having gamma-ray-producing decay modes. The gamma-ray spectra from such annihilations are presented here. They are based on the results of recent accelerator experiments on antiproton annihilation and also include cosmological distortions of local annihilation-gamma-ray spectra.

2. THE LOCAL ANNIHILATION-GAMMA-RAY SPECTRUM

The annihilation gamma-ray spectrum (AGS) for proton-antiproton interactions involving kinetic energies less than 286 MeV (the threshold for non-annihilation

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pion production) is given by the expression

$$I_A\left(E_\gamma\right) = B\int dv\, v\, f(v) \sum_s \int dE_s\, \sigma_s\left(E_s;\, v\right) \sum_d \zeta_{\gamma d}\, R_{\gamma d}\, f_{ds}\left(E_\gamma;\, E_s\right) \tag{1}$$

where $\underline{v}$ is the relative velocity of the proton and antiproton, $f(v)$ is the normalized distribution function over this velocity, $\underline{s}$ is an index representing the particular type of particle produced in the annihilation, $\sigma_s\left(E_s;\, v\right)$ is the cross section times multiplicity of particles of type $\underline{s}$ and energy E_s produced in a collision of velocity $\underline{v}$, the index $\underline{d}$ specifies a specific decay mode with a branching ratio, $R_{\gamma d}$, which produces $\zeta_{\gamma d}$ gamma-rays with a normalized energy distribution, $f\left(E_\gamma;\, E_s\right)$. The quantity, B, is defined as the product of interacting proton and antiproton densities integrated over a line-of-sight path-length ℓ, i.e.,

$$B = \int_0^{L_{max}} d\ell\, n_p(\ell)\, n_{\bar{p}}(\ell) \tag{2}$$

It can be shown that for energies less than 286 MeV, the production cross section, $\sigma_s\left(E_s;\, v\right)$ can be written as

$$\sigma_s\left(E_s;\, v\right) = \sigma_s\, \zeta_s\, v^{-1}\, c f_s\left(E_s\right) \tag{3}$$

where $f_s\left(E_s\right)$ is again a normalized distribution function and σ_s and $\underline{\zeta}_s$ are approximately constant production cross sections and multiplicities (Stecker 1967).[3]

With the help of Equation (3), Equation (1) reduces to

$$I_A\left(E_\gamma\right) = Bc\sum_s \sigma_s\,\zeta_s\int dE_s\, f_s\left(E_s\right)\sum_d \zeta_{\gamma d}\,R_{\gamma d}\,f_{ds}\left(E_\gamma;E_s\right)\;. \tag{4}$$

Fortunately, it is not necessary to use the general form of Equation (4) in order to evaluate the local AGS. Recent accelerater data on proton-antiproton annihilations indicate that only about 20% of the gamma-rays produced arise through nonpionic meson production (see references and discussion in Stecker 1967).[3] Furthermore, the largest nonpionic contribution to the AGS is due to the ρ-meson decay schemes

$$\begin{array}{l} \rho^\pm \rightarrow \pi^\pm + \pi^0 \\ \qquad\qquad\quad \hookrightarrow \gamma + \gamma\;. \end{array} \tag{5}$$

(The decay scheme, $\rho^0 \rightarrow \pi^0 + \pi^0$, is forbidden by the conservation of isospin in strong decays.) Gamma-rays from ρ-meson decay possess an average energy of 210 MeV, not much different from the 190 MeV average energy given to gamma-rays from the directly produced pions that are an order of magnitude more frequent. Other mesons being even less frequently produced than the ρ-mesons, we can conclude that mesons other than pions have a negligible effect on the total gamma-ray spectrum from proton-antiproton annihilation.

