THE COSMIC GAMMA-RAY SPECTRUM FROM SECONDARY PARTICLE PRODUCTION IN THE METAGALAXY

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ABSTRACT

The purpose of this paper is to discuss the form and intensity of the spectrum of cosmic gamma-rays resulting from the production and decay of neutral pi-mesons produced in metagalactic cosmic-ray p-p collisions. It is assumed that intergalactic space contains ionized hydrogen gas at a density of $10^{-5}$ cm$^{-3}$ as indicated by recent X-ray observations in the 1.5 - 8 keV region.

Using the Friedmann solution to the Einstein field equations of general relativity as a description of our expanding universe, a discussion is presented of the effects of red-shift and spatial curvature on the generation and distortion of the local gamma-ray spectrum from the decay of neutral pi-mesons. Numerical calculations are presented for the Einstein-de Sitter solution, which is found to be an adequate model for these calculations. Various models are presented to represent the possible flux of metagalactic cosmic-rays. In calculating metagalactic gamma-ray spectra, the effect of gamma-ray absorption at large redshifts is taken into account.

A discussion of the results is given. The results indicate that future gamma-ray experiments in the 1 - 100 MeV region may yield valuable information.

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relating to cosmology, cosmogeny, and the metagalactic cosmic-ray flux. In particular, the metagalactic gamma-ray spectra predicted tend to peak near $70 (1 + z_{\text{max}})^{-1}$ MeV where $z_{\text{max}}$, the maximum red-shift at which cosmic rays are produced, may correspond to the age of the universe at the epoch of galaxy formation.
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INTRODUCTION

In recent investigations (Stecker, 1967; Stecker, Tsuruta and Fazio, 1968) the author made use of recent accelerator and cosmic-ray data to determine the details of the cosmic gamma-ray spectrum from the secondary particles produced by cosmic-ray collisions in the galaxy. The purpose of this paper is to determine the cosmic gamma-ray spectrum from secondary particles produced by cosmic-ray collisions in the metagalaxy. This spectrum will differ from the galactic (or local) gamma-ray spectrum because most of the generating collisions take place at large distances where we are looking back to a time when the universe was more compact and collisions were more frequent. These "early" gamma-rays will be of lower energy due to the progressive red-shift of the general cosmic expansion. Although various estimates of the flux of these metagalactic gamma-rays have been made (Ginzburg and Syrovatskii, 1964a, b; Gould and Burbridge, 1965; Garmire and Kraushaar, 1965), none of these workers have taken cosmological factors into account in order properly to calculate a spectrum.

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THE COSMOLOGICAL EQUATIONS

For the purpose of these calculations, we may consider models of the universe which are both homogeneous and isotropic on a large scale. Such models can, in general, be described by the Robertson-Walker line element

$$ds^2 = c^2 dt^2 - d\ell^2 = c^2 dt^2 - R^2(t) du^2$$ \hspace{1cm} (1)

The time-separable form of the metric is a reflection of the postulated uniformity such that at every moment of world-time the three-space metric is the same at all points and in every direction. Such a three-space is a space of constant Riemannian curvature which may be positive, zero or negative. These three alternatives will be designated by $k = +1, 0, -1$ respectively. If $k = +1$, the universe is closed and finite; if $k = 0$ the universe is Euclidean, open and infinite; if $k = -1$ the universe is open, infinite and increasingly divergent in time. More precisely,

$$du^2 = \frac{dr^2}{1 - kr^2} + r^2 \left( d\theta^2 + \sin^2 \theta d\phi^2 \right),$$ \hspace{1cm} (2)

so that $du$ measured along the radial direction is given by

$$u = \int_0^r \frac{dr}{\sqrt{1 - kr^2}} = \begin{cases} \sin^{-1} r & \text{for } k = +1 \\ r & \text{for } k = 0 \\ \sinh^{-1} r & \text{for } k = -1 \end{cases}$$
Gamma-rays travel along geodesics such that $ds = 0$. Assuming a gamma-ray is emitted at a time $t_e$ in an interval $\Delta t_e$ and received at time $t_r$ in an interval $\Delta t_r$, it can be shown that

$$u = c \int_{t_e}^{t_r} \frac{dt}{r(t)} = \text{constant}$$

and

$$\frac{c \Delta t_r}{c \Delta t_e} = \frac{R(t_r)}{R(t_e)}$$

(For a more detailed discussion of the cosmological relations, the reader is referred to the excellent articles by Sandage referred to in the text.) The time interval, $\Delta t_e$, is therefore dilated so that

$$\frac{1}{\Delta t_e} = \frac{R(t_r)}{R(t_e)} \frac{1}{\Delta t_r}$$

The gamma-ray is therefore shifted to lower energy by an amount

$$z = \frac{\Delta \lambda}{\lambda} = \frac{R(t_r)}{R(t_e)} - 1$$
We thus obtain the important relation between red-shift and radius of the universe given by

\[
\frac{R(t_r)}{R(t_e)} = 1 + z(t_e)
\]  

(6)

It follows from (6) that in a universe where most of the energy density is in the form of matter

\[
\frac{n(t_e)}{n(t_r)} = (1 + z)^3
\]  

(7)

\[
\frac{T_\gamma(t_e)}{T_\gamma(t_r)} = (1 + z)
\]  

(8)

and

\[
\frac{n_\gamma(t_e)}{n_\gamma(t_r)} = (1 + z)^3
\]  

(9)

where \(n(t)\), \(T_\gamma(t)\) and \(n_\gamma(t)\) are the average particle density of matter and temperature and photon density of cosmic blackbody radiation in the universe.

We will hereafter designate local \((z = 0)\) quantities with a subscript zero. Let \(f(E_\gamma)\) be the gamma-ray spectrum generated by the galactic cosmic-ray spectrum, \(I_x(E_p)\) in traveling a unit particle length (1 cm \(^{-1}\)) through the intergalactic medium. (This spectrum is the same as the quantity \(I(E_\gamma)/\langle nL \rangle\) calculated by Stecker (1967).)
We now assume that some ubiquitous generating mechanism causes cosmic-rays to be produced with the same power law throughout the universe as observed at the earth, so that the metagalactic cosmic-ray spectrum differs only in absolute intensity from the galactic cosmic-ray spectrum. It follows that the form of the cosmic gamma-ray spectrum anywhere in the metagalaxy, when observed in the co-moving frame at that point, will be the same as the form of \( f(E_{\gamma}) \).

We may then write down an expression for the integrated metagalactic gamma-ray flux in any direction as

\[
I(E_{\gamma}) = \int_0^{\ell_{\text{max}}} d\ell \, n(\ell) \, \frac{I(\ell)}{I_g} \, \frac{f(E_{\gamma}, \ell)}{1 + z (\ell)} \, e^{-\tau(E_{\gamma}, \ell)} \tag{10}
\]

where the factor, \((1 + z)\), takes into account the reduction in flux due to the time dilation factor and \( e^{-\tau} \) represents absorption of gamma-rays along the line of sight, \( I_g \) is the galactic cosmic-ray flux and \( I(\ell) \) is the cosmic-ray flux at a distance \( \ell \). Equation (10) may be put into a much more convenient form by expressing it as an integral over \( z \). We then obtain

\[
I(E_{\gamma}) = \int_0^{z_{\text{max}}} dz \, n(z) \, \frac{I(z)}{I_g} \, \frac{f(E_{\gamma}, z)}{1 + z} \, e^{-\tau(E_{\gamma}, z)} \, \frac{d\ell}{dz} \tag{11}
\]

Since the energy of a gamma-ray is directly proportional to its frequency, it follows that

\[
f(E_{\gamma}, z) = f [(1 + z) E_{\gamma}] \tag{12}
\]
It also follows from (7) that

\[ n(z) = n_0 (1 + z)^3 \]  

(13)

The quantity

\[ \frac{d\ell}{dz} = R(z) \frac{du}{dz} \]  

(14)

depends, in general, both upon the cosmological model involved and the epoch of world-time which defines the acceleration (or deceleration) of the expansion.