We need therefore include in Equation (4), only the contribution from neutral pion decay, thus eliminating the summation over s. The form of the distribution function, $f_{ds}\left(E_\gamma;E_s\right)$ is well known (see, for example, Stecker 1966),[4] and there is only one important decay mode to consider, viz., $\pi^0 \to 2\gamma$, thus eliminating the summation over $\underline{d}$. Equation (4) then reduces to

$$I_A\left(E_\gamma\right) = 2B\sigma_\pi \zeta_\pi c \int_{E_\gamma + \left(m_\pi^2/4E_\gamma\right)}^{\infty} dE_\pi \frac{f_\pi\left(E_\pi\right)}{\sqrt{E_\pi^2 - m_\pi^2}} . \tag{6}$$

3. PION PRODUCTION IN PROTON-ANTIPROTON ANNIHILATION

It now remains only to evaluate the quantities σ_π and ζ_π and the production function $f_\pi\left(E_\pi\right)$ in Equation (6). Of the annihilation processes which yield neutral pi-mesons, the process

$$p + \bar{p} \to \pi^0 \tag{7}$$

is, of course, forbidden by conservation of momentum. The process

$$p + \bar{p} \to \pi^0 + \pi^0 \tag{8}$$

is also forbidden when it is noted that proton-antiproton annihilations near rest occur predominantly from the S states of the proton-antiproton system. It has been shown by Lee and Yang (1956)[5] that reaction (8) is then forbidden by the conservation of G-conjugation parity (see also Stecker 1967 for a more detailed discussion).[3] Therefore, the extremum gamma-ray energies that one would expect from proton-antiproton annihilation would result from annihilations of the type

$$p + \bar{p} \to \pi^+ + \pi^- + \pi^0 \tag{9}$$

which produce neutral pi-mesons with a maximum c.m.s. energy of approximately 870 MeV. Such mesons can produce gamma-rays only within the energy region

$$5 \text{ MeV} \leq E_\gamma \leq 865 \text{ MeV} . \tag{10}$$

(The electromagnetic process, $p + \bar{p} \rightarrow 2\gamma$ may also occur, but is rare enough to be neglected (Stecker 1967).[4]

The product, $2\sigma_\pi \zeta_\pi$, has been determined experimentally to be

$$2\sigma_\pi \zeta_\pi \simeq 1.44 \times 10^{-25} \text{ cm}^2 \tag{11}$$

(see references in Stecker 1967).[4]

The function $f_\pi(E_\pi)$, was taken from the calculations of Maksimenko (1958),[6] based on the statistical theory of multiple particle production. It has been shown (Matsuda 1966)[7] that the statistical theory of multiple particle production presents excellent agreement with the data in describing annihilations into three or more mesons.

The resulting gamma-ray spectrum, up to 750 MeV is shown in Figure 1. Frye and Smith (1966)[8] have calculated the form of this spectrum up to 500 MeV, based on recent measurements by the Columbia University group on charged pion production in $p\bar{p}$ annihilation. The excellent agreement between the results of Figure 1 and the calculations of Frye and Smith not only serves as a mutual check on the calculations, but also supports the conclusion that mesons other than pions have a negligible effect on the total gamma-ray spectrum.

4. THE METAGALACTIC ANNIHILATION-GAMMA-RAY SPECTRUM

The metagalactic annihilation-gamma-ray spectrum will differ from the local spectrum calculated in the previous section due to contributions at non-zero redshifts, an effect which has been discussed previously (Stecker 1968).[9] Therefore, Equation (6) must be modified to include the cosmological effects of curvature, volume and density changes in an expanding universe, time dilation, and energy redshift. In a Friedmann-type expanding universe with a Robertson-Walker metric the proper relativistic formula for calculating the spectrum becomes

$$I_A(E_\gamma) = 2\sigma_\pi \zeta_\pi c \int_0^{z_{max}} dz\, n_p(z)\, n_{\bar{p}}(z) \frac{f_\gamma\left[(1+z)E_\gamma\right]}{(1+z)^3} \frac{d\ell}{dz} \tag{12}$$

where

$$f_\gamma(E_\gamma) = \int_{E_\gamma + \left(m_\pi^2/4E_\gamma\right)}^{870\text{ MeV}} dE_\pi \frac{f_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}}, \tag{13}$$

and $\underline{z}$ is the cosmological redshift. The curvature factor, $d\ell/dz$ is given by

$$\frac{d\ell}{dz} = \frac{cH_0^{-1}}{(1+z)^2\left(1+2q_0 z\right)^{1/2}} \tag{14}$$