In Friedmann-type solutions to the Einstein equations, it is found that the expansion of the universe is decelerating. The magnitude of this deceleration is usually denoted by the deceleration parameter \( q \). In the usual notation, the Hubble expansion parameter, \( H \), and the quantity \( q \) are defined by the relations

\[ H = \frac{\dot{R}(t)}{R(t)} \]  

(15)

and

\[ q = -\frac{\ddot{R}(t)}{R(t) H^2} \]

In a decelerating universe, therefore, \( q > 0 \). Solutions to the Einstein equation with zero pressure and a cosmological constant of zero may be expressed in
parametric form in terms of a development angle, \( \theta \) (Sandage 1961b) as

\[
R = a(1 - \cos \theta),
\]

\[
t = \frac{a}{c} (\theta - \sin \theta).
\]  

(16)

for \( k = +1 \), and

\[
R = a(\cosh \theta - 1),
\]

\[
t = \frac{a}{c} (\sinh \theta - \theta).
\]  

(17)

for \( k = -1 \), where \( a = 4\pi G \rho R^3/3c^2 \) and \( \rho \) is the density of matter in the universe (so that \( \rho R^3 = \) constant).

For the Euclidean case of \( k = 0 \), \( R(t) \) can be expressed explicitly in terms of \( t \) by the relation

\[
R(t) = (6\pi G \rho R^3)^{1/3} t^{2/3}
\]  

(18)

From (15) and (18) it then follows that for \( k = 0 \) that

\[
q = \frac{1}{2} \quad \text{for all } t.
\]  

(19)

For \( k = +1 \), it follows from (15) from (16) that

\[
q = \frac{1 - \cos \theta}{\sin^2 \theta}
\]  

(20)
For \( k = -1 \), it follows from (15) and (17) that \( q \) is given by

\[
q = \frac{1 - \cosh \theta}{\sinh^2 \theta}
\]  
(21)

For \( \theta \ll 1 \), corresponding to an early epoch of the expansion, (20) and (21) both reduce to the Euclidean case of \( q = 1/2 \). The Euclidean (Einstein-de Sitter) model is therefore a good approximation to the universe if it has not yet reached a highly evolved state. It is also compatible with the most probable values of \( q \) as discussed by Sandage (1961a, 1962), based on the observed magnitude-red shift relation, and with the recent determination by Henry, Fritz, Meekins, Friedman and Byram (1968) of a mean metagalactic gas density of the order of \( 10^{-5} \) cm\(^{-3}\).

Under the assumption of a Euclidean model, we will now determine the cosmological effects on the metagalactic gamma-ray spectrum. It can be shown (Sandage 1961b) that

\[
\frac{d\phi}{dz} = \frac{cH_0^{-1}}{(1 + z)^2 (1 + 2q_0 z)^{1/2}}
\]  
(22)

where \( cH_0^{-1} = 10^{28} \) cm. In the Euclidean case, \( q_0 = 1/2 \) and we may take in equation (11)

\[
\frac{d\phi}{dz} = \frac{10^{28}}{(1 + z)^{5/2}}
\]  
(23)
ABSORPTION OF METAGALACTIC GAMMA-RAYS

An excellent discussion of the absorption processes affecting cosmic gamma-rays has been given by Fazio (1967). The principal absorption process to be considered is that of electron-positron pair production through interaction with the universal black-body radiation field, i.e., the reaction

\[ \gamma + \gamma \rightarrow e^+ + e^- \]  

(24)

Detailed calculations of the energy-dependent absorption probability for this process have been performed by Gould and Schrédéer (1967). They have shown that for a gamma-ray of energy \( E_\gamma \) interacting with a black-body radiation field of temperature \( T_\gamma \)

\[ \frac{d\tau}{d\xi} \simeq \frac{\alpha^2}{2\pi \Lambda} \left( \frac{kT_\gamma}{mc^2} \right)^3 \sqrt{\xi} e^{-\xi} \]  

(25)

where

\[ \xi = \left( \frac{mc^2}{kT_\gamma E_\gamma} \right)^2 \gg 1 \]

where \( \alpha \approx 1/137 \) is the fine-structure constant, \( \Lambda = \hbar/mc = 3.86 \times 10^{-11} \) cm, and \( k \) here is Boltzmann's constant. The local black-body temperature has been found by Stokes, Partridge and Wilkinson (1967) to be

\[ T_0 \equiv 2.7^\circ K. \]  

(26)
so that the condition $\xi >> 1$ corresponds to the condition

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

(see equation (8) and (12)).

We will restrict ourselves here to a determination of the gamma-ray spectrum below 1 GeV and $z \leq 10^3$ (as will be discussed later) so that the approximation given by equation (25) will be generally valid. Therefore, from (23) and (25), we find

$$\tau(E_\gamma, z) = 3.9 \times 10^8 E_\gamma^{-1/2} \int_0^z dy \frac{\exp \left[ -\frac{1.12 \times 10^6 E_\gamma}{(1 + y)^2} \right]}{(1 + y)^{1/2}}$$

(See appendix for further discussion.)

THE METAGALACTIC COSMIC-RAY SPECTRUM

It now remains only to specify a suitable model for the metagalactic cosmic ray flux. We will assume that at some early epoch, corresponding to $z \geq z_{\text{max}}$ conditions were unsuitable for the acceleration of cosmic-rays. We will consider $z_{\text{max}}$ to correspond to the epoch of galaxy formation and consider two possible models for the origin of a metagalactic cosmic-ray flux. For model I, we will assume that the metagalactic flux arises through a constant leakage rate from the halos of galaxies from $z = z_{\text{max}}$ to $z = 0$. For model II, we will assume
that this flux was created primarily in a burst at the time of galaxy formation. Thus, model I and model II correspond to the two extreme cases which may be expected.* For \( z_{\text{max}} \), we will also consider two extremes. One extreme is \( z_{\text{max}} = 10^3 \), which corresponds to the earliest epoch when galaxy formation could probably occur. At \( z = 10^3 \), the black-body temperature of the universe was of the order of \( 10^3 - 10^4 \text{K} \), cool enough for ionized hydrogen to combine to form a neutral gas. According to Peebles (1965), \( z = 10^3 \) also corresponds to the epoch when gas clouds may begin to form gravitationally bound systems.

The other extreme for \( z_{\text{max}} \) which we may consider corresponds to the highest red-shift yet observed for a quasar, viz., 2.2. This is, of course, an extreme which is technique-limited rather than being limited by any physical criteria, and it is included mainly for purposes of discussion. We will also consider various intermediate values for \( z_{\text{max}} \) of 4, 9, and \( 10^2 \). (Doroshkevich, et. al. (1967) suggest that galaxy formation took place at \( z = 10 - 20 \) whereas Weymann (1967) suggests \( z = 10^2 \).)

It is important to note here that the upper limit, \( z_{\text{max}} \), may be effectively restricted, not by the epoch of galaxy formation, but by attenuation of the metagalactic cosmic-ray flux due to the collisions themselves. The cross-section for inelastic cosmic-ray p-p collisions is of the order of 30 mb. Therefore, the lifetime of the metagalactic cosmic-rays against collisional losses is given

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*Models allowing for the possibility of increased cosmic-ray production by galaxies in the past, as well as other possibilities, will be considered in a future paper. In particular, it may be of interest to examine the possibility that the isotropic X-ray spectrum may be a red-shifted \( \pi^{0} \)-gamma-ray spectrum, a hypothesis which may explain both the intensity and power-law form of the spectrum.
The lifetime of the universe at a red-shift $z$ is given by

$$\tau_u \approx 10^{17} (1 + z)^{-3/2} \text{sec}$$

The condition $\tau_c/\tau_u = 1$ therefore defines a critical value of $z_{\text{max}} = 10^2$ beyond which a further buildup of metagalactic cosmic-rays cannot occur. With these limitations on $z$ in mind, we will now consider the various ideal models for describing the metagalactic cosmic-ray flux.

Model I: In this model, we assume that the galaxies were created on the order of $10^{10}$ years ago, as indicated by stellar evolution studies in our own galaxy. We will assume that ours is a typical galaxy for which the leakage time of cosmic rays from the halo is on the order of $10^8$ years. Therefore each galaxy has emitted about $10^2$ halo-volumes of cosmic-rays since the time of galaxy formation. The ratio of the volume of one galactic halo to the volume of
the universe is
\[
\frac{V_g}{V_u} \approx \left( \frac{5 \times 10^{22} \text{ cm.}}{10^{28} \text{ cm.}} \right)^3 \approx 10^{-16}
\] (31)

Taking the cosmic-ray flux in our galaxy as an average for all galaxies and taking the number of galaxies in the universe to be \(3 \times 10^9\) (Allen, 1963), we find that

\[
I_0 \approx 10^{-16} \times 3 \times 10^9 \times 10^2 I_g = 3 \times 10^{-5} I_g
\] (32)