(Sandage 1961)[10] where $\underline{c}$ is the speed of light, H_0 is the present value of the Hubble parameter and q_0 is the deceleration parameter. We consider the values $q_0 \simeq 0$ and $q_0 = 1/2$, corresponding to the low density and Einstein-de Sitter cosmological models respectively. We also assume that the densities of interacting matter and antimatter are inversely proportional to the volume of the universe and therefore are proportional to $(1+z)^3$. Such would be the case if matter and antimatter were effectively separated by a primordal baryon inhomogeneity (Harrison 1967)[2] so that only a small fraction annihilates through peripheral interactions involving these inhomogeneities. Under this assumption, Equation (12) reduces to

$$I_A\left(E_\gamma\right) = 2B_0^{int}\,\sigma_\pi\,\zeta_\pi\,c\int_0^{z_{max}} dz\,(1+z)^\alpha\,f_\gamma\left[(1+z)\,E_\gamma\right] \tag{15}$$

where

$$B_0^{int} \equiv n_{p,0}^{int}\,n_{\bar{p},0}^{int}\,cH_0^{-1} \tag{16}$$

$n_{p,0}^{int}$ and $n_{\bar{p},0}^{int}$ are the present densities of interacting matter and antimatter respectively, and the index α is equal to 1 for the low density model and 1/2 for the Einstein-de Sitter model of the universe.

It is of interest to note that since $f_\gamma\left(E_\gamma\right)$ is nonvanishing only within a restricted energy range (given by Equation (10)), there exists an energy region

$$\frac{865\ \mathrm{MeV}}{\left(1+z_{max}\right)} \lesssim E_\gamma \lesssim 5\ \mathrm{MeV} \tag{17}$$

where the integral in Equation (15) is independent of the form of $f_\gamma\left(E_\gamma\right)$ and the resultant spectrum has power-law form. In actuality, the power-law form of the spectrum is a valid approximation even over a wider energy range where a change of the limits of integration over $f_\gamma(E_\gamma)$ does not significantly affect the value of the integral. In this case, we find

$$I_A(E_\gamma) = 2B_0^{int} \sigma_\pi \zeta_\pi c K E_\gamma^{-(\alpha+1)} \sim E_\gamma^{-(\alpha+1)}$$

where

$$K \equiv \int_{5\ \mathrm{MeV}}^{865\ \mathrm{MeV}} dE_\gamma E^\alpha_\gamma f_\gamma(E_\gamma) \tag{18}$$

Equation (15) was used to evaluate the form of the metagalactic annihilation-gamma-ray spectrum for various values of z_{max}. These spectra are shown in Figures 2 and 3 for the Einstein-de Sitter universe and Figures 4 and 5 for a low density universe. It can be seen from these figures, as well as from the previous argument, that as z_{max} becomes very large, these spectra take on a power-law form. Indeed, the spectrum predicted for the low-density model is compatable with the observed isotropic X-ray spectrum (Metzger, Anderson, van Dilla and Arnold 1964)[11] as well as a possible observation of the cosmic gamma-ray flux above 100 MeV (Clark, Garmire and Kraushaar 1968),[12] provided the mean product of interacting matter and antimatter densities $\left(n_{p,0}^{int}\, n_{\bar{p},0}^{int}\right)$ is of the order of 10^{-18} cm^{-6}.*

*Gamma-rays resulting from metagalactic cosmic-ray collisions will produce spectra similar to annihilation spectra, which peak near 70 $(1 + z_{max})^{-1}$ MeV as will be discussed elsewhere. The most noticeable observational difference between these spectra lies in the region above several hundred MeV where the annihilation spectrum drops sharply to zero while the collisional spectrum will have a power-law form. It may also be shown that the metagalactic gamma-ray spectrum resulting from cosmic-ray collisions will peak above or near 1 MeV and therefore cannot account for the observed isotropic X-ray spectrum.

The explanation most often considered for the isotropic X-radiation, is that it arises through Compton interactions of high-energy electrons and blackbody photons in the metagalaxy (Felten and Morrison 1966).[13] However, such an explanation is beset by various difficulties, as has been previously pointed out (Fazio, Stecker and Wright 1966;[14] Brecher and Morrison 1967[15]).

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FIGURE CAPTIONS

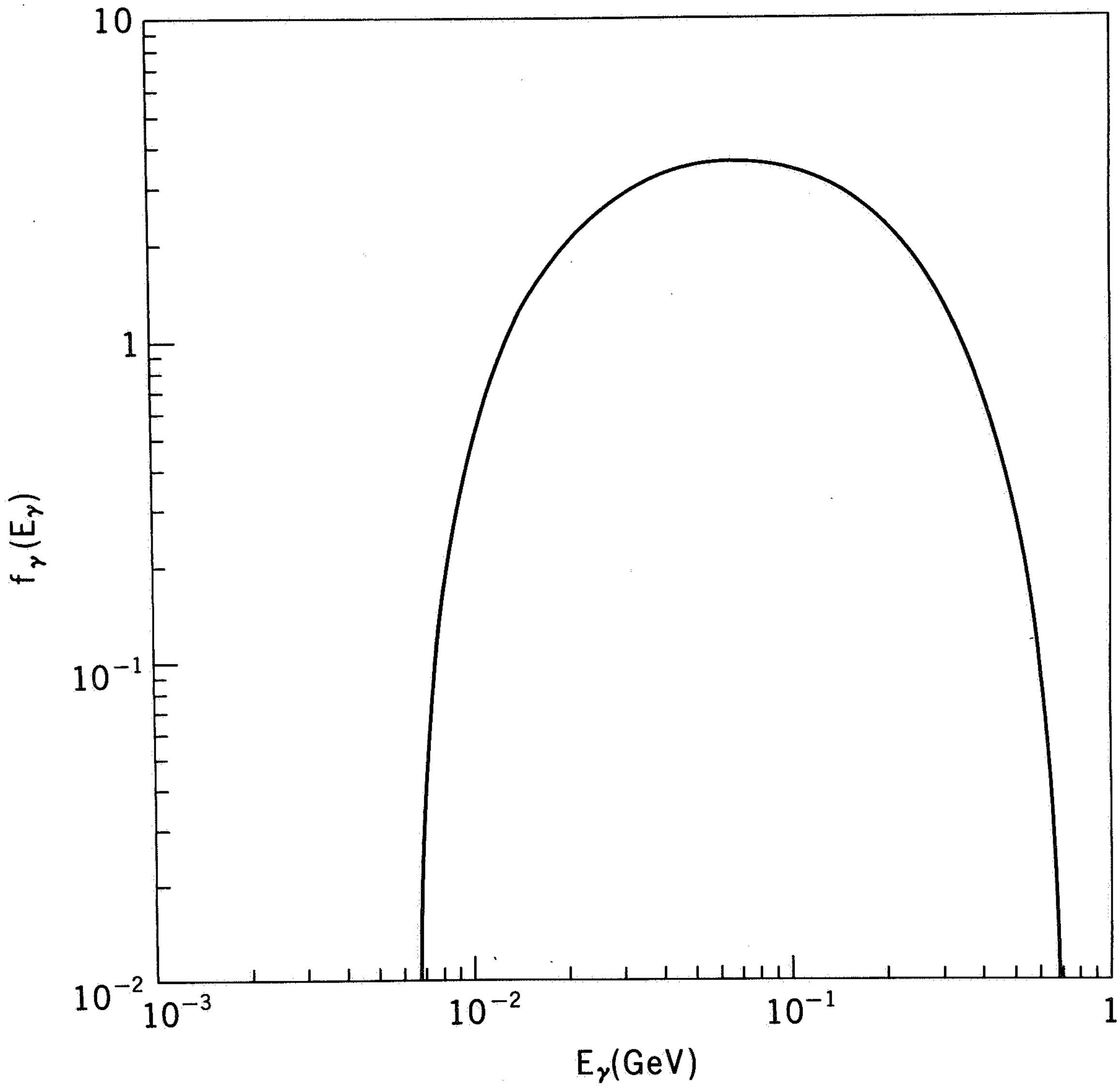
Figure 1. The normalized local differential gamma-ray spectrum from proton-antiproton annihilation.