We assume a constant leakage rate so that the total number of cosmic-rays in the metagalaxy is proportional to the time elapsed since galaxy formation. It follows from (18) that this time is given by

\[
\tau_g \approx 10^{10} \left[ (1 + z)^{-3/2} - (1 + z_{\text{max}})^{-3/2} \right] \text{ yrs}.
\] (33)

The cosmic-ray density will then increase with redshift according to the relation

\[
\frac{I'(g)}{I_g} \approx 3 \times 10^{-5} (1 + z)^3 \left[ (1 + z)^{-3/2} - (1 + z_{\text{max}})^{-3/2} \right]
\] (34)

However, the cosmic-rays which produce the neutral pi-mesons necessary for gamma-ray production are only those above a threshold energy, \(E_{\text{th}}\), of about
300 MeV (Stecker, 1966). We must therefore determine

\[ I(z) = I'(E > E_{th}'; z) \]  

(35)

For a power low cosmic-ray spectrum of the form

\[ I(>E) \sim E^{-3/2} \]  

(36)

it follows from the red-shift relation that

\[
I(E > E_{th}; z) = I' \left( E > \frac{E_{th}}{(1+z)} \right) \\
= I'(z) \left[ \frac{1 + z}{1 + z_{\text{max}}} \right]^{-3/2}
\]  

(37)

so that we must use an effective flux of

\[
\frac{I(z)}{I_g} \simeq 3 \times 10^{-5} (1 + z)^3 \left[ \frac{1 + z}{1 + z_{\text{max}}} \right]^{3/2} \left[ (1 + z)^{-3/2} - (1 + z_{\text{max}})^{-3/2} \right]
\]  

(38)

Model II: In this model we assume that the metagalactic cosmic-rays were created in a burst at the time of galaxy formation. Assuming that the total number of cosmic-rays released in the initial burst is equal to the total number released over \(10^{10}\) years in model I, we find

\[
\frac{I(z)}{I_g} = 3 \times 10^{-5} (1 + z)^3 \left[ \frac{1 + z}{1 + z_{\text{max}}} \right]^{3/2}
\]  

(39)
Model III: For a final comparison, we compute the integrated gamma-ray flux generated in the galaxies themselves and determine their contribution to the metagalactic-gamma-ray flux. We take the average amount of matter in galaxies to be about 1% of the total matter in metagalactic space and assume that on the average, a fraction of $5 \times 10^{-2}$ of this matter is in the form of gas (Allen, 1963; Roberts, 1963). Then taking $I(z) \geq I_g$, we find that in this case

$$\frac{\langle I(z) n(z) \rangle}{I_g n_0} = 5 \times 10^{-4} (1 + z)^3$$ \hspace{1cm} (40)

Using the models defined by equations (34), (38), (39) and (40), together with equations (11), (12), (13), (23) and (28), we have calculated the metagalactic gamma-ray spectra produced by models I, II and III. These fluxes are given in Figures 1, 2 and 3 respectively. Figures 1 - 3 also show the gamma ray flux expected from the galactic halo in the direction of the pole, taking $\langle nL \rangle = 3 \times 10^{20}$ cm$^{-2}$ and based on previous calculations (Stecker, 1967).* It can be seen that the local gamma-ray spectrum from the galactic halo can be distinguished from the metagalactic gamma-ray spectra because the latter are red-shifted and peak at lower energies. The metagalactic gamma-ray spectra tend to peak near $7 \times 10^{-2} / (1 + z_{\text{max}})$ GeV, being weighted toward higher red-shifts by the effect of greater densities at earlier epochs. Because of the density effect, a cosmic-ray burst

*Thus $I_{\text{pole}}(E_{\gamma}) = 3 \times 10^{20} f(E_{\gamma})$.  

15
at large red-shifts is much more effective in producing gamma-rays than a continuous production of the same number of cosmic-rays. In Figures 1 - 3, we have also indicated the experimental upper limit on the gamma-ray flux from the Explorer XI data (Kraushaar, Clark, Garmire, Helmkin, Higbie and Agogino, 1965), assuming an integral flux above 0.1 GeV of $3 \times 10^{-4}$ cm$^{-2}$ sec$^{-1}$ sr$^{-1}$.