Figure 2. The metagalactic differential annihilation spectrum given for various maximum redshifts for an Einstein-de Sitter universe as discussed in the text.

Figure 3. The metagalactic integral annihilation spectrum given for various maximum redshifts for an Einstein-de Sitter universe as discussed in the text.

Figure 4. The metagalactic differential annihilation spectrum given for various maximum redshifts for a low density universe as discussed in the text.

Figure 5. The metagalactic integral annihilation spectrum given for various maximum redshifts for a low density universe as discussed in the text.



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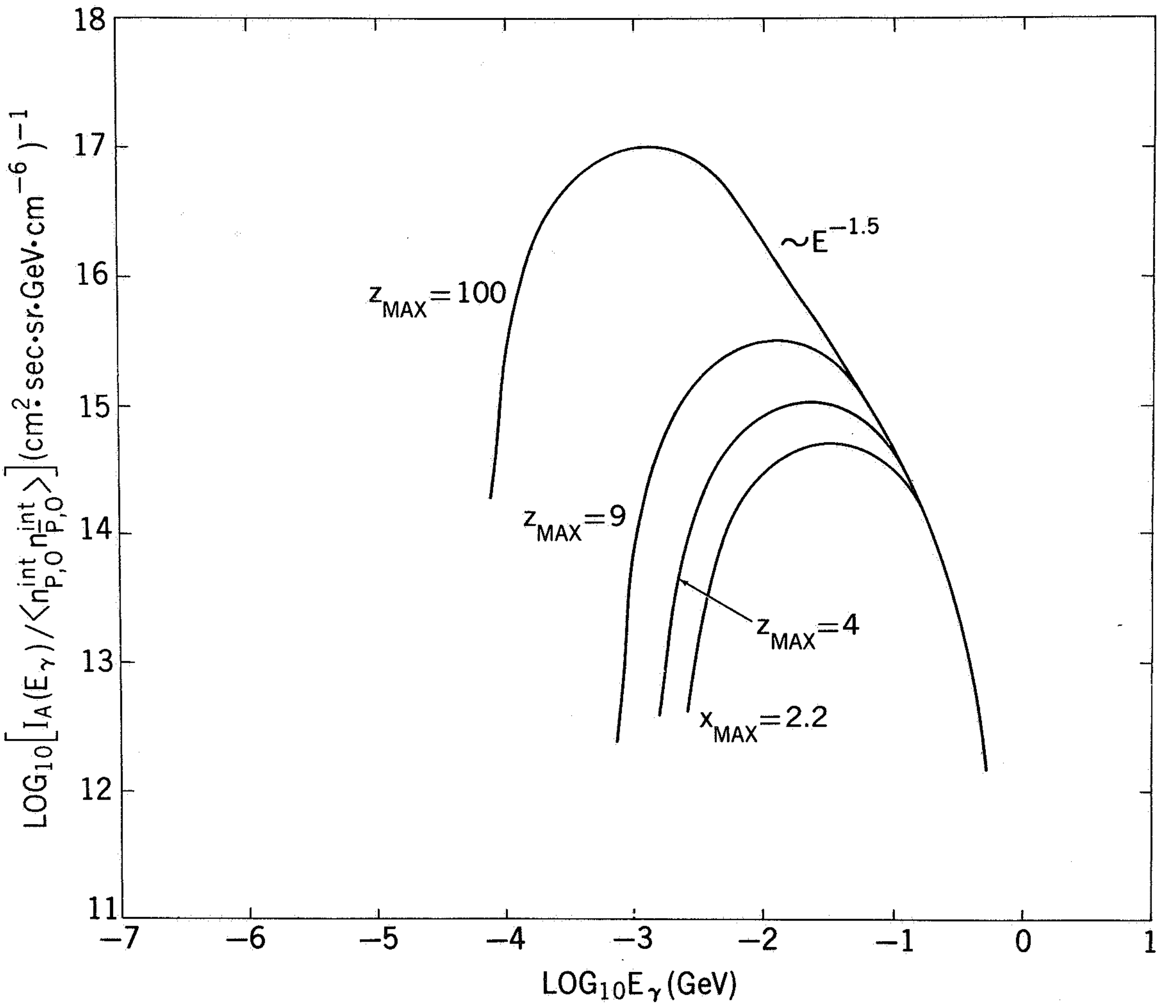