CONCLUSIONS

Present evidence about the flux of cosmic-rays between the galaxies is quite meager. The most promising way to study the flux is by a satellite experiment measuring the isotropic gamma-ray flux in the region between 1 and 100 MeV. Such gamma-rays can supply us with direct information on metagalactic cosmic-rays, because they travel to us in straight lines and suffer little absorption. Theoretical metagalactic gamma-ray fluxes from $\pi^0$ decay are presented here under various assumptions as to the metagalactic cosmic-ray flux. These predictions indicate that an experimental determination of the isotropic gamma-ray spectrum at high galactic latitudes and in the energy range 1 - 100 MeV, could supply valuable information, not only about metagalactic cosmic-rays, but also about such fundamental questions as when the galaxies were formed, since the metagalactic gamma-ray spectrum will peak near $70 (1 + z_{\text{max}})^{-1}$ MeV.
ACKNOWLEDGMENTS

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REFERENCES


It has been shown in the text that the gamma-ray absorption from pair production through interaction with the universal radiation field is given by the factor $e^{-\tau}$ where

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

with $E_\gamma$ expressed in GeV. As an intermediate solution to the problem considered in the text, numerical solutions were obtained for the implicit relation

$$
\tau(E_\gamma, z_\gamma) = 1 \quad (A-2)
$$

which defines the red-shift, $z_\gamma$, beyond which the universe becomes opaque to gamma-rays of local energy $E_\gamma$. It was found that the numerical solution to equation (A-2) may be quite well approximated by the relation

$$
1 + z_\gamma \simeq 2.30 \times 10^2 E_\gamma^{-0.484} \quad (A-3)
$$

Since the age of the universe corresponding to a red-shift $z_\gamma$, is given by

$$
t_\gamma \simeq 10^{10} (1 + z_\gamma)^{-3/2} \text{ years} \quad (A-4)
$$
the earliest epoch from which gamma-rays of energy $E_\gamma$ can supply us with information is found from (A-3) and (A-4) to be

$$t_\gamma = 2.9 \times 10^6 E_\gamma^{3/4} \text{ years}.$$  \hspace{1cm} (A-5)
FIGURE CAPTIONS

Figure 1: Metagalactic gamma-ray spectra from cosmic-ray p-p interactions based on a cosmic-ray flux produced by constant leakage from other galaxies (Model I) and shown for various maximum red-shifts as discussed in the text. Also shown are the local gamma-ray spectrum from the galactic halo in the direction of the pole and the upper limit implied by the Explorer XI gamma-ray experiment.

Figure 2: Metagalactic gamma-ray spectra from cosmic-ray p-p interactions based on a cosmic-ray flux produced by a burst of cosmic rays at $z_{\text{max}}$ (Model II) as discussed in the text. Also shown are the local gamma-ray spectrum from the galactic halo in the direction of the pole and the upper limit implied by the Explorer XI gamma-ray experiment.

Figure 3: Metagalactic gamma-ray spectra from the superposition of gamma-ray spectra produced in all the galaxies taking red-shift, density and curvature effects into account as explained in the text (Model III). Also shown are the local gamma-ray spectrum from the galactic halo in the direction of the pole and the upper limit implied by the Explorer XI gamma-ray experiment.
BURST MODEL (MODEL II)

\[ I(\gamma)(cm^2 \cdot \text{sec. sr. GeV})^{-1} \]

- \( Z_{\text{MAX}} = 100 \)
- \( Z_{\text{MAX}} = 9 \)
- \( Z_{\text{MAX}} = 4 \)
- \( Z_{\text{MAX}} = 2.2 \)

KRAUSHAAR, ET. AL. (1965)

GALACTIC HALO TOWARD POLE
GAMMA-RAYS FROM OTHER GALAXIES (MODEL III)

\[ I(E_\gamma) \text{ (cm}^2 \text{ sec. sr. GeV)}^{-1} \]

\[ E_\gamma \text{ (GeV)} \]

\[ Z_{\text{MAX}} = 1000 \]

\[ Z_{\text{MAX}} = 100 \]

\[ Z_{\text{MAX}} = 9 \]

\[ Z_{\text{MAX}} = 4 \]

\[ Z_{\text{MAX}} = 2.2 \]

KRAUSHAAR, ET. AL. (1965)

GALACTIC HALO TOWARD POLE