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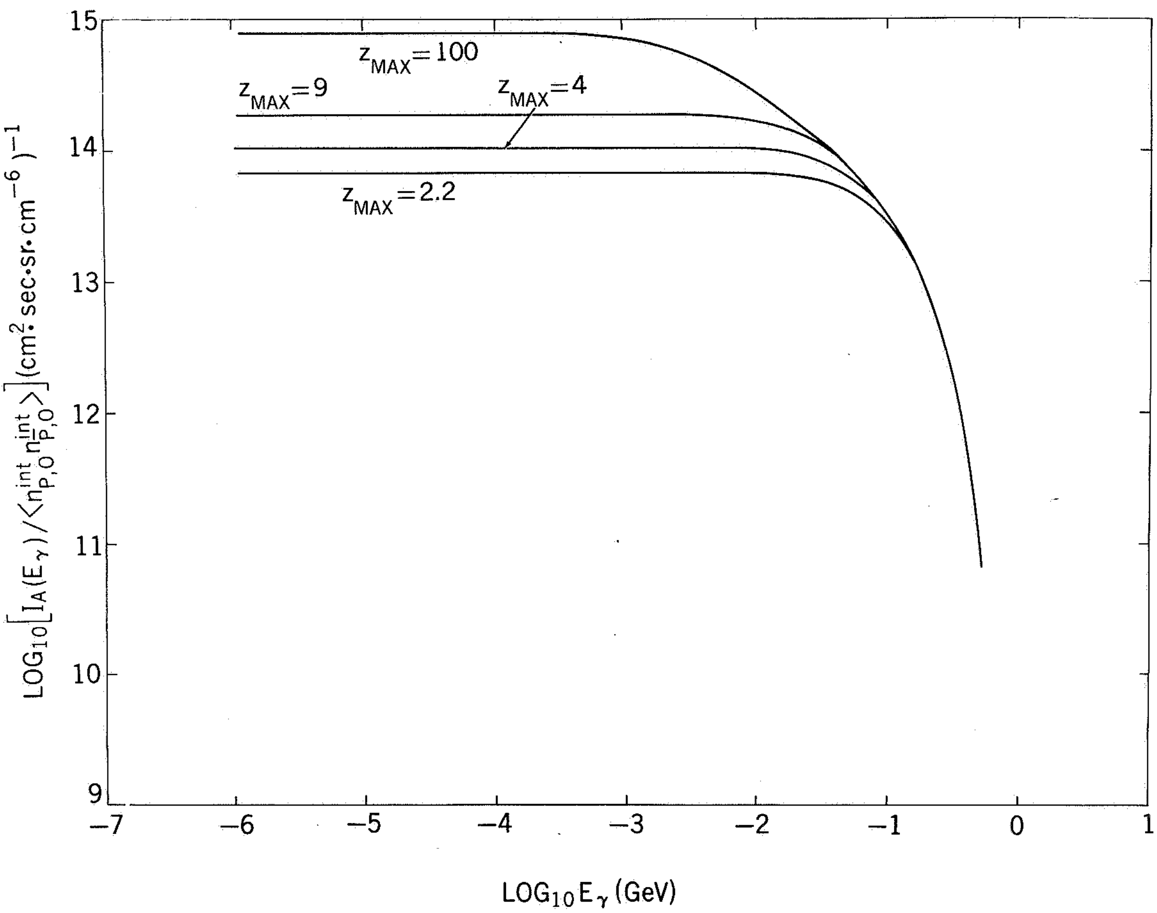

Figure 3. The metagalactic integral annihilation spectrum given for various maximum redshifts for an Einstein-de Sitter universe as discussed in the text.

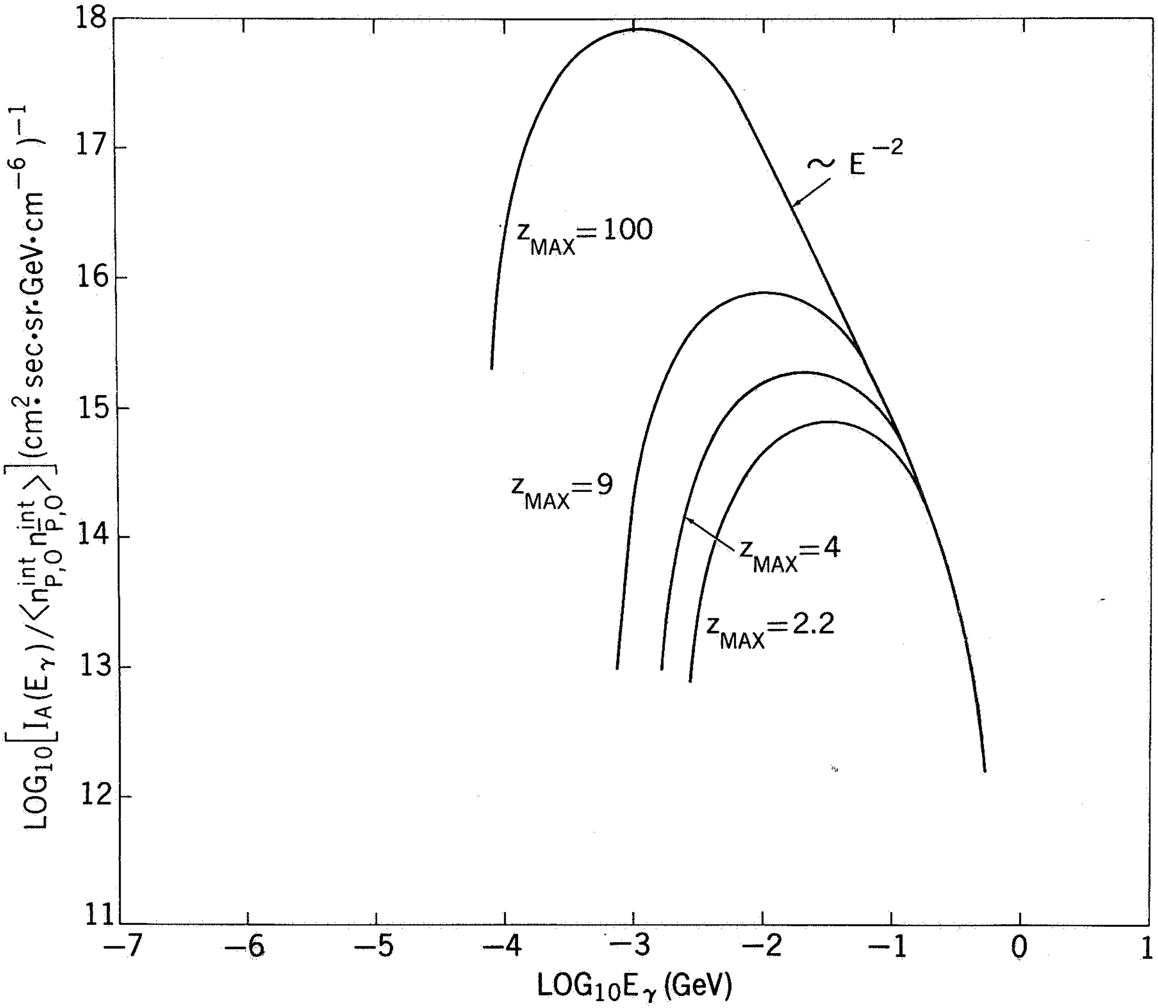

Figure 4. The metagalactic differential annihilation spectrum given for various maximum redshifts for a low density universe as discussed in the text.

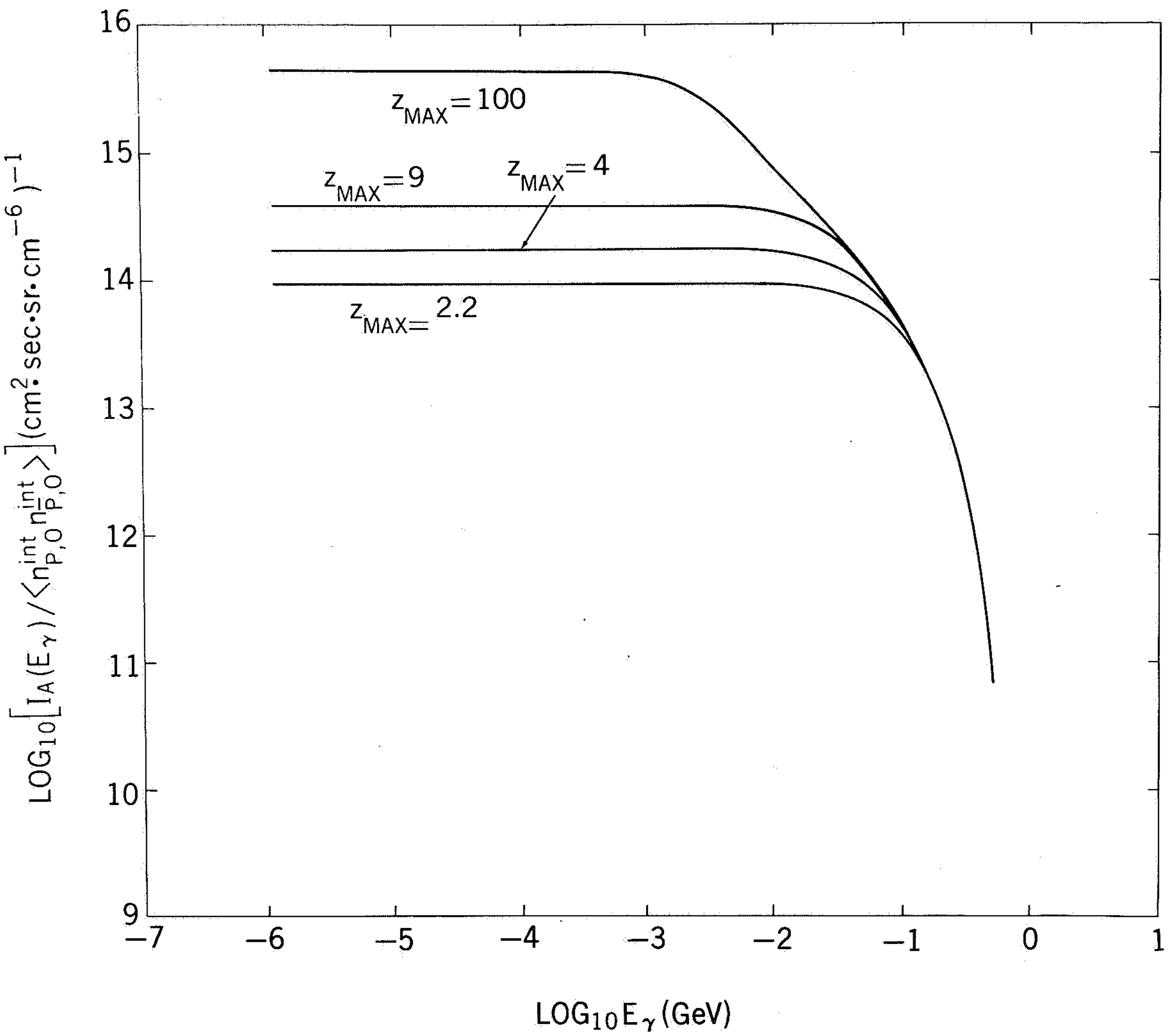

Figure 5. The metagalactic integral annihilation spectrum given for various maximum redshifts for a low density universe as discussed in the text